



Risto Hienonen & Reima Lahtinen

Corrosion and climatic effects in electronics

VTT PUBLICATIONS 626

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ISBN 978-951-38-6991-5 (soft back ed.)

ISSN 1235-0621 (soft back ed.)

ISBN 978-951-38-6992-2 (URL: <http://www.vtt.fi/publications/index.jsp>)

ISSN 1455-0849 (URL: <http://www.vtt.fi/publications/index.jsp>)

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JULKAISIJA – UTGIVARE – PUBLISHER

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Cover picture: Salt creeps easily along surfaces and absorbs water from air also. The wineglass in the cover picture is half-filled with 10% salt solution two weeks before the picture was taken. Salt crept along the inner side up to the edge of glass in eight days and continued over the edge.

See Section 3.1 Climatic corrosion and its time span.

Hienonen, Risto & Lahtinen, Reima. Corrosion and climatic effects in electronics. Espoo 2007. VTT Publications 626. 242 p. + app. 173 p.

Avainsanat corrosion, electronics, electronic equipment, design, verification, atmosphere, climate, moisture, humidity, pollution, quality, quality control, temperature, corrosive gas, measurement, tests, environmental tests, Finland

Abstract

Corrosion control in electronics and know-how concerning various protection methods have become an important field of design since electronics is increasingly used as integrated into different devices in highly corrosive conditions. On the other hand, the increase of the packaging density of electronics has resulted in electronics that is sensitive to the corrosive effects of the environment even in milder conditions.

The project charted the mechanisms through which the climate, humidity, contamination, other environmental factors, the way of use of the device and its structure as well as the manufacturing process affect the corroding and faults of the electronics. A method was developed for solving these problems by which both the experienced and the beginning designer can check the feasibility of the applied corrosion protection technique and foresee possible corrosion problems in the structure of the device as well as find new approaches for solving them.

The report also presents an evaluation method for the corrosive effect of the usage environment. In addition, various types of corrosion mechanisms and protection against them are described, corrosion analysis and measurement methods introduced and testing methods used for quality assurance regarding corrosion discussed. Comprehensive lists of standards and literature concerning corrosion and climatic effects are appended to the report.

This report is available in English and in Finnish (VTT Publications 623, <http://virtual.vtt.fi/inf/pdf/publications/2007/P623.pdf>)

Preface

The aim of the project was to describe the effects of climatic corrosion, device structure and methods of use on the corrosivity of the products and to develop a method for solving the corrosion problems whereby both the experienced and the beginning designer can verify the correctness of the used corrosion protection technique and also find new approaches for solving the practical problem in question. To gain experience on the developed review method, a certain product family and its production process were reviewed in each of the participating industrial companies.

Since corrosion as a phenomenon is always a complex combination of situations resulting from the environment, materials and the method of use of the device, sophisticated measuring and testing technology is needed for charting the corrosive effects of the environment and the sensitivity to corrosion of the device. Therefore, information was also gathered on what kind of measurements, analysis methods and tests can be used for studying the problems related to corrosion and for ensuring an adequate quality level.

The project was carried out under the heading “Corrosion and Climatic Effects in Electronics” as a part of the Technology Development Centre of Finland (Tekes) research programme “Electronics for the information society-ETX”, which was launched in 1997. This project was funded by Tekes, VTT, ABB Industry Ltd Technology Department, Benefon Ltd, Efore Ltd, Kone Elevators Ltd and Nokia Mobile Phones Ltd. The project was carried out at VTT in co-operation with the above companies and with Tampere University of Technology Microelectronics.

The managing group for the project consisted of:

Jarmo Ruohonen	Nokia Mobile Phones Ltd, chairman
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Reima Lahtinen	VTT

Risto Hienonen, MSc, of VTT was responsible as project manager for the carrying out of the project in practice and for the drafting of this publication and the pictures in it. Reima Lahtinen, MSc, of VTT wrote and collected data on materials especially, corrosion of metals, coatings, failure mechanisms and glossary. He also participated in all the reviews in the various companies. Antti Turtola, MSc, of VTT wrote Sections 6.6 and 6.7 and Helge Palmén, Lic. Tech. assisted in the gathering of material on VCI materials.

Jukka Vahter, engineer, completed his thesis for MSc within the project. The topic of the thesis was *Corrosion susceptibility evaluation of electronic products*. The thesis was submitted to Tampere University of Technology, Department of Materials Engineering.

I would like to thank on behalf of the managing group of the project and myself all the persons participating in the project and the companies and persons assisting in the reviews and data collection as well as the financiers for their support to the project. I would also like to thank Professor Tero Hakkarainen and other persons reviewing the content of the publication for their valuable contribution.

Espoo 9.5.2001

Risto Hienonen
Project Manager

Preface of the second edition

The second edition is completed with some new failure mechanisms, the references to standards and internet sources are updated and the failures observed in the first edition are corrected.

Espoo 31.1.2007

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Corrosion glossary

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1. Corrosion in electronics

Corrosion control of electronics and know-how of various protection methods have become a major field of design in order to ensure product reliability and competitiveness on a demanding market. Electronics is increasingly used as integrated into various machines and also as such in outdoor conditions where corrosivity is great. On the other hand, the packaging density of electronics has become so great in all major product areas, mobile phones, telecommunications equipment, computers, automation and high power electronics, that it makes the electronics sensitive to the corroding and contamination effects of the environment also in relatively mild conditions.

The aim of this publication was to chart and demonstrate the effect mechanisms by which the climate, contamination and other environmental factors, the users, the methods of use of the devices and their structure as well as the manufacturing process affect the corrosion and faulting of the electronics. Another principal aim was to develop a method for solving these problems (Section 5 *Control methodology of corrosion* and Appendix 3 *Review methodology of the corrosion control*) which could be used by the experienced and the beginning designer for verifying the feasibility of the corrosion prevention techniques applied. The presented methods also help to foresee possible corrosion problems in the structure of a new device and facilitate the discovery of new methods of problem solving.

The publication also presents an evaluation method for the corrosivity of the conditions of use. In addition, various types of corrosion are described (Appendix 1. *Basics of corrosion and failure mechanisms*) as well as protection against them, analysis and measurement methods for corrosion and the test methods used in the study of sensitivity to corrosion and quality assurance. The appendices of the publication contain extensive catalogues of standards and literature on corrosion and climatic effects.

Additional knowledge about climatic corrosion is available in the following publications, which offer rapid way for becoming familiar to the corrosion.

[Henriksen et al. 1991] Corrosion of electronics. Korrosionsinstitutet

[Leygraf & Graedel 2000] Atmospheric Corrosion. Wiley-Interscience

[Roberge 2000] Handbook of Corrosion Engineering

[Roberge 2006] Corrosion Basics: An Introduction, 2nd Edition.

1.1 Corrosion as a phenomenon and the significance of corrosion

The ongoing increase in the packaging density of electronics causes harmful disturbances to devices to a growing extent. The products are increasingly sensitive to the harmful effects of humidity and corrosion. In electronics, corrosion and climatic effects increase the contact resistances of the joints, leakage currents between the wires and decay materials, which can be seen in various operational faults, increase in electromagnetic disturbances and surfaces that appear ugly (Figure 1.1). These faults almost always appear before the mechanics of the device suffers. In electronics, even slight corrosion and surface contamination can be destructive with regard to the operability of the device. A patch of corrosion measuring only nanometre in a component may prevent normal functioning of the device, whereas in large-scale steel structures a corrosion area of millimetres causes no problems [Ishikawa & Ozaki 1999].

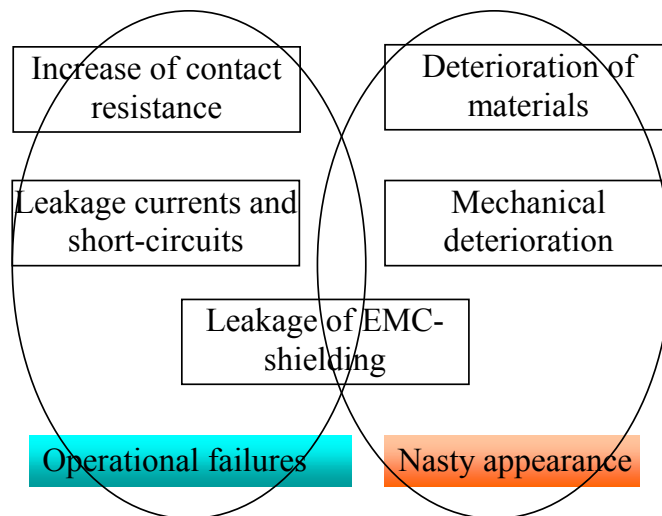


Figure 1.1. Basic problems caused by corrosion in electronics.

According to a simplified definition “*corrosion is destruction of material*”.

The material may be metal, mineral or organic compound such as plastic that can all be destroyed also through corrosion reactions! Corrosive reactions do not require high temperatures. Most harmful effects of corrosion take place at temperatures ranging from +0...+40°C. Corrosion does not usually take place in freezing temperatures or it is very slow (e.g. a salt solution is liquid also on a few degrees below zero centigrade, when corrosion proceeds). In high temperature > 55°C, corrosion reactions accelerate even in dry conditions of use causing the decay of materials. Simplified one can say that *corrosion is present always and everywhere there is water, oxygen and microbes*.

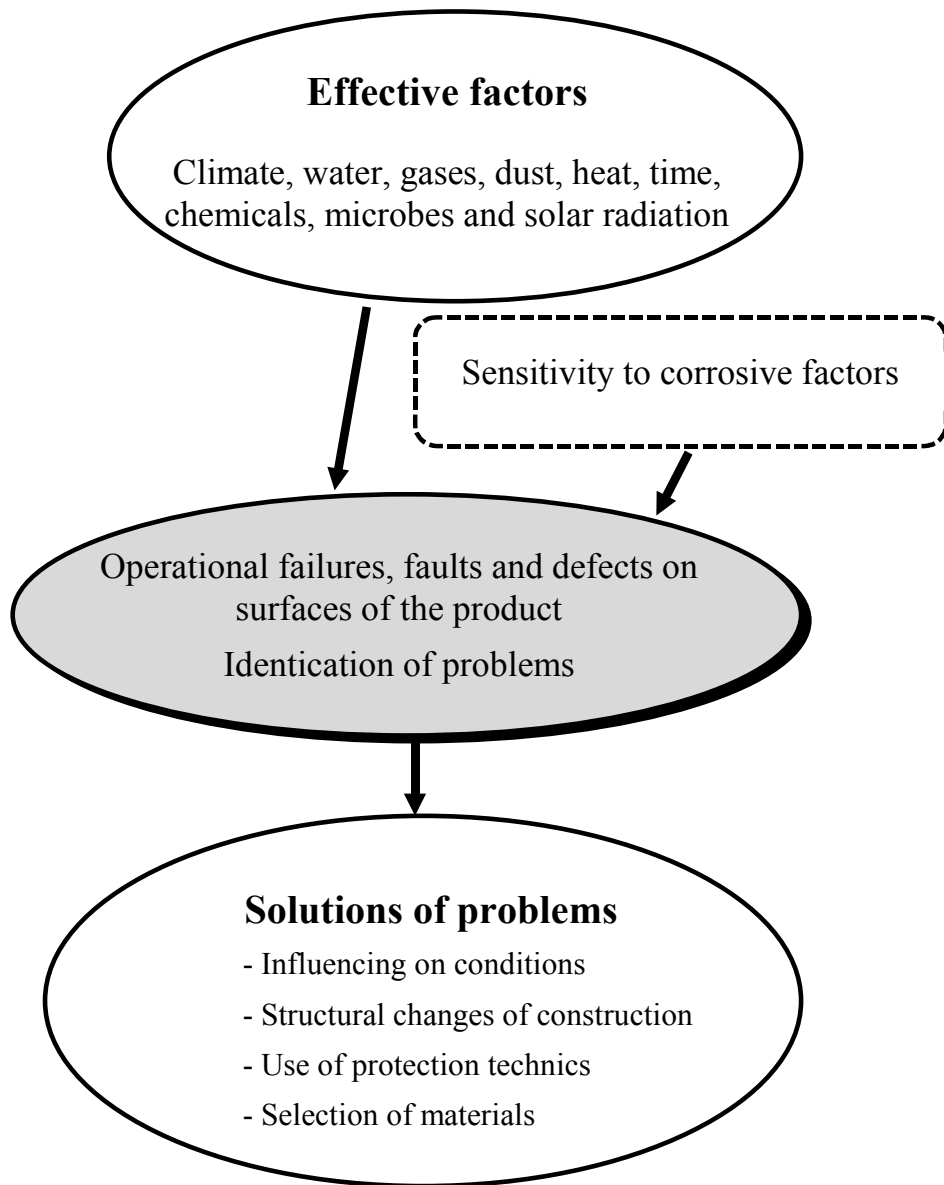


Figure 1.2. Basic elements of the appearance and the control of the corrosion problem.

Standardisation organisations have defined corrosion somewhat more narrowly [SFS-ISO 8044]:

“Corrosion is a physical-chemical reaction of metal with its environment which causes changes in the properties of the metal and which can often lead to damages of the metal, its environment or the technical system.”

Climatic effects (Figure 1.2) cause accumulation of water and impurities on the surfaces whereas heat and sunlight also decay the products and accelerate the progress of corrosion and other harmful effects.

Water, dust, gases and organic compounds cause leakage currents, short-circuits and mechanical changes. The increase of leakage currents caused by contamination and corrosion can cause crosstalk or occasional “soft errors” in the memory pointing [Comizzoli et al. 1992 and 1999]. The effects of corrosion can sometimes be compared to the soft errors caused by particle radiation from outer space. These errors occur at random and cause temporary or permanent malfunctions to the devices.

The effects of corrosion can be quite radical and quick even in ordinary environmental conditions. Corrosion becomes visible as loss of operational capacity of the products, ugly appearances even within a few weeks from the start of use or after a weeklong transportation if the product is subjected to water and corrosive ingredients.

Even in the most difficult conditions it is usually possible to find a working solution for the corrosion problem since the causes for the problems are usually detectable. It is often more difficult to grasp the problems occurring in mild conditions because the electrical and mechanical design of the device have a great effect on the harmfulness of the faults. If the device has inferior design, in other words it incorporates fault mechanisms (leakage currents, serial resistances, EMC problems) which make it sensitive to operational disturbances, even slight corrosion which is difficult to locate can cause additional problems. On the other hand, the mechanical construction of the device can be such that it facilitates corrosion. For example, the accumulation of water on the connecting surfaces or the inside of the device, the sensitivity to fretting caused by mechanical resonances and the circulation of too much ventilation of uncleaned air into the electronic parts.

The gradual progress of contamination and corrosion is usual in electronics. This can be seen as occasional disturbances in the operation and as small but painful flaws in the surface coating. The contact resistances and the leakage currents increase causing various disturbances. This is especially disturbing to the device manufacturers, since the causes behind the faults often remain unidentified and there can be considerable numbers of products among those reported as faulty by the customers which cannot be identified as “actually malfunctioning” by maintenance. In other words, the real reasons for the faults remain a mystery.

It can even be claimed that if the share of unsolved faults is considerable, the company has a serious quality problem, which can be for example corrosion, EMC (electromagnetic compatibility), thermal design or all of the above combined as if often the case in practice.

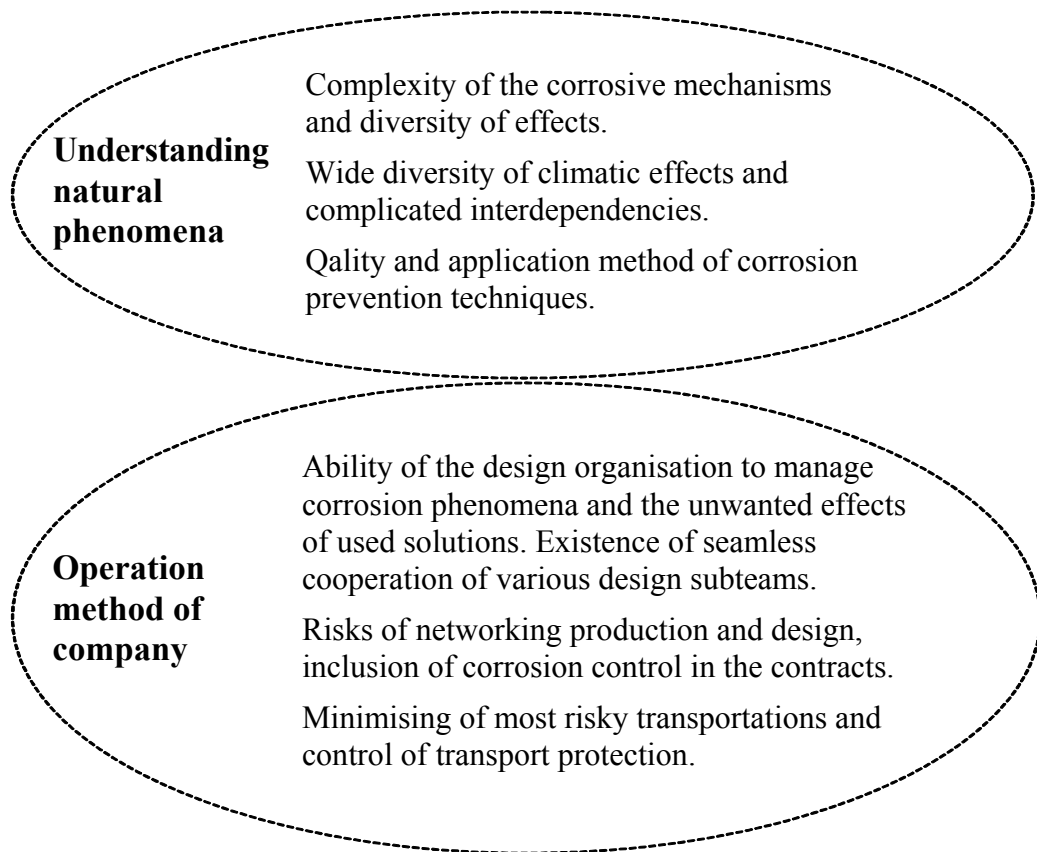


Figure 1.3. Risk and problem areas of corrosion management.

Here corrosion and climatic effects in electronics are addressed on a wide scale in order to familiarise the reader to the conditions and phenomena causing corrosion and other decay in electronic products. The survival of the product in the conditions of use can only rarely be ascertained in the prevention of corrosion and other mechanisms causing decay by using only one or even a few technical solutions (Figure 1.3). If there is no knowledge of the interaction of matters, the designer may end up solving a partial problem and inadvertently create a couple of new problems. The designers should comprehend a number of background phenomena in order to select the solution methods for the corrosion problem as a whole that are feasible for each detail. In addition, the product should be designed in such a way that it is as insensitive as possible to small changes in the parts and components.

Corrosion control is not merely control of the properties of the product (Figure 1.3). In order to ensure the economic result, product quality and customer satisfaction, the entire operational logistics and planning system of the company must adopt operational procedures and methods with which climatic and corrosion problems can be controlled.

Corrosion control in itself is a multidisciplinary activity but it is crucial in the control process and in the minimising of its effects to achieve co-operation of logistics, electrical operations, EMC, mechanics, thermal design, components and ergonomics designers and constructors in the planning process in order to reach a solution feasible both overall and economically.

In practice, if the background and effects of corrosion have not been carefully considered, the company may need re-evaluation of the company logistics and the entire structure and design of the products as a result of the problem solving process. In addition to this, the materials and components may also have to be renewed.

The agreement of how to handle the various issues concerning corrosion control has an especially great significance in a networking production and planning process. The problem cannot be assigned to the subcontractors only even though these do have a crucial role as coaters of parts, but the entire logistics chain must participate in the corrosion control of a product by performing the right measures at each stage of the production and transportation.

Each transportation stage increases the handling of the products and subjects them to uncontrollable climatic and mechanical stress. In very fragmented production, the transportations between the various factory units can be numerous. In all transportations, the parts should be protected from climatic, environmental and mechanical stresses in order to avoid mechanical faults, corrosion and contamination during these transportations and interim storage. The same naturally applies to the finished products.

The design of the product and production cannot just be an exercise with building blocks where the blocks are organised with a view on smooth assembly, but where the physical characteristics and the sensitivity of the blocks to various environmental stresses is neglected. It should especially be ensured that unprotected transportations are not organised between sub processes where the parts are especially prone to damage and contamination. Knowledge of the physical and chemical effects that in the last instance determine whether the product will function and if it can be sold to the customer in the longer run should be incorporated into the design process.

1.2 Conditions corroding electronics

The most critical conditions with regard to corrosion and contamination threat of electronic devices include getting wet either from water condensing from the air or from dripping water. If the immediate environment of the device is relatively

dust free and dry, relative humidity of the air is less than 40% and there is no dripping water, the main share of corrosion problems in temperatures below 40°C is erased or corrosion becomes so slow that it will not have much effect during the life span of the product. In reality, such conditions can be maintained only in air-conditioned indoor premises. It is difficult to achieve these conditions outdoors, which is demonstrated by the weather statistics in Figure 1.4.

Figure 1.4 presents the division of the **average** temperatures and relative humidity during the calendar year in temperate and cold climatic regions. What is extremely significant to the corrosion risk is the fact that the relative humidity of the air exceeds 60% at all times. The only periods with relative humidity below 80% on average outdoors can be found from May to the end of August. In tropical areas and close to the sea the values of relative humidity exceed even these (look Appendix 1, Section 1.7 *The relative humidity of air*).

Chapter *Environmental standards* presents the IEC standardised temperature and humidity categories which are recommended to be applied when determining the environmental classification of devices and components [IEC 60721-1 and IEC 60721-3-9]. The latter standard classifies the temperatures and relative humidity inside the devices (microclimate). The standard defines microclimate as the place where the components of the product have been installed. Only the temperature and humidity have been included in the description of the microclimate.

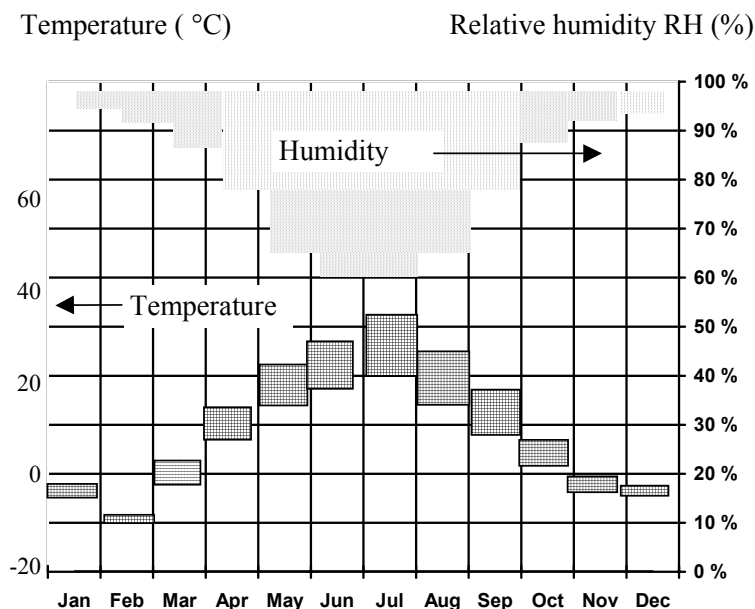


Figure 1.4. Weather averages of temperate and cold regions during various seasons (Middle Europe, Canada and northern parts of United States) [Gellerstedt 1995 and STANAG 1980].

Figure 1.5 lists conditions increasing the risk for corrosion. The airflow speed, the speed of changes in the temperature and in the relative humidity has an effect on the speed of corrosion and contamination of the surfaces. The designer of the device can influence these with his decisions, the best situation with regard to corrosion would be to keep these speeds of changes and their absolute levels as low as possible.

In free outdoor conditions, a considerable increase to the risk for corrosion is provided by sunlight, which decays all materials subject to it. The direct negative effect of solar radiation on plastic materials and painted surfaces is very great compared to the negative effects on metal surfaces.

Gaseous and ionic substances in the air and dust have basically spread evenly and everywhere in urban conditions. Concentrations exceeding the average considerably are only met in the vicinity of heavy traffic flows, industrial plants and power plants, which increase the risk for corrosion form the usual. Thus the risks for corrosion have spread rather evenly everywhere.

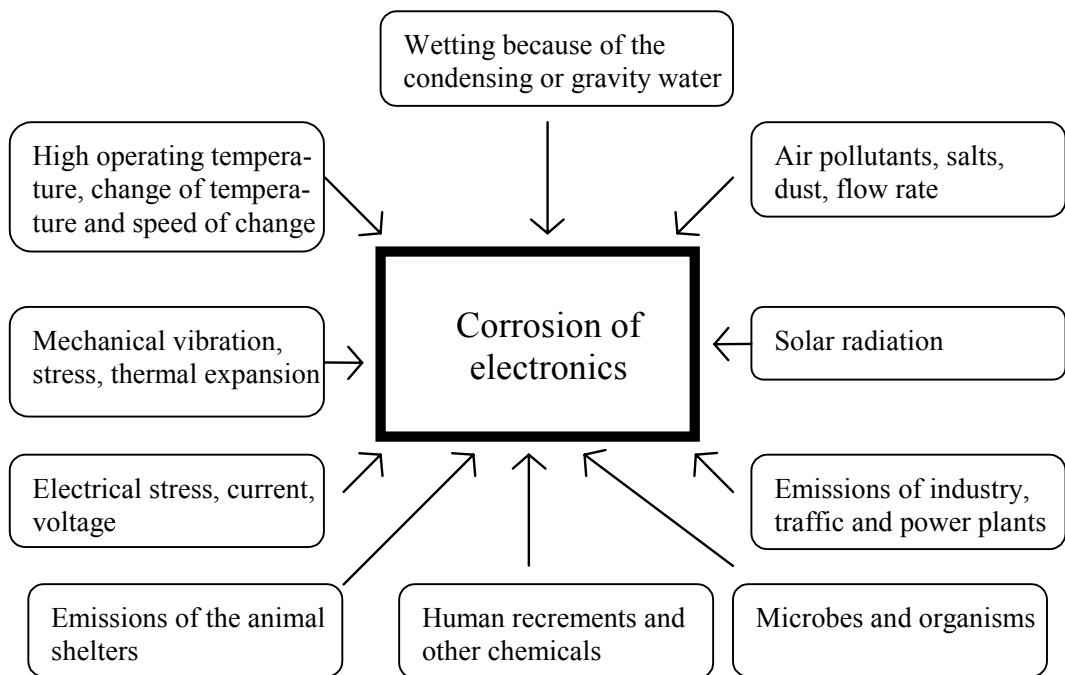


Figure 1.5. Conditions increasing the risk of corrosion.

Nature’s own emissions often cause a great corrosion risk. Of these risk factors, the most common one is probably salt from the sea water (chlorides) which can spread in the air as far as 50 km from the coasts. On the other hand, 250 m inland the chloride contents in the air can be only a tenth of the content by the sea (25 m). Storms may at times cause heavy spreading of salt or sand dust in certain

areas. For example, the Arabian Peninsula used to be under the sea in ancient times, which made the sand salty, and therefore the sand dust contains salt as well. Similar problems are created by local volcanic sulphur gas or ash emissions and emissions from hot springs.

When the background pollution due to the air and human activity have a combined effect on the risks generated by the structure of the device, the choice of materials, transportation and use, a combination that shows itself as premature faulting of the final product due to contamination and corrosion is easily created.

Considerable fluctuations in the temperature which occur daily in outdoor conditions always result in risk for water condensation on the surfaces whereby gases in the air and other impurities together with water form corrosive compounds, such as sulphuric, nitrogen and hydrochloric acids on the surfaces. These corrode all metals. Also temporary wetting of the devices during transportation or because of human action causes a relatively great and frequent risk for the start of corrosion.

Mechanical vibration and changes in the temperature cause fretting of the male and female connectors against one another. This abrasive motion results in wear and fretting corrosion which can increase the contact resistance radically [see Section 6.8 and Appendix 1, Section 2.14].

The increase in the packaging and power densities of the devices has often resulted in an increased flow of cooling air inside the device. This increases considerably the contamination and gas contacts of the surfaces. [Lobnig et al. 1999].

Agriculture and animal husbandry, which are closely related to human activity cause very strong gaseous and liquid emissions. The most problematic of these are ammonia and thio-compounds (hydrogen sulphide), which are products of chicken coops, pigsties and cow byres as well as of plants rotting in nature. Everybody knows the earthy smells of spring, which is caused by rotting plant debris and the sulphuric compounds emitted from them. Also human excretions, such as sweat, saliva and various skin conditioning products, washing liquids or powders and alcohol cause various faults in the devices. Also the results of the human metabolism create carbon dioxide, methane and aldehydes (breath and perspiration). The smoke of tobacco contains tar and other compounds which may cause corrosion and contamination problems.

Electrical stress also speeds up corrosion. For instance, strong current can heat the solder joint and gradually weaken it. In dense wiring patterns the high field

intensity between the wires increases leakage currents and accelerates corrosion on contaminated surfaces. In microcircuits where the wire widths are measured in micrometres at the most, metallic migration may occur (wire breakage) because of the high density of the current. (Appendix 1, Section 4.4 *Electromigration*).

1.3 Magnitude of corrosion

According to figure 1.6 the majority of reasons for faults in electronics devices are related to heat and humidity. The temperature readings cold/hot their fluctuation and humidity always affect the physical and chemical properties of materials and components. The scale of these effects determines when a change or absolute level of temperature or the level of humidity becomes significant for the properties or reliability of the product.

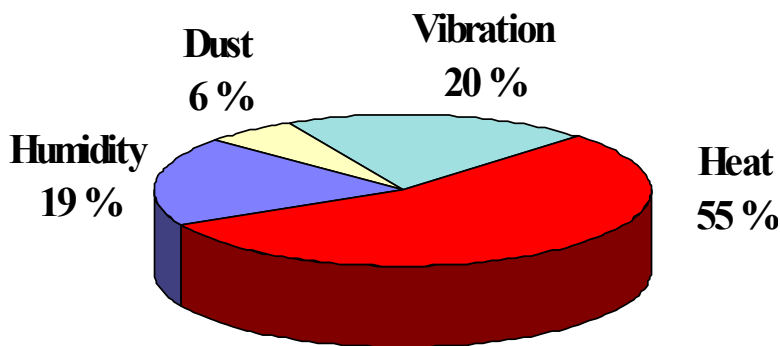


Figure 1.6. Reasons for failures of electronics in aviation (Flomerics, US Air Avionics Integrity Program, Journal of the IEST).

All environmental effects presented in Figure 1.6 accelerate the occurrence of corrosion and therefore result in increased fault frequency of the device in use. All these stress factors affect the operation of the device directly, the properties of the materials used (parameter changes for components) and the quality and quantity of the faults through the corrosion mechanism.

1.4 Corrosion control strategy

Due to the many faces of corrosion it is often difficult to grasp the phenomenon. When examining a single fault, it is relatively easy to discover the basic pattern of corrosion, but the initial reason and a sensible preventive repair procedure are easily left in the dark. The existence of corrosion may be known but it is difficult for the staff in quality or planning to find out when and where it becomes a

significant fault mechanism in the product. The basic principle should read: first *identify the real problem* and then *find the reasonable solution*.

In a practical working environment it is only possible to control corrosion by developing the planning and the quality system. Planning creates new ideas, solutions and quality systems and provides feedback on how the planning and production have succeeded.

Corrosion control can be summarised in two principles:

- produce a fault tolerant device and
- use as inert materials as possible.

Fault tolerance here means the capability of the device to operate despite the changes in the properties of its parts with e.g. temperature and in time. Fault tolerance can considerably alleviate the effects of gradual corrosion on the operability of the product. Fault tolerance ensures the operability of the production even though corrosion results in for example increased contact resistances and leakage currents.

No material is completely inert (chemically passive) but the components, component boards and metal parts and plastic structures can be made relatively inert to climatic, chemical and also corrosive effects with reasonable work. If an inert material is too expensive, other simple and often cheap means of protection have to be introduced for obtaining an acceptable risk level with regard to corrosion problems.

The strategy, which will solve the corrosion problem in the product under production, should be chosen in the design of electronics. There are in fact only a few acceptable basic principles (Figure 1.7) but there are an endless number of technical solutions for carrying these out.

These basic principles can be applied individually or together for each case in question. In fact, almost the entire corrosion problem could be tackled by carrying out the activities in the first three principles presented in Figure 1.7, which can be summarised as follows:

- Use optimal materials in the contacts, which tolerate corrosive conditions and guarantee a stable contact resistance.
- Use good quality insulators (lacquers, paints) on the surfaces to be protected.
- Optimise tightness and mechanics of the package with regard to corrosion.

The situation becomes more complicated because the product must survive varying conditions during transportation, storage, installation and in the end final use. Therefore there is no single complete procedure for addressing the corrosion problem.

When developing the planning and quality systems of a company it is crucial to include reviews and documentation for developing the attention to corrosion and promoting the use of quality feedback with a knowledgeable quality department. It is important to link corrosion know-how and its control technique in this as in other areas of the planning requiring high-level know-how. It should also be included as a part of the general know-how of the designers in other areas.

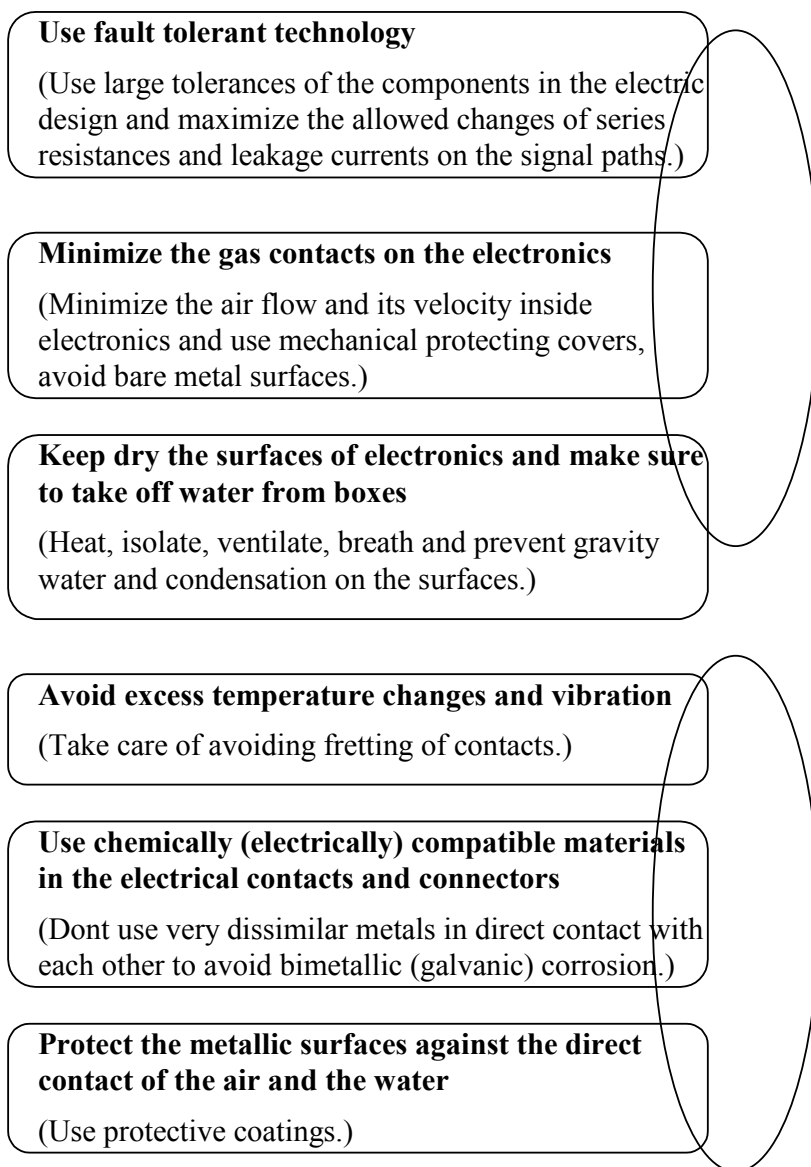


Figure 1.7. Physical basic principles of corrosion control.

Adherence to the principles presented in Figure 1.7 creates controversial situations easily. For example, in most electronics, high temperature of use naturally dries the inside of the device, but accelerates oxygenation and decay of material which results in corrosion surfacing in another form, such as decay of the solder connections or embrittlement of insulators. On the other hand, effective cooling with rough or humid outside air increases the gas contacts and relative humidity of the air inside, which results in more corrosion and contamination in the contacts in the component leads. In dry and dusty conditions the air going inside the product brings in dust (also sand dust) and makes the surfaces conductive, which increases leakage currents and causes electric breakdowns (ref. [RTMG/RAC 1995, p. 49 Impingement cooled modules, and MIL-HDBK-454A]).

In practice, the basic principles stated in the above can be realised after analysis of the conditions of use for example by selecting the

- tightness/packaging class
- cooling system
- protection level of the insides (lacquer or no lacquer)
- coatings of contacts and connecting wires
- heat category of components
- quality of the box surfaces
- fault tolerance level of electrical planning for the product.

By analysing the alternative technical realisation methods and price levels, the solutions can be identified. Then, the corrosion risks can be further analysed and the product can be constructed so that the desired quality level is obtained.

Whatever the chosen corrosion control strategy, it must be ensured in its realisation that the overall operation is as desired without new problems. Effective interaction and teamwork of the designers of various areas is an asset in this.

1.5 Recognition of most risk prone areas in the product

In an electronic product, the corrosion problem should be viewed on the one hand from the point of view of electrical and mechanical functionality and, on the other hand, from the point of view of the general condition and appearance of the mechanics, since the harmful phenomena in these areas are very different by degree and by nature (Figure 1.8).

When assessing the operability of a device, one must decide how serious a malfunction or fault is included in the quality criteria. In principle, corrosion and contamination progress continuously from the point of manufacture in an electronic device gradually causing short malfunctions the nature and seriousness of which vary. When conditions change, the faults may also disappear and it is typical that products with “no detectable fault” arrive into service.

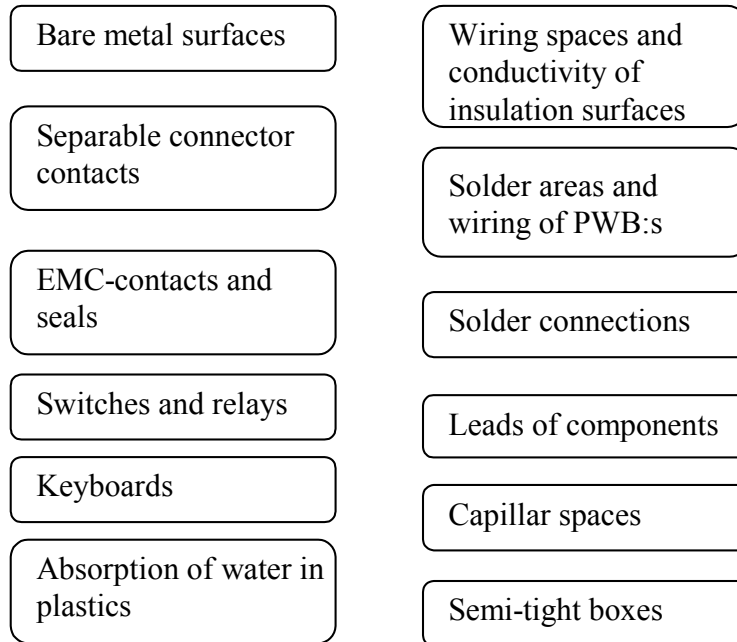


Figure 1.8. Areas with corrosion risk in electronics.

The operational faults of an electronic device caused by corrosion typically appear in the form of serial resistance and increasing leakage currents in

- connectors that can be opened
- solder connections
- EMC-contacts and seals
- wire gaps (conductive surfaces)
- switches and relays
- keyboards.

External corrosion is also present to a lesser degree in microcircuits and high-power components, where the main problem is internal corrosion due to high operating temperatures and in extreme cases the breaking of connections due to heating of the lead connections (Appendix 1, Section 2.10 *Stress corrosion cracking and fatigue*). However, the maintenance of wiring isolation in microcircuits manufactured with extremely dense external wire gaps (for example

flip-chips) is a problematic area, which calls for cleaner manufacturing processes and better protection of the surfaces against outside contamination and moisture.

In mechanics, structures that tend to absorb condensed water or water on the surfaces are easily created. Mechanical capillary gaps (less than 1 mm) between parts resting against one another belongs to such structures. The most common capillary gap exists under the parts and the components mounted on the circuit board. If there are bare metal surfaces in such a space, corrosion will proceed very rapidly and connective bridges appear between the leads/conductors because water cannot evaporate from the narrow spaces. Semi-tight packaging/box structures cause basic problems if water seeps into the case and then does not get out of the device.

The above-mentioned gradual contact faults can be foreseen by including tolerance reviews in the electrical planning. Varying serial resistors are added to the wiring routes of components, leakage current is increased in areas with narrow wiring spaces, contacts that can be opened and dense wiring patterns in the reviews. Fairly quick analysis should identify the targets where acceptable variations in the serial resistance and leakage currents are critical. The situation can be remedied either by changing the electrical design or the wiring pattern or connectors. When the actual electrical demands have thus been identified, the right electromechanical solutions, coatings and protection for each area can be selected and the harmful effects of corrosion and contamination can be blocked.

An analogical analysis to the above is the analysis of fluctuations in component parameters as a function of the temperature. This analysis examines whether the device can function within a certain temperature range. It is characteristic of components that all parameters change as a function of temperature, and thus the designer may use the components in a too wide temperature range. No fault will occur in the component, but the change of parameters usually causes recurring operational faults that surface near extreme conditions.

During production, a typical corrosion problem is created by the difficulties sometimes encountered during soldering. It is common that the components do not wet properly. Inferior soldering properties can result from corrosion of the coating materials of component leads or the wiring pattern of the circuit board during transportation or storage or from an unsuitable flux. In complex soldering processes with many stages, where components are soldered on both sides of the printed board in several phases, the soldering temperature and fluxes may corrode the bare soldering areas of the printed board, which deteriorates the soldering properties in later stages.

Another climatic problem area related to soldering is the tendency of plastic packaging to absorb water during transportation and storage, which can result in diffusion of the ionic impurities and swell of packages. Even explosions of the components may happen in the soldering temperature since the volume of water expands 1200 fold during the vaporisation process. This phenomenon is known by the name popcorning [Pecht 1995 and 1994].

[<http://www.calce.umd.edu/general/demos/defects/defects/ppcrack.html>]

1.6 Design, manufacture and feedback from the field

In corrosion control, the biggest effect on the chances of a product to survive during use and transportation without harmful corrosion can be created by introducing these issues during the planning phase and by including corrosion resistance into the success strategy” (Figure 1.9).

It is relatively easy to affect greatly the chances of a product to survive in use during the planning of its mechanical, thermal and electric properties. On the other hand, it is easy to commit simple mistakes in these design areas, which ruin the quality of the product. The quality of the connectors, coatings and method of use all have a fairly great effect on the electrical operation of the product. Thermal design can contribute to successfully keeping the product dry or to getting it repeatedly wet, for instance when blowing cold cooling air into the device. The electrical designer may choose seals that only function a couple of months because of corrosion as EMC contacts.

The aim of the mechanical structure of the product is to protect and support the inside. This results easily in designing a product which is good on the outside but in more difficult conditions begins to corrode in use, for instance because water has access inside the product and cannot come out again or excess cooling air which cannot be dried or purified is blown inside the device. This results in unintentional creation of favourable conditions for corrosion.

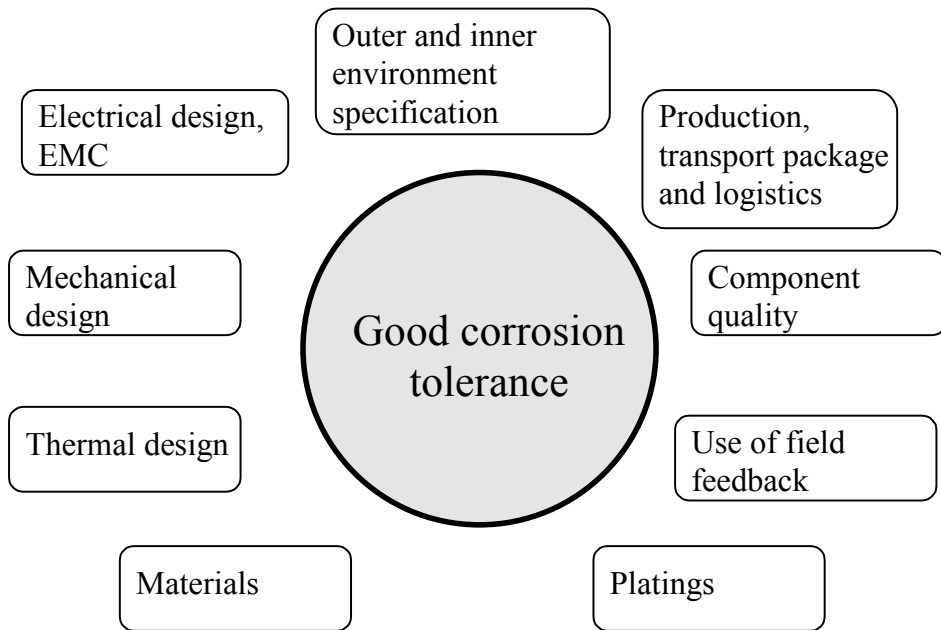


Figure 1.9. Sub-areas of the design for corrosion tolerance.

The prevention of wetting of the components prior to production in order to ensure soldering properties is one of the most significant factors, since usually no corrosive chemicals harmful to the products are used during the assembly.

The manufacture of the parts of the device, in other words components, circuit boards and metal parts as well as the quality of the used materials and coatings have the largest effect on corrosion resistance as has the degree of corrosion of the surfaces during transportation and intermediate storage, for example. The mistakes made during these phases can no longer be corrected in the assembly production.

It is usually difficult to recognise malfunctions and device faults caused by corrosion. This is in part due to limited knowledge among the staff about how to identify the effects of corrosion. Therefore, it is important for a company to create a mechanism in the quality system for obtaining products returned from the field for a closer fault analysis close to the product development groups. Further processing of the feedback data from the field in such a way as to create an opportunity to discover even the faults due to corrosion gives the designers a chance to improve new product versions and to learn from their mistakes or from the knowledge available from user experience in general.

2. Possibilities of corrosion control

2.1 Analytical approach

In principle, corrosion always presents a problem in all electronic products during their entire life span. A chemist would put this as follows:

“As long as there is oxygen, water and heat on earth, the occurrence of corrosion everywhere and in all products is certain.”

Corrosion often progresses in secret and becomes apparent in various forms. It can appear entirely unexpectedly in situations that have not been accounted for by the designer.

Therefore, it is worthwhile to take a thorough look at the qualitative and quantitative analysis of the problem. Obvious observations of the company's product as well as the entire design and manufacturing process should be methodically reviewed as presented in Figure 2.1.

The problems can be tackled by addressing the concrete faults but this entails the danger of researching only a limited problem area and thus making the wrong conclusions about the content and scope of the necessary actions. A more productive way is to introduce a preventive method by initiating the development of the company's product and quality system as one, where changes are carried out in the design, production and logistics that reduce the corrosion risk in the manufacture, installation and use of the product.

When individual fault instances are studied the positive identification of the corrosion problem and the tracing of the failure mechanisms and the preceding events is crucial prior to initiating corrective action in the manufacture and use of the product. When the nature and the scope of the problem are known the technical and economical significance to the company's operation can be estimated and the action can be scaled and directed according to this to targets also economically feasible.

There are fuzzy or unexpected failures may be because of corrosion

Study/review of product, production and use environment, standpoint on corrosion, taking care of results of studies and failure analyses.

Design process

Design actions taking care of possible danger for corrosion
Environmental requirements, customized
Unsensitize product on corrosion
Consider the user actions
Mechanics, platings, electrical-, EMC- and thermal design, effecting on use conditions (environment)

Logistics

Parts and components
- transport packages
- transport conditions
Own products
- transport packages
- transport conditions
- intermediate storages
Assembly
- assembly conditions

Production

- receiving
- intermediate storage
- factory environment
- assembling and soldering
- final assembly
- testing
- package for customs

Structures

- connectors, contact areas, - switches
- PWBs, components, platings, box

Corrosive environments

Transportation, production, assembly on field
Use conditions (environment), user actions

Figure 2.1. Analytic approach to corrosion control.

2.2 Familiarisation with the conditions

It is important in corrosion control to recognise the fact that the environmental stress factors affecting a product (Figure 2.2) can be influenced by various often simple protective actions (roofing, rain cover, protective netting, heat insulation,

painting etc.) Problems arising from humidity can often be remedied with appropriately constructed heating, which keeps the surfaces, dry despite a humid environment.

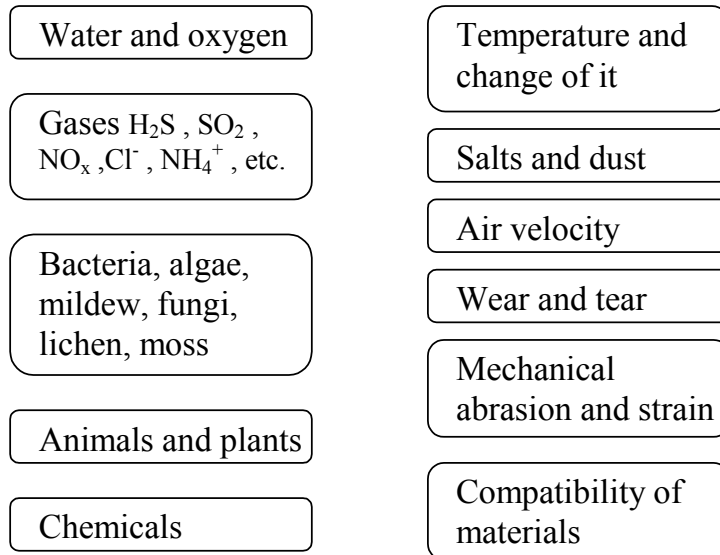


Figure 2.2. Corrosive environmental effects.

Water from the air, oxygen and pollution in the air are important stress factors with regard to corrosion. There are thousands of reactive substances in the air and in the transportation and user environments of the product. These substances occur as gases, liquids, ions, suspensions or solids, such as sand dust in the air.

Temperature, airflow speeds, mechanical abrasion (connectors, switches) and for instance stressing of metal (mechanical load) also affects corrosion. Biological organisms such as bacteria, algae, mildew, fungi, lichen and moss as well as various animals and their excretions also add to the problem.

Contamination of surfaces

Substances from the surrounding space always adsorb on the surfaces of materials. Normal air contains not only oxygen and nitrogen, but also water vapour, carbon dioxide, various nitrogen oxides, sulphuric compounds, sand dust, soot etc. All these accumulate (adsorb) on the surfaces and also desorb (leave the surface) when the surrounding air flows across the surface. There is a metabolic balance on the surface. If the conditions become favourable, this balance will break and the substances began to react with one another. Corrosion takes place on the surfaces and the electric properties of the surfaces change.

One of the harmful effects of the loose and solid particles accumulating on the surfaces is the fact that fine particle dust, for instance, which can consist of almost anything, usually contains sulphur and various salts [Burnett et al. 1992, Lobnig et al. 1999, Comizzoli et al. 1992 and 1999]. Most salts are real electrolytes, in other words they are conductive also in the solid form and therefore make the surfaces also partially conductive [Appendix 1, Section 3.6 *Water solutions and electrolytes*]. The particles collecting on the surfaces also absorb water easily, which makes the surfaces conductive.

In fact, the leakage current and corrosion caused by surface contamination are more harmful than the effect of gaseous impurities in the air [Comizzoli et al. 1992]. Therefore, protection of the devices and especially their inside from solids transported with air is a good method of reducing the corrosion risks. Also filtering of the air and minimisation of the airflow are effective means. The leakage current measurements presented in Figure 2.3 have been conducted by pressing the outside teflon filters used for collecting dust against the wiring pattern of the circuit board and by then measuring the leakage current in various relative humidity values of the air. The measuring voltages used were 5 V, 10 V and 15 V. The current was almost linearly proportional to the voltage in the various cases and almost constant in relation to time.

The locations of the dust filters (Figure 2.3):

K10	outdoors, Embassy of the United States, Kuwait, spring
Bronx	outdoors, New York
K47(MH)	outdoors, Murray Hill, NJ
K48(MH)	outdoors, Murray Hill, NJ
W.VA.	outdoors, West Virginia.

If the wiring pattern is very dense or there are gaps in the protection, the leakage currents between the wires become easily too great. Due to this, the surfaces of devices become slightly humid during periods when the relative humidity of the air is high exceeding 75% and various unidentifiable malfunctions occur because of leakage currents or unexplainable breakdown happen along the surfaces in high voltage circuits. These disturbances can be classified as EMC or other problems of use and it is difficult to eradicate them since the real reason can remain undetected. Short-term humidity on the surfaces can occur also in indoor conditions, for example during a storm. In these cases, the disturbances and faults are usually interpreted as being caused by lightning.

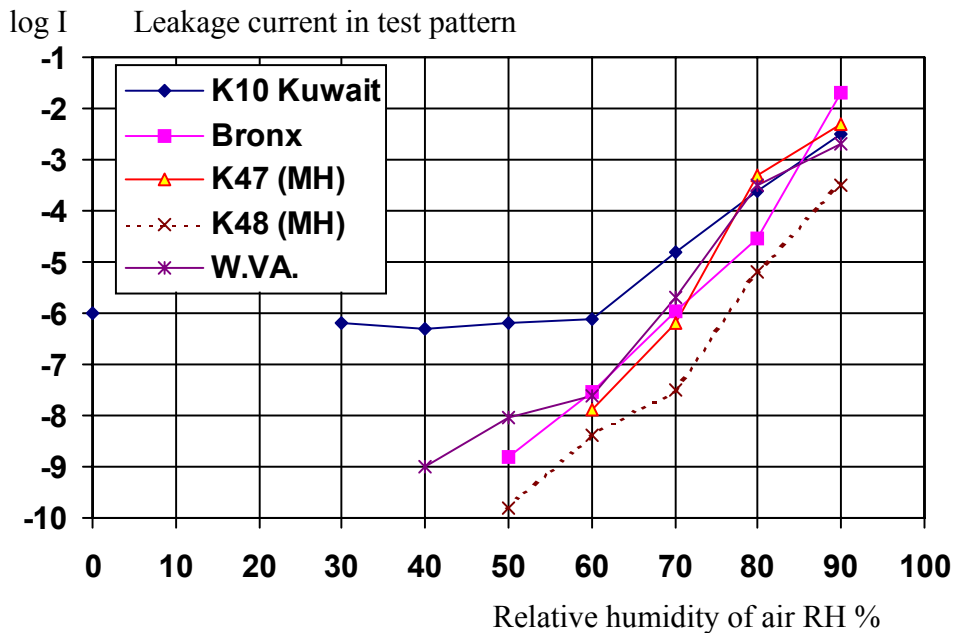


Figure 2.3. Effect of relative humidity of air on conductivity of a surface contaminated by dust with soot and various conductive elements. Leakage current was measured from the test pattern using 15 V DC [Comizzoli et al. 1992, Figure 4.].

Significance of water

Water plays a crucial role in the occurrence of corrosion. In normal conditions, a layer of 1...3 molecules of water is adsorbed on the surface of a solid substance (0,2...0,6 nanometres) without triggering the corrosion mechanism. When this layer increases to 20...50 molecules (4...10 nm) corrosive reactions become dominant [White 1992]. The above discovery applies to steel surfaces but also gives an idea of the general conditions for corrosion.

Corrosion is also an electrochemical event; in other words, corrosion always causes a small corrosion current. The electrochemical cell created on the surface of a metal always has a voltage difference between the anode (the corrosion area) and the cathode. The voltages of the corrosion cells are typically 0,5...1,5 V and the currents 10^{-12} ... 10^{-6} A. If the voltage difference is less than 0,3 V the progress of corrosion is already very slow. In early corrosion it is always a question of an undetectable phenomenon (picoamper currents and nanometres of physical sphere). Usually corrosion is detected only when corrosion products begin to show. With regard to the electronics, this is already too late and usually the operation of the electronics is disturbed a long time before the corrosion products are detected. Therefore, it is very difficult to prove that the reason for an electronic malfunction is corrosion.

Microbiological effects

Also microbes and other fauna always accumulate on the free surfaces in a similar way to various chemical substances. The microbes begin to function when there is enough water on the surfaces of the device as always in maritime and coastal conditions and in tropical regions. Microbial biofilms always develop on surfaces directly in contact with water. (Appendix 1, Section 2.17 *Microbiological corrosion*). Biofilms are water absorbent and porous. They consist of cells linked to one another, which penetrate the structure of organic polymers. Biofilms contain solvents, heavy metals and inorganic particles in addition to cell elements. The chemical conditions on the surface of the biofilm (acidity, pH, dissolved oxygen and organic and inorganic compounds) can deviate radically from the conditions in the near environment. Micro-organisms can accelerate the corrosion mechanisms and also change their character [Naval Research Laboratory 1999].

Users and production

For an electronics manufacturer, it is very important to form an as complete picture as possible of the conditions where the manufactured product is transported and used. After mapping the geographical area of use and the climatic conditions, which may take place mainly through publicly available data, the environmental specification for the product can be designed using for example the environmental classification defined by International Electrotechnical Commission, IEC, (IEC 60721 Classification of environmental conditions) as a model. This classification must always be complemented with product specific amendments or additions. Only then will a comprehensive picture be formed of most environmental factors having an effect also on corrosion.

The IEC 60721 environmental condition classification provides access to the temperature, humidity and gas concentration, which must be taken into account in any case. This condition data leads to the testing requirements and further to the actual demands on the structure of the product, the materials and the coatings.

The behaviour of the users of the products and cultural characteristics have an effect on what types of chemicals the people use and how for example living and working spaces are washed. These can have considerable local effect on the corrosivity of the conditions.

The conditions may be exceedingly corrosive in many workplaces where various chemicals are handled or which produce corrosive substances as a by-product

(chemical industry, pulp industry, power plants). Even more difficult conditions can exist in various animal shelters, such as pigsties, chicken coops and cow byres.

2.3 Fault sensitivity and manner of use of a product

A product that is totally insensitive to internal changes of the component parameters and the structure and to external disturbances would be ideal with regard to corrosion. The changes and faults caused by corrosion would not have a disturbing effect on the operation of the product. It is possible to approach this ideal condition even in practice by adopting the principle of designing the product as fault resistant as possible with reasonable cost.

It is possible to design in such a way with regard to fault types caused by corrosion, such as diminishing surface resistance, increase of leakage currents, decay of contacts and material and electrical and mechanical functions of the product, that moderate corrosion will not affect the operation of the product. On the other hand, the corrosion of a product can be slowed down considerably by alleviating the effects of external environmental stress by utilising suitable protection techniques.

In situations that call for more restricted tolerances and high quality plating in order to ensure the selling of the product, as good platings and protection techniques as economically and technically feasible should be used.

2.4 Know-how of corrosion mechanisms

The failure mechanisms causing corrosion in an electronic device (Appendix 1 and Chapter 3) should be studied according to their sphere of effect in order to classify better the corrosion prevention itself. Corrosion and climatic effects concentrate on the following four groups:

- electrical functionality
- mechanical functionality
- structural durability
- appearance.

All typical environmental stress factors, water, gases, micro-organisms and surface contamination can have an effect on all these categories. When these effects are studied and their significance emphasised, it should be checked which

faults are critical for the quality of the product. Based on this, it should be estimated which individual failure mechanisms that have been addressed in more detail in Appendix 1 and Chapter 3 should be taken into account when developing corrosion protection.

Figure 2.4 presents a few typical fault categories occurring in the devices because of corrosion and climate. Failure mechanisms on the component and circuit board level have a major effect on the electrical properties.

Corrosion and climatic effects	
Electrical functionality	<ul style="list-style-type: none"> Change of series resistance in contacts Breaks of conductors Change of insulation resistance Leakage currents, soiled surfaces Short-circuits Change of dielectric constant of materials Faults of component packages Faults of component leads Breaks of cables
Mechanical functionality	<ul style="list-style-type: none"> Increase of friction Hindering of movement Weakening of spring Fault of contact mechanism Fault of switch mechanism Sudden breaks during heat and mechanical stresses
Mechanical strength	<ul style="list-style-type: none"> Break of mechanical actuator Break of supporting structure Break of solder joint
Appearance	<ul style="list-style-type: none"> Nusty appearance Faults in outer surface Color changes of platings Soiled surfaces Disappearance of markings
Malfunction	<ul style="list-style-type: none"> Intermittent failure Groundless change of new component Rejection of nearly intact device Failure of software EMC-fault, fault in electric supply or LAN

Figure 2.4. Classification of corrosion effects according to category.

Since the failure mechanisms have a different effect on different materials a wide range of mechanisms, the most common ones being failure mechanisms of the component board, connectors, keyboards and switches, need to be studied in order to ensure the electrical functions. The wirings and their contacts can become a significant fault source in decentralized device systems.

The faults in the mechanical functions usually surface after the electrical faults when the device has already been rather obviously corroded. It is fairly common, however, that the frame structures or individual parts are mechanically uncertain and perhaps incorrectly measured which can result in for example thermal fluctuation and mechanical vibration causing breaks in wire connections and connectors even in new devices. If the male and female plugs in a connector move against each other because of the above, this also advances corrosion (fretting corrosion or fretting) which can result in momentary breaks or in time permanent changes in the electrical functions. It is very important to ensure in the making of the connectors that they operate without mechanical faults during the entire life span and that they will not become damaged in normal use.

Mechanical durability is usually one of the last problems to emerge because of corrosion. The frame structures may sometimes become damaged in extreme conditions. It is more common for various small parts and solder joints to crack due to the corrosion. The mechanical strength of the solder connections may degrade because of the mechanical and thermal stresses. These are effected by the properties of the used solder and plating materials [Mattila 2005, Vuorinen 2006 and Roslund 2002].

A fairly common failure in electronics is the gradual decay of the solder connections especially in hot spots. The decay of both the flux and the eventual great thermomechanical forces affecting the connection wear out the connections before their time (Appendix 1, Section 2.10 *Stress corrosion cracking and fatigue*). The most common fault in this category to the general public is television fires in private homes. The component connections with greater mass where only electric wires are used for the connection can break as a result of the combined effects of vibration and heat. Also the lack of tension relief of the wires/cables causes breaks quickly and easily.

The users form an opinion about the product quality based on appearance. Although pretty appearance is not necessary in the inside or in the outside parts of the device if only it's technical functionality is considered. However, the appearance will very quickly tell if the product has been subjected to conditions more difficult than on the average and also if a plating process has possibly gone

awry. The most critical part of the appearance is the coating of the external surface of the package. When acquiring components and part assemblies the coating of the various parts has a considerable effect on the corrosion resistances. The quality of the final product should be ensured in the specification of the manufacturing process of the coating and of the properties of the coating itself. In many cases, a neat and even coating is a sign of a successful coating process, but there are cases where corrosion protection has been the main aim and the result is a blotchy appearance (for instance chromating) even though it has been carefully finished. The markings on the device can sometimes be erased or rot due to humidity. This is the case for instance with stickers containing cellulose, which make a good base for mildew growth when, wet (Appendix 1, Section 2.18 *Growth conditions for mould*).

Figure 2.4 states as the last category a malfunction, which means here an occasional fault that occurs at random, the cause of which, may not be identified. A large number of explanations can be found for these faults ranging from improper use to inferior design of the device. In reality, the causes for occasional “unidentified” faults can be for example

- reversible changing of component parameters due to change in the temperature or slow change of the values in time
- corrosion in the connections
- leakage currents of surface of the component board in humid weather
- leakage currents of soiled surfaces
- breaks in connectors or wires due to thermal expansion
- deterioration of EMC contacts or external grave EMC disturbance
- faults caused by ESD eruptions
- breaks due to vibration
- contact faults caused by inferior contact spring material or design
- stickiness of the keyboard due to chemicals of human origin
- problems of the mechanical structure
- software disturbance
- disturbance in data transmission or power supply.

If there are considerable numbers of faults in the fault data the cause of, which remained unidentified, the devices reported as faulty should be analysed in more detail. Are the surfaces contaminated, are there faults on the connector surfaces, are the contact springs and the EMC seals intact etc. The basic assumption is that disturbances in electrical functions usually progress gradually and the effects

usually combine with sources of other undefined faults, such as EMC problems, random component faults and incorrect software operations.

2.5 Testing and feedback from the field

Product development usually needs the support of experimental studies to ascertain that the result of product development meets the set aims. Various quick tests or more controlled standardised testing gives fairly accurate information on the corrosion resistance properties of the products.

This testing should be undertaken whenever the product is changed so that the changes may affect the tolerance for environmental conditions. When using new materials and components it should be checked that these actually function in the user conditions of the product.

Corrosion and climatic tests	
Failure analyse methods	Visual inspection, fotography Microscopy Measurement of resistance Measurement of coatings Material analysis, SEM, ESCA...
Rapid test methods	Water, humidity, salt solution, acid fume Scraping, tape adhesion test Chemicals, perfumes
Heat tests	Dry heat and cold (short and long period) Change of temperature Combined cold/heat and cyclic humidity
Humidity tests	Cyclic damp heat Long period humidity at high temperature Accelerated tests for components e. g. 85°C/85% RH
Gas tests	Multigas tests, H ₂ S , SO ₂ , NO _x , Cl ⁻ , NH ₄ ⁺ etc.
Salt mist tests	Spraying salt solution mist
Tightness	Mechanical, dust and water tightness
Mechanical tests	Vibration and shock tests and fretting corrosion tests

Figure 2.5. Tests used in the study of corrosion resistance.

Since the range of components and materials of the products is usually rather varied an individual manufacturer cannot test all parts or even the assembled device to check everything. Therefore, the main emphasis should be on the design and the choice of materials and components (specifications) which are complemented with appropriate climatic and corrosion tests, especially in those details of which previous experience does not exist.

The testing should concentrate on the use of for example the general tests presented here which ascertain a fair share of the field. Chapter 5 gives more detailed information on the application of individual testing methods for various purposes. The testing and analysis methods listed in Figure 2.5 are used for various coatings, component boards, components and entire devices.

These methods are also suitable for the study of devices returned to service from the field. The feedback from the field should first of all aim at identifying the real reasons for the faults. When the failure mechanisms are discovered it is also possible to identify worthwhile corrective action, at least for the next product generation. The requirement for this is that the devices coming in for service can also be examined by the designers in product development in order to obtain authentic and correct feedback concerning the conditions and quality level of the devices in the field.

To collect feedback from the field, it is sufficient to analyse a certain number of samples. It is important to find out if the faults are very common or only random cases. If a considerable share and a large absolute number of the returned devices have unidentified faults it is worth examining these devices even for corrosion. If the reasons for the faults can be identified, corrective actions can also be prescribed.

2.6 Corrosion prevention techniques

As stated in the above, in Section 1, Figure 1.7, *Physical Basic Principles of Corrosion Control*, there are several means to improve the tolerance for corrosion and the climate. When selecting the means, it would be important to recognise at first the basic principles, which can be used to curb environmental stresses. When these have been used, the concrete means for protecting the component board, for example, or ensuring the functionality of the connector contacts should be studied. The following means for improving corrosion resistance can be mentioned as examples of applying the basic principles in Figure 1.7.

Using of fault-resistant technique

Corrosion and climate cause changes to the properties of all components and materials. If the device could be designed to function including wide scale changes of component parameters, most devices would tolerate also corrosion quite well. Corrosion causes mostly small gradually progressing changes in electronics, which slowly deteriorate the properties of the device.

If the electrical/mechanical functionality of the device requires very small tolerances in the signals, leakage currents or the size or quality of the impedances in the circuits (humidity affects the dielectric constant ϵ_r), the device will be sensitive to corrosion, since corrosion of the surfaces, contamination and humidity affect not only the metal surfaces but the electrical properties of the surfaces of the insulators as well.

These changes in the serial resistances of the joints (connectors, solder joints, switches), leakage currents between the wires and insulation resistances caused by corrosion should be included in the sizing of the electric circuits in the designing of the device. Numerical tolerances for these should be calculated and these used for informing the corrosion experts and manufactures of the components in order to identify the correct level of protection measures.

The most problematic areas with regard to the corrosion risk are usually the electromechanics: connectors, switches, relays and connections of other components and displays as well as the wiring pattern of the circuit board. In the most difficult conditions, which prevail for instance in a typical coating plant, faults in the electromechanics where corrosion plays a part include more than half of all the occurring faults. Minimising of the number of electromechanical connections, especially unprotected connections that can be opened, is a good means of reducing the corrosion risk. Practical reasons support the use of electric connections that can be opened in the devices, for example EMC seals, connector sockets of displays, keyboards and plug-in units and outside cable connectors. This means that the fault tolerance must be built on also developing the properties of these parts affecting corrosion resistance.

Minimisation of gas contacts

Gas contacts as referred to here mean the contact of substances in the air with the outer or inner surfaces of an electronic device. The contact of gas and dust particles with the surfaces becomes more frequent with faster airflows and higher contents of gases and dust in the air. To put it simply, this means that the

probability of chemical reactions (corrosion, humidification) and contamination is higher if the surface is in constant contact with these undesirable particles.

It has been observed in practical structures that even simple mechanical cover significantly reduces the contamination of the surfaces and therefore also corrosion and other surface phenomena. The inside of a device may reveal a completely contaminated circuit board on one side because of the airflow while the backside appears clean and flawless. In the same way, a two-part edge connector may look neat on the inside even though the outside has been contaminated. The explanation to this is simply the few gas contacts in a mechanically protected space.

The reduction of polluted airflow inside the device is one of the best means to prevent corrosion if temperature of the device can be controlled by smaller or closed airflow. However, it should be remembered that humidity and condensation also cause problems in too tightly sealed cases (see Appendix 1, Section 1.8 *Condensation of moisture on the surfaces*).

The basic general principle in designing electronics could be the reduction of the airflow for instance by using a double layered structure where the dense wiring of the electronics and small components are insulated against the external flow of air and only the parts necessary for cooling remain in contact with the strong flow of air.

Taken further, this would mean casting the electronics in an inert mass, which does not absorb water. In such a case, the device would consist of small packages cooled with a relatively free choice of means.

Keeping the cases and electronics dry

The insides of the device cases and the electronics should be maintained as dry as possible in all situations since the presence of water always increases the risk for corrosion considerably and weakens the isolation of the surfaces. A relatively tight device case is the best solution. The problems in fact begin with the design of the case, what kind of case is the best?

Since the cases usually let outside air in them the heat from the device itself should be used to minimise the harmful effects of humidity in order to keep the device dry and to ensure the removal of possible moisture inside the device. If the various parts of device could always be kept warmer than its surroundings it would be easy to keep it dry. The cooling air inside the device provides a natural

help in the removal of moisture but if the flow is based only on weak natural convection or ventilation through cracks in the seals, precautions must be taken against long term effects of internal moisture and the inside surfaces must be better protected.

It would be important to stop the dripping of water resulting from condensation onto the component boards or the connectors in indoor and outdoor conditions.

Compatibility of materials at the joints

There are various boundary surfaces of materials in electronics, for example on the circuit board, wiring patterns, connectors, switches and microcircuits. If the device is subjected to the corrosive substances present in air and to water and since water is always in contact with all the surfaces, at least to some extent, galvanic corrosion occurs always when two metals are in contact with one another. High temperature and humidity accelerate these reactions.

The smallest risk for corrosion exists between two surfaces of the same metal. If the metals are different, the least corrosion occurs between surfaces where the electric surface potentials are as close to one another as possible. The galvanic series described in Appendix 1, Section 1.2 *The electrochemical and galvanic voltage series of metals* can be used to help in the choice of materials. If the materials differ much in this respect, the probability for corrosion is great, if there is water and if there are corrosive gases in the air and on the surfaces.

It is rather difficult in electronics devices to avoid contacts between different materials, such as contacts of the EMC seals with the circuit board and the outer case of the device. These are naturally in contact with various metals. The solution for this case also is to design the seams of the seals mechanically in such a way as to stop the penetration of moisture at least to the centre parts of the contact area of the seam, even if there is a zone sensitive to water and corrosion around the edges.

When using tin-lead solder, it should be checked that the circuit board or the component wires do not carry excessively thick layers of gold which forms intermetallic alloys with tin. The mechanical strength of these alloys is weak and they corrode quickly in heat.

Isolating coatings

It is necessary to protect the wiring pattern against effects of contamination and moisture if the quality of the air flowing inside the device cannot be affected and the device case is relatively open. The coatings protect the boards also from mechanical stress in connection with assembly and service. In dry conditions the solder resist coating alone gives some protection against the harmful effects of temporary humidity even though it lowers the isolation resistance of the surface especially when wet. This phenomenon has been addressed in more detail in Appendix 1, Section 2.17 *Effect of moisture and geometry on the isolation resistance of the circuit board*. Component boards meant for difficult conditions should be lacquered by immersing them into protective lacquer since water adsorbs easily under the components and into the leads and wiring otherwise.

2.7 Sub-contracting, logistics and feedback from the field

The quality and quantity of the company's subcontracting carries a very great effect on the possibilities of the company to influence the corrosion resistance of its own products in general and their survival during transportations and use (Figure 2.6).

In subcontracting and purchase of components the qualitative management of the acquired service or goods and the transportation of the goods without increasing the corrosion risk are the main objectives for the company to focus on when aiming at controlling also the corrosion.

The know-how of the subcontractor or the supplier of components concerning corrosion should be at the same level or better than that of the device manufacturer since the quality of the purchased goods cannot be influenced during the final phases of the device production, which typically include only the setting and connecting of the components and the final testing of the assembly. If the manufacturer of the final product cannot specify the demands on corrosion resistance, the subcontractor should be able to do this and also carry out the specifications even though the final user does not demand it all. However, the subcontractors have only rarely the opportunity to know which special demands concern the delivered goods concerning corrosion resistance and general tolerance for environmental conditions. Only a few subcontractors guarantee life span information for certain coatings or protection methods and materials that could be used as such in the determination of the life cycle of the product.

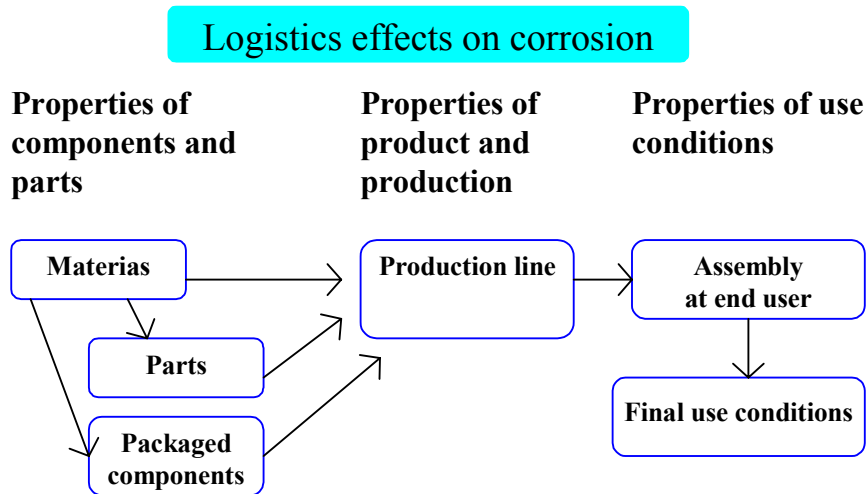


Figure 2.6. Influence of logistics and sub-contracting on corrosion resistance.

Since this situation is dominant in most of the subcontracting and acquisitions of components, co-operation where the manufacturer of the final product specifies the issues related to corrosion resistance with the subcontractor as thoroughly as possible should work best with regard to quality assurance. Existing standards on the product, coatings and testing methods provide assistance in this. Naturally, separate specifications which describe the technical properties, possibly address the manufacturing techniques to be used (for example coatings) and define the means for verifying the quality of each part will have to be drafted for each case. The manufacturer of the final product should have a thorough overall view on the environmental endurance of the product and the demands concerning this and on the meaning of the life span as well as on the manner of realising the corrosion resistance (manufacturing processes, choice of materials, protections, coatings, packaging, method of transportation) in order to have a healthy critical opinion about the solutions offered by the subcontractors.

The following two well-specified items are always needed for **the specification of subcontracting and purchasing** and the delivery contracts in order to reach the aims on corrosion resistance:

- well-specified components and parts including corrosion prevention techniques
- carefully defined parts packaging, transportation and storage method.

The transportation of parts and components all over the globe result in a paradoxical situation with regard to corrosion faults, since a part of the product, a bare micro chip, metal part, circuit board etc. at its most sensitive to corrosion is packaged (sometimes well sometimes badly) and shipped to another factory for the next phase. If the buyer/supplier does not realise that the products are

subjected to uncontrollable environmental stress (temperature changes, humidity, air pollution, dust etc.) the most during transportation, permanent damage or damage difficult to repair will be caused to the next production phase (especially soldering) and to the life span of the final product. The costs for such quality mistakes can be covered by transportation insurance but this is not enough to compensate for the damage caused to the overall qualitative image of the final product.

It is difficult to shift the responsibility of the functionality of the final product and its parts to the subcontractors. Therefore the only securing factor is the know-how of the manufacturer of the final product, which is used to organise the acquisition of parts, their quality and the manufacturing and design of the product

What is most important is that the acquired part will actually function in the final product in the specified conditions. In subcontracting as in the company's own activities, good results can be achieved only by information and by utilising the logistic know-how of the subcontractors.

Acquisition of feedback from the field is necessary in order to carry out corrective actions. It is relatively easy to recognise corrosion faults in extreme cases but in most situations arising in practice the faults occur coincidentally and clandestinely and the identification of the real reasons for them is a challenging task even technically. In practice, the delivery of the feedback from the field directly to the designers requires active acquisition of data. The acquisition of feedback should be organised in co-operation with the service and sales organisations by making agreements with these concerning the return of the faulty devices, for example in connection with warranty exchanges. The manufacturer of the final products should not settle with reports from the service alone. It should be routine to send products with various faults to the designers for analysis. Only by examining these can useful information be obtained for the corrective actions and first of all, improvement of the company's know-how.

Since in most products a large number of unidentified faults are included in the feedback on faults and, on the other hand, corrosion related faults may not have been mentioned in the instructions, the feedback for this part remains relatively worthless. If the company's quality system includes active return of the faulty products to be inspected by the designers of the company, the chances to track the actual faults increase substantially. What remains to be considered and organised is how and how many faulty products are delivered over to the designers for inspection. Guidelines may be drafted for the designers, as in Chapters 4...6 and Appendix 3 *Review methodology of the corrosion control*) for analysis and recognition of the corrosion problem.

3. Corrosion and moisture in electronics

Many of the corrosion mechanisms and the effect of humidity on electronics are presented in Appendix 1 *Basics of corrosion and failure mechanisms* and in other contexts, which is why this paragraph addresses only some of these phenomena. Humidity control in the devices and their transportation packages is discussed in chapters 2, 5 and 6.

3.1 Climatic corrosion and its time span

The factors affecting climatic corrosion are temperature, moisture, humidity and air impurities. There is a lot of textile dust in an environment where people work daily. This dust as such does not create problems but it binds other particles from the air on its surface and these particles can create problems. In an industrial environment, the dust consists of mainly inorganic particles. How damaging these are to electronics depends on their composition. Carbon/soot particles and particles containing rust/metal dust are the worst.

The main factor affecting climatic corrosion is perhaps temperature through humidity, since it affects the prevailing humidity conditions. Temperature as such has an accelerating effect on chemical reactions according to the Arrhenius equation. Corrosion caused by humidity can progress quickly even at 0...30°C temperatures. When the temperature changes the relative humidity of the air also changes. If the temperature drops, the relative humidity will at some point exceed 100% RH and a layer of water is formed on the surface. After the water layer is formed, the speed of corrosion also accelerates to several thousand times faster than at the starting point. In normal conditions (RH < 50%, Appendix 1, Section 3.6) a layer of water 1...3 molecules thick can be adsorbed onto the surface without starting the corrosion reactions. If the layer grows to 20...50 molecules thick, the corrosion reactions start to prevail. When the temperature rises again, the water evaporates and corrosion nearly stops. Time of wetness (TOW) of the surface is a general term when estimating the speed and seriousness of the corrosion phenomenon.

Seepage of water through organic films (paints) takes place quickly (see Appendix 1, Sections 1.5 and 1.6). Times of a few minutes have been measured for alkyd paints at a film thickness of 20 µm [Feser & Stratmann 1991]. In immersion tests with epoxy coatings [van Westing et al. 1994], it has been noted that water forms a permanent layer under the coating in a few hours and a permanent layer of

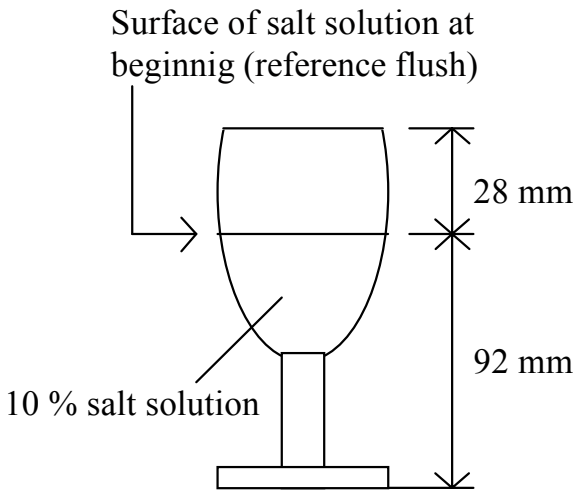
corrosion is formed in about a hundred hours. The water layer which was formed in a couple of hours also took approximately the same time to dry.

The water amount corresponding to equilibrium state, which has accumulated in the paint film within a few hours, does not yet cause damage, since at this stage the film is able to repair the damage and dry back to what it was. The start of corrosion is always somewhat sluggish; in other words corrosion does not begin to form under the film immediately. After corrosion products have begun to form, the film can no longer recover to its former shape. An analog situation to these phenomena is at hand with flux residue on a solder resist coating. Only when the residue penetrates through the film all the way to the copper, will corrosion begin to take place.

The corrosion time of metal subjected to a water solution varies according to the composition of the solution and the subjected metal. Clean water needs a continuous exposure of several weeks or months (e.g. aluminium in clean water hardly reacts). Saline solutions can cause the birth of harmful corrosion product in a couple of hours, even minutes in parts under voltage. This must be kept in mind when protecting device cases for outdoor conditions with various paints and other coatings. Water always contains salts originating from the air and other corrosive elements in outdoor conditions. The worst situation is created if the water stays on the surfaces or in the capillary gaps, because in such a case even a well-protected surface can corrode. Based on the above, it can be estimated that a few temporary exposures to humidity do not necessarily cause any harm but frequent wettings with an increased time of wetness will already cause damage.

Figures 3.1–3.3 present the tendency of salt (ordinary table salt or Pan-salt) to creep along the surfaces or gaps. Figure 3.1 presents the initial stage of the test and the measurements of the test vessel. Figure 3.2 presents the travelled distance by the salt on the inside of the glass and the level of the surface of the saline solution compared to the initial stage. Figure 3.3 presents the photographs of the behaviour of the salt during ten days from the start of the test.

The sequence (Figure 3.3) shows that the salt creeps along the inner surface of the glass reaching the outside of the glass in less than five days and in seven days already reaches 10 mm from beyond the edge. In the case of the picture sequence the salt was mixed in tap water producing a solution of about 10%, which was poured into a glass and left undisturbed. The temperature in the surroundings was about 24 °C and the relative humidity 40...50%.



The composition of the Pan-salt used in the test was:

- potassium chloride 28%,
- magnesium sulphate 12%,
- lysine hydrochloride 2%,
- potassium iodide 0,0036%,
- sodium chloride 57% and
- silicon dioxide 1% (anti clotting agent).

Figure 3.1. Salt experiment.

The salt travels as follows: After the solution is poured into the glass it rises somewhat along the inside of the glass due to surface tension. Water evaporates from the solution that has risen along the inside, which results in an increase in the saline content of the solution on the surface and the crystallisation of some of the salt on the surface of the glass. Adsorption of water into the salt crystals follows from both the solution and the surrounding air. Water is transported through the crystallised salt from the more humid areas to the dryer areas and salt along it.

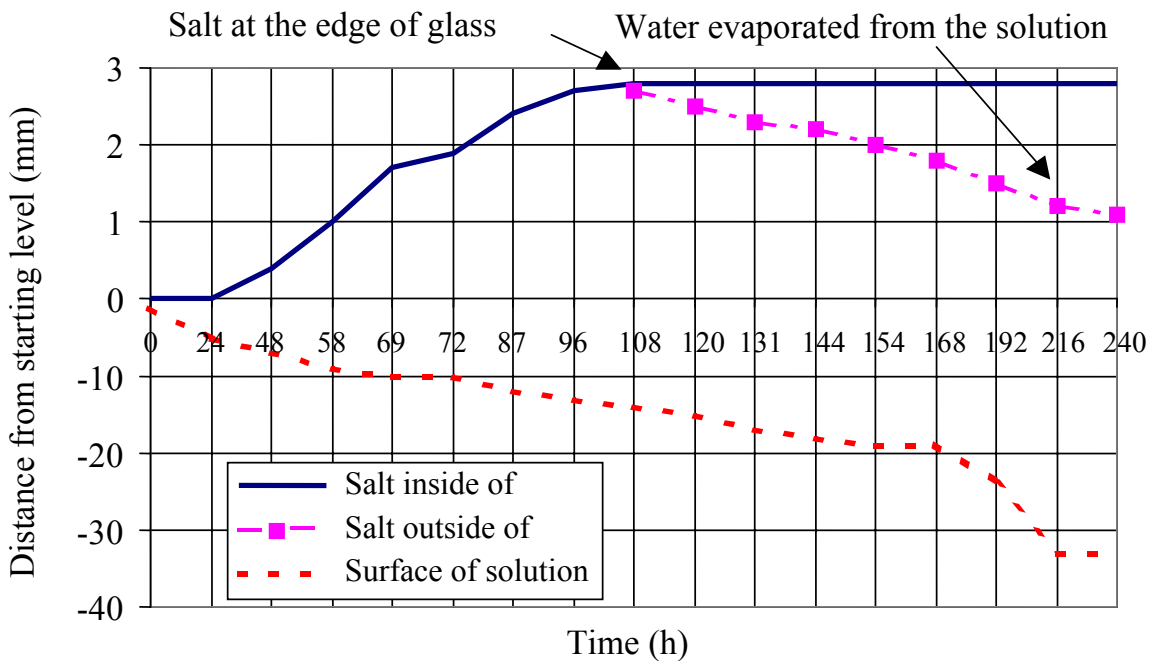


Figure 3.2. Creeping of salt in a wineglass during test.

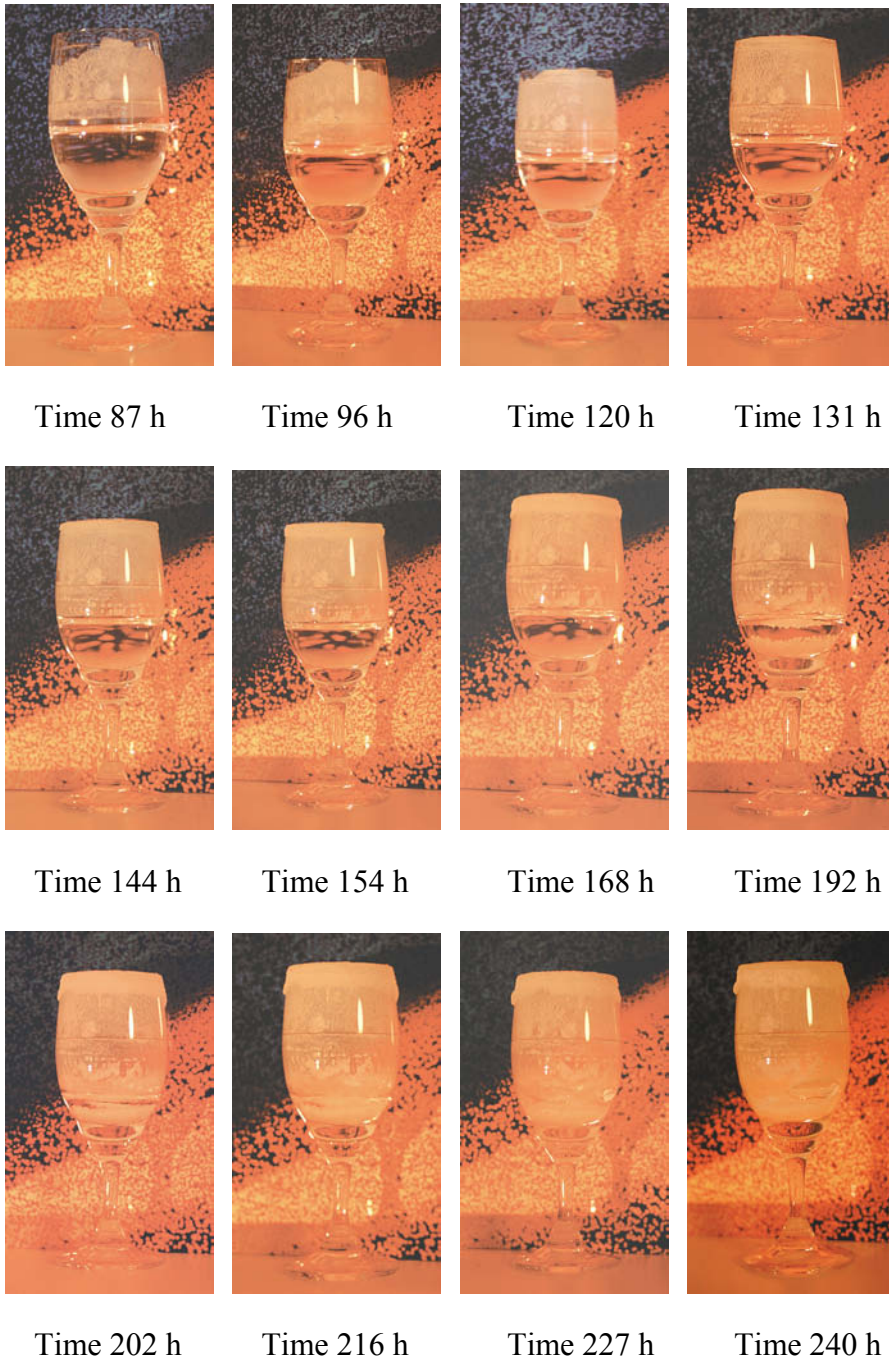


Figure 3.3. The picture sequence presents the creeping of salt from the inside of the wineglass to the outside. The times of photographing are marked under the pictures in hours from the start of test. The glass was initially half full (28 mm down from the edge) of 10% saline solution. At the end of test, in ten days, the water had evaporated and the salt crept about 17 mm down from the edge on the outside.

The salt in the frontline that has been wetted again creeps forward along the surface of the glass due to surface tension. The drying phases of the saline solution and the wetting phases of the salt alternate which results in the salt

creeping from the solution and the water creating wavy zones of crystallised salt on the glass surface (not unlike the annual rings in wood), which progress to the surroundings at the speed and in the direction determined by the surface quality, salt crystallisation and wetting conditions. The following two basic mechanisms affect the travel of the salt:

- The surface tension between the glass and the saline solution is less than the surface tension between the glass and the air, which is why a greater force affects the liquid along the glass surface away from the solution than towards the liquid. In other words, the wetting angle of the saline solution is less than 90° on the surface of the glass making the solution spread also upwards on the glass surface (see Appendix 1, Section 3.4 Figure 3.4).
- Salt is hygroscopic and adsorbs water also from the air (see Appendix 1, Section 5 *Factors affecting the progress of corrosion*).

The said hygroscopic quality of salt and its tendency to creep relatively long distances along surfaces and capillary gaps in a few days is the reason why salt penetrates into a device quickly even from narrow gaps and accumulates and gathers water onto the mechanical boundary surfaces (see Appendix 1, Section 3.5 *The capillary effect*). The accumulation of water in this fashion onto the various boundary surfaces, for example in the contact zones of membrane switches and elastic EMC seals always causes strong corrosion together with other impurities. In humid conditions, the saline solution can gather so much water that it results in short cuts in the wiring patterns of the electronics. In a paint coating, salt can cause filiform corrosion in a few weeks if the surface gets wet (Appendix 1, Section 2.9 *Filiform Corrosion*).

3.2 Effect of humidity in electronics

Humidity and water affect the devices for instance through the following:

- Humidity of the air absorbs into the materials and adsorbs onto the surfaces. (For example 200 h, 25°C , 61% RH drives 0,15% of its weight of water into IC-case plastic [Lind 1995].)
- the water absorbed into the materials increases material loss and changes conductivity and the dielectric constant ϵ_r .
- Ionic impurities in the plastic cases of components dislodge and the cases swell mechanically.

- Humidity of the air condenses as water on surfaces cooler than the air. The change in the air temperature enables condensation.
- Water/humidity diffuses through materials due to humidity difference, air pressure or temperature differences.
- Hygroscopic materials in the transportation packages yield water inside the package.
- Dripping water accumulates in gaps or uneven spots in the structures.
- Rain penetrates the device due to strong air/water pressure and also because rain cools the devices which makes them absorb water.
- The sun heats one side of the device, which makes water condense on the cold side [Gellerstedt 1995]. Correspondingly the surface pointing towards a cold sky cools effectively and creates a condensation/frost risk.
- The inside surface of the device placed on a cold surface accumulates condensing water when the outside air warms.
- The device is placed into water or operates in water.
- Human activity causes water damages for example various washing situations or water damage (see Table 3.1.).

Table 3.1. Effects of humidity on equipment [IEC 60068-1, table I].

Humidity	Principal effects	Typical failure
High relative humidity	Moisture absorption or adsorption Swelling Loss of mechanical strength Corrosion and electrolysis Increased conductivity of insulators Increase of dielectric constant ϵ_r	Physical breakdown, insulation failure, mechanical failure, increase of dielectric losses
Low relative humidity	Desiccation Embrittlement Loss of mechanical strength Shrinkage Abrasion of moving contacts	Mechanical failure, cracking

3.3 Water and chemicals

Clean water is not harmful as such. It has a great surface tension and therefore its wetting effect on surfaces is only slight. Clean water has, however, a great capacity of dissolving other substances from the environment, which changes the situation. In other words, water never stays or exists clean in nature. The substances dissolving into the water usually lower its surface tension and the ability of dirty water to wet surfaces are therefore much better.

During the manufacturing process of circuit boards, the surface tension of water is intentionally lowered in order to make the coating solutions penetrate the holes drilled into the board. Since smaller and smaller holes not always piercing the board are being introduced, residue of the coating process may accumulate into these. No regular behaviour pattern can be detected in these cases, but the residue is found at random in some of the holes. Holes of 0,1 mm or less in diameter cause problems in this respect.

Solvents, such as alcohol, usually leave the same way as they came. The damage caused by solvents usually remains undetected if the surface is not thoroughly wiped. Then the wipe marks become visible on the surface softened by the solvent. Some plastics and solvents are not compatible, however. The plastic may be ruined because the solvent produces stress cracking in the plastic or simply dissolves it. For example polycarbonate (PC) is destroyed due to stress cracking caused by acetone (nail polish remover).

Detergents used in the house, soaps and chemicals may contain substances that are surprisingly harmful with respect to electronics. Normal dishwashing liquid may contain alcohol, which can be absorbed into the plastic cover of a mobile telephone, for example. Many other detergents contain alcohol, for instance Sinol. The same applies to many cosmetic products, such as after-shave lotion.

Greasy substances and substances lowering surface tension (soaps) cause damage in polymer structures, such as plastics. The most harmful quality of greasy substances is that they travel long distances from the place of absorption due to changes in the temperature and the damage may be caused in wholly unexpected places. The destroying effect of greasy substances is based on their ability to act as softeners. The plastic swells and in the worst instance becomes viscous losing its mechanical strength totally. Softened plastic can also absorb for instance water, which markedly increases the corrosion risk. Some soaps contain lotion for skin care, which are selected according to their ability to be absorbed into polymers such as the human skin! The effect of such substances is visible in that the plastic parts swell or soften on the surface and begin to feel sticky and collect dirt.

Human emissions from breathing, palm sweat and grease, hair, dandruff and skin care lotions contain chemicals which can have corroding qualities or qualities softening plastic. These chemicals include for example carbon dioxide, aldehyde, methane, skin creams, powders, solvents in perfumes. In addition, cigarettes release tar, ammonia, acetone, formaldehyde and nitrogen oxides. The aldehydes in human breath and sweat penetrate silicon rubber, which is used for membrane keyboards, for instance. Silicone rubber also reacts with aldehydes and can secrete like glue compounds, which are harmful for the operation of the keys.

It is well to remember the old guideline about cleaning dirty surfaces. Wipe clean with a rag dipped in clean water and if using detergent, use a neutral one, perhaps slightly alkaline soap!

3.4 Emissions from materials and components

The organic materials used in electronics may evaporate or otherwise discharge corrosive elements or elements that disturb the operation of the device. These emissions usually consist of some fatty acids such as formic acid or acetic acid or their aldehydes which oxidise when in contact with metal and form corresponding fatty acids. The harmful effects of these substances usually become obvious only if the relative humidity of the air is high (>50% RH). Magnesium already corrodes at a relative humidity of 30% RH where corrosion can be very frequent. In addition to fatty acids, hydrochloric acid, hydrogen sulphide, phenoles, amines and ammonia can be emitted. Low air pressure can accelerate the emissions. High temperatures (>60...75°C) greatly accelerate emissions and the ageing of materials. High temperature also accelerates the corrosion mechanisms.

Since the emissions of organic materials are usually gaseous, an effective way of avoiding their harmful effects is to maintain adequate ventilation near the devices and inside them. High ventilation inside a device can be harmful, however, if it enables high levels of humidity and also effects of emissions from outside the device. According to several sources [e.g. Henriksen et al. 1991, IPC-A-610, pp. 5–6 and BS 7195] the following substances emit corroding elements:

Silicone

Silicone seals discharge acetic acid and ethyl alcohol if the seal has been vulcanised at room temperature (RTV).

Silicone rubbers, which have been vulcanised at room temperature, discharge acetic and formic acid.

Silicones themselves easily creep along surfaces and form isolating films, for example in the contacts of connectors and switches.

In the production of printed boards and assembly, creams and perfumes are especially harmful since they may contain silicone oil which reduces solderability and the adhesion of protective coatings on the surfaces to be protected [IPC-A-610, pp. 5–6, 1996]

Resins

Phenol resins emit phenols (phenolic/carbolic acids).

Cast resins emit ammonia gases.

Softened plastics emit esters and organic acids.

Rubbers

Rubbers emit sulphides (sulphuric gases).

For example EPDM rubber seals may release different corrosive agents as carbon oxide sulphide (COS) and carbon disulphide (CS₂) depending on the vulcanizing method. These agents corrode e.g. Cu, Ag, and Zn. When COS and CS₂ react with oxygen and water they develop hydrogen sulphide and sulphur dioxide. EPDM rubbers (ethylene-propylene-diene rubbers) are usually vulcanized with sulphur compounds, therefore the EPDM material contains sulphur. If the vulcanization is done with peroxide, the contents of sulphur is no more a problem.

Plastics and coatings

PVC plastic discharges hydrochloric acid under UV light and at temperatures exceeding 70°C. In connection with fires, burning cables with PVC emit highly corrosive gases into the environment, one of the main ones being hydrochloric acid.

Epoxies discharge amines

Polyamides (nylons) emit acetic acid at temperatures exceeding 60°C.

Polyvinylacetate without additives discharges formic acid. With suitable stabilising and inhibiting agents it is non-corrosive.

The following substances are considered harmless with regard to corrosion at normal environmental temperatures: polyolephine, polyester, polycarbonate, polystyrene, and polysulphone.

Oil paints and varnishes drying at room temperature emit formic acid, especially when fresh.

Packaging materials

Papers and cardboards emit sulphuric gases.

Wood and plywood emit organic acids, mostly acetic acid. Oven dried wood especially emit formic acid and other organic acids in addition to acetic acid.

Brown wet strength packaging cardboard or chipboard containing groundwood pulp can discharge corrosive elements when wet. Sensitive metals such as brass, zinc or aluminium should never be enclosed in these packages without additional protection (plastic bag etc.). Fresh wood also contains a number of evaporating substances. It is advisable to use plywood or other such material instead of wood.

Padding emits sulphuric gases or acids.

In [Henriksen et al. 1991] it is recommended that organic materials, which are the most contaminating, should not be used in electronics if possible. These materials include PVC, neoprene, phenol and polysulphide materials. Organic resins should be well cured or aged before use. Wood containing materials are considered corrosive, which is why electronics should be, protected from their effects in the transportation packages as well as in use.

Other substances and effects

Polysulphide sealing materials evaporate sulphuric gases.

Organic fluids, tool grease, lubricants, glues, pressure sensitive tapes, elastomers, bearing grease and cast plastics not well enough cured can emit various corrosive gases. They can also contain silicones that form isolating films on surfaces and are harmful for soldering and coating the products.

The tin used in soldering by hand contains for instance protective resin, which can be evaporated into the environment. Resins can contain phenol compounds. These substances have a corroding effect on brass alloys.

Battery technology (accumulators) has also shifted to closed structures in batteries containing traditional diluted electrolytes, mainly lead batteries. If using too high charging voltages, hydrogen may form in these batteries, which can then be released from the pressure valve of the battery together with electrolytic mist containing sulphuric acid. Sulphuric acid mist corrodes nearly all materials. Ventilation airways must be reserved for battery discharges with no materials corroding in the electrolytic mist. The batteries must be kept in an upright position in order to prevent the electrolytic fluid from blocking the pressure valves. If the batteries are laid on their side, even small internal pressure caused by hydrogen formation forces the battery fluid out through the pressure valve, which can result in a greater corrosion risk and damage.

Most miniature batteries are “closed” so nothing comes out. If these batteries are charged with too high voltage, they can explode. The electrolyte in miniature batteries is alkaline, and if it is discharged in exceptional circumstances, it causes damage to materials sensitive to alkalines. Materials sensitive to alkalines include for example aluminium, copper and tin. Plastics are fairly resistant to alkalines but they can swell because of the alkaline metal ions absorbing into them, which leads to deterioration of the mechanical properties of the plastic.

Chlorinated hydrocarbons (containing chlorine) which are banned substances due to their toxic nature, disintegrate forming chlorine hydrogen or hydrochloric acid when in contact with water. For instance (paint) spray guns made of Al/Mg alloy must not be cleaned with chlorinated hydrocarbons because of the danger of producing hydrochloric acid, a hydrogen explosion in a spray gun is a serious matter.

There is a pressure valve in aluminium and tantalum liquid electrolyte capacitors for preventing the capacitor from exploding due to rise in its internal pressure. There is liquid electrolyte in these “wet” electrolyte capacitors, which always produces some hydrogen gas due to the effect of the leakage current; the purpose of the pressure valve is to let this hydrogen out. If the seals of the capacitor leak the electrolytic fluid may drip out. Since it is acid it corrodes the wiring pattern of the circuit board. In order for the hydrogen gas not to include electrolyte, large liquid electrolyte capacitors should be mounted with the connecting wires facing upwards so that the electrolytic fluid does not block the pressure valve.

Halogenised hydrocarbons (containing chlorine and possibly bromide and fluorine) dissolve and disintegrate the oxide film when in contact with the isolating film of the aluminium electrolyte capacitor thus ruining the capacitor. These hydrocarbons may penetrate and react with the capacitor seals and end up on the inside of the capacitor. This is why capacitors should be washed only with

halogen free detergents, such as ethanol, propanol and isopropanol (or alternatively the exposure times should be minimised) [Aluminium Electrolytic Capacitors 1999].

BS 7195

The standard guideline BS 7195 (1989) *Prevention of corrosion of metals caused by vapours from organic materials* gives a fairly detailed list of emissions of corrosive elements from organic substances and guidelines on how various metal surfaces should be protected against such emissions.

BS 7195 divides metals into the following categories according to their sensitivity to the corroding emissions of organic substances. The classification was not drawn up with regard to the corrosion sensitivity of electronics but it can be considered a guideline at least when evaluating the corrosion sensitivity of case and support materials.

Group 1: Series corrosion sensitivity

Carbon steels, lead and lead alloys, zinc, zinc alloys, magnesium, magnesium alloys and cadmium (the use of cadmium is nowadays prohibited).

Group 2: Moderate corrosion sensitivity

Copper and copper alloys.

Group 3: Slight corrosion sensitivity

Aluminium and aluminium alloys, nickel and nickel alloys.

Group 4: Durable materials

Austenitic stainless steel, chromium, gold, molybdenum, silver, tin, titanium and titanium compounds.

Also silver has been categorised in the most durable group although it is not recommended for contact surfaces in electronics, if the operation is in small-signal conditions with voltages less than a few volts and there are sulphuric compounds in the air, which is usually the case. Silver is suitable for contacts with high currents and voltages for instance in switches and relays since it is resistant to sparking (arc flame erosion) in opening/closing switches.

BS 7195 presents the following procedures and more detailed descriptions of them as means of protection:

- removal of unsuitable materials
- drying of the air
- ventilation
- protective coatings.

3.5 External connectors and switches

External connectors and wirings of electronic devices are one of the problematic sections in the control of problems caused by corrosion. Periodic cut-offs are very common failures in external connectors. The usual reason for these is the gradual corrosion or dirtying of the contact coatings, wear of the contacts and fatigue of the springs.

The contacts that are opened in use must tolerate repeated mechanical stress, they should be watertight and the contact coatings should tolerate humidity and mechanical wear caused by changes in the external temperature. In addition the adhesion of the wires to the connector frame must be ensured against jerks by suitable clamps.

In devices operated outdoors, the prevention of the corrosion risk can be improved by mechanically supporting the wiring, by conducting the wires to the inside under the device to prevent draining of water directly on the contacts and by choosing the materials so that the wiring can take bending, changes in the temperature and the continuous presence of water.

Nearly all devices have at least a few switches (keyboard) for operating the device. These days, membrane switches are used in many devices. The advantage of these is cheap price and the possibility to obtain watertight structures that can tolerate also touch. In most devices, the user interface is operated with bare hands (elevator control, mobile telephone, computer terminal, access control). This subjects the switches to several chemicals and also washing. Since the switches are on the outside surface of the device, they are also subjected to changes in the air temperature and to humidity. This is why the tightness of the switches, chemical tolerance and resistance to mechanical wear are crucial in most devices to the operation of the product. Corrosion is a significant factor in the fault mechanisms of switches.

3.6 Case and frame structures

The basic task of casing is to protect the sensitive parts of the device from external stress. Corrosion of the outer surfaces usually affects the looks of the product, but in the worst case the tightness and strength of the structures may suffer from excess corrosion. Ensuring the tightness of the cases in products designed for wet conditions is very important for maintaining the operability of the device, the shape of the case and the properties of the seals should keep throughout the life span of the product. A considerable part of the corrosion problems of casing centres on various seams, lids that can be opened and on doorframes. Since electric conductivity is also needed in these seams, troublesome metal pair corrosion enters the picture. In the protection of outer surfaces of the cases in outdoor conditions it is important to design the shapes of the surfaces and seams in such a way that draining water or condensing water has no place to stay for long.

The outsides of the cases are usually painted. The paints are materials cured at elevated temperatures or two-pack paints that form a chemical net. There are no discharges from the cured two-pack paints to the environment. Powder coating is used more and more frequently, which gives better protection for corners and edges than solvent paints. The emissions from powder coatings are less than from solvent paints, but the curing process always requires an elevated temperature. During the recent years the powder coatings curing at low temperatures have entered the market. These are designed especially for painting plastic. (See Section 6.9 *Casing materials*).

The most important factors with regard to corrosion of plastic case materials and plastic device covers are: sensitivity to ultra violet light, chemicals and the changes in the properties of the material due to water absorption. The effect of chemicals has been addressed in Section 3.3 *Water and chemicals*. The sensitivity of the material to UV light depends on the polymer structure and the stabilisers used in the plastic. It can be stated as a general rule of thumb that the less the plastic is exposed to UV lights the longer it will last. Note: UV light is also present in small doses indoors in fluorescent lamps.

The inside structures of the cases must be strong enough structurally to bear the stress of mounting the components/printed boards. The structure usually acts as grounding too, so it must be conductive, in other words metal. Zinc electroplated and yellow chromate steel is a usual choice of material for connector rails/frames because it is cheap whereas hot dip galvanized, skin pass rolled thin sheet is used for other structural case material.

Good yellow chromating yields usually a life span of several years in the conditions prevailing inside the case. In addition to yellow chromating, also thinner clear chromating (blue passivation) is used especially for fixtures. The chromating of skin pass rolled thin sheet is also clear. Clear chromating does not give equal protection to yellow chromating because of a thinner layer. Therefore it is odd that usually rails and other heavier structures are well protected, in other words yellow passivated and the screws that are used for fixing the heavier structures are usually clear chromated. This results in corrosion in the screws, which is seen as feathery white rust in the screw heads. Bad passivation or electroplating may lead to the flaking of the coating, which may cause short cuts on a dense circuit board. The control of the plating process and the quality of the plating should therefore be paid more attention than previously.

White rust does not usually occur on a skin pass rolled thin sheet under the same conditions since skin pass rolling increases the durability of the surface. However, red rust may occur on the edges of the sheets as a result of corrosion of the steel material of the thin sheet. There is no easy and cheap solution for the prevention of rusting of cut steel edges. The only way of blocking the phenomenon is to either zinc phosphate and paint the entire piece or to change the microclimate inside the device to such that there is no corrosion. Painting only the edges is not usually feasible due to the complex shape of the piece. The rust dust flaking off the edges creates a potential danger to the environment because of its conductivity. The rust dust also affects plastic materials [Kemisk Tidskrift 1986]. Rust dust, humidity and UV radiation act as catalysts in the disintegration of plastics that can lead to problems for example in electric premises where some UV radiation is always present in the fluorescent lamps.

The directive of European Union, EU, [RoHS] concerning the restriction of the use of certain hazardous substances in electrical and electronic equipment limited from the June 2006 the use of such materials as lead (solder), mercury (batteries), cadmium (accumulator), hexavalent chromium (Cr_6 , chrome plated aluminium and zinc, bright chromium plated decorations, keyboards and boxes), and halogenated fire retardants (printed wiring boards). The RoHS directive changes a lot the materials used in electronics. The limited use of lead only, causes quality problems in the production processes and components, and increasing demand for the higher heat endurance of components.

4. Definition of corrosion resistance of a product

Here, corrosion resistance means the ability of a product to function as intended and to tolerate corrosion and climatic effects during a certain life span without the product causing danger to its environment.

4.1 Corrosion resistance

Corrosion resistance is formed of two entities:

- factors increasing the corrosion risk and
- protective measures, in other words methods preventing corrosion.

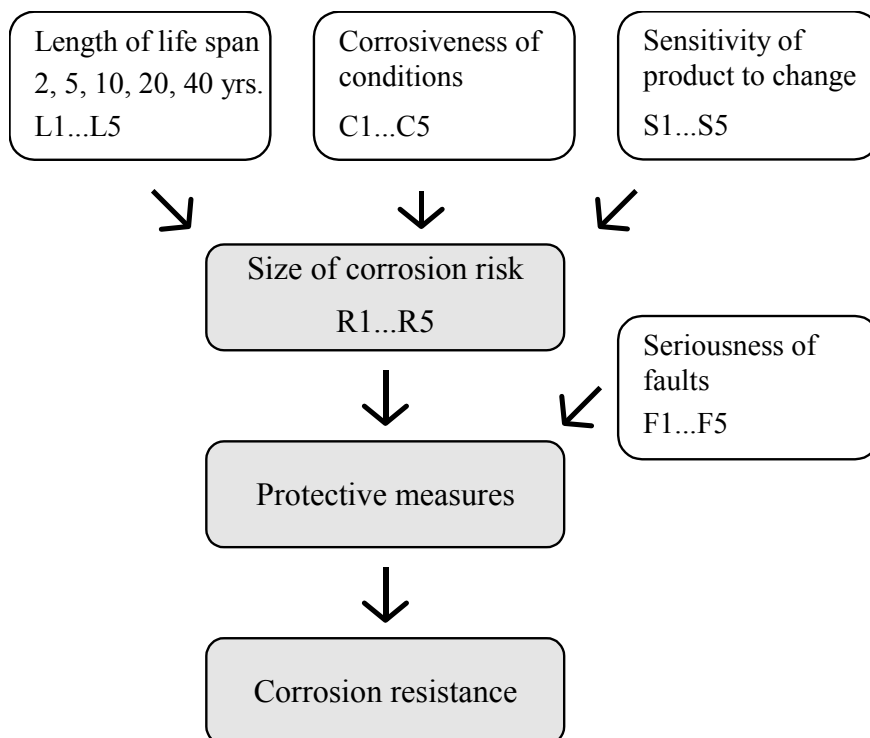


Figure 4.1. Definition of corrosion resistance of a product.

The basic aim here is to draft a methodology that would yield a practical way of expressing and measuring corrosion resistance. This methodology can help in making the right decisions on action to optimise product reliability and corrosion resistance in product design.

When defining the corrosion resistance of a product, the factors increasing the corrosion risk should be taken into account as presented in Figure 4.1: the aimed

life span, corrosivity of the environmental conditions, sensitivity of the product construction to changes caused by corrosion and various protective measures or measures limiting corrosion. The risk level in Figure 4.1 is presented on a scale 1...5, where 1 is the lowest and 5 the highest level of risk. In addition, the harmful effects of each fault category caused by corrosion on the function of the product should be evaluated in order to account for all factors. The more harmful a fault is, the more should be invested in its prevention. Each risk factor can be categorised to produce a measure for the effect of the said factor and a combined measure for the total product risk and, based on the protective action, a measure for the corrosion resistance of the product.

It must be kept in mind that corrosion here means all the decaying effects that corroding substances, oxidising and climatic and other environmental effects produce through corrosion mechanisms in the function and appearance of the devices. Therefore, the concept of corrosion resistance is a sum of several factors.

4.2 Effect of the length of life span

The amount of corrosion is proportional to the time of effect. The lengths of life span can be used as a categorisation, for example 2, 5, 10, 20 and 40 years. The length of the product life span affects most of all the extent of changes that should be anticipated in the properties of the device and the variety of failure mechanisms that should be taken into account when designing the corrosion resistance. Some of the changes caused by corrosion have rapid and drastic effect if the conditions and construction are favourable, but a considerable share of the effects of corrosion progress relatively slowly, especially if the conditions are clearly corroding only at times (Figure 4.2).

If the aimed life span is ten years, the corrosion risks increases already because the probability of corroding conditions is at least periodically great, the cumulative effects of contamination are seen and various mechanisms have time to develop and cause changes in various parts of the device.

Even a life span designed very short, for example two years, does not allow for great freedom in the design of the device, since all kinds of events increasing the corrosion risk have time to take place in two years. On the other hand, the risks of corrosion damage are greatest during transportation, installation and the first months of use. A short life span enables cheaper solutions in more protected sections of the device, since slowly progressing faults are not likely to have time to

affect the functionality. In such a case, thinner protective coatings may be a good solution. The real risk lies in conditions that are highly corrosive even for a short period of time (high humidity, lots of corroding substances). Then, thin coatings functioning well under normal circumstances may give in even after a few days.

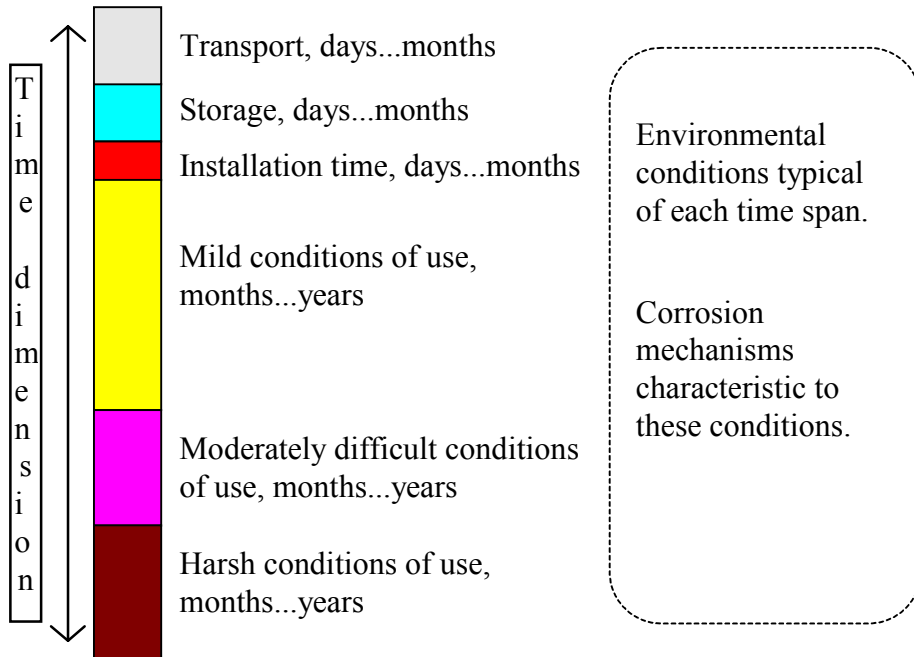


Figure 4.2. Division of the life spans into typical exposure periods.

Products that are used all over the globe are especially vulnerable to changing conditions. This results in the corrosion risk exceeding the saving opportunity in the level of protection offered by a short life span, for instance five years.

Because of variance in these circumstances, the product life span must be split into sections for evaluating each time the length of the section and the prevailing conditions and the typical fault mechanisms in order to grasp the effect of the length of the life span.

4.3 Sensitivity of the product to change

The sensitivity of the operation of the product to changes in the properties of components, connections, wiring patterns and isolations has a great effect on when a climatic or corrosion effect becomes visible in the operation of the device. It makes sense to use the changes in the basic quantities of electric properties of the products as the measure for the sensitivity of the product.

These basic quantities are the impedances in the conductors (signals, power supply) and the properties of the insulation gaps, which have an effect on all the functional properties of a device in the end.

- serial resistance in the conductors
- leakage current between conductors
- dielectric constant (ϵ_r)
- capacitance
- conductor inductance.

It would be ideal in electric design if all these “disturbing parameters” could be allowed very wide tolerances so that reasonable changes caused by humidity, changes in temperature, mechanical stress and corrosion would not noticeably affect the operation of the device.

Knowledge of the magnitude of change in electrical properties caused by temperature, humidity and corrosion mechanisms and, on the other hand, analytical data on the acceptable values for the disturbing parameters make it possible to evaluate and classify quantitatively and qualitatively the corrosion sensitivity of the device. In practice, similar sensitivity classification cannot be applied to all signal channels and isolation gaps but the circuit designer can analyse in detail how great changes in the disturbing parameters can be allowed in the various contacts and wirings.

The most critical parts with regard to the serial resistance of the current channel, for example, are soldering joints, connector contacts and undersized wires for the strength of the current. Ordinary serial resistance for soldering joints and connectors is within the range of milliohms or parts thereof. The resistance of a soldering joint may increase with decay of the joint and corrosion several times over as well as the resistance of the connector contacts.

The slight contact force and instability in mechanically very small contacts that can be opened may cause great changes in the resistance. When such a change becomes disturbing depends on the circuit solution in question. The designer must deduce himself, however, what kind of specifications is drawn up for each current channel.

These days the resistances of the current channel in common film/membrane switches are about 100 ohms or even greater which is why the effect of other parts than the changes in the resistance of the membrane switch itself is slight.

On the other hand, the leakage current between the conductors may become an important player in the disturbance.

In a dry environment, the leakage currents between the conductors in the wiring pattern of the circuit board and in the connectors are typically at nanoampere level at voltages less than 50 V. The leakage currents may increase 3...7 decades due to humidity and especially because of contamination or corrosion. Appendix 1, Section 2.19 *Effect of humidity and geometry on the insulation resistance of the printed board* addresses the factors affecting the leakage currents in the wiring pattern in more detail.

Humidity and temperature affect the electric dielectric constant of the insulation materials, which is why a change in this for example in high frequency circuits causes, the quality factor and resonance frequencies of the circuits to change. Corresponding changes may take place in the inductances especially since corrosion changes the geometry of the conductors and causes short-circuits.

The corrosion of the contacts in the metal cases inside a device used for electromagnetic protection weakens the EMC protection and can cause interference in the operation of the circuits. The basic rule of protection has been an electrical contact of the seams of a sealed case at distances of at least one tenth of the wavelength. The resistance of the contact spots should be in the range of milliohms. If the contacts corrode, the seam of the case may turn into a slot antenna, which relays the disturbances from the inside out and vice versa. Since the required level of protection depends on the necessary shield dampening the designer has to analyse the necessary strength of the contact. After this, the level of corrosion protection and the materials needed for realising it can be estimated.

4.4 Corrosivity of conditions

When estimating the corrosivity of the conditions, one must take into account the corrosivity of the transportation, storage and use conditions of the device. The combined effect of these determines what kind of technical solutions should be used in ensuring the operation of the device. It is crucial to recognise that the construction of the device (casing, thermal design) and changing the conditions of use can have a great effect on how corrosive the conditions will finally be with regard to the electronics contained in the device.

Feasible methods have been invented at various organisations for categorising the corrosivity of the climate, for example the corrosion classification described

in Section 5.2 *Corrosivity of the conditions of use* is well suited for the purpose. The corrosion categorisation of the conditions has to be separately conducted for each section of the device life span, as presented in Figure 4.2. When the duration of each section is taken into account, a weighted value for the corrosivity is obtained which can be used as a basis for the design. One should remember, however, that short-term exposure to harsh conditions might cause faults in the device although the probability of this happening is fairly small.

In order for the evaluation of the conditions to give a more realistic picture of the environment experienced by the device, the corrosivity of the conditions must be estimated separately outside the device, in the vicinity of the device and separately inside the device. The openness of the casing of the device has a crucial effect on how harsh the inside conditions of the device are and which of the fault mechanisms become the most significant.

4.5 Magnitude of corrosion risk

A measurement figure for corrosion risk can be obtained as a total of the physical factors of the risk caused by corrosion of a product: length of the life span, corrosivity of the conditions and sensitivity of the product to change. This figure is directly proportional to these factors which have a simultaneous effect, therefore the risk can in principle be calculated as a product of these factors. The problem is naturally the physical and mathematical realisation of the commensurability of the various factors. Since the presented classifications of the effects of the various factors are logarithmic in nature, the total risk is obtained as the sum of scoring these classifications, if the mathematical expression is wanted. This method yields the following sum for the corrosion risk:

$$R_{cor} = L + C + S, \tag{4.1}$$

R_{cor} is the corrosion risk

L is the length of the life span 1...4 (5), 5 points \approx 40 years

C is the corrosivity of the conditions score 1...5, 5 points highly corrosive

S is sensitivity to change, score 1...3 (5), 5 points highly sensitive.

This method yields for example the following overall classification for the corrosion risks, if each sub factor is evaluated on a scale 1...5.

The corrosion risk category obtained by equation (4.1) and table 4.1 should be modified with the following addition in order to consider exceptional corrosion risk caused by one factor:

If the scoring of a factor, length of life span, corrosivity of the conditions or sensitivity of the product to change is two categories higher than the risk class of the sum, the next category above the sum shall be taken as indication of the corrosion risk.

Table 4.1. Classification of corrosion risks.

Corrosion risk category	Risk score R_{cor}	Description of corrosion risk category
R1	3...4	Very slight corrosion risk
R2	5...7	Slight corrosion risk
R3	8...10	Intermediate corrosion risk
R4	11...13	High corrosion risk
R5	14...15	Very high corrosion risk

For example in a case where the scoring of the length of the life span is 2, the scoring of the sensitivity to change is 1 and the corrosivity category of the conditions is 5, the sum is eight points. Based on this sum, the corrosion risk category would be R3, but since the conditions are so harsh, the category is upgraded to R4 based on the given rule of exception. This example shows the effect of harsh conditions on the corrosion risk, which basically cannot be influenced. In practice this can be taken into account by constructing the device case in a suitable way which reduces the corrosion risk significantly inside the device.

4.6 Protective measures

The following paragraphs present information on protective measures. Nearly all of these measures have a quality/level classification, which can be used as such as the measure of efficiency for the protection. By combining these various protective measures a reasonably good estimate can be obtained for the total effect of the protection techniques along similar lines to the estimation of the corrosion risk presented in the above.

The protective measures against corrosion are targeted on the following:

- coatings of conductors
- quality of soldering joints
- quality of EMC contacts
- tightness of case
- transportation packages
- production processes
- logistics chain
- materials, coatings and mechanics of contacts
- protective coatings of wiring patterns (masses and lacquers)
- case materials and coatings
- ventilation of cooling air, humidity and cleanness.

It is naturally crucial that the protective measures are targeted to preventing actual failure mechanisms and to those targets which have the most significance to the corrosion resistance of the product. It is also important to carry these procedures out on a wide enough scale in order to influence those various failure mechanisms typical of corrosion. In this way, the corrosion resistance of the product and its quality can be gradually upgraded.

4.7 Classification of failures

Classification of product failures is used for creating a picture on how the various faults affect the operation of the product and the safety of using it and what effect they have on the maintenance cost of the product. Own classifications based on the operation of the product and important values of the company may be used or the failure classifications presented in the standards. For example, in standard *IEC 60300-3-9 Dependability management. Part 3: Application guide- Section 9: Risk analysis of technological systems (1995-12)* a risk level evaluation method is presented which takes into account the frequency of the fault occurrence and the seriousness of the fault. A method like the example is presented here, where the names of categories and the quantities deviate from the model based on the proposal [IEC 56(Secretariat)353]. A guideline on the needed analysis and the level of the corrective measure is also given. Table 4.2 presents the measures required by the nature and frequency of the fault marked with letters corresponding to the risk level of the fault T, L, I and H. The analytic action called for is depicted as follows:

- | | | |
|---|------|---|
| T | (F1) | Insignificant risk, no action required |
| L | (F2) | Low risk, qualitative analysis. |
| I | (F3) | Intermediate or moderate risk, semi-quantitative analysis |
| H | (F4) | High risk, detailed quantitative analysis. |

Table 4.2. Evaluation of the risk level, effects of severity of the fault and fault frequency on the quality of corrective measure (T, L, I, H).

Frequency of fault occurrence	Severity of fault			
	Catastrophic	Major	Minor	Negligible
Frequent	H	H	H	L
Probable	H	H	I	L
Occasional	H	I	I	T
Remote	H	I	L	T
Improbable	I	L	L	T

The actual corrective measures on the product and production are implemented based on the analysis. Tables 4.3 and 4.4 present the definitions for the severities of the faults and the fault frequency.

Table 4.3. Classification of severity of faults.

Description	Technical definition	Health risk
Catastrophic	Total failure or system loss	Death
Critical	Major system damage	Severe injury or occupational illness
Minor	Minor system damage (change of property)	Minor injury or occupational illness
Negligible	Failure without harmful effects	Less than minor injury or occupational illness

Table 4.4. Classification of fault frequency probability.

Fault frequency ¹⁾	Specific individual item	Inventory ²⁾
Frequent	Likely to occur frequently	Continuously experienced
Probable	Will occur several times in life of an item	Will occur frequently
Occasional	Likely to occur sometime in life of an item	Will occur several times
Remote	Unlikely but possible to occur in life of an item	Unlikely but can reasonably be expected to occur
Improbable	So unlikely, it can be assumed occurrence may not be experienced	Unlikely to occur, but possible

¹⁾ Definitions of descriptive words may have to be modified based on quantity involved.

²⁾ The size of the inventory should be defined

4.8 Overall level of corrosion resistance

Corrosion resistance can be defined based on the above as:

“Corrosion resistance is the ratio of the efficiency of corrosion protection to the corrosion risk.”

Since the efficiency of corrosion protection cannot be exactly defined, field data on the efficiency of corrosion protection and their classifications must be relied on here. There are good recommendations on the use of painting and metal plating of contacts, for example, with ready classifications. (See for example Section 6.10, ISO 12944). In practice the use of this data can yield a fairly good estimate on the efficiency of various protections and the corrosion risk.

When analysing and developing corrosion resistance a more realistic picture of the whole is obtained if the differences between corrosion control of the outside and the inside of the device is kept in mind during both risk evaluation and the realisation of the protective measures. The conditions outside and inside the device are different, so are the fault mechanisms. Both must be analysed separately considering also the corrosion risks covering the entire life span.

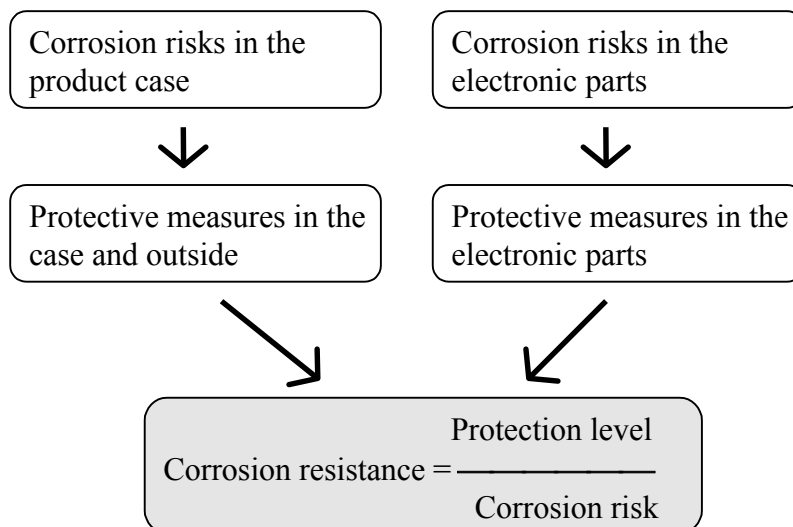


Figure 4.3. Definition of overall level of corrosion resistance.

5. Corrosion control methods

5.1 Verification of corrosion resistance and its incorporation into product development

The planning of corrosion resistance of an electronic device is an important sector of product design affecting the reliability and operating characteristics of the device. The planning of corrosion resistance is closely associated with the design of the mechanical and thermal properties of the device and with the measurements and tests by which the results from the planning are assessed. The verification of the actual planning of corrosion resistance [cf. Hienonen et al. 1997] means the procedures (Figure 5.1 and Appendix 3 *Review methodology of the corrosion control*) used to ensure that the results of the corrosion resistance design correspond to the defined targets and that the planned physical device performs in accordance with those targets in the environment where it will be used during its life cycle.

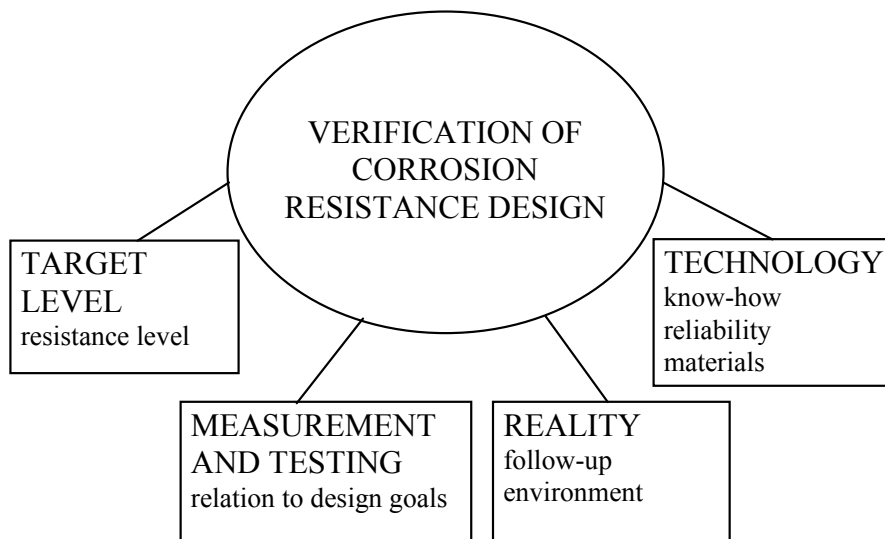


Figure 5.1. Points of verification of corrosion resistance design.

The aim of the verification is to ensure

- the validity of the target level in relation to other characteristics
- the appropriateness of product planning and validity of results
- conformity of the device to the design targets
- the application of correct measuring and testing technique
- identification of the existence of potential reliability risks
- incorporation of the targets of the various sectors of product planning
- definition of planning targets for corrective measures.

Design areas significantly affected by the design of corrosion resistance are shown in Figure 5.2. The same applies also in the opposite case, i.e. when a certain level of corrosion resistance is targeted, it is important to know how the various sectors affect the corrosion resistance in order to ensure the result.

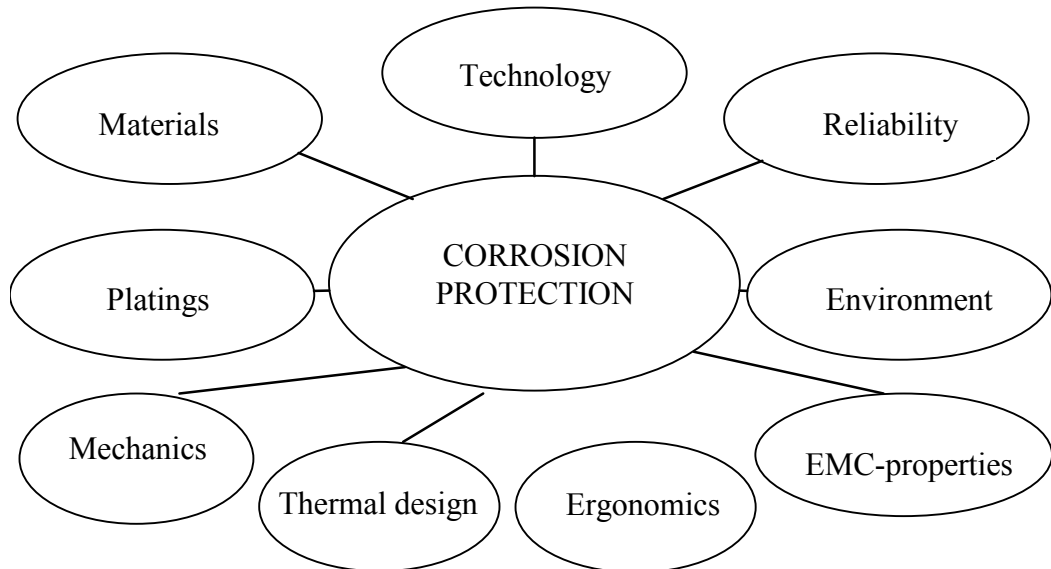


Figure 5.2. Various effects on corrosion protection technique.

The verification is done during the various phases of product development (Figure 5.3) as a gradual multiphase operation as the planning progresses so that the design can be altered and redirected at need. A more detailed design review methodology, especially designed as a tool of corrosion control in an electronics company is set out in Appendix 3. In order to reap full benefits from the verification, it must be incorporated together with the planning of corrosion resistance into the product development process from the start, in other words the corrosion specialist must take part in the definition of the product and its development process from the very beginning.

The reason for this is that certain corrosion resistance targets may cause radical changes in the customary product structures, the cooling technique of the device, logistics applied in the manufacture and subcontracting and the transport packages.

The verification should include elements that actively improve the level of planning instead of being merely a passive inspection of the methods used. If questions on what can be done or should be left undone to improve corrosion resistance are asked during the inventive and planning stage, the end result will be definitely better than by a passive implementation of the prescribed demands.

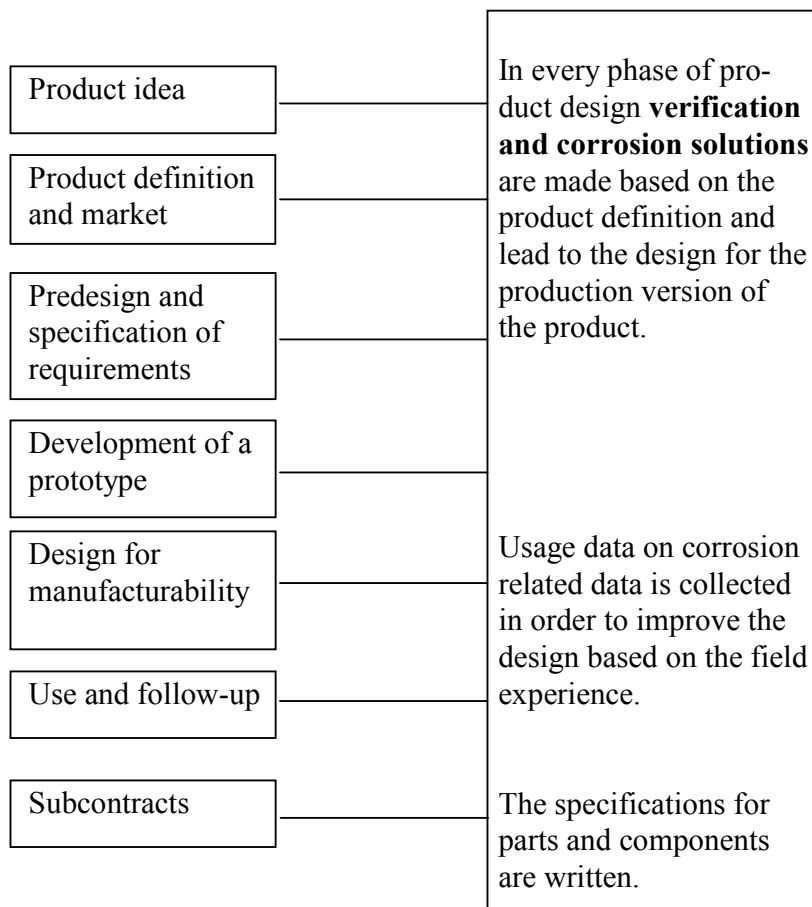


Figure 5.3. Implementation of corrosion resistance planning into product development.

Here the goal-setting, actual planning and results are scrutinised from different perspectives:

- corrosion resistance demands set on the product
- comprehensive utilisation of the protection technique, whether different possibilities of improving the product have been utilised
- validity of planning, identification of basic faults
- results from measurements and tests
- utilisation of feedback from the field
- any other areas to be improved technically and/or economically.

A requirement of successful verification is that the verifier is familiar with the case on hand by having identified the general aims of the planning, the nature of the product, the experimental background of product development, etc. Only

after forming a comprehensive picture of the verification task, the planning of the actual verification process suited for this particular project can be started.

A list of those matters to be taken into verification procedure of corrosion control is given here [Hienonen et al. 1997, p. 15].

General contents of the verification process

- 1 Definition of the object of verification
- 2 Timeline for design reviews
- 3 Organisation (participating persons)
- 4 Reporting method
- 5 Design of corrosion resistance
- 6 Analytic methods and measurements
- 7 Testing
- 8 Utilisation of field data
- 9 Assessment of design- and test data
- 10 The relationship of verification to design goals.

In addition to corrosion experts, it is recommended that electrical, mechanical, heating, EMS and logistics designers and representatives of other sectors of product development and production participate in the verification reviews in order to achieve sufficient coverage of the areas of expertise pertaining to the product. Since a considerable share of the work affecting corrosion tolerance is subcontracted, e.g. the manufacture of circuit boards, metal parts, partial assembly, etc. it is particularly important to inspect the specifications according to which the purchases are made. The problem here is that only the manufacturer of the end product has the expertise needed for corrosion control, whereas the subcontractors apply methods they have found to be good, although they may not always be good enough for the end product.

5.2 Corrosivity of user conditions

Various classifications have been developed for assessing the corrosivity of the operating conditions of the products. By these the product designer can assess the stress of the environment where his product is going to be used, on the one hand, and the standard of corrosion protection that should be used in the interior and exterior parts of the device, on the other.

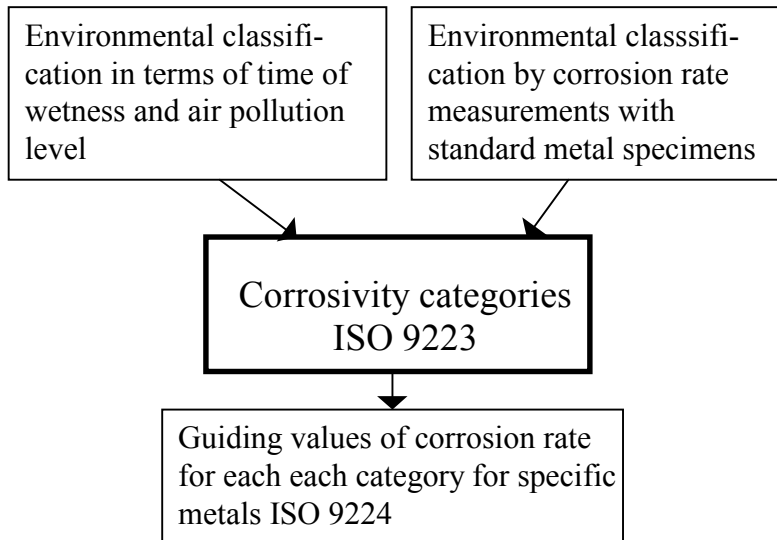


Figure 5.4. Specification of corrosivity classification according to ISO 9223 and ISO 9224.

Figure 5.4 illustrates the two principles by which the designer can assess the climatic corrosivity of a certain operating condition. Another method is to study the humidity and contamination factors of the operating conditions of the device and deduce the corrosivity class from them. Yet another method is to measure their corrosion speed with the help of standard metals and deduce the corrosivity class of the conditions from the results. There are various classifications of conditions and measuring methods of corrosion speed for the determination.

Classification of the environmental conditions

A suitable method to perform a corrosivity assay is, for example (Figure 5.5), to proceed stepwise starting from an assay and determination of the environmental conditions of the product and then assessing the corrosivity of use conditions, as set out here.

Because direct measuring is often time-consuming, it is worth while to begin the assessment of the conditions by determining the probable environmental classification of the device, in other words the level of the actual environmental stresses to which the device will be subjected during its life span. A suitable tool is the standard series published by IEC, IEC 60721 **Classification of environmental conditions**. This set out the actual conditions prevailing in the various parts of the world, on the one hand, and gives stress classes for each environmental parameter (temperature, humidity, wind, vibration, air pollution, etc.) and for typical location applications, on the other. When this classification is done taking into account the transport, storage, installation and operating

conditions in various user locations, we get a good idea of almost all the important environmental stresses that the device will be submitted to during its life span (see Chapter *Environmental standards*).

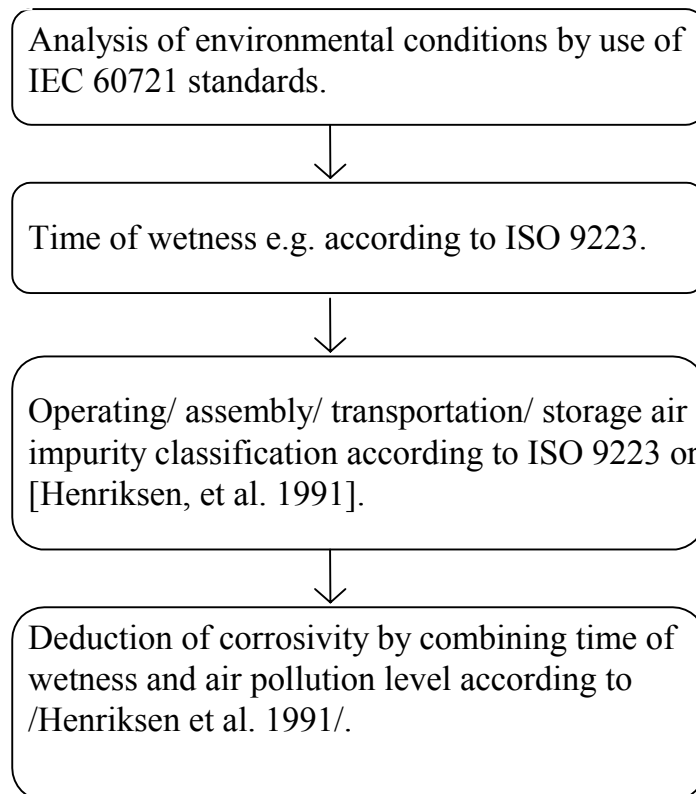


Figure 5.5. Corrosivity determination procedure.

IEC 60721-1 Classification of environmental conditions – Part 1: **Environmental parameters and their severities** lists the standard numerical values for all environmental quantities, such as temperature, humidity, mechanical vibration and various parameters describing the quality of air.

IEC 60721-2 Classification of environmental conditions. Part 2: **Environmental conditions appearing in nature** describes all groups of the environmental conditions prevailing in nature all over the world and the values of their stress degrees covering transport, storage and user conditions.

IEC 60721-3 Classification of environmental conditions. Part 3: **Classification of groups of environmental parameters and their severities** sets out the groups of environmental conditions by the types of the location of the device during transportation, storage and use. The standard covers the following areas of application in various global climatic regions:

- Storage
- Transportation
- Stationary Use, Weather-protected
- Stationary Use, Non-weather-protected
- Ground Vehicle Installations
- Ship Environment
- Portable and Non-stationary Use
- Microclimates inside products.

In addition, the data collected from the field and from other sources shall be included in order to be able to take account of relatively uncommon, unclassified conditions, such as chemical and physical stress caused by the action of human beings and animals.

It is very important to keep in mind that the conditions prevailing inside and outside the device are often very different if relatively well-protected cases are used. Here, the determination of the microclimate of the interior is as important as that of the external conditions. The atmospheric classification of the interior of devices is set out in the following standard, but only in respect of temperature and humidity.

IEC 60721-3-9 (1993-07) Classification of environmental conditions – Section 9: **Microclimates inside products.**

Existing corrosion speed classifications can be used in direct measurements of corrosion speed as a point of comparison with one's own measurements. They also indicate the corrosivity class into which the conditions of one's own product belong. The corroding speed in various environmental conditions of for example steel, copper, zinc and aluminium are used as points of comparison. [ISO 9224, ANSI/ISA, Henriksen et al. 1991].

The limits of the IEC environmental classes discussed in the above have usually been selected so that in nature the conditions exceeding the limit value occur at a probability of maximum 1% [SFS-handbook 108, Classification of environmental conditions and environmental testing]. In practice, the distributions of the conditions vary according to the nature of the stress (temperature, humidity, impurity contents, and vibration) and according to the geographical area, but in principle they are as pictured in Figure 5.6.

The occurrence frequency in Figure 5.6 can mean the probability in relation to time or geographical location. The limit values of the environmental classes are only rarely reached but they can be temporarily or locally exceeded. When the effect of a certain environmental factor on the probable amount of corrosion, these occurrence probabilities of condition stress factors must be taken into account.

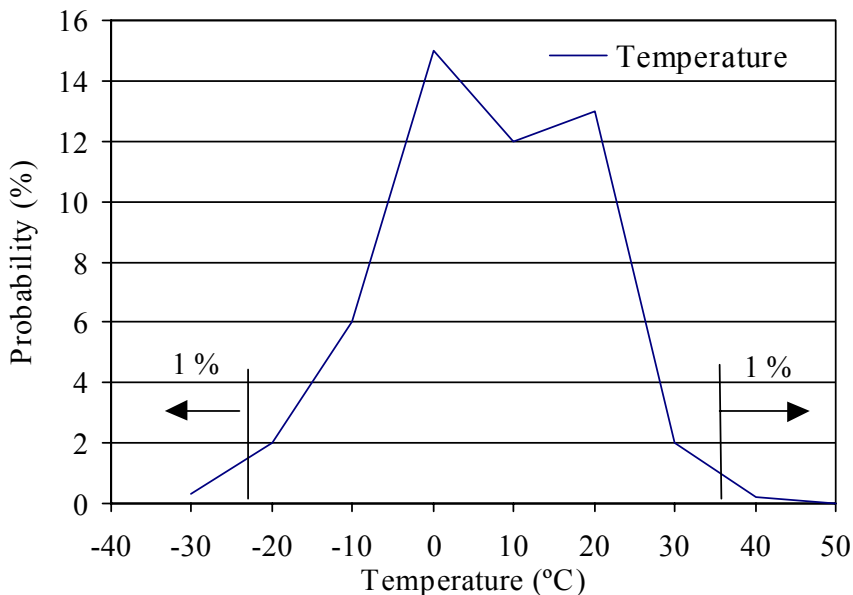


Figure 5.6. Distribution of air temperature (example).

Wetness classification according to ISO 9223

Standard ISO 9223 Corrosion of metals and alloys – Classification of corrosivity of atmospheres sets out the following table for the assessment of the classification of the time of wetness. In the ISO classification the times of wetness include the times when relative air humidity is > 80% and temperature > 0°C.

In principle, time of wetness means the time during which the metal surface is covered by an electrolyte causing climatic corrosion, i.e. water and substances dissolved in it. This determination is of a relatively general nature because, in addition to relative humidity, the wetness of surfaces is affected by condensation, rain, the quality of metal, heat conductivity, form of the surface, mass of the piece, number of corrosive products and the nature of the contaminants accrued on the surface.

In wetness class τ_1 there is next to no condensation. Likewise, in class τ_2 the probability of liquid film formation on metal surfaces is small. In classes $\tau_3... \tau_6$ there may be rain and condensation may occur.

Table 5.1. Classification of time of wetness (TOW) [Henriksen et al. 1991] adapted according to ISO 9223.

Class	Time of wetness TOW ¹⁾		Example of occurrence
	hour/year	% of use time ³⁾	
τ_1	< 10	< 0,1	Air-conditioned indoor, controlled humidity and temperature
τ_2	10...250	0,1...3	Indoor condition in normal rooms for living or work places
τ_3 ²⁾	250...1 000	3...10	Indoor air in storage rooms.
τ_4 ²⁾	1 000...2 500	10...30	Indoor air in some production rooms. Outdoor air in cold zone, dry zone, and part of temperate zone.
τ_5	2 500...5 500	30...60	Outdoor air in all other zones than cold and dry zones. Indoor air in animal shelters (barn, piggery) and stores.
τ_6	> 5 500	> 60	Outdoor air in tropical zone. Indoor air in greenhouse and non-conditioned stores.

¹⁾ TOW is determined at a time when air temperature is > 0°C and relative humidity > 80%.

²⁾ In ISO 9223 τ_3 and τ_4 are included in the same class, here is given classification of [Henriksen et al. 1991]!

³⁾ Percentual share means time of wetness expressed as a percentage of the total exposure time in the atmosphere in question.

The wetness class takes account of natural conditions, the conditions of the location and the user's actions. The classifier must decide the ISO wetness classification of the product on the basis of his product-specific classification of conditions and the use of the device.

When the influence of humid conditions on the corrosion of an electronic device is assessed one must keep in mind that corrosion occurs even in conditions where relative humidity is well below 80%. A rapid change of temperature also increases relative humidity and localised condensation, so that humidity classification according to Table 5.1 is not alone sufficient when assessing corrosion risks [Henriksen et al. 1991]. The classification is fairly rough, but due to the climate and the versatile and incidental behaviour of the phenomena affecting corrosion it is not possible to produce a more exact classification.

Classification of air pollution level

The classification of air impurities are set out in Standard ISO 9223 and in source [Henriksen et al. 1991, Chapters 4.3–4.5]. Also the sources of various impurities and their effects on various materials are listed. ISO gives classifications only for sulphur dioxide (SO₂) and the salinity of air. The salinity of air is given as deposition rate of chloride (Cl⁻). These are presented in Table 5.2.

Table 5.2. Classification of air pollution in ISO 9223.

SO ₂ -class	Deposition rate of SO ₂ (mg/(m ² d))	SO ₂ -concentration (µg/m ³)	Airborne salinity class	Deposition rate of Cl ⁻ (mg/(m ² d))
P ₀	≤ 10	≤ 12	S0	≤ 3
P ₁	10...35	12...40	S1	3...60
P ₂	35...80	40...90	S2	60...300
P ₃	80...200	90...250	S3	300...1 500

The values have been calculated from the mean values of measurements during a minimum of a year.

Only a deposition rate value has been given to chlorides, because saline occurs in the air mostly as NaCl particles instead of gaseous chloride Cl⁻.

A corrosivity classification similar to ISO 9223 is also set out in standard IEC 60654-4 Operating conditions for industrial-process measurement and control equipment. Part 4: **Corrosive and erosive influences**. It sets out an air quality classification for industrial process and measuring devices with the following classes as presented in Table 5.3:

- Class C1: Industrial clean air
- Class C2: Moderate contamination
- Class C3: Heavy contamination
- Class C4: Very high contamination.

IEC 60654-4 classifies sea salt mists as aerosols:

- Class C1: Locations at a distance of over 0,5 km from the sea
- Class C2: Sea coast less than 0,5 km from the shore
- Class C3: Off-shore installations.

Table 5.3. Classification of air pollutants in IEC 60654-4 with average values (mm^3/m^3)¹⁾.

Chemically active contaminants in air	C1	C2	C3	C4
	Industrial clean air	Moderate contamin.	Heavy contamination	(Very high contamin.)
SO ₂	< 10	< 100	< 5 000	≥ 5 000
NO _x	< 50	< 500	< 5 000	≥ 5 000
H ₂ S	< 3	< 50	< 10 000	≥ 10 000
Wet chlorine Cl ₂ RH > 50%	< 0,5	< 5	< 50	≥ 50
Dry chlorine Cl ₂ RH < 50%	< 2	< 20	< 200	≥ 200
Ammonia NH ₃	< 1 000	< 10 000	< 50 000	≥ 50 000
Hyd.fluoride HF	< 1	< 10	< 100	≥ 100
Ozone O ₃ or other oxidants	< 2	< 25	< 100	≥ 100
Solvents ²⁾ Trichloroethylene	..	< 5 000	< 20 000	≥ 20 000

Oils ($\mu\text{g}/\text{kg}$)	< 5	< 50	< 500	≥ 500
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¹⁾ Here units are mm^3/m^3 , see table 5.4 the analogy units $\mu\text{g}/\text{m}^3 \rightarrow \text{mm}^3/\text{m}^3$

²⁾ Solvent vapours can precipitate to form on surfaces puddles which can become corrosive, especially to the electrical parts of instruments.

An air pollutant classification was made according to Table 5.4 in a Scandinavian corrosion study [Henriksen et al. 1991]. It corresponds fairly well to the classification used by ANSI/ISA and Battelle Institute, Columbus, Ohio. When applying this classification in the assessment of corrosivity, a location/space is considered to belong for example to pollutant class P3 if even one pollutant concentration falls within this class. The actual corrosivity assessment has to be made by scrutinising the time of wetness (TOW) simultaneously with the air impurity content.

Table 5.4. Classification of air pollutant concentrations in source [Henriksen et al. 1991], the concentrations are weekly mean values ($\mu\text{g}/\text{m}^3$).

Pollutants of air	P1 very low	P2 low	P3 medium	P4 high	P5 very high
SO ₂	< 10	10...30	30...100	100...300	> 300
NO ₂	< 25	25...150	150...500	500...1 000	> 1 000
H ₂ S	< 3	3...10 ¹⁾ 3...20 ²⁾	10...50 ¹⁾ 20...100 ²⁾	50...100 ¹⁾ 100...200 ²⁾	> 100 ¹⁾ > 200 ²⁾
Chlorine Cl ₂	< 1	1...2	2...5	5...10	> 10
NH ₃ + NH ₄ ⁺	< 10	10...250	250...1 000	1 000...10 000	> 10 000
Chloride Cl ⁻	< 1	1...5	5...10	10...50	> 50
Soot	< 2	2...20	20...75	75...150	> 150

¹⁾ Limits if silver is used

²⁾ Limits for other materials than silver

Corresponding gas concentrations between units of weight and volume are:

SO₂ 1 $\mu\text{g}/\text{m}^3 = 0,38 \text{ mm}^3/\text{m}^3$ NO₂ 1 $\mu\text{g}/\text{m}^3 = 0,53 \text{ mm}^3/\text{m}^3$

H₂S 1 $\mu\text{g}/\text{m}^3 = 0,71 \text{ mm}^3/\text{m}^3$ Cl₂ 1 $\mu\text{g}/\text{m}^3 = 0,34 \text{ mm}^3/\text{m}^3$

NH₃ 1 $\mu\text{g}/\text{m}^3 = 1,43 \text{ mm}^3/\text{m}^3$

Classification of corrosion rates

Standard ISO 9223 gives corrosion rate classes of climatic corrosion for certain metals: carbon steel, zinc, copper and aluminium. The corrosion rates are expressed as micrometres per year. The corrosion rates of this standard ($\mu\text{m}/\text{year}$) are slightly higher than in standard ISO 9224, since the values in the first mentioned are the speeds of the first year of exposure and in the latter mean values for ten years.

Table 5.5 sets out the corrosion rate classification of ISO 9223, which gives the average corrosion rates for the first year of exposure for different metals. In fact, the speed classes are actually corrosivity classes reflecting the general magnitude of corrosion. Climatic corrosion is generally more rapid in the beginning and levels to a more or less constant rate toward the end of the ten years. The various classes in ISO 9223 are:

- C 1 Very low corrosivity
- C 2 Low corrosivity
- C 3 Medium corrosivity
- C 4 High corrosivity
- C 5 Very high corrosivity.

Table 5.5. General corrosion rates for the different corrosivity categories in ISO 9223.

Metal	Average corrosion rates r_{corr} ($\mu\text{m/a}$) for the first year exposure for the corrosivity categories C1...C5 (aluminium, average rates for ten years)				
	C1	C2	C3	C4	C5
Carbon steel	$\leq 1,3$	1,3...25	25...50	50...80	80...200
Zinc	$\leq 0,1$	0,1...0,7	0,7...2,1	2,1...4,2	4,2...8,4
Copper ¹⁾	$\leq 0,1$	0,1...0,6	0,6...1,3	1,3...2,8	2,8...5,6
Aluminium >99,5% ²⁾	$\approx 0,01$	$\leq 0,025$	0,025...0,2	³⁾	³⁾

¹⁾ Values are valid also for copper alloys, where Cu-content is $\geq 60\%$.

²⁾ Values of aluminium are according to ISO 9224

³⁾ In corrosivity categories C4 and C5, a marked increase in corrosion rate may be expected and local corrosion effects become important on aluminium.

In Table 5.6 is the corrosivity classification according to IEC 60654-4 and in Table 5.7 the classification of ISA (Instrument Society of America). The standard ANSI/ISA-S71.04-1985 Environmental conditions for Process and Measurement and Control Systems: **Airborne Contaminants** gives a corrosivity classification based on the corrosion rate of copper G1...GX. The unit of measurement of the corrosion rate is the amount of copper compounds during the first month of exposure measured using a test plate specified in the standard. The amount of copper compounds is expressed as nanometres or Ångstroms per month.

Table 5.6. Classification of corrosivity in IEC 60654-4, table B I, measured by reactivity of copper (nm/30d).

Corrosivity class (contamination)	Copper corrosion rate (nm/month)	Approximate visual description of corrosion of copper test plates
C 1 Low		No change
C 2 Moderate	< 150	Brown tarnish
C 3 Heavy	> 150	Black or blue-black tarnish

Table 5.7. Classification of corrosivity ANSI/ISA-S71.04 [Henriksen et al. 1991, table 4.3], first month rates.

Corrosivity class	Copper reactivity (nm/month)	Explanation
G1 Mild	< 30	Corrosivity is not a factor in determining reliability
G2 Moderate	< 100	The effects of corrosion are measurable and may be a factor in determining equipment reliability.
G3 Harsh	< 200	There is high probability that corrosive attack will occur. Environmental control or specially designed and packaged equipment is recommended.
GX Severe	≥ 200	Only specially designed and packaged equipment would expect to survive. Specification of equipment in this class is a matter of negotiation between user and supplier.

When comparing the classifications of ISO, IEC and ISA (Tables 5.5–5.7) we see that the corresponding classes for copper are according to Table 5.8.

ISA-S71.04 Appendix C contains the following equation for calculation of the normalized thickness of the corrosion layer on copper during one month.

$$x_1 = x \left(\frac{t_1}{t} \right)^A,$$

x_1 is the equivalent film thickness after one month (30 days) conditioning,
 x is measured film thickness after time t ,
 t is actual test time (days), and t_1 is 30 days.

The value of A is in various corrosivity classes: 0,3 for G1, 0,5 for G2, 1 for G3 and GX.

Table 5.8. Comparable corrosivity classes of various standards, measured with OFHC-copper corrosion rates in air.

ISO 9223	IEC 60654-4	ANSI/ISA-S71.04
C 1
C 2	C 1	G 1
C 3	C 2	G 2
C 4	C 3	G 3
C 5	..	G X

Corrosivity of various environments

In a study conducted as a Nordic joint venture [Henriksen et al. 1991] air humidity and pollutant contents were followed in all the Nordic countries at 48 different locations which were classified into typical condition groups (Table 5.9):

- outdoor conditions, city and industry
- instrument rooms, also cleaned air
- food production industry (fish and meat industry)
- animal shelters
- moderately contaminated industrial conditions
- heavily polluted industrial conditions
- seashores
- car cabins
- greenhouses.

Each test site also contained metal sheet samples according to the ISA standard and electronic components; the corroding of which was monitored under a period of six years. Based on these results, the description presented in Figure 5.6 was obtained on the location of each type of environment on the humidity/ impurity scale and the corrosivity of the conditions prevalent in each case. The measurement results of the 48 locations are given in Appendix 2 of [Henriksen et al. 1991] including the averages of temperature, relative humidity, SO₂, NO₂, H₂S, Cl₂, NH₃+NH₄⁺, Cl⁻ and particle fall (soot) during six consecutive weeks.

Table 5.9 presents a summing of the results of these test sites as six-week averages in an environment typical of each case.

Table 5.9. Air temperature, humidity and pollutants ($\mu\text{g}/\text{m}^3$) in typical Nordic environments [Henriksen et al. 1991].

	Out-door	Instr. room	Fish/meat	Anim shelt.	Indus -try	Harsh indus.	Sea-shore	Car cabin	Green house
T °C	5	23	17	20	26	25	6,5	8	25
RH%	78	40	57	82	36	49	73	43	95
SO ₂	30	3,5	0,5	0,2	19	550	4,1	2	0
NO ₂	28	17	43	24	59	23	15	30	4
H ₂ S	4,6	5,3	7,5	40	32	135	0,9	0,9	0,5
Cl ₂	0,9	0,5	2,1	0,6	3,9	15	1,6	0,3	0,8
Cl ⁻	0,2	0,3	5,7	3,4	1,1	6,2	180	0,3	0,3
NH ₃	0,3	0,9	47	424	9	21	0,3	11	0,5
NH ₄ ⁺	1,2	1	3,7	106	3,9	14	0,5	2,3	0,5
Soot	17	2,5	15	24	38	19	5,2	17	8
Num	4	10	7	6	8	6	1	4	1
TOW	$\tau_{5...6}$	$\tau_{1/2}$	$\tau_{2...4}$	$\tau_{5...6}$	$\tau_{2...4}$	$\tau_{2...4}$	$\tau_{5/6}$	τ_3	τ_6
P	P2/1	P1	P2	P3	P3/4	P5	P5	P2/1	P1
ISA	G3	G1	G2	GX	G3	GX	GX	G1	G2

Num number of locations including in the average of the material

TOW time of wetness class as in Table 5.1

P cleanness class as in Table 5.4

ISA corrosivity class as in Table 5.7.

Figure 5.7 shows the main part of these typical condition groups.

In Figure 5.7 categories P1...P5 describe the cleanness class of the air (P5 dirtiest, Table 5.4) and $\tau_1... \tau_6$ the time of wetness classification of the ISO 9223 (Table 5.1). Air impurities here are for example substances like SO₂, H₂S, NO_x, Cl₂, Cl⁻, NH₃ + NH₄⁺ and the dust and soot in the air.

As seen in Figure 5.7, a considerable share of ordinary industrial and office conditions fall into the category of moderate corrosivity, G2.

Corrosivity G1...GX as a function of time of wetness and air pollutant concentration

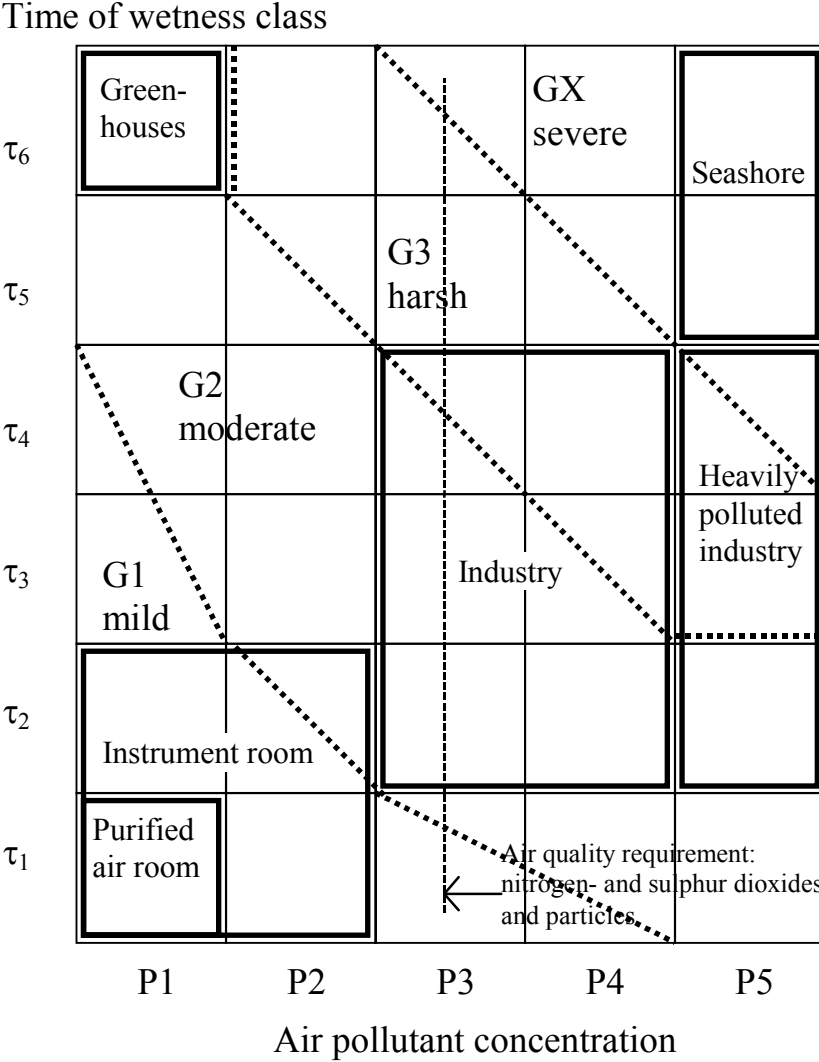


Figure 5.7. Corrosivity of typical environments [Henriksen et al. 1991].

Time of wetness is in Table 5.1 and air pollutant concentration in Table 5.4.

The harshest indoor conditions are found in the paper and chemical industry, for example. Of outdoor conditions, seashores, islands and ships represent the most difficult ones (see Section 6.10, ISO 12944, corrosivity category C5-M). Corrosivity of greenhouses is G2, although the impurity level is low, but the humidity level is continuously high. Of animal shelters, chicken houses, pigsties, cow byres and stables fall into corrosivity categories G3...GX because of an elevated ammonia content and high humidity.

Figure 5.7 also presents the location of *guideline values of air quality* as stipulated in the Council of Finnish State Decision 19.6.1996 on the vertical dotted line at P3 of the air pollutant classification (see Appendix 2 *Quality requirements of the Air*). The guideline values fall into the pollution category P3 and correspond to the median of the daily values set for sulphur and nitrogen dioxide and particle fall. There is no requirement on salinity. The permissible maximum values reach P4 category. Since the guideline values apply to outdoor air, this means that in ordinary outdoor conditions, where relative humidity usually exceeds 80%, the corrosivity of the air these guideline values fall into category *G3 harsh corrosivity*.

Figure 5.7 also shows plainly the significance of humidity to corrosivity. For example, the corrosivity of heavily polluted air (P4/P5) is at its lowest around G1/G2, if the times of wetness can be maintained in τ_1/τ_2 . Correspondingly, the corrosivity of clean air becomes great if the relative humidity exceeds continuously 80%.

Figure 5.7 gives mainly an indication of how great the corrosivity may be in the various conditions of use. In individual instances the detected corrosion may be considerably smaller or greater than the typical corrosion class (G1...GX) due to variation in the local conditions. On the other hand, the corrosion resistance of an electronic device may differ considerably from that of the base metals (copper, tin, steel, zinc, aluminium). For example, in very mild G1 conditions, the operation of a device may be seriously hampered by corrosion and contamination if the conditions momentarily change or the device is highly sensitive to faults in the keys etc. caused by corrosion. Therefore, the need of protection should always be verified separately for each product.

5.3 Production and installation conditions

The production facilities of electronics should be kept as clean as possible and well organised in order to minimise contamination of the components and the final product. The production air should be filtered, dust free and preferably regulated as to temperature and humidity. A temperature of 18...23°C and relative humidity of 40...50% RH in the incoming store, production facilities and product packaging facilities are ideal with regard to corrosion and humidity damage and the discharge risk of static electricity (see SFS-EN 100015-1 *Basic specification. Protection of electrostatic sensitive devices. Part 1: General requirements* and IEC 61340-5-1 *Protection of electronic devices from electrostatic phenomena*).

With regard to the wetting risk, corrosion and water damage (leachate) form a continuous threat in the handling of incoming goods. They are caused either through wetting during transportation or in the wintertime by water condensing on the surface of goods brought inside from the cold. The wet goods should be dried as soon as possible. The transportation boxes brought in from the cold should not be immediately opened but let warm closer to the temperature of the reception area in order to avoid condensation of water to the cold parts (see Appendix 1, Section 1.8 *Condensation of moisture on the surfaces*).

Due to the fault risk caused by water possibly absorbed by solderable plastic cased components the watertight transportation packages of these types of components, if applied, should be kept sealed in order to prevent the components from absorbing water during storage.

In actual production, the main activities increasing the corrosion risk are hand assembly, soldering, washing and parts handling in connection with testing and final assembly. If possible, the products should be handled with protected hands to avoid contamination, especially when assembling the component board. Soldering and production of the component board are discussed in more detail in sections 6.5–6.7.

The subcontractors should also be advised of the required production conditions, level of cleanness and quality of transportation packages in order to avoid contamination, wetting and corrosion of the parts before installing them into a product.

Even during product packaging care should be taken not to have too high humidity levels in the packaging boxes (see Sections 5.11 and 6.18 and Appendix 1, Section 1.7 *Relative humidity of air*). This problem is especially current in late summer when relative humidity may reach 80...90% even indoors. When the packaged products are taken out from the warm indoors, the relative humidity of the insides of the packages rises rapidly due to the humidity in warm air. This problem is alleviated by the fact that the heat capacity of the packages and the product slows the dropping of the temperature of the products, which enables the outer parts of the package at least to evaporate water absorbed into them before the temperature drops to the level of the environment.

At the installation sites the conditions often correspond to demanding outdoor conditions, which means that protecting of the products to be installed from climatic effects becomes important. The sites often have dust and sand due to construction. The transportation packages should be stored in as dry storage as

possible after the acceptance review; a rain shelter at least should be organised. Special care should be taken not to wet the products and shield them from contamination by the dust and sand on the site. The installation should be organised, if possible, to take place in the last minute before operational tests in order to minimise the exposure of still open units to outside air.

During the installation, the electronics should be protected with temporary protection gear such as shelters, lean-tos, covers and removable protective films. The connectors of fixed wiring should be protected with plugs or plastic bags in order to stop dirt and water from entering during construction. During cabling, one should ensure that water dripping along the cables has no direct access to the connectors, in other words the cables should be joined to the connectors from under them [see SFS-EN 50173].

If test runs are made at an unfinished construction site with dusty and perhaps otherwise contaminated air, temporary air filters should be placed in the ventilation gaps of the devices for the test runs in order not to contaminate the insides of the devices prematurely and not to block the actual operational (see Section 6.2 *Selection of site*).

If the conditions are periodically difficult during the actual use of the device, the corrosion and humidity protection of the device should be designed to tolerate such conditions.

5.4 Transportation and storage

The need for protection during transportation and storage depends on the device, the manner of transportation and the length of the journey/storage time. A device with transportation lasting only a week can survive with less protection than a device with a transportation time of several weeks and possibly combined with outdoor storage for several weeks at the installation site prior to installation. It is typical of transportations that the conditions are unpredictable, which means that the operational strategy to be adopted has an effect on whether a risk is taken as bad packaging or whether the products are packaged well and the increased cost endured for more secure deliveries.

The planning of the transportation logistics and packaging should always start from the transportation conditions and the conditions on the site of reception. The basic aim is to reduce the wetting and corrosion risk caused by the varying transportation conditions (see Section 6.16 *Removal of moisture from transportation packages*).

Transportations by road, sea and air usually always include great variations in temperature, humidity and air impurities. The conditions are usually fairly corrosive, especially because of eventual moisture and possibly rain. All transportations also include great mechanical stress that promotes corrosion for example in the joints.

Fully airtight transportation packages are used for minimising the risks during transportation. The device may be enclosed for instance in a tight heat sealed ethene plastic wrap, which has been filled with dry nitrogen gas and/or where all excess air has been removed and a **sufficient amount** of moisture absorbent material has been enclosed into the package (silica gel, bentonite). Closing the package to a padded board or cardboard box further ensures the unbreakability of the device package.

When designing the transportation package, the unpredictability of the circumstances and the ever present wetting risk must be considered on the one hand, and the risks caused by the package itself regarding the development of corrosion, on the other (see Sections 3.5 and 6.16–6.18). Transportation of components always means accepting a moderate risk since many of them may be especially sensitive to climatic corrosion.

For example the following basic principles may be used in the prevention of wetness and corrosion:

- enclosing the device/component in an airtight package and removing the moisture from the inside so that no condensation or frosting takes place in the transportation temperatures
- protecting the device with a semi-tight package and including desiccants for the inside air and/or corrosion inhibitors
- using cardboard packages based on wood pulp and impregnating them with corrosion inhibitors
- using packaging materials based on wood pulp as such.

The first alternative is used quite commonly in the transportation packages of microcircuits when one wants to prevent the absorption of water into the plastic case and maintain the solderability of the connection leads.

The second alternative is may be the most recommended method for keeping the devices well protected during transportation.

The biggest problem with the last two packaging methods is the tendency to absorb water and thus subject the device to the corrosive effect of humidity. The use of inhibitors as an additive in packages based on wood pulp is a possibility worth considering, especially if a recyclable packaging option is sought. The feasibility of the method must be tested prior to use for each product using the actual devices.

Figure 5.8 presents problems of ordinary pallet transportation. The products are packaged in paperboard boxes using styrofoam as support material. The products are wrapped in open plastic bags (no heat sealing). The transportation packages are stacked on the pallet and tied to it by shrinking a plastic film around them.

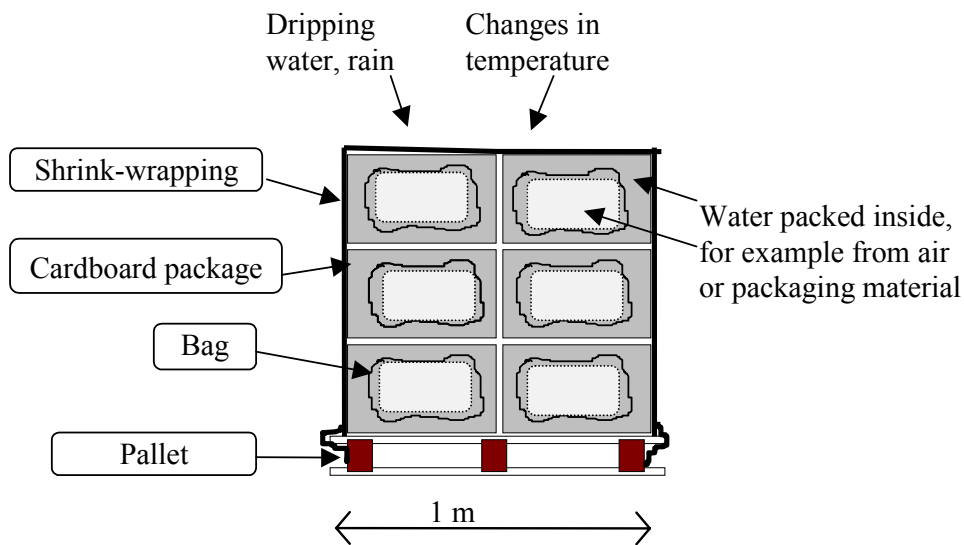


Figure 5.8. Transportation of devices tied to a pallet.

The following problems are encountered with this way of packaging:

- The pallets may be transported in containers on board a ship, where they may get wet from water accumulating in the containers, the storage time is usually between two and six weeks.
- When packaging in the warm indoors (22°C/50% RH) so much water is left in the packages that the relative humidity of the inside of the package can nearly reach 100% when the temperature drops. This takes place if the shrinking plastic film of the pallet is tightly wrapped. In practice, the humidity remains lower since some of it is adsorbed into the materials.
- The plastic shrink-wrapping of the pallet has been wrapped from top to bottom and is basically open at the top edge. Draining water enters through the seams of the wrap from the top and the sides due to the capillary force. If the wrapping were performed from bottom to top, draining water could not enter from the sides. This has significance if water drips or rains on the pallet.

- The wrapping plastic of the pallet slows down considerably the direct entrance of water from the outside to the inside (draining water presents problems if the wrapping order is wrong) and from the inside to the outside.
- An open plastic bag with no desiccants inside protects the products inside a cardboard box (desiccant unnecessary since the bag is open and not airtight).
- Some of the styrofoam contains lots of water due to a faulty manufacturing process. The water maintains high humidity inside the packages.

The packaging and transport procedure described here is very common but the risks included in it, such as wrong wrapping order of the shrink-wrapping of the pallet, function of the protective plastic bag only as a mechanical shelter and most of all, the water left in the styrofoam during the manufacturing process may cause great problems. In a case studied at VTT Automation, the galvanized parts of the device were covered in white rust due to these factors, the cut edges of the plates were rusty, corrosion had taken place in the nickel plated jackets of the connectors, the labelling stickers were mouldy and the devices and the transportation packages bore evidence of wetting. The products looked “bad” despite functioning electrically. Nevertheless, the electronic parts appeared intact superficially based on visual inspection.

The pallet packaging method in question was later tested at VTT in a temperature variation test by placing 100...300 g of water absorbed into paper in some of the packages (time 14 days, daily cycles, lowest temperature: 5°C/95% RH 10 h and highest temperature 20°C/70% RH 10 h, transfer time 2 h). The relative humidity of dry cardboard boxes after the test was 70% RH and of the insides of wet packages, 80...93% RH, according to the amount of added water. When the pallet was left at 23°C and less than 40% RH for six days, the humidity of the packages dropped only about 10%. When the outer shrink-wrapping of the pallet was removed and the boxes were left on the pallet as such, the humidity in boxes dropped 30% within 24 hours, in other words very near to the prevailing humidity of the environment, 30...40% RH. This reflects well the ability of cardboard boxes to wet through quickly, two to three hours is sufficient for obtaining the same humidity inside the package as outside it and the packaging material itself obtaining its equilibrium humidity in the prevailing conditions.

Based on the test discussed in the above, the shrink-wrapping retains water effectively. The shrink-wrapping used in pallet transportation should be removed as soon as possible during storage in order for the humidity retained in the packages to evaporate.

The cardboard packages used in the pallet were $49 \cdot 50 \cdot 60 \text{ cm}^3$ as to size. Such an empty packaging box weighs about 1830 g at 23 °C and 50% relative humidity. At 40°C and 93% relative humidity the same package weighs about 2050g, in other words it absorbs some 200g of water. The cardboard loses the main part of its mechanical strength under such levels of humidity. Cardboard materials absorb water from the air about 15...20% of their weight if the relative humidity is 100% at about room temperature. The amount of water is almost independent of temperature within the range of 5...40 °C. At a relative humidity of 50% RH, the water content is about 8% and at a relative humidity of 90% about 16% of the weight of the cardboard [Paronen & Toroi 1959].

Recycled mass made out of waste paper and the pressed products made from it (“egg cells”) absorb fair amounts of water due to their porous structure. When badly wetted through they ruin the product packaged into them, but because of their structure and absorption ability they can even out great changes in the humidity and even limit condensation in the immediate vicinity of the product.

5.5 External protection and influencing the immediate conditions

At the location of use of the device, the immediate conditions can be influenced through mechanical design (see Section 6.2 *Selection of site*). It is central to use auxiliary structures, such as lean-tos, auxiliary walls and shelters to limit direct sunshine, dripping of water, rain, wind, exposure to washing chemicals and the effect of the outside temperature on the outside surfaces of the electronics. Thermal isolation can also be used inside the device, which prevents the changes in the outside temperature due to heavy rain or changes in the air temperature from relaying to the inside.

Possibly the most central task is to prevent the access and accumulation of draining water to the sensitive parts of the electronic device, such as connectors, wiring connections and the circuit board. Exit routes should always be provided for draining water in order to prevent long-term exposure.

Another important issue is to ensure that the electronic cases are sufficiently breathable so that the water naturally penetrating the case can also leave it when the device warms.

External protection of devices under shelters or in unheated buildings is relatively easy since the needed extra shelter from rain and sun radiation is less than outdoors.

5.6 Components, wirings and connections

A good part of the corrosion risk of electronic components and wirings centres on the contacts of switches, connection wires and soldering joints. All joints that can be opened in the connectors, switches and relays require good compatibility of the mechanical and electric functions as well as materials. Since these joints are often sensitive to effects of the air they should be designed fairly inert to climatic effects. At the same time, stress caused by the use, such as dirtying and mechanical wear should be taken into account.

The manufacture of all stable solderable or adherend wiring connections (external connections of the components) and, on the other hand, their decay forms an important entity. The wiring connections are stressed for example by mechanical forces due to the varying thermal expansion factors of the materials when the temperature and the electric loading of the connections vary (see Appendix 1, Section 2.10 *Stress corrosion cracking and fatigue*). In surface mounting technique with wiring gaps of even less than 0,2 mm these factors have a great effect on the life of the joints. The problem is enhanced by the fact that the amounts of solder for the connecting wires are extremely minute which may result in their mechanical strength being too weak in relation to the occurring thermal stress. The significance of stress corrosion is great in all structures where various materials connected to one another have to be used. This applies to all components and connectors soldered onto the circuit board. A corresponding thermal stress problem also exists in the internal structures of the components.

The corrosion resistance of the components is based mainly on the quality control of their casing. Today, the best plastic cases are even more reliable than hermetic cases because of quality problems in the manufacture of hermetic cases (Appendix 1, Section 1.6 *Moisture permeability of materials*) [Sinnadurai 1996] and [British Telecom]. In difficult moisture conditions, the inlet of wires is always a risky area, since microscopic holes usually remain for water and gases to enter (see also KOTEL 212).

Maybe the most common but in practice rather frequent corrosion problem at the component level is maintaining sufficient solderability of the connection leads of the components. This is affected by the coatings of the connection leads, quality

of the transportation packages, the complexity of the soldering process and the solder materials and the fluxes used. Ensuring the solderability in both components and on the circuit board is one of the most important areas influencing reliability in the devices.

5.7 Paints, plastics and climatic effects

The paints of electronic products are usually baking paints curing at elevated temperatures or powder paints or two pack paints chemically netting at low temperatures. Therefore, the cured paint film does not emit anything to the environment.

Several types of plastics are used in the electronics industry. For example, polycarbonate, various acrylic plastics and also mechanical alloys, such as PVC/ABS are used for device cases. The plastics are painted and plated with various metal platings, which also reduces emissions. The emissions of plastic do not usually originate from the basic polymer – with the exception of externally softened PVC – but from the additives/ agents in the plastic, such as UV stabilisation chemicals, heat stabilisation chemicals and colourings/pigments. The migration of these substances from the plastic usually takes years in normal conditions (5...15 years) which means that the peak contents in the environment remain below the observation level. Only if the environment naturally contains solvents or oily substances or these accumulate on the surface of the plastic, for instance from hand lotions, the above processes accelerate enough to become significant. For electronics enclosed in a case, even this does not create problems since the plastic case is damaged before the operation of the electronics is disturbed.

Climatic effects depend greatly on the quantity of impurities (aerosols) entering with the cooling air, for instance. Even without forced ventilation, the operation of the device always produces a certain amount of heat and when switched off, the inside air of the device correspondingly cools. This always leads to some type of ventilation between the inside and the outside spaces resulting in aerosols entering the device unless the case is fully hermetic.

Depending on the consistency and structure of the aerosol particles, various molecules are adsorbed on the surface of the particles. The surface of inorganic particles (such as sand dust) is nearly always covered by a monomolecular, one molecule thick, layer of water. A similar layer of water also usually covers metal surfaces. The layer is maintained by a weak van der Waals force, which, despite

its name, are so strong on a molecular level, that the layer of one molecule can be extracted from the surface only by elevating the temperature or by creating a vacuum around the object. A layer of one molecule of water is not thick enough to cause corrosion but affects like glue to the adhesion of dust on metal surfaces. The particles remaining on the surface form capillary structures around them, which promote the adhesion of moisture in the structure (see Appendix 1, Section 3.5 *The capillary effect* and Section 3.6 *Water solutions and electrolytes*).

5.8 Negative effects of protective action

The design areas of electronics, electrical, mechanical, thermal, EMC, corrosion resistance, ergonomic and logistic design always produce demands and solutions contradicting one another.

The development of corrosion resistance would require minimising the airflow inside the device, use of isolating coatings resistant to corrosion, good protection during transportation, low temperatures of use, well isolated joints between metals etc.

The mechanics designer may ignore the gradual corroding of coatings and the right sizing of the contact forces when designing the connectors, for example. The cases can be made too open or sealed, the thermal designer may concentrate only on effective cooling and increase the airflow unnecessarily, the EMC designer may not be aware of corrosion in the contacts when using various material or the adverse effects to cooling caused by the realisation of electrical tightness.

A beautiful looking shiny surface may corrode very quickly when the product is handled. Water sprinkled on the device may ruin it because there are holes or cracks on the surface. Correspondingly, at the system level the greatly varying environmental conditions of the various parts of the device may not be considered but the same basic technique used everywhere. The harshness of conditions may come as a surprise or the action of the device users or maintenance or cleaning may produce unpredictable situations if the condition charting for the product has not been carefully done.

All sub-areas have a great significance on the price, operability and reliability of the product, which is why no sub-area may be ignored to avoid quality problems. The most important issue is to ensure the feasibility of the chosen solutions and

to eliminate their negative effects by organising joint reviews for the designers of the various sub areas and at least by sharing the information on the solution proposals of one designer to all the others.

5.9 Specification of the product with regard to corrosion

When compiling the specification for definition and control, of the corrosion resistance of the product, the actual physical aspect of the product, its method of use and the logistics of assembly and delivery to the customer should be studied. This specification can be carried out by using the review methodology described in Section 5.1 in the above and in Appendix 3 and by addressing the details of each issue to be specified. The specification formulates the views on the desired level of corrosion resistance (Section 4) and the method of realising it (Section 6) and collects the technical solutions of the various sub-areas of the design.

In practice, at least the issues presented in Figure 5.9 should be documented in the product specification. These also include the review and suitable documentation of the issues mentioned in Figure 1.8 *Areas with corrosion risk in electronics*.

The actual product specification of the device can be fairly simplified but the specifications must be studied carefully in manufacturing and acquisition of the parts and components in order to achieve the desired corrosion resistance level without serious risks due to an unspecified matter.

The specification also addresses the basic technology for realising the product and also determines the limits of the electrical, thermal, EMC and ergonomic design to which corrosion prevention must conform. On the other hand, the limitations due to the corrosion prevention aims to other technical solutions are also presented.

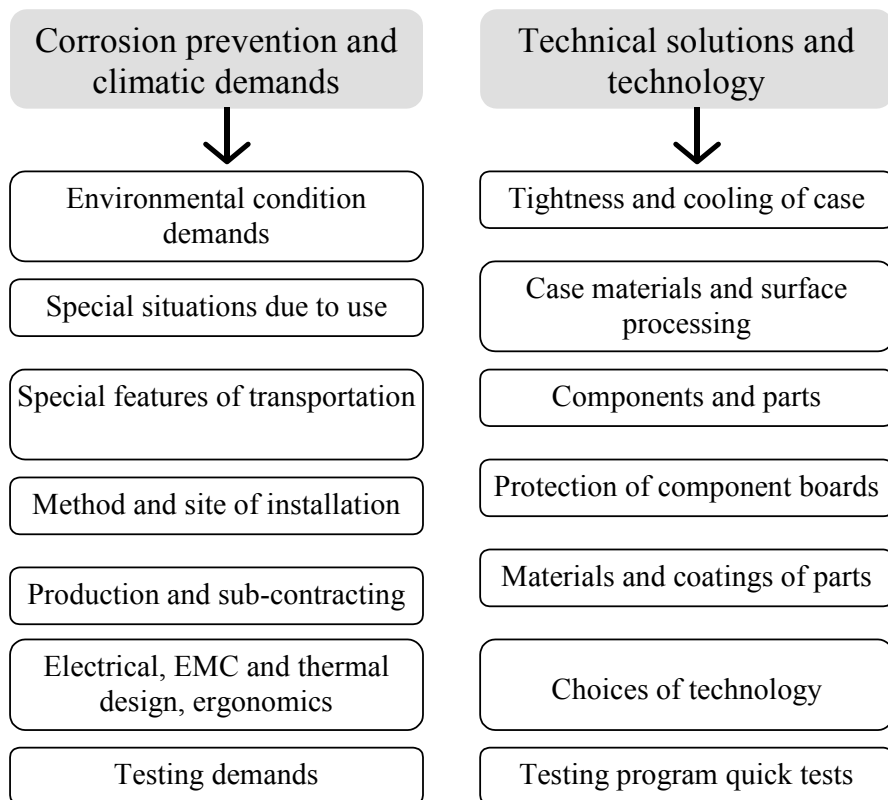


Figure 5.9. Specification of the product with regard to corrosion.

5.10 Feasibility of corrosion tests

The final conditions of use of the product must always be considered in the choice of the corrosion tests (Table 5.10) The tests should be planned in such a way that as reliable a picture as possible of the behaviour of the product in actual conditions is obtained. It is difficult to achieve comparability of tests and real world because real conditions alternate locally and they are very different on various areas of earth. Also the behaviour of peoples and difference in various cultures effect on how corrosive certain conditions are. In tests the conditions are seldom the same as in real environment, tests has to be done by few stresses a test, for example humidity, heat and 2...3 gases. In publication [SFS-handbook 108, *Classification of environmental conditions and environmental testing*] are described the principles of environment classification and testing. Also some guidance on selection of stress levels has been given for planning environmental tests of equipment.

In all corrosion tests, the first consideration is whether to test the device or its module open or closed or whether to test only individual components and basic materials.

If the properties of the coatings used in the connectors, circuit board or component leads are desired to be shown, the tests should be performed on open components and on material samples without an electric current heating them. By doing the test in this way, data on the qualities of the various coating in relation to one another is obtained, but no data on how the device case affects the corrosion. Such open testing gives the best result on corrosion tolerance, however if the earlier used and new coatings and switch structures are simultaneously compared. The large number of samples and the amount of work easily create problems in this kind of component level testing.

When a general picture of a new device construction is desired, component boards and modules of the device, as well as some of the most important connectors can be chosen for testing and these tested either separately or simultaneously with the device enclosed in its case. In such a case the tested parts and the device should be without an electric current to prevent drying due to heating. This method of testing gives a good picture on what effect the device case has on the corrosion and also on how the various materials react to the conditions of the test. Testing without a current corresponds well to temporary interruptions in the use, when for instance humidity is at its highest. This method of testing the device and its parts open is well suited for small devices, such as mobile telephones, power sources, measuring devices and microcomputers, if knowledge of the effects of the protective case is desired. If the device case has significant gaps, the differences between testing open or closed diminish.

When performing corrosion tests in the way discussed above on entire devices and their parts, one must remember that individual tests such as the mixed gas test or salt spray test are not designed to be all comprehensive testing methods. By combining the humidity, heat, mixed gas and salt spray tests, however, a reasonably good picture of the properties of the various parts of the device may be obtained.

However the environmental stress tests are performed, it would be crucial to perform a detailed analysis on what has actually taken place in the various parts of the device during the test. A mere operates/ does not operate trial after the tests is not enough but all metallic platings and wiring gaps should at least be visually inspected for possible corrosion marks. Based on this, the corrective action can be targeted right.

Corrosion tests are often accelerated tests. The accelerating factors are humidity, elevated temperature and aggressive substances. The field tests and transportation condition tests near the conditions of use are closer to practice.

The lengthy tests times and the requirement to test the product in various environments at the same time in order to obtain at least adequate correspondence to the varying conditions that the electronics may have to face during its life span create problems, however.

With regard to the stress levels of accelerated tests it should be remembered that too great a difference between the stress level of the test and that of reality leads to the wrong conclusions. For example the raising of gas or humidity contents usually leads to a particular corrosion reaction gaining predominance. In real conditions of use, there are usually several reactions but even one is enough to start corrosion. The excess raising of temperature in the tests can turn some metallic surfaces passive and stop corrosion entirely (see Appendix 1, Figure 1.1 and Section 2). It always help in bringing the results into practice, if the tests include materials or pieces the behaviour of which in actual conditions is known, in other words an internal standard is included in the test.

An examination of the combined effects of humidity, temperature and corroding gases by an accelerated test is a swift way of testing the durability of e.g. protective coatings and identifying residual process chemicals in the holes of circuit boards. The verification of the test conditions in the test chamber – the measurement of temperature and relative humidity, gas concentrations – is a requirement for an accelerated test. The control of test conditions is limited by the analysing technique of gases. Only fluorescence methods are sensitive enough for low gas concentrations, but they do not function if the gas to be analysed contains too much water. The danger here is that water condenses inside the analyser and may even destroy the device – due to corrosion! In practice 30°C and 75% RH are the maximum conditions that the analysing equipment tolerates.

Many debates have been going on about the gas concentrations used in the tests. The basic principle can however be that there has to be enough gas for it to be free in the air of the test chamber. If there is too little gas, it may adsorb onto the structures of the test chamber and subsequently too good test results are obtained. Chlorine (Cl_2) as such is only rarely a pollutant source in nature, except in the vicinity of a paper or pulp mill. In humid conditions, chlorine quickly disintegrates into hypochlorite (ClO^-) and chloride (Cl^-). Hypochlorite is a strong oxidant. In the IEC 60068-2-60 tests, chlorine is used because of its oxidising effect and formation of chlorides. Chlorine has a strong synergetic effect with hydrogen sulphide H_2S because both sulphuric acid and hydrochloric acid are created in its presence. Chlorides have an ability to penetrate the oxides protecting metals and thus increase their corrosion.

Appendix C of the IEC 60068-2-60-standard informs that chloride adsorbs onto the walls of the test chamber, which are then very difficult to clean. Therefore, the chamber must not be used for any other tests unless chlorine as an ingredient is included in that test. Another alternative is to clean the insides thoroughly and replace the gas pipes before performing other tests.

Another warning regarding IEC mixed gas tests concerns tests with hydrogen sulphide after which the chamber should not be used for pure sulphur dioxide tests prior to replacing the pipelines and the interior surfaces. The reason is that hydrogen sulphide can react with sulphur dioxide creating sulphur. The vapour pressure of sulphur in the test conditions is already so great that it evaporates into the air in the chamber in the following tests causing a sulphidation reaction on metal surfaces, although normally hydrogen sulphide causing sulphidation were not present.

Sulphur compounds are generally considered to involve the greatest corrosion hazard, but nitrogen oxides, prevalent especially in the air of cities on account of heavy traffic, have an even greater influence on the reactions. Nitrogen oxides have been found to have a catalytic effect on corrosion, particularly in sulphur oxide reactions. [Arroyave & Morcillo 1995]. Nitrogen oxides may be present as reducing (protective) or oxidising (corroding) agents depending on the concentration, other aggressive gases and metal surfaces in the surroundings. Therefore, it is important to obtain information about future field conditions and the uncovered metal coatings of the product when planning tests involving nitrogen oxides.

Chloride corrosion is extremely difficult to trace. Chloride corrosion is achieved in a gaseous atmosphere only by chlorine gas! In humid conditions, chlorine quickly disintegrates into hypochlorite (ClO^-) and chloride (Cl^-). A homespun version is to spray the surfaces prior to exposure to other corrosive gases with a well diluted, less than 5 mg/L or 10^{-5} ... 10^{-4} mol/L NaCl solution, which is dried off immediately. This procedure leaves salt residue on all the surfaces of the test specimen.

Appropriate test and analysis methods

When examining a product or its components to identify faults that may have been induced by air pollution and/or corrosion, the appearance of the exterior and interior components should be thoroughly scrutinised and all observations recorded. It is important to do a meticulous first survey and not cause any extra

contamination on the surfaces for instance from hands or dust, which might settle on previously, dust free surfaces (Table 5.10).

Prior to more thorough material analyses, it is equally important to examine the electrical functioning of the product or its units in an attempt to identify the location of the fault and whether for example leakage current between the wires on account of surface contamination or corrosion causes the fault.

The third sector to be examined is to try to identify the operating and environmental conditions in which the disturbances or faults have occurred. Details of a thunderstorm, wetting, high/low temperature or other exceptional conditions would be valuable causes for the fault and for the assessment of the risk of their recurrence.

The fourth but by no means the least item to be assessed is to check also in the specification of the faulty product which coatings, materials and protective techniques have been used in the manufacture of the product before looking for the cause of the fault in local conditions. If inferior manufacturing techniques seem to have been used, it may be best to concentrate on the observation of the nature of the faults and the specifications for their location and make decisions on corrective action on the basis of these observations.

Table 5.10 contains a list of such methods that are valid for the research of corrosion related failure mechanisms and quality control.

Elevated temperature

The dry heat and cold tests used in the tests concerning the operability of the device give fairly little information on the corrosion resistance of the product since in dry air the speed of climatic corrosion is slow and the failure mechanisms are related to thermal decay. (IEC 60068-2-1/2, tests A and B). If the time span of the heat tests is increased and the device is charged electrically faults due to oxidisation and decay of joints become visible in typical reliability tests (duration hundreds or thousands of hours). It is important, however, to perform life cycle tests since they give real information on the decay of various materials and components, since high temperature is the most important physical stress factor causing decay of the products in addition to water. The guideline IEC/TR 61026 (1991) gives advice on performing the heat resistance tests on isolation materials.

Table 5.10. Testing and observation methods for corrosion.

Method	Application and applicability
Visual inspection, enlargements 2x...40x...	Appearance, quality of surfaces water damage, corrosion, markings
Photography Optical or electric and use of magnifying under a microscope	Recommended for corrosion observation and documentation since the nature and location of phenomena and the birth / progress of a fault can be traced
Quick tests spraying of water, humidity, immersion into water, saline solution, hot air blasting, acid vapour, tape testing, scratching, chemicals results immediately or in a couple of hours	Evidence of sensitivity of a product or coating to basic stress factors already during design, also suited for acceptance inspections.
Testing of substances of human origin Human emissions, hands, hair, dandruff, skin cosmetics and smoking Sweat, breathing air, carbon dioxide, aldehydes, methane, skin creams, powders, perfumes, alcohol, tar	Evidence of the effect of human secretions and skin cosmetics and tobacco on materials in contact with humans when using the device. Reaction of plastics, contamination, corrosion of metals. Look e.g. DIN V 53160-1 spit- and DIN V 53160-2 sweat testing, and IEC 60068-2-70 abrasion of markings.
Measuring thickness, smoothness, adhesion, porosity of a coating results in part immediately, could take days	Feasible in design and production to obtain assurance of quality of coating.
Material analyses, SEM, XRF, HS GC-MS, IR... results immediately or within days	In depth corrosion research media, consistencies of substances, quality and mechanisms of corrosion, reasons for faults.
Humidity tests RH 50...100% cyclic tests from a few days to a few weeks, static tests from week to months	Humidity and corrosion tolerance of coatings, materials and components Quick first hand data of corrosion properties, correspond fairly well to outdoor conditions.

Change of power and temperature from a few days to months	Simultaneous heat cycle stress and switching the power on and off disclose changes due to thermal expansion and weak joints. Also applicable to study of fretting corrosion with heat.
Temperature changes -40...+55°C... test times from a few hours to two weeks, in life span tests a few months	Changes caused by heat expansion of structures and joints, less harsh than test with power alterations.
Elevated temperature from a few hours to months	Accelerates corrosion in materials and coatings and joints and correlates well with use, especially if the device is used dry. Corrosion shows only in tests lasting for weeks, life span tests last for months.
Elevated temperature and mechanical pressure days or weeks	Feasible for testing of elastic properties of sealing materials. Change of shape and retaining of shape after removing pressure is easy to measure.
Mixed gas tests H ₂ S, SO ₂ , NO _x , Cl ⁻ , NH ₄ ⁺ elevated temperature and high humidity simultaneously (static) test times from a few days to one month	Corrosion of coatings of components, contacts and circuit boards, non-voltage component boards Also applicable to assembled devices if the drying of surfaces due to indigenous heat from the device is recognised and first reactions only are desired and long-term effects ignored.
Salt spray tests various standard salts as water solutions, sprayed on the device and the device is kept in humidity days or weeks in between the sprays	Feasible for metal parts and metal cases of the support frames. Can be used in light form to study function of capillary cracks since salt water absorbs into cracks and travels up even bare vertical surfaces. Can be used in light form to imitate increase of conductivity in the wiring pattern of the electronic component board due to surface contamination.
Dust and water tightness tests	Suitable for examining the actual tightness of the product in extreme conditions. Help to identify method of transfer of air and humidity to the inside of the product.
Field tests sites, covered and uncovered outdoor sites test times months and years	In field tests conditions actual outdoor conditions can be created but these rarely correspond to conditions of use, suitable for basic research of coatings and materials.
Profession typical conditions	Products placed for fixed periods of time into typical profession conditions, such as farm work, tractors, chicken coops, pigsties etc. product subjected to actual conditions in the profession.

Mould fungus growth test test times 28...84 days	Evidence of sensitivity of materials to growth of mould fungi in humid conditions. Applies especially to organic materials and coatings.
Vibration tests from one hour to a day, random vibration or sinusoidal vibration	Exposes spots where movement or fretting of contacts may cause problems in use. Calls for more detailed visual analysis in connection with tests to save considerable time in the location of most fault prone spots in coatings. Discloses bad soldering joints.
Shock test, dropping test test time minutes or hours	Disclosed bad joints and weak structures, in other words production and design errors, not applicable to corrosion research unless performed several times.
Testing of fretting corrosion from hours to weeks amplitude 1...10...100 μm , frequency 1...10... Hz (fretting corrosion, friction corrosion)	Suitable for study of corrosion and wear of opposite metal surfaces due to mechanical movement. Test setup is difficult. Vibration test is feasible as pretest, which gives quick data on possible spots prone to fretting.

Change of temperature

The cyclic temperature change tests with a test time of a few days only and used as basic tests are suitable for testing the manufacturing defects, and material, component and contact defects (IEC 60068-2-1/2, tests A and B). Change of temperature is an effective means to disclose early faults in the device or for the reliability stress screening testing. [KOTEL 239 Reliability stress screening 1999] or [IEC 61163-1 and IEC 61163-2]. Temperature change can be used for testing the stress corrosion of the soldering joints and fretting corrosion properties of the connectors. Change of temperature also discloses the fault sensitivity of the component cases and structures due to different thermal expansion coefficients of different materials. If mechanical vibration is combined to temperature change, an effective combination test is created for quick disclosure of the operation and damage limits of all joints (IEC 60068-2-50 Z/AFc cold and -51 Z/BFc dry heat).

The temperature change test is often combined to cyclic humidity tests, which produces a strong wetting effect, after that freezing and then quick heating (IEC 60068-2-38/61 Z/AD and Z/ABDM). This stresses all materials where water absorbs and reveals bad contacts and isolation gaps and the faults on the boundary surfaces of materials

Static humidity tests

In the static humidity tests, 93% RH relative humidity of the air and temperatures 30, 40 and 55°C (IEC 60068-2-3, test Ca) are used on the device level. These tests that typically last a few weeks or months, the humidity absorbs and corrosion takes place. Since the device is usually without voltage in the tests, the conditions correspond to those of storage in humid conditions. Therefore, the corrosion mechanisms become obvious in different ways than in a device with voltage. If the device has voltage in these tests, the test corresponds better to the use situation but due to indigenous heat production the inside conditions are drier than in devices tested without voltage.

There is a number of accelerated tests for testing components, where the temperature is for instance 110, 120 or 130°C and the humidity 85% RH (IEC 60068-2-66, test Cx) or the commonly used 85°C/85% RH (IEC 60068-2-67, test Cy). These are discussed in further detail below.

Cyclic humidity test

The temperature typically alternates in a cyclic humidity test, for example 25/55°C or 25/65°C and the humidity is high, 90...100% RH (IEC 60068-2-30, test Db). This tests pumps moisture effectively into the materials and cases. Condensation takes place during the test, which is why the device surfaces drain water during these tests. Due to the short test times, the tests can be very effective for studying the effects of moisture. This test cannot duplicate well conditions where recurring condensation does not take place.

Salt mist test

Salt mist tests are designed for testing the metal parts and the device cases when simulating maritime and coastal conditions (IEC 60068-2-52, test Kb). The test is not feasible for testing the corrosion of the electronic parts, such as the component board or components, since salt mist is sprayed onto the tested parts making it too harsh to correspond to the actual conditions during transportation and use.

The test can be used indirectly, however

If knowledge on how easily water penetrates the cracks in the case to the inside and how it travels there is desired, salt mist spraying reveals fairly quickly the spots where water penetrates into the device through capillary cracks.

In another procedure, the salt mist test is performed in a sealed device with electronics inside. The assumption is that some salt will enter the device in connection with the spraying. After the spraying the device is kept at high relative humidity. The insides of the device are also examined after the test to detect possible corrosion.

It is possible to combine salt mist tests with flowing gas tests. E.g. [ISO 21207] describes one week test period, where the equipment is alternately in salt mist test [ISO 9227] and thereafter in flowing gas test. This method makes it possible to simulate the difficult outside conditions.

Single gas tests

Climatic corrosion was tested earlier by using either SO₂ or H₂S gas, 25°C temperature and 75% RH humidity (IEC 60068-2-42/43 tests Kc and Kd). SO₂ is suited for benchmark poriness test of gold platings and the testing of protectiveness of the cases. The H₂S test is meant for benchmark testing of silver platings and silver alloys and for testing of the protectiveness of the case. The gas contents are high in each test. Therefore, the tests are not recommended for simulation of field conditions since they give a fairly one-sided result on corrosion in actual conditions. Instead, mixed gas tests are recommended since in those, the synergy effects of the various compounds can also be read.

Flowing mixed gas tests

Mixed gas tests are best suited for testing the corrosion caused by gaseous impurities in the air SO₂, H₂S, NO₂ and Cl₂ (Table 5.11). In the test, a continuous flow of air including corrosive gases is directed through the test chamber. In this way, the repeatability of the test conditions can be guaranteed. The consciously chosen humidity level, 70...85% RH is essential in these tests, as is the simultaneous use of two or more gases. This method produces tests revealing certain failure mechanisms fairly well and tests copying certain environmental conditions. The test conditions as such do not correspond to for example office or traffic conditions, since the actual conditions vary and contain several other compounds than the ones used in these tests. The tests do, however, produce similar failure mechanisms to those discovered in field tests.

The tests are primarily applicable to the testing of various coatings and electromechanical components, such as connectors, switches and relays. They can also be used for the testing of the circuit/component boards if one desires to know whether any creeping of corrosion products takes place in them.

These tests are also suitable for general reviewing of the corrosion sensitivity of the electronic units and components, in other words they can be used in the study of which parts and coatings and existing device constructions they corrode.

In the test method IEC 60068-2-60 Test Ke: Flowing mixed gas corrosion test, Method 1 (H₂S + SO₂), the predominant fault mechanism is pore corrosion, so it is suited for pore corrosion testing of gold and palladium coatings copying mild indoor conditions. The recommended test times are 10...21 days (see. Appendix 1, Section 2.4 *Pore corrosion*).

The creep of corrosion products can be detected with humidity and heat tests and mixed gas tests. IEC 60068-2-60 Method 3 (H₂S, NO₂, Cl₂), can be used for corrosion product creep tests since the predominant fault mechanism in the test is the creep of corrosion products in addition to pore corrosion. The test is suitable for copying (simulating) more demanding industrial conditions.

The recommended test times for IEC 60068-2-60 (1995) tests are 4, 7, 10, 14 and 21 days. The test air should be replaced 3...10 times an hour.

IEC 60:M2 in table 5.11 equals Battelle II and IEC 60:M3 equals Battelle III. [Henriksen et al. 1991] states that a test of ten days in Battelle II conditions corresponds to ten years of use in G1 conditions and 20 days of testing in Battelle III conditions corresponds to ten years of use in G3 conditions (see Figure 5.7) Also NEBS GR-63-CORE in clause 4.5.2 says that a ten days (indoor and outdoor) test corresponds to roughly 15 years of equipment service life and the 14 days test corresponds to 20 years of service life.

Table 5.11. Conditions of mixed gas tests [IEC 60068-2-60, Henriksen et al. 1991, and NEBS GR-63-CORE] Unit of gas content (mm^3/m^3).

	T (°C)	RH (%)	SO ₂	NO ₂	H ₂ S	Cl ₂	Weight ¹⁾ increase
IEC ..60:M1	25	75	500	..	100	..	1,0...2,0
IEC ..60:M2	30	70	..	200	10	10	0,3...1,0
IEC ..60:M3	30	75	..	200	100	20	1,2...2,2
IEC ..60:M4	25	75	200	200	10	10	1,2...2,4

NEBS indoor	30	70	100	200	10	10	1,0...1,4
NEBS outdoor	30	70	200	200	100	20	3,1...4,1
Battelle II	30	70	..	200	10	10	..
Battelle III	30	75	..	200	100	20	..
IBM	30	70	350	610	40	3	..
Traffic ²⁾	25	85	450	650
Tele ²⁾	25	75	250	1 800

Marine/traffic ISO 21207 ³⁾	25	95	500	1 500	.	..	5,9
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¹⁾ [$\text{mg}/(\text{dm}^2 \text{ day})$] IEC 60068-2-60 gives the corresponding weight increases of test sheets made of OFHC copper (Cu-OF / ISO 431 Copper refinery shapes) in these tests. The weight increases (corrosion amounts) measured from these test sheets are used for ensuring the uniformity of the tests with this standard. The thickness of the test sheets is $\leq 0,5 \text{ mm}$ and the area is $0,1...0,2 \text{ dm}^2$.

²⁾ The last tests of traffic and telecom exchange are tests used in connection of the Nordic corrosion study [Henriksen et al. 1991]. The tests were considered to correspond to typical traffic conditions and indoor conditions of telecom exchange in a city environment.

See Table 5.4 for unit conversions $\mu\text{g}/\text{m}^3 \rightarrow \text{mm}^3/\text{m}^3$.

³⁾ ISO 21207 contains first salt spray and conditioning at $25^\circ\text{C}/50\% \text{ RH}$ and thereafter conditioning in mixed gas test, the total period being one week. This period will be repeated several times according to the specification [Eriksson et al. 2001].

The corrosivity of various flowing mixed gas tests may be almost the same although the gas concentrations are different. Therefore when one is looking for a valid test for his own application, it should be ensured that the actual use/transport condition has good correlation with the test conditions. It is recommended that those tests, which contain all the four gases in Table 5.1 will be used, then the conditions correlate with a wide variety of use/transport conditions.

Also the standard [ISO 10062] contains two- and three-gas tests. The gas concentrations are some higher than those of the IEC tests. In the tests of ISO the condition of temperature 40 °C and relative humidity 80% RH are contained also.

The standard [ISO 21207] describes two-gas tests, which are used with the salt spray test of [ISO 9227]. The test simulates conditions at seaside/marine and traffic. The test is suitable for the boxes of electronics.

Solar radiation (UV)

Sunlight has great significance for the corrosion (decay) of outdoor surfaces. Especially the ultraviolet light in sun radiation causes decay to all surfaces and materials. However, the entire radiation intensity, which is about 1000 W/m² effectively, heats all surfaces exposed to the radiation. The effect of solar radiation on the wetting of surfaces is discussed in Appendix 1, Section 1.8 *Condensation of moisture on surfaces*, which also presents the energy spectrum of the solar radiation, used in the tests.

In a test according to IEC 60068-2-5 (1975) *Simulated solar radiation at ground level*, the effect of direct solar radiation on earth can be tested. The recommended radiation intensity is 1120 W/m² and the test times 3, 10 or 56 days with varying exposure times ranging from 8 h/day, 20 h/day or continuous radiation. The environmental temperatures are 40°C or 55°C. This standard is complemented by the guideline IEC 60068-2-9 *Guidance for solar radiation testing*.

Accelerated humidity tests (85/85 and HAST)

These accelerated static humidity tests 85°C/85% RH and HAST are used to test the humidity resistance of non-hermetic components usually encapsulated in plastic. The tests are specified among others in standards IEC 60068-2-66, IEC 60068-2-67 and EIA/JESD22-A101-B, JESD22-A102-B, JESD22-A110-B and JESD22-A112-A, which give details of their applicability and application. These tests are not actual corrosion tests, but they are well suited for the assessment of moisture permeation of the casings in order to ascertain whether certain types of casing can survive certain types of climate with e.g. high temperature and humidity. In the tests, high temperature and relative humidity force water through the structure of the casing. When water reaches the surface of a microcircuit and gets into contact with the wires, ionic impurities are set into motion and metal is corroded causing faults and malfunctions, which indicate that water has penetrated the casing in these tests.

[Sinnadurai 1996, Plastic..] has compared the applicability of accelerated humidity tests in the assessment of the reliability of various components. He has presented Table 5.12, which is based on his model describing moisture resistance of plastic casings [Sinnadurai 1985, Handbook of Microelectronics Packaging and Interconnection Technologies], which takes account of the absorption and permeability of water in plastic casings. According to the model, a 1 000 h HAST test equals 20 years' use in a temperature of 29°C and a humidity of 86% RH. A corresponding test in conditions of 85°C/85% RH takes about 5 100 h. Moreover, Sinnadurai point outs that the reliability test data correlates well to the data collected from the field in India. HAST and 85/85 tests are well suited for assessing the moisture resistance of components encapsulated in plastic and for comparing the function of various types of component packages.

Table 5.12. Testing times of accelerated reliability tests for microcircuits encapsulated in plastic in various simulated environmental conditions [Sinnadurai 1996, Plastic..].

Climatic zone / conditions (average)	85/85-test time (h)	HAST-test time (h)
	85°C, 85% RH	108°C, 90% RH
Temperate, instrument room (30°C, 25% RH)	300	60
Temperate, common (12°C, 72% RH)	500	100
Tropical, coverage 95% of Indian conditions (29°C, 83% RH)	4 100	850
Tropical, coverage 95% of Indian conditions (29°C, 86% RH)	5 100	1 000
Tropical, severe (35°C, 90% RH)	10 000	2 000

$$t_s = \frac{t_{life}}{\exp\left\{0,00044[(RH_{test})^2 - (RH_{amb})^2] + 7000\left(\frac{1}{T_{amb}} - \frac{1}{T_{test}}\right)\right\}} \quad (5.1)$$

- t_s = required testing time for simulation (h)
- t_{life} = the length of life span to be simulated (h)
- RH_{test} = relative humidity in test (%)
- RH_{amb} = relative humidity in use (%)
- T_{test} = test temperature (K)
- T_{amb} = operating temperature (K).

This Sinnadurai-HAST model for the assessment of the duration of moisture tests can be used when designing moisture resistance tests for microcircuits encapsulated in plastic.

The use of humidity tests is discussed also in [Peck 1987] publication Accelerated Testing Handbook, which discusses in general accelerated reliability tests of semiconductor components.

Growth test of mould fungi

The growth of mould at high humidity is usually a visual problem in electronics, but as such it can sometimes be a nuisance since the mould fungi grow in the packaging materials and other organic materials which feed them.

Table 5.13. Mould cultures recommended for the tests [IEC 60068-2-10 1988].

	Name of mould culture	Nature
1	<i>Aspergillus niger</i>	Grows profusely on many materials and is resistant to copper salts
2	<i>Aspergillus terreus</i>	Attacks plastic materials
3	<i>Aureobasidium pullulans</i>	Attacks paints and lacquers
4	<i>Paecilomyces variotii</i>	Attacks plastics and leather
5	<i>Penicillium funicolosum</i>	Attacks many materials especially textiles
6	<i>Penicillium ochrochloron</i>	Resistant to copper salts and attacks plastics and textiles
7	<i>Scopulariopsis brevicaulis</i>	Attacks rubber
8	<i>Trichoderma viride</i>	Attacks cellulose textiles and plastics

IEC 60068-2-10 (1988) *Test J and guidance: Mould growth*. defines the various mould growing tests in electronics performed with mould spores (Table 5.13). IEC recommends to test practices, in the first, a clean surface is exposed as such to a water suspension including mould spores and in the second version, a solution with nutrients promoting fungal growth is spread on the surfaces which are then contaminated with the mould spore suspension. The testing temperature is 28...30°C and the relative humidity of the air >90% RH. Condensation is not allowed. See also [MIL-HDBK-454 Guideline 4: Fungus inert materials, MIL-T-152, and MIL-STD-810, method 508].

5.11 Use of analysis methods

The study and detection of corrosion is relatively easy if there are clearly detectable corrosion products on the surface. In most cases scrutiny under a light stereo microscope at 10...50 times magnification gives a clue of the passage of events. It makes sense in the use of analysis methods to proceed from the simpler methods to the more sophisticated ones by weighing the results in the meantime. When performing failure analyses, it is worthwhile to photograph the entire device and its parts, for instance as well as the likely spots for corrosion in order to verify the reasons for corrosion and the interpretation of the results during the progress of the analysis. Electron microscopy (SEM) and the analysis methods linked to the microscope (EDS, AFM, ESCA, SIMS), and XRF, HS GC-MS, IR are among the most effective analysis methods for sustained damage and corrosion products.

The disadvantage of electron microscopy is that it does not give much information on organic substances. The best methods for analysing these are the infrared (IR) analysis methods; these days even directly from the surface of the sample. By combining organic and inorganic analytics a very reliable picture of the corrosion phenomena leading to the damage can be obtained.

Although the analytics offers possibilities, the results obtained must always be verified for practice by using various test methods. These are especially needed when there are no telltale signs of corrosion and the reasons for the faults remain obscure.

The analytics needed for observing the conditions sometimes places limitations on the use of the test methods. For example, there are limitations to the use of mixed gas tests. The verification of the test conditions in the chamber – temperature and relative humidity, gas concentration is a requirement for the tests. The gas analysis technique limits the measuring possibilities of the test conditions. At low gas concentrations, only fluorescence methods are sensitive enough but they will not work if the gas under analysis contains too much water. In practice, 30°C and 75% relative humidity are the maximum conditions for use of the fluorescence method.

5.12 Monitoring of conditions

Knowledge of the conditions of use of the devices is necessary for setting the environmental requirements as realistic as possible. Simultaneous data on air temperature, humidity and corrosivity in the vicinity of the devices and inside them is needed for making conclusions about the conditions inside the device. The continuous measurement of a single corroding gas may be needless, since there is a variety of corroding substances in the air.

Perhaps the most feasible method of monitoring the conditions of a device would be to place temperature, humidity and corrosion sensors inside it with a data collecting microcircuit to issue data on the actual conditions inside the device during its life cycle. The same metals used in electronics, copper, silver, nickel, steel and zinc can be used in the detection of corrosivity. In the ISA-S71.04 Airborne Contaminants standard, the corrosion of copper is used as a benchmark for the corrosivity of various conditions (Table 5.7).

Purafil has realised a separate measuring device based on the corrosion of metals. The device monitors constantly the corrosivity of the air space. The sensor metal in the Purafil device is copper, silver or gold plating the corrosion and contamination of which is measured by detecting the change in the mass of the sensor using the quartz crystal microbalance method (QCM), see [Jaeger 1997 and Muller 1999]. QCM can detect the corrosion caused by less than $1 \mu\text{g}/\text{m}^3$ gas concentration and it enables constant monitoring of the overall concentrations. This method gives data on the total corrosivity of the air space under scrutiny. Individual corroding elements cannot be directly separated with the method unless a substance analysis is carried out on the surfaces. The method in question can be used in the monitoring of corrosivity of the clean rooms in semiconductor manufacturing in conditions set out in [SEMI Standard F21-95].

6. Improvement of corrosion resistance

6.1 Influencing the microclimate

The quality of the air in the vicinity of a finished device can be influenced on three levels:

- choice of location in indoor/outdoor conditions (see 6.3)
- influencing the conditions in the immediate vicinity
- influencing the conditions inside the device.

Various means can be used in each device/use application to alleviate the corrosive effects of the existing macro climate or instrument room. In all cases the aim is to reduce dust and other such contamination, prevent wetting and minimise gas contacts.

Immediate surroundings

The most appropriate means in indoor use is to ensure by appropriate instructions that the operating conditions of the device are satisfactory and the device is located in heated, dry premises. In some cases air conditioning and even removal of airborne gaseous contaminants may be necessary. The instructions for use should include cleaning directions and a warning about corrosion risks that various chemicals may cause. Even in the absence of air conditioning, one should ensure that the device does not get wet, it is not kept outdoors, dusty air is not blown into it, there are no powerful heat sources nearby and that it is protected from direct sunlight and that structural protective measures are used in permanent installations to counteract the most severe conditions.

In industrial applications where the amount of corrosive substances may be very high (process industry) the location of the devices should be carefully planned and e.g. a clean-air blower used at the location.

Temporary corrosion protection can be used in the transport packages of the devices and components (VCI materials, Volatile Corrosion Inhibitor), e.g. silica gel or bentonite for drying the air of the package, and materials that absorb corroding gases (SAP Surface Active Paper). These methods function only in a fully sealed space. The amount of silica gel must be sufficient to absorb all the moisture from the space. If all moisture is not absorbed, silica gel becomes a moisture-maintaining material and the situation is even worse than without it. The situation with VCI-inhibitors is analogical, if the amount of the inhibitor is

too small, the corrosion speed increases because the metal surface is protected only in places – anode-cathode pairs are formed on the surface and an opportunity for corrosion is created. The usefulness of SAP materials is based on their ability to absorb corrosive gases without releasing them back into the space to be protected [Kelly 1999].

When devices are stored at the installation site, shelters or protective sheds should be used and the installed structures should be protected from direct soiling and wetting.

Conditions inside the device

From the point of corrosion risk, it is essential to ensure that sufficiently dry and clean conditions prevail inside the device and temperature fluctuation is minimised. The most common practical problems are:

- excessive ventilation increases contamination and/or elevates moisture level,
- high temperature or temperature changes increase corrosion risk,
- moisture is accrued inside the device as a result of insufficient ventilation.

In respect of a closed device casing, e.g. a mobile telephone, the most suitable solution is to make the cover relatively tight and breathing so that water can get in only through capillary cracks and, in the form of vapour, through the materials (see Appendix 1, Section 3.5 *The capillary effect*). Water vapour exits through semi-permeable films (see Appendix 1, Section 3.9 *Water repellent and permeable materials* and GORE-TEX®). Gases enter the device similarly to water, but dust and liquid chemicals remain mainly outside. The warming of the device itself dries it and decelerates corrosion substantially. The moisture level inside and outside the device is the same during transport.

Moisture and air impurities accrue on the coldest surfaces in a closed space. If the temperature of one of the surfaces is below condensation limit, it attracts water and dries the air. This can be utilised both ways. The device can be made as isothermal as possible in order to avoid condensation or, alternatively, an element colder than the rest can be included to collect water to prevent the more sensitive elements from getting wet.

In an open device casing, e.g. an efficiently cooled motor control, the problem is excessive contamination of electronics. Contamination can be minimised by arranging the cooling so that the needed large amount of cooling air is directed only to the passive cooling fins and the rest of the electronics is sealed semi-

tightly with eventual breathing vents. This will keep the electronics clean and the effect of moisture will be less than in a contaminated device.

A less efficient but adequate dust cover is to put a screen or casing around the more sensitive elements to prevent contamination carried by cooling air.

Two-part electric connectors, where the contacts are protected by the frame provide fairly good protection against corrosion by airborne dust and gases. The effect is mainly based on mechanical protection of the contact area provided by the frame minimising gas contacts and migration of dust to the contacts.

In outdoor device cabinets with an efficiency of hundreds of watts it is possible to decrease corrosion risks by transferring heat by a passive or active heat exchanger and by circulating only clean dry air inside the device. Here, the use of outdoor air is minimised. An additional problem may be created by condensed water formed by sunshine and night-time radiation of heat to the sky or by the cooling effect of rain and, in extreme cases, water dripping on the electronics. This effect can be limited by using heat insulation on the outer surfaces. Another method is to distribute waste heat of a continuously functioning device evenly to the outer surfaces including the floor space to minimise condensation.

Problems may arise if connectors are placed at the bottom close to the air vents of outdoor device casings, because they are cold and condensation occurs. This problem can be avoided by conducting the heat of the device itself to the connectors to prevent condensation.

6.2 Selection of site

The location of the device and local protection technique may be crucial in respect of problems ascribed to contamination, wetting or heat both indoors and outdoors.

A typical problem is that some equipment or units supplied to the customer develop faults or begin to perform inaccurately sooner than expected on account of contamination, moisture or solar radiation. When these faults occur, new coating materials are tried or the problem is construed as local contamination etc., even though the fundamental reason may well be that the device or its element has been installed in a wrong place on the user site.

It is possible to minimise the effects of airborne dust, gaseous contaminants, rain, dripping water, water condensation and direct solar radiation by selecting the right place for the actual device e.g. a sensor observing the environment and by local external protection technique. All these harmful facts affect the outer surfaces of the devices and, in addition, cooling air and heat conductivity paths affect the interior parts.

Methods of limiting contamination

Since air always contains dust and other corrosive particles caused by traffic, wind and other sources, the worst surface contamination both indoors and outdoors occurs in places where the airflow is discernible even by human senses (flow rates $> 0,1$ m/s). Vicinity to fresh air vents in ventilated spaces and wall surfaces above radiators attracting visible soot and dust residue are good examples of such locations. If a sensor observing the environment (temperature, humidity, smoke, movement) is placed in such a location, it may become contaminated or defective or give slightly erroneous readings after a surprisingly short time.

Wind screens or shelters can be used outdoors to limit the problems caused by the airflow (even a flimsy barn gives good protection).

Ways to limit wetting

Various water damage, washing the equipment or the premises and condensation may cause indoor wetness. If washing the surfaces of the device or its vicinity is part of its normal use, the device or its elements should be placed so that water coming in contact with the surface can freely drain away and it should be ensured that there are no capillary cracks in the casing to adsorb water and various chemicals.

Pressurised water is sometimes used to wash the devices and the strong flow of cold water cools the device rapidly. This creates a vacuum, which absorbs additional air and water into the casing. The means to minimise the accrual of water are correct location, tightness of the casing and adequate ventilation.

In buildings, a situation may arise where warm and humid inside air is let through the wall or ceiling structures which makes the water in the air condense on all colder outside surfaces. If electronics or wiring connections is installed in such a place they may be wet for most of time which means an extremely great corrosion risk.

Rain and changes in the air temperature cause outdoors wetting. Quickly starting rain effectively cools the outside surfaces of devices, which may cause condensation and absorption of rainwater into the device. Using a small shelter above them can protect sensors and various terminals most simply. When using larger devices, a shelter or a removable cover offers adequate protection from the rain and the condensation problems caused by direct sunlight and radiation of heat taking place at night (see Appendix 1, Section 1.8 *Condensation of moisture on the surfaces*) an unheated protective building would be even a better alternative.

With regard to various antenna masts both rain and condensation water run down the structures because a mast always collects water for structural reasons. Condensation is common because the structures are outdoors and cool to a temperature below that of the surroundings at night collecting water on their exterior and interior surfaces. The top of very high masts (television) is often in the clouds where water condenses on all solid surfaces.

Tubular mast structures may create problems because water condensed on their interior surfaces cannot evaporate and perhaps not even drain away resulting in high humidity and corrosion inside the tube. The problem is further aggravated by the fact that the interior surfaces of the tubes may be insufficiently protected. The structures should be ventilated and the drainage of water secured.

Outdoors placed cables collect water on their exterior and interior surfaces if they are uncoated and exposed to rain and draining water. Moreover, condensation water is collected on account of night-time cooling. Water inside the cable and on the external surfaces drains downward and may corrode the device connections unless the cable has a downward bend before the connecting point [see SFS-EN 50173].

Selection of installation base

Small device casings, measuring apparatus, alarms etc. should not be installed on a concrete or steel base without heat insulation in outdoor conditions and unheated indoor premises, because the time constant of the change in the base temperature and heat conductivity may produce substantial condensation and moisture in the electronic components.

In the case of Figure 6.1 when the air gets warmer after a cold period, the massive base remains cold and water begins to condense on its surface and the parts against it. If the casing of the device and the installation surface are good

heat conductors, the device follows the temperature of the base. This results in condensation of water on the cold interior surface which drains/drips on the electronics and causes rapid corrosion. This phenomenon is difficult to detect, because similar devices may function flawlessly on wooden or otherwise insulated surfaces, since they remain dry on account of slower temperature fluctuations.

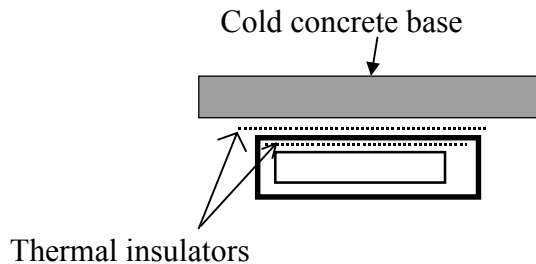


Figure 6.1. Outdoor/indoor installation of a sensor on a cold massive surface.

If heat-insulating material, i.e. material with poor heat conductivity, is placed inside the device or on its external surface, condensation will not cause problems because temperature of the device will follow sooner the air temperature.

A similar problem occurs in various measuring elements at night-time when heat radiates from the surfaces (cf. Appendix 1, Section 1.8 *Condensation on the surfaces*) which are cooled to a temperature of up to twenty degrees below that of the surroundings, which regularly results in condensation and frost. Even in this case a “screen” between the sky and the measuring element would reduce the risk of condensation significantly. This technique is in general use at meteorological stations where the measuring elements are surrounded by a “bird box”. However, in most cases the best way to avoid condensation is to heat the surfaces.

6.3 Selection of tightness of the casing

The basic task of casing (enclosure) is to protect the electronic components from corrosion by

- reducing mechanical stress
- minimising the gas and dust contacts inside the device
- preventing the access of water, dust and organisms to the interior
- reducing the risk of water condensation
- reducing temperature fluctuation in the interior parts.

The structure of the casing should also permeate the waste heat created by the electronics and ensure adequate electro-magnetic protection (EMC properties).

The tightness of the casing should be adapted to the corrosion resistance of the electronic elements in accordance with the operating conditions of the device (outdoor installation, mobile use, transport vehicle, indoor location) in order to identify a suitable and reasonably priced solution.

Multi-layer technique can be used in the manufacture of casings. The layers may have the following selected protective properties starting from the outermost layer:

- The outermost layer protects the structure from solar radiation (radiation from thermal, ultraviolet and visible light sources), rain, wind in addition to mechanical protection (shed, roof, outermost mechanical covering).
- The middle layer counteracts temperature fluctuations and minimises the transfer of gases (water vapour, etc.) from the outside to the inside.
- The innermost layer in component boards and components protects the actual casing around the electronic components from incoming moisture and impurities.

In an ideal model, the outermost layer prevents direct access of external stress factors and contaminants into the interior parts of the device as well as circulation of air between the interior and exterior parts. Since clean, dry air circulates in the interior parts, inexpensive materials and coatings can be used in the electronic components. The ideal model also has an efficient heat transfer system to transfer waste heat from the interior part to the outside and outer parts are kept a little warmer than outside air keeping parts dry.

In principle, a similar multi-layer technique can be used both in large-size equipment and in small mobile phones.

Depending on the application, one of the following may be chosen as a strategic starting point for the selection of the tightness of the casing of an electronic device (protection classification IP, see Section 6.4):

- tight closed casing (watertight or IP 66, no open holes)
- breathing open casing (at least open capillary vents, e.g. IP 65)
- open casing, natural convection (IP 21...)
- open casing, forced convection (IP 21...)
- open frame (IP 00 no covering casing structures).

A tight closed casing provides an opportunity of using inexpensive coating and dense packaging techniques inside the device. Corrosion risk decreases significantly and it is possible to use contact coatings which are normally suited only for moderate indoor conditions. Very dense wire patterns may be used because of a smaller risk of leakage current and metal migration.

A tight closed casing usually prevents the entry of water and gases or retards their access so that the interior parts remain dry and clean. Risk of condensation is small unless humid air has remained in the interior during the production phase. When manufacturing a tight casing, protective gas or vacuum should be used to ensure that the casing is free from moisture which would condensate on the surfaces when temperature sinks below the dew point (see Appendix 1, Section 1.7 *Relative humidity of air* and Section 1.8 *Condensation of moisture on the surfaces*).

A difficulty in the use of this type of casing is to maintain the tightness of the casing in severe outdoor conditions throughout its planned life cycle. In the long run, water may seep in and this increases the risk of corrosion. An inferior “tight” casing can be a worse choice than an open breathing casing.

It is particularly difficult to produce a sufficiently tight casing for conditions where powerful waterspouts occur and the water is saliferous. These conditions prevail at sea and on the roads where ice-control salt is applied. Salt water is absorbed through capillary cracks into the casings and it corrodes the metal parts efficiently. Signal lights and lamps of transport vehicles are examples of products submitted to these conditions. The problem is aggravated by the fact that plastics have fairly good water permeability and consequently it is difficult to keep the electronic components functioning for even a few months without well protected and coated wire patterns on printed wiring boards or closed casing.

A solution similar to a tight casing is a device cast in protective mass with no airspace. This is feasible in respect of small devices and units. When the product is serviced, the unit is replaced.

A breathing open casing protects the interior parts from the immediate effects of outdoor air and water. However, the films and packaging of the casing, which permeate water and water vapour, allow air and moisture pass in and out when air pressure changes (inside and outside temperature fluctuations). If respiration is adequate, there is sufficient ventilation inside the device to dry the air assisted by the warmth of the device itself. Moisture may accrue inside due to condensation and therefore attention should be paid to the quality of the coatings

and the wire spacing on circuit boards. This type of casing is perhaps the best compromise in respect of tightness for fixed outdoor installations and mobile devices, e.g. mobile phones and various measuring and radio equipment for field use.

An open casing structure using natural convection protects the interior parts mainly from mechanical contact and potential splash water and allows free circulation of outdoor air through the interior of the device. The circulation is not necessarily very marked, but in high-power ($\cong 100$ W) applications the air circulation may be fairly strong.

In an open structure, airborne gases, dust and moisture have fairly easy access to the interior of a device, and consequently it is important to invest in the quality of coatings, topical protection of the wire pattern (solder resist and lacquer coating) and the protection provided by the structure of the components themselves. Repeated condensation and wintertime freezing is to be expected in outdoor installations.

A suitable strategy when using open casings is to use better encapsulated components, high-quality connector coatings and well-protected circuit boards to ensure adequate corrosion resistance of the components.

When forced convection is used, an open casing structure may be necessary for cooling high-power devices. In this alternative, untreated outside air (indoor or outdoor air) is sucked or blown into the device to cool the electronics. When the airflow touches the electronic components, dust is easily accrued on the surfaces, air humidity has an effect equal to that of outside air and airborne gaseous impurities have direct access to all interior parts. Air blown with a relatively high velocity (>1 m/s), maintains a greater corrosion risk than stationary outdoor air (1 m/s equals a decrease of temperature of approximately one degree on the water evaporation scale, i.e. an increase of 5% RH in the apparent relative air humidity). This construction is especially risk-prone if the air is taken directly from the outside with moisture and corrosive dusts (sand, salts, etc.) accruing directly on the electronic components and connectors.

In this case the best way is to arrange the cooling so that raw outside air is blown only to the cooling fins and the rest of the electronics is protected from direct air blow or placed in a breathing casing. In this construction, appropriate thermal design may make it unnecessary to cool the electronic components by outside air.

Light mechanical screens may be used in structures needing powerful ventilation to prevent direct airflow to e.g. connectors and unprotected wire patterns from. This helps to avoid the accrual of dust on sensitive metal surfaces and contacts. The frame of a common two-part edge connector provides surprisingly effective protection against airborne corrosive gases and especially dust, since air circulation is minimal in the interior parts of the connector body which houses the contacts.

In the case of an open frame the electronic components are fully exposed to the ambient conditions. In this alternative the use of electronics is possible only if the surroundings are clean and the air is dry. In this case the methods of protecting the electronics are similar to those used with open casings.

6.4 Degrees of protection by enclosures, IP-code

The protection classification presented here (Figure 6.2) is laid out in the standard IEC 60529 Degrees of protection provided by enclosures (IP Code, IP is International Protection).

According to it, the protection class of various enclosures is expressed by a four/six digit code (Figure 6.2). The protection classification indicates the possibility for a person to touch the live elements of an electric device (first numeral) with his hand or with various tools and the protection class indicating the harmful effect of water (second numeral).

If a characteristic numeral is not required, letter X, for example IPX5, which means that the mechanical protection class is not specified, shall replace it. Tables 6.1 and 6.2 contain the IP-codes of IEC classification.

If a device meets the protection classes IPX7 or IPX8, it does not necessarily tolerate pressurised water jets and has to be separately tested for protection classes IPX5 and IPX6 when necessary.

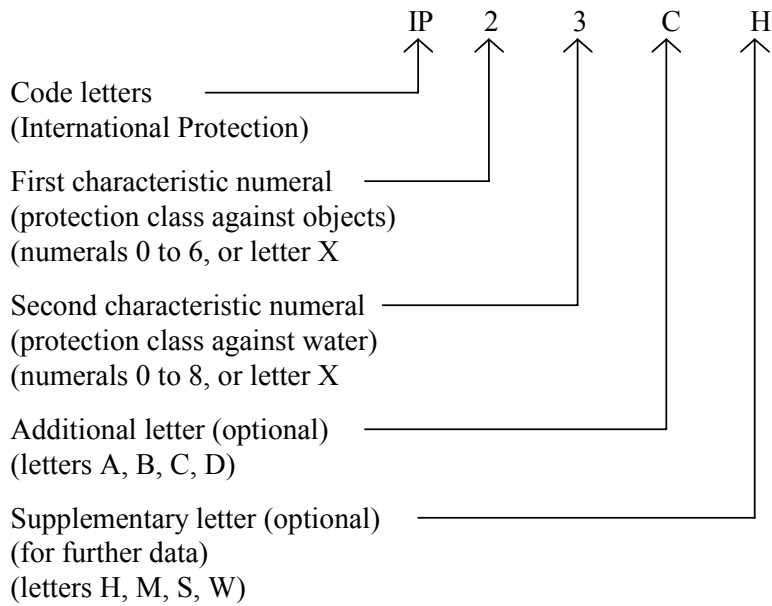


Figure 6.2. Degree of protection provided by an enclosure, IEC IP Code.

Table 6.1. Degrees of protection against **solid foreign objects** indicated by the first characteristic numeral of IP Code.

First numeral	Description of protection degree	Definition of test
0	Non-protected	..
1	Protected against solid foreign objects of $\geq 50 \text{ mm } \varnothing$	The object probe, sphere of $50 \text{ mm } \varnothing$, shall not fully penetrate
2	Protected against solid foreign objects of $\geq 12,5 \text{ mm } \varnothing$	The object probe, sphere of $12,5 \text{ mm } \varnothing$, shall not fully penetrate
3	Protected against solid foreign objects of $\geq 2,5 \text{ mm } \varnothing$	The object probe of $2,5 \text{ mm } \varnothing$, shall not penetrate at all
4	Protected against solid foreign objects of $\geq 1,0 \text{ mm } \varnothing$	The object probe $1,0 \text{ mm } \varnothing$, shall not penetrate at all
5	Dust-protected	Ingress of dust is not totally prevented, but dust shall not penetrate in a quantity to interfere with satisfactory operation of apparatus or to impair safety
6	Dust-tight	No ingress of dust

The additional letter (fifth symbol, e.g. IP24C) is used to express the protection class for personal safety if it is higher than the actual mechanical protection class (letters A, B, C and D are used). The sixth symbol (supplementary letter) is used to indicate additional properties of the device (e.g. H = high-voltage device), e.g. IP54XH. See also the test IEC 60068-2-68 Environmental testing – Part 2: Tests – Test L: Dust and sand.

Table 6.2. Degrees of protection against **water** indicated by the second characteristic numeral of IP Code.

Second numeral	Description of protection degree	Definition of test
0	Non-protected	..
1	Protected against vertically falling water drops.	Vertically falling drops shall have no harmful effects.
2	Protected against vertically falling water drops when enclosure tilted up to 15°.	Vertically falling drops shall have no harmful effects when the enclosure is tilted at any angle up to 15° on either side of the vertical.
3	Protected against spraying water.	Water sprayed at an angle up to 60° on either side of the vertical shall have no harmful effects.
4	Protected against splashing water.	Water splashed against the enclosure from any direction shall have no harmful effects.
5	Protected against water jets.	Water projected in jets against the enclosure from any direction shall have no harmful effects.
6	Protected against powerful water jets.	Water projected in powerful jets against the enclosure from any direction shall have no harmful effects.
7	Protected against the effects of temporary immersion in water.	Ingress of water in quantities causing harmful effects shall not be possible when the enclosure is temporarily immersed in water under standardised conditions of pressure and time.
8	Protected against the effects of continuous immersion in water.	Same as for numeral 7 but conditions of pressure and time shall be agreed between manufacturer and user and they must be more severe than for class 7.

6.5 Printed board

In this report, printed (wiring) board (PWB) denotes insulation plates used in electronics with one or several layers of conductive patterns (e.g. metal).

With regard to corrosion control, the printed board is one of the most important components and its properties have a very significant influence on the production characteristics and reliability of the device in operating conditions. The critical

properties of the printed board when assessing the potential effects of corrosion are:

- electrical conductivity of the conductors and their connections
- good electrical insulation of the conductors intended to be insulated
- moisture absorption properties of materials
- insulation of conductive patterns against external contamination
- corrosion resistance and chemical inertia of materials.

The manufacturing process of printed boards includes a number of different chemicals and water which, unless removed from the board, may cause soldering problems and accelerate corrosion. In simple terms, a good finished circuit board is dry and clean, the conductive pattern is chemically and mechanically well protected and the soldered areas and other exposed metal patterns have good, corrosion resistant coatings.

By dimensioning the conductive pattern correctly, the electronics designer can contribute a great deal to the corrosion resistance of the printed board. The fundamental rule for the design is simple: The isolation spaces and conductor widths are maximised and the conductive pattern is protected against external contamination. In practice, very thin conductors and narrow, long conductor spacing should be avoided as far as possible. A bad combination is two broad wires with very narrow spacing. The insulation resistance of this combination is small and there is plenty of corroding material. The field intensity of narrow conductor spacing is high and this accelerates corrosion.

The design of the thermal properties of printed boards should be as symmetrical as possible to ensure their soldering resistance (heat resistance). The metal areas of each wiring layer should be balanced and the various layers should be positioned symmetrically to avoid bending of the board during soldering.

The manufacturing process of a printed board creates a number of properties promoting corrosion and accumulation of water. The manufacturing process leaves various conductive ionic impurities on the printed board, the printed board material may remain moist, and water may be adsorbed into the holes of the wire pattern. The boards may be wrapped in plastic too soon resulting in condensation of water when the package cools. The board package may also get wet on account of rain. Moreover, the soldering properties of the printed boards may be poor. If the soldering areas have time to age, the surfaces oxidise and corrode when exposed to air and its impurities [Erickson-Natishan et al. 1999]. The conductive pattern may also be damaged if moisture remains in the printed

boards, when water vapour tears the structures of the board during soldering at over 200°C.

The printed board conductors are coated to protect the copper pattern from corrosion on the one hand, and to ensure the soldering properties of the soldering areas, on the other. Uncoated copper and tin, silver or nickel coatings oxidise and corrode fairly rapidly in transport and storage conditions. Moreover, if a multiphase soldering process is used, i.e. the components are soldered on both sides of the board in two or three stages, the previous soldering stages cause rapid corrosion of the unsoldered conductor areas due to high temperature and/or the soldering flux. This may result in impaired soldering properties during the subsequent phases of the project. Correct coating of the conductive pattern and the use of an appropriate flux are essential to avoid these problems.

Source [KOTEL 243] sets out the possibility of using organic coatings (OSP) to preserve soldering properties in place of the traditional tin-lead coatings (HASL Hot air solder levelling). Their advantages in comparison to tin-lead and other metal coatings include thinness of the coating, evenness of surface, good precision and anticorrosive properties during transport, storage and repeated soldering. Humidity tests (85°C/85% RH, 500 h) performed on organic protective coatings demonstrated no reliability problems or harmful corrosion. The test results were in certain respects better than those for boards coated using the HASL technique. Because the component is joined directly to the copper surface with tin-bearing solder paste when OSP coatings are used, there is the risk that a mechanically brittle Cu-Sn compound is formed at the copper-tin junction. Prior to applying OSP coatings the function of the intended combination of OSP coating, flux and paste should be checked. Other sources for OSP coatings include [Artaki 1993, DeBiase 1993, Roslund et al. 2002, Parquet et al. 1995].

The conductive pattern of printed board is usually protected by solder resist, which directs the solder solely to the soldering areas and protects the conductive pattern mechanically (IPC-SM-840C). The thickness of the solder resist is usually below 25 µm.

Moisture permeates easily through this surface. In humid conditions a thin solder resist can be compared to a wet rag placed on the surface of the board. However, some corrosion protection is also provided by the resist, because water permeating a carefully applied resist forms a water film of a thickness of only one molecular layer on the resist and on the surface/conductors of the printed board. Since migration of ions requires several molecular layers of water,

corrosion and metal migration is slower than on a bare surface. Because the solder resist has good water permeability, the insulation resistance of conductive patterns coated with it is smaller than that of uncoated patterns (Appendix 1, Section 2.19 *Effect of humidity and geometry on the insulation resistance of the printed board*). The greatest benefit of the soldering resist is its capacity to protect the conductive patterns from external contamination and this diminishes the risk of corrosion.

6.6 Manufacture of component boards

A component board, printed board assembly, is a printed board on which components have been installed. The manufacturing process of component boards include assembly, soldering, handling of conductors, testing and corrective measures and eventually a coat of protective lacquer.

In respect of corrosion prevention, the first main task is to ensure that the insulation between the conductors is good and that there is no residual tin or other electrically conductive material in the conductor spacing.

Another essential area in corrosion prevention is to ensure that the standard of the soldering and other joints is good, since all mechanical and other faults expose the device to the effects of corrosion. If the joint is of inferior quality, it may degenerate rapidly and lose its normal thermal and mechanical stress resistance. The quality of the soldering materials has a crucial effect on the long-term durability of the joints and the occurrence of various corrosion mechanisms. Ensuring the soldering properties of both the soldering area (cf. Section 6.5) and all the components to be installed on the board is one of the best ways of avoiding degeneration of the joints in use.

One of the problem areas of the design is to ensure that the component boards heat as evenly as possible during soldering in order to avoid cold areas with poor soldering properties and the overheating of other areas. The design of the component board should aim at an even distribution of components over the entire area. Connection of components to big metal areas constitutes problems of another type. These include ground levels, to which RF components in particular should have good contact. Large copper areas “suck” heat effectively leaving the soldering area too cold and resulting in an incomplete joint. At the same time, reaction of the flux may be incomplete leaving chemicals on the board surface. These chemicals may later cause a surprisingly rapid corrosion. On the other hand, excessive heat may create fractures in the coatings, intermediate metals and

reactions of process chemicals, all of which may undermine the reliability of the product.

The third main area of corrosion prevention is the need to produce as clean boards as possible, with only a minimum of ionic and/or water absorbing impurities, e.g. residual flux. Since a significant share of the impurities is derived from the workers' hands and skin during the assembly, component boards should not be handled with bare hands. These requirements are partly at cross-purposes with the no-clean aim.

The quality control of the soldering process should include observation of how residual flux is spread on the printed board. If flux accrues clearly on certain areas, e.g. on the edges of the board, corrosion problems and leakage current are likely to occur in this area.

When using no-clean fluxes, which remain on the component board after soldering, it should be ascertained that the flux residues are not chemically active, water absorbing or corrosive. The adhesion of the residue should be good in order to avoid the formation of a water-absorbing layer on the conductive pattern. If the intention is to use no-clean fluxes in lacquered circuit boards, the combination should be tested for adhesion, stability and the risk of moisture accrual by appropriate accelerated humidity tests (e.g. 85°C/85% RH) to ensure good performance. If residual flux reacts with the lacquer, it may cancel the protective effect of the latter.

If the component boards are protected by lacquer [MIL-I-46058C] or adhesive films, they must be thoroughly washed prior to the protection, because residual flux and other impurities undermine the adhesion of the protective material and form a conductive intermediate layer between the protective film and the conductors, where corrosion may occur as a result of ionic and metal migration, particularly if water is present. The use of gummed protective films involves a risk, since capillary cracks always remain under the film. The cracks collect water, which has no outlet, and this accelerates corrosion substantially.

6.7 Cleanness of board manufacture

The KOTEL report [KOTEL 207] "*Washing methods in surface-mounting technique*" lists the most common impurities present on a component board. The report divides them into particles, e.g. hair and soot, organic substances, e.g. skin ointments and substances and materials used in the manufacturing process,

inorganic substances, e.g. salts and acids, and microbials, e.g. viruses, bacteria and fungi. From the point of corrosion, organic and inorganic substances are the most important ones. If the substances absorb water and ionising materials are present, leakage currents and chemicals created by electrolysis accelerate the ageing of the printed board. Inorganic substances have a tendency to ionise and become conductive.

An example of the purity requirements of printed boards is given in standard ANSI/J-STD-001B Chapter 8 *Purity requirements of circuit boards before soldering* (8.1.2) and *of component boards following soldering* (8.3). According to this, the conductors of the circuit board and components should be sufficiently clean to meet the soldering property requirements. If washing is one of the requirements, it should be done as soon as possible following soldering, preferably within an hour in order to remove residual flux. The amounts of residual flux are classified into three categories in point 8.3.5 of the standard

- 1 < 200 $\mu\text{g}/\text{cm}^2$
- 2 < 100 $\mu\text{g}/\text{cm}^2$
- 3 < 40 $\mu\text{g}/\text{cm}^2$,

when the measurements are performed in accordance with IPC-TM-650, test method 2.3.27. An additional requirement is that the maximum ionising or ionisable flux residue is 1,56 $\mu\text{g}/\text{cm}^2$ measured by IPC-TM-650, test method 2.3.26 (dynamic) or 2.3.26.1 (static) calculated as NaCl equivalents.

This amount of ionic impurities equals the recommended surface resistance value of $> 2 \cdot 10^6 \Omega\text{cm}$ [KOTEL 222] given in IPC-A-600E / IPC-6012. In corrosion prevention painting, the surface is deemed to be clean when its maximum NaCl content is 1 $\mu\text{g}/\text{cm}^2$ (10 mg/m^2). Standard SFS-EN ISO 8502-6 sets out the so-called Bresle method for analysing the purity of the surface to be painted. If the printed board is protected by solder resist, it should be ensured that no ionic impurities remain under the resist since they conduct electricity and promote corrosion when moist.

Standard ANSI/J-STD-001B point 8.3.9 give guidelines for the use of IPC-TM-650, test method 2.3.38, for controlling the amount of organic non-ionic impurities on the printed boards. The resolution of this method is in the region of 10 $\mu\text{g}/\text{cm}^2$ of organic residue in the components or on the board. The requirement limit is decided individually.

Separately spread fluxes or fluxes mixed with paste are used to ensure successful soldering. The fluxes contain activators, which react with metal surfaces and form gaseous substances at the soldering temperature. Following soldering the activators and the reaction products are nowadays usually bonded to their position on the printed board. For example in resin-based fluxes they are trapped in the resin. If such a printed board is reheated beyond the melting point of resin, the reactions are reactivated and mild corrosion may result. If the amounts are excessive and the heat too low, inert activators may remain on the board. On the other hand, extended soldering time or excess heat may trigger undesirable chemical reactions and the generated chemical compounds may create problems.

The resin contained in glass fibre laminate may react with flux acids and form esters. They may remain on the surface of the circuit board in a no-clean process. If the flux contains chloride ions they may react with bromated phenols (fire retardant) and release bromide ions. These react with lead on the surface of the solder into white lead bromide. In the presence of humidity and airborne carbon dioxide the lead bromide may form lead carbonate which may increase leakage currents. The flux often contains glycols and their derivatives, which may react with the solder resist coating in typical soldering conditions. According to literature, the result is reduction of surface resistance.

The appearance and reliability of a component board can be summarised according to report [KOTEL 230] *Water based fluxes*: Visual cleanness, reliability and the amount of ionic residue do not always correlate when using fluxes of low solid matter, because various residues differ in respect of their corrosive properties and constitute a reliability risk at least as accumulated impurities [see IPC-J-STD-004].

Previously, the boards were washed at the final stage of the manufacturing process. The aim was to remove process residue from the surface of the component board. It enabled the use of more active fluxes to guarantee better soldering properties of complicated components. Nowadays most producers no longer wash and are using a so-called no-clean process, whereby the resulting impurities are trapped on the surface of the printed board as described above [KOTEL 223]. At present, washing is usually not a good solution for two reasons. Firstly, the fluxes are designed for a no-clean system meaning that washing does not necessarily detach the impurities from the surfaces and secondly, washing the underside of dense structures between printed board and large components cannot always be done and there is the risk of accrual of impurities close to the dense structures causing leakage currents and various other problems.

The KOTEL 222 report *Impurities of the component board* contains information collected from the literature on factors affecting the reliability of no-clean component boards. The report lists contamination sources, gives details on the substances contained in fluxes of low solid matter content, describes the reaction between various substances and discusses the effect of various contaminations and the assessment of the purity of the printed board.

Contamination causes corrosion, increased leakage currents, migration, fungal growth, loosening of coatings and formation of insulating contact surfaces. The most general type of corrosion on component boards is electrolytic corrosion which can occur in the presence of an electric field between adjacent wires and moisture, or voltage induced between different metals [Lea, A Scientific.. 1988] (see Appendix 1). Leakage currents are a much more common problem than corrosion, because the wires are nowadays close to one another and a transfer to high impedance components has been made in the semiconductor industry. Ionic impurities and moisture cause leakage currents. Relative humidity need not be high, typical room air of 40...50% RH is sufficient, since hygroscopic substances and various fibres adhering to the surface can absorb enough moisture to the critical areas.

Moisture, impurities and voltage are necessary to form migration paths. Migration occurs on a component board with copper and tin-lead, and the phenomenon is especially strong with pure silver [Lea, After CFC? 1992]. Fungi-related problems occur mainly in tropical conditions and indicate inadequate cleaning of the product (see Appendix 1, Section 2.18 *Growth conditions for mould*). Surface impurities may be the reason for poor adhesion and loosening of the protective coating. Visible white spots on the board are a clear indication that ionic impurities were present on the board already at the time when the protective coating was spread. Insulating contact surfaces are created when e.g. resin remains on the contact surfaces and the test contact areas of the circuit. There is a publication concerning problems caused by electrochemical migration: IPC-TR-476A, Electrochemical Migration: Electrochemically Induced Failures in Printed Wiring Boards and Assemblies, July 1995.

6.8 Connectors

The mechanical design of the connector springs and the contact area, material selection and coatings are factors influencing the sensitivity of a contact to corrosion, i.e. how fast the electrical resistance of the contact becomes excessive. High contact pressure reduces the effects of corrosion at its initial stage; a

chemically inert coating (gold) does not corrode. But a thin ($< 1 \mu\text{m}$) noble-metal coating is always porous allowing a relatively rapid corrosion of the underlying less precious metals (Cu, Ni). When using small contacts and contact pressures there is the problem that even a very slight fault in the coating of the contact surface may block the signal path on account of minor corrosion. The opening and closing of connectors wear the surfaces and may temporarily lower the resistance, but wearing accelerates corrosion and promotes damage.

Figure 6.3 is a basic illustration of the contact area. The actual contact area in respect of electrical and thermal conductivity and mechanics is regulated by the design of the contacts and the quality and hardness of the surface of the coating material.

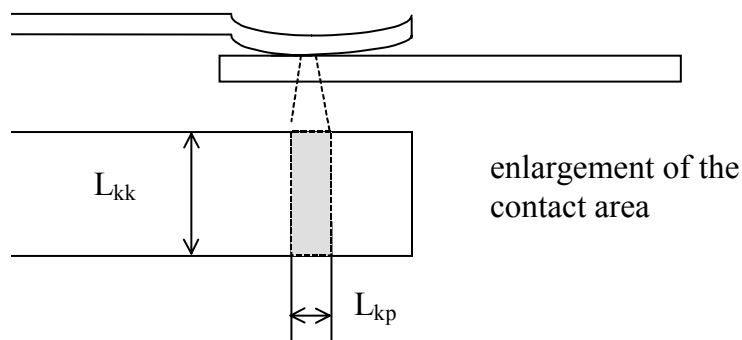


Figure 6.3. Contact area A_c .

If the contact coating is soft, the halves of the contact are partially pressed inside one another and a number of gas-tight contact points are formed in the contact area (Figure 6.4). The roughness of the contact surface regulates the thermal and electrical conductivity and wear resistance. The number of contact points on a rough surface is small and current and heat are funnelled to a small part of the entire physical surface. The surface should be as smooth as possible.

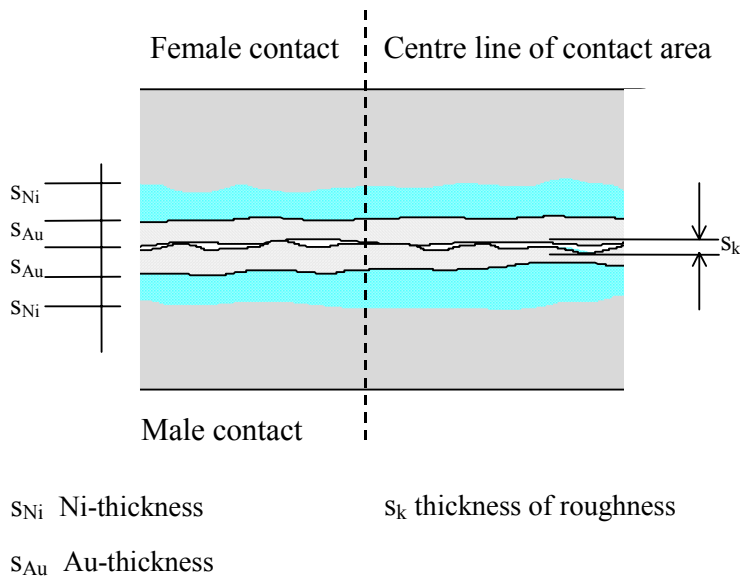


Figure 6.4. Structure of contact area.

If there are corrosion products on the surfaces, they will block some of the current paths. An increase of the contact pressure and/or the use of e.g. a few volts' voltage, local breakdowns, which penetrates the corrosion products, are generated.

Small-signal contact ($I < 100 \text{ mA}$ and $U < 1 \text{ V}$) or a higher-signal contact is deduced from the magnitude of the current and voltage. Even minor corrosion products can cause disturbances in the contacts in small-signal contacts, because no electric breakdown occurs on the contact surfaces contrary to currents and voltages of greater magnitude. Report KOTEL 3 *Contact and conductor coatings in electronics*” the electric loading of the contacts is grouped into three areas with individual fault mechanisms.

Area 1	$U \leq 1 \text{ V}$	$I \leq 10 \dots 100 \text{ mA}$
Area 2	$U = 1 \dots 10 \text{ V}$	$I = 10 \dots 1000 \text{ mA}$
Area 3	$U \geq 10 \text{ V}$	$I \geq 1 \text{ A}$.

In area 1, the most common coating for connectors is gold and its alloys and palladium of the platinum metals. In area 2, tin and eutectic solder-tin are suitable provided that the connector is not opened very often ($< 10 \dots 25$ times). In area 3 silver, silver alloys and nickel can be used in addition to gold and tin depending on the current and the load.

The coating materials are selected on the basis of environmental conditions, contact current, contact forces and the number of times of opening/ connecting [KOTEL 3 and KOTEL 13]. In practice, surface coating materials of only Au, Ag and AgPd are suitable for small-signal connectors. Since materials containing

Ag corrode relatively easily in a sulphurous atmosphere, the selection is rather limited. Ag and Ni coatings are suitable for higher-current contacts, because the voltage/current penetrates at least thin oxide, silver sulphide and similar corrosion product films. Ag coatings are suitable for high-current and high-voltage applications because they tolerate high currents. A connector coated with Sn functions well when the contact force is high and the connector needs to be opened only a few times. The resistance of Sn to corroding conditions, e.g. maritime climate, is good. Soft tin forms a gas-tight contact point, which does not corrode if the contact pressure is adequate.

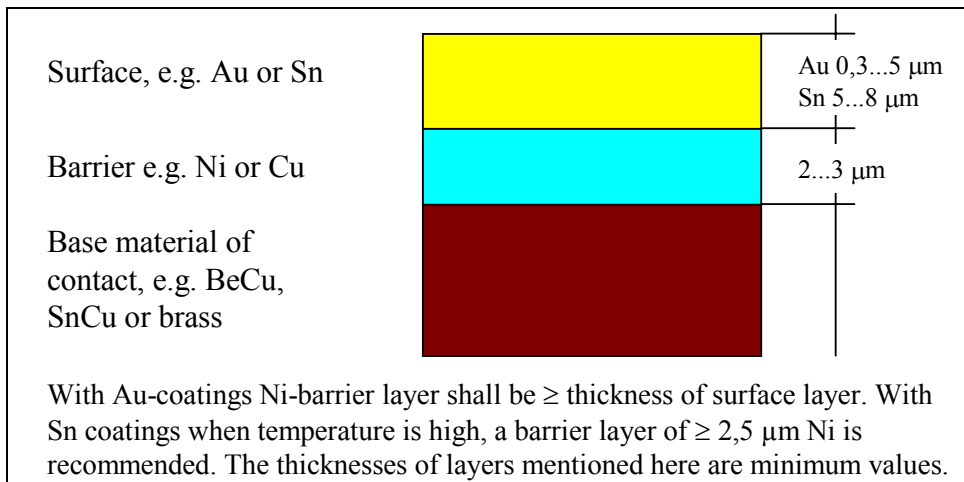


Figure 6.5. Structure of connector contact and usual coatings.

Figure 6.5 sets out the basic structure of contact coatings. The task of the uppermost layer is to form a layer of good electric conductivity and corrosion resistance on the surface of the contact. In most cases, a contact coating containing only gold or tin does not function well, because zinc or copper which are used as the base material of the contact may diffuse through the porous surface. Moreover, the base metal may be too uneven or the adhesion of the coating poor. For this reason an intermediate layer (barrier layer) of either nickel or copper is used beneath the topmost layer. Copper smooths out the surface of the basis metal and improves the adhesion of the topmost coating. However, the most appropriate material for the intermediate layer is nickel of appropriate thickness, especially as it forms an excellent diffusion barrier for the substances of the basis metal.

The main tasks of the intermediate layer are:

- to improve the adhesion of the coating
- to level the unevenness of the basis metal

- to prevent diffusion of the basis metal substances (Zn, Cu) to the topmost coating
- to mend holes in the coating
- to improve mechanical resistance to wear.

Coatings, which primarily protect the contact metal from corrosion and secure the linking of the connecting wires by soldering or by a wire-wrap contact, can be used in the external parts of the actual contact area. SnPb coatings of a thickness of 5 or 8 μm are commonly used in these areas. When gold is used, the thickness of the coating can even be in the region of 0,1 μm , which mainly ensures soldering properties. It is advisable to use an intermediate layer of e.g. 2 μm Ni underneath these coatings at least in more severe environmental conditions.

The hardness and evenness of the coating improve resistance to wear. A relatively hard coating has a better wear resistance, but the contact surface is smaller than when softer coatings are used. Softer coatings can be used in connectors who are seldom opened and the quality of the electric contact is better than with hard coatings. Moreover, a softer coating is flexible and may form a nearly gas-tight contact, which corrodes more slowly than a worn hard coating.

The basic material properties of coatings are:

- composition of the coating material (purity grade)
- composition of intermediate layer, if any
- composition of the basis material
- layer thicknesses and their evenness
- hardness of the coating layers
- porosity of the coating
- adhesive attraction of the coating (adhesion of various layers)
- roughness of the surface.

Requirements concerning gold coatings are given in standard MIL-G-45204C (1983) Military specification, Gold plating, electrodeposited, which has since been replaced by the vehicle engineering standard SAE Society of Automotive Engineer: AMS 2422E.

See standards listed in [KOTEL 3] and [KOTEL 13].

The basic problem with very thin coatings is their poor mechanical durability and porosity. The thickness of thin coating in electronic connectors is less than one micrometre.

The processing method of metal coatings and the finishing treatment of coatings (polishing, lubrication, passivation) may have a significant effect on the corrosion of the coating. Lubricants are sometimes used in contacts that can be opened to minimise friction and to protect the contact area. The evaluation and assessment of these properties can usually only be based on corrosion resistance tests and user experience.

The properties of spring contacts must be adequate (sufficient contact pressure, long life span). Brass (e.g. CuZn36) yields, and the springback factor fatigues in use. Only a few connecting times may cause permanent deformations. A contact spring made of beryllium copper (BeCu) or phosphorized bronze (e.g. CuSn6) allowing adequate movement ensures that contact pressure is retained throughout the life cycle of the product.

Excessive bending of the contact springs in use may in some cases be problematic if the yield strength is exceeded or the hard coating of the spring cracks. Appendix C of standard SFS 4446 on electroplated coatings of nickel sets out a method of testing the tenacity of nickel coating on steel surface. A minimum requirement is that the coating tolerates an 8 per cent elongation without breaking. According to the standard the test is performed on nickel coating of a thickness of 25 µm. Similar elongation is created in the contact if the bending radius is too short. Bending tests for electronic components which can also be used to test coated connectors and contacts are set out in standard IEC 60068-2-21 (1999-01) *Part 2-21: Tests – Test U: Robustness of terminations and integral mounting devices*.

The number of mating times limits the choice of the thickness and hardness of the coatings. Contacts that are continuously opened require thicker and harder coatings and moderate surface pressure. Softer and thinner coatings and a greater surface pressure making the contact area gas tight and less susceptible to corrosion can be used in contacts that are opened only occasionally (< 10...25 times).

Fretting, which means the rubbing motion of the contact surfaces against one another may in certain contact constructions cause corrosion of the contact area (fretting corrosion, abrasive corrosion, friction corrosion). A mechanical fretting motion detaches metal particles from the coating and may catalyse polymers from airborne gases e.g. on palladium compounds. Tin coatings are particularly susceptible to fretting corrosion, because tin is soft and oxidises rapidly. The oxides and other compounds formed on the contact area have poor conductivity of electricity. If very thin and soft coatings are used, fretting may uncover the basis metal or a hard coating may fret through the opposite softer coating [Antler 1984, Mottine & Reagor 1984].

Mechanical fretting of the contacts is usually created by mechanical vibration, the electro-mechanical force caused by high alternating currents and fluctuation of the ambient temperature. The amplitude of the motion may range from a few to one hundred micrometres.

The (structural) susceptibility of the connectors to mechanical fretting are checked in the design review as well as the fluctuation of temperatures and the likely amplitudes of electro-mechanical forces, and the materials and the contact pressures used in the coatings are reviewed.

The contacts should be located in the frame and the frame designed so that slight position errors when coupling the connectors will cause no harm (bending, etc.). In addition, an adequate bending margin should be allowed so that the connection will not cause permanent deformations.

The necessary insulation resistance and maximum voltage endurance must be taken into account when decreasing the conductor spacing. With conductor spacing of less than 0,2 mm there is a great risk of an inter-conductor short circuit because it may be induced by even relatively small loose particles (e.g. metal particles). Moreover, the risk of migration of metals and corrosion products over the conductor spaces increases substantially.

The size of the contact mating and separation forces may be used as an indicator of the mechanical performance of the entire connector structure. The mating and separation forces of the connector vary according to the number of contacts and the properties of the contact springs. Very high forces are apt to cause mechanical damage to both the contact coatings and the frame structure and hinder the mating. On the other hand, in case of very small contact forces the connector may extract as a result of mechanical vibration in the absence of a locking mechanism.

Attention should be paid to the mechanical strength, stability and sufficiently small resistance values of high current connector contacts, because even a small increase in resistance of a poor contact is apt to cause sizeable power dissipation. For example, at a resistance of 10 mΩ the dissipation at 1 A current is 10 mW, at 10 A current 1 W and at 20 A current 4 W. The power of one watt heats the surroundings sufficiently to ignite the insulating materials of printed wiring boards or connector body (see Appendix 1, Section 2.10 *Stress corrosion cracking and fatigue*).

The support of the background wiring of the connectors must be checked for mechanical stress e.g. tension, bending and vibration. In this connection it should also be ensured that any water condensed on the wires or draining down their surface has no direct access to the connectors.

Spring materials

Brass is commonly used as connector contact material. It is anodically coated with an appropriate metal, e.g. nickel or tin. The best known corrosive phenomena of brass are stress corrosion cracking and dezincification. Dezincification is a corrosive phenomenon where zinc is leached from brass (selective dissolution). This phenomenon is evident in brass in contact with seawater or hot water. By alloying arsenic (As), antimony (Sb), and boron (B) or phosphorus (P) with brass can counteract it.

Stress corrosion leads to rupture in the stressed (e.g. cold-worked) metals following exposure to nitrogenous substances, e.g. ammonia or amines. They corrode the brass grain boundaries and the tensile stress breaks the structure of the brass that has been weakened by corrosion. This can be prevented in advance by electrolytic nickel coating (at least 15 μm) or a protective lacquer coating. Copper or bronze (BeCu or SnCu) can be used instead of brass to avoid the problem of season cracking.

Contact lubricants

Contact lubricants are used to improve the operation of the contacts in corrosive conditions [Abbot & Antler 1995 and Antler 1995]. These substances function well in new contacts. Their operational mechanism is to form an electrolyte where ions migrate from one contact to another, they increase the electro-conductive area, retard oxidation and form metal dendrites between the contacts short circuiting potential corrosion products. Mineral oils and sealing waxes are used as lubricants. These lubricants polymerise in the long run and create operational problems by forming an insulating film on the contact surfaces. They can be used only on new and clean connector contacts. Another detrimental quality is their tendency to collect dust, which can be problematic especially in respect of sand dust, if the connectors of the device have to be opened frequently during use.

Some manufacturers sell also chemicals for the treatment of corroded contacts [Gao & Shangguan 1999], e.g. glycol ether polymer. Its action is based on forming dendrites over the corroded contact areas (see Appendix 1, Section 4.1

Dendrite). The chemical acts as electrolyte leaching metal ions from the contacts and forming a conducting path from them over the insulating areas [Gao & Shangguan 1999].

A number of contact lubricant patents have been published with descriptions of the action of the substances.

US Patent 4529531: Electrical contact lubricant composition and method of lubrication. July 16, 1985. 4 p.

US Patent 4530772: Method of electrical contact lubrication. July 1985. 3 p.

US Patent 4415694: Contact enhancing composition. Nov. 15, 1983. 7 p.

6.9 Casing materials

The most common materials for casings of electronic and electric appliances (table 6.3) continue to be steel and aluminium, and their outer surface is usually painted at the finishing stage. Plastics and especially coated plastics are the most popular casing materials for smaller devices. Corrosion and its prevention are important in the manufacture of casings of both material groups. The corrosion resistance properties of the casings depend largely on the coating technique used. From the point of view of corrosion and climatic conditions the most demanding products are mobile phones which are in constant use, on the one hand, and products designed for outdoor conditions and severe industrial conditions, on the other.

High visual quality of the external surfaces is necessary for most products, because attractive appearance is often a deciding factor for the customer's willingness to buy the product. It is not always possible to produce an attractive product with good corrosion resistance, but by using appropriate materials and coating techniques these requirements can support one another in the manufacture and the final result is a technically superior, attractive surface which can have excellent corrosion resistance. The opposite is not necessarily true, because a clean and relatively even surface is no guarantee for good corrosion resistance.

Metal casing materials

Metal casings are made for both indoor and outdoor use. Casings for outdoor use are usually manufactured of sheet metal, which is either ready precoated or coated (painted) following the manufacture of the casing. An aluminium pressure-cast casing may be used for severe conditions.

Uncoated sheet steel is the most common basic material for casings. The normal procedure in the manufacture of casings is the assembly (welding, grinding, etc.), zinc electroplating (actual corrosion protection), chromating or phosphatising followed by painting if needed. The durability of the casing is the result of the joint effect of zinc plating and painting and is in the region of 20 years with the most commonly used paints. This type of casing is suitable for all indoor and outdoor conditions.

Precoated sheet steel is an increasingly popular coating material. Tin roofs are its better known application. A casing manufactured of this material has a nice surface and no painting is necessary. However, the cutting edges of the sheet are unprotected and turn rusty fairly rapidly (1...3 months) in unfavourable outdoor conditions (even indoors in coastal areas). For this reason, casings made of precoated sheet steel can be primarily recommended for indoor use.

Galvanized and aluminium zincified sheet steel is suitable as such for dry indoor conditions and structures inside other casings. Aluminium zincified sheet looks better than a hot galvanized (and rolled) surface. The corrosion behaviour of these differs from one another in that in humid environment white rust – a porous fluffy corrosion product – accumulates on hot galvanized surface and a black, solid corrosion product on the aluminium zincified sheet. It would appear that the durability of aluminium zincified sheet is better in the long run in severe climatic conditions. The cutting edges behave similarly to precoated sheet steel so that in the absence of additional treatment also these materials can be primarily recommended for indoor use. The most common additional treatment is chromating (sometimes also phosphatising) and painting.

Aluminium pressure cast casings are suited for severe operating conditions and locations, which need not be visited for years at end. The wall thickness of these casings is several millimetres. Aluminium forms a natural passive layer to protect the surface and its resistance against climatic corrosion is excellent. Moreover, the walls of the casing contain so much material that minor corrosion has no harmful effects. In consequence, the surface does not need an additional special treatment but it can be painted with paints suitable for aluminium.

Thin aluminium plate is also used for casings. The electrical conductivity of the surface of chromated aluminium is good and the thermal conductivity is known to be excellent. Aluminium is the material of choice for applications where these two properties are important. Such applications are usually located inside appliance cabinets where the risk of corrosion is relatively small. In these conditions chromated aluminium lasts as long as the device itself. Without additional treatment, chromated aluminium cannot be recommended for outdoor

use. It should always be painted and the parts where electrical conductivity is required should be treated separately.

Metals are not always airtight. Metals are suitable for the manufacture of hermetic structures (see Appendix 1, Section 1.7 *Relative humidity of air*). When producing watertight structures, which permeate neither water vapour nor air, metals are a suitable alternative. However, the designer should ensure that the material he intends to use and its manufacturing technique allow for a truly tight structure. If for example pressure cast aluminium is used, there is a great risk of producing a leaking casing which even draining water can penetrate. This is due to the porosity of pressure cast aluminium. By using appropriate manufacturing technique it is possible to make gas tight casings also by using the pressure casting technique.

Plastic casings

Unpigmented (undyed) plastic casings cannot be recommended for outdoor use, because the durability of unpigmented plastic in outdoor conditions is limited on account of solar radiation. The plastic material used also governs the durability of pigmented plastic. Pigments retard the disintegration of plastic by limiting the disintegration to the surface of the material. Plastic can also be painted and if this is done, the durability is governed by the durability of the paint used. The maximum durability of high-quality paints in average outdoor conditions (e.g. inland city atmosphere) is 10...15 years. Plastic casings cannot be recommended for extreme conditions (e.g. seashore or high mountains). In addition to pigments, the materials of plastic casings usually contain reinforcing agents (with the exception of transparent lids) which increase the creep and twist resistance of the plastic product.

Metallised plastics are used in water fittings, domestic appliances, decorations, logos, cosmetic packages and even in mobile phones. Metal coating adds rigidity and gives an attractive appearance to a plastic casing. Chrome and gold surfaces are durable without any further treatment. Other coatings are intended as decorations and always need a lacquer or some other metal coating. The durability of metallised plastics depends on the corrosive properties of the external surface metal and the adhesion of the plastic and the metal used. The quality/adhesion of the metal depends on the coating process. It is a tedious and many-phased process.

Metallised plastic casings (e.g. EMC covers) inside various devices form a group of their own. The properties of their coatings have been selected primarily with an eye on the operational qualities. The durability and corrosion resistance of these casing materials should be reviewed similarly to other electronics.

Table 6.3. Properties of casing materials.

Casing material	Recommended use	Life span	Remarks
Aluminium pressure cast	Outdoor and indoor, severe conditions	Tens of years, in severe conditions painting is recommended	Seals harden too soon if selection of materials is not correct
Sheet aluminium (usually chromated)	Equipment bay etc, dry indoor; painted also outdoor use	Painted: as long as aluminium pressure cast; inside equipment bay same as the life of equipment	Chromated aluminium conducts electricity well
Precoated sheet steel	All indoor; appropriate outdoor use	Indoor tens of years, outdoor over 20 years	Corrosion of cutting edges may be problem indoor and outdoor
Hot galvanized sheet steel	Equipment bay, cabinets and other dry indoor places	Inside equipment bay same as the life of equipment	Corrosion of cutting edges may be problem; wetting of surfaces causes white rust
Aluminium zincified sheet steel	Equipment bay, cabinets and other dry indoor use; especially when appearance is important	Inside equipment bay same as the life of equipment	Corrosion of cutting edges may be problem; wetting of surfaces develops black dense corrosion product
Sheet steel Zinc electro-plated and chromated and painted	Chromated for inside equipment bays, painted for outdoor use	Painted over 20 years, inside equipment bay same as the life of equipment	Chromated zinc electro plated surface conducts electricity well
Plastic (pigmented, reinforced)	Indoor; and outdoor if protected against UV-light (direct sunshine)	Indoor from five years to tens of years; outdoor the glaze of surface is disturbed in 5 years, mechanical properties in 10...15 years	Plastic materials require special know-how, old design rules are invalid

6.10 Plating methods of metals

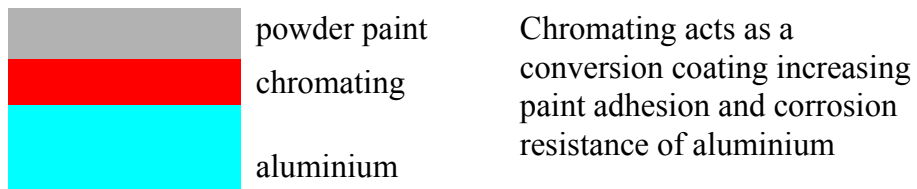
Basics of plating

There are a few basics of metal plating to be considered when using the platings. The plating starts by cleaning the metal to be plated. Especially in electrolytic plating the cleaning has a crucial effect on whether the manufactured plating functions or not. In electrolytic plating metal is precipitated (deposited) onto another metal. The first layer of the plating metal sets according to the grid structure of the base but the following molecular layers precipitate according to the grid structure of the plating metal. The quicker the plating structure is to change, the better the plating adheres to the surface. If there are impurities on the surface of the base metal the quality of the plating deteriorates. Impurities may cause bubbling and flaking of the plating even after a long time. For example in alkaline baths a precipitated zinc coating may flake and cause short cuts after several weeks [O'Grady 1999].

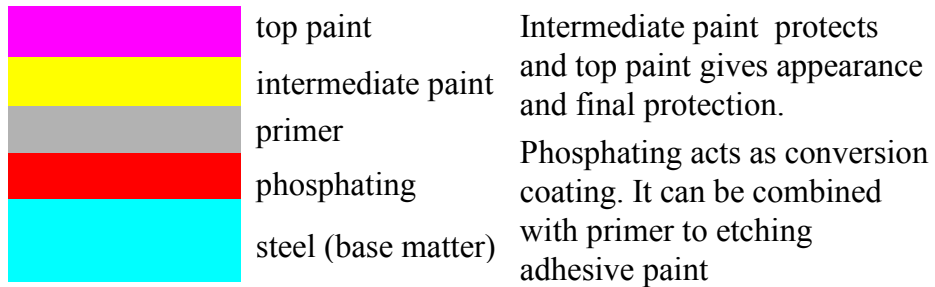
Most plating metals cannot be directly precipitated onto another metal due to the great differences in the metal properties. For instance, a decorative chromium plating cannot be precipitated directly on steel. Chromium is harder and more rigid than steel, which is why it cannot be precipitated as a thin layer onto the steel. Copper is precipitated onto steel first, nickel on top of that and then chromium which also gives the plating its name. Correspondingly, gold cannot be precipitated directly on copper because copper diffuses into the gold and corrodes easily. Here, nickel must be used as an intermediate layer to prevent the diffusion of copper.

In multiple layer platings the first intermediate layer acts as the adhesive layer in the direction of the base metal and the plating on top. In decorative chromium the copper adheres well to the steel and to the nickel and chromium adheres well to the nickel which prevents the diffusion of copper into the surface. Copper is used as an adhesive layer due to its good adhesive properties also when plating plastics with metal. In addition to copper, nickel is nearly always used to prevent the diffusion of copper into the surface.

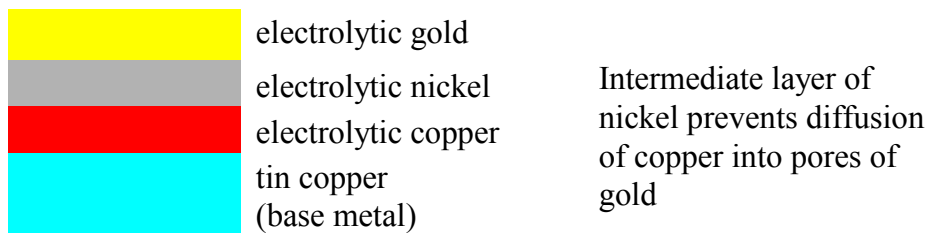
Powder paint on aluminium



Steel and traditional painting method



Multiple layer metal plating, connector switch



Metal plated plastic

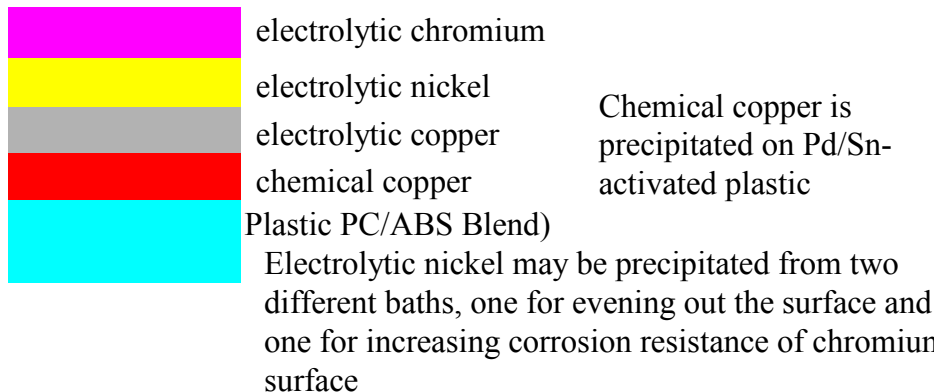


Figure 6.6. Plating structures of metals.

A separate primer is often used as an adhesive layer when painting. The primer ensures that the paint will stay on the surface. The task of the top layers is to protect the painted surface from outside effects, such as water. By increasing the thickness of the layers, surfaces more resistant to chemical and mechanical stress may be obtained.

Thus, each layer of multiple layer coatings has its own task, it is central to attend to the cleanness of the part to be coated in each phase.

- carefully cleaned basic matter – base metal
- adhesive layer – adheres to base metal and intermediate layer
- intermediate layer – adheres to adhesive layer and top layer, properties in between these
- top layer – adheres to intermediate layer giving final appearance and surface qualities.

Figure 6.6 shows examples of various plating structures of metals.

Coatings of electronics and corrosion

The metal platings of electronics are mainly manufactured by electroplating. Painting with conductive paint and various vacuum vaporising methods are also used for EMC protection of cases and device shells.

The moving force of corrosion is always moisture accumulating on the surfaces. Corrosion accelerates several decades when corrosion products begin to appear on the surfaces. This happens because the corrosion products can retain more and more water since they are always more porous than the original material.

The clearest cut plating method with regard to corrosion is the vacuum vaporising methods. The corrosion of these coatings is determined solely by the properties of the vaporised metal, which makes their corrosion behaviour well predictable.

The corrosion phenomena of conductive paints (and conductive EMC seals) consisting of metal particles mixed in a binding agent are more complicated. The properties of both the binding agent and the metal particles affect the corrosion resistance. Some sealing masses consist of two conductive materials, which means that galvanic pairs can form between these starting corrosion reactions or material erosion with the least humidity also in other substances in contact with the material. For example as sealing mass with copper and silver flakes mixed in silicone resin being in contact with gold plating corrodes easily on the surface.

Corrosion caused by the following factors may take place in the sealing masses, paints and the surrounding materials:

- 1) reactions between water and the metals
- 2) reactions between water and the binding agent of the mass
- 3) reactions between corrosion products of metal and the binding agent of the mass
- 4) reactions between disintegration product of the binding agent and metal.

Electro precipitated platings (electrolytic platings), for example metal case structures and printed boards are manufactured using a complex chemical process where each phase can leave residue on the plating affecting its durability (connector contact coatings, see Section 6.8). The biggest mistakes are noticed in the visual inspection of the appearance performed immediately after the plating process and the faulty product is removed from the line. Impurities remaining in the plating cause latent faults possibly resulting in flaking or cracking of the plating after weeks or premature rapid corrosion.

The properties of successful electro precipitated plating are equal to those of plating metal and the corrosion behaviour is thus well predictable as with vacuum vaporised platings.

The following books and standards listed in references provide information on electro precipitated and electrochemical coatings and their properties:

Kemiallinen ja sähkökemiallinen pintakäsittely. Part I 1996 and Part II 1999, Suomen Galvanoteknisen Yhdistyksen julkaisuja No. 5 ja No. 6.

Jack, W. D. Electrodeposition, The Materials Science of Coatings and Substrates. Noyes Publications, 1993.

Einar Mattsson, Basic Corrosion Technology for Scientists and Engineers. Second edition. The Institute of Materials. Bourne Press, 1996.

Mattsson, E. Elektrokemi och korrosionslära. Bulletin nro 100. Korrosionsinstitutet, 1987.

SFS-EN-ISO 1461 fi/en 1999. Hot dip galvanized coatings on fabricated iron and steel articles. Specifications and test methods.

SFS-EN ISO 14713 fi/en 1999. Protection against corrosion of iron and steel in structures. Zinc and aluminium coatings. Guidelines.

SFS-EN 22063 fi/en 1994. Metallic and other inorganic coatings. Thermal spraying. Zinc, aluminium and their alloys.

Surface processing of case structures

The outside surfaces of cases are usually painted. Materials curing at elevated temperatures are used as paints because they do not emit anything to the environment. Powder paint is increasingly used for better protection in the corners/edges than with solvent paint. Powder paints are low emission paints so cases painted with them are recommended over cases painted with traditional solvent paints.

If painting has been chosen for the surface finishing, the following quality assurance tests at least are routinely performed: The gloss of the paint film is determined by (SFS 3632), the film thickness by (SFS 3644) and its adherence. The adherence of the paint film can be determined by a simple bending test where a painted test sheet supported in the vertical position is bent 90° in both directions until the paint film loosens. If painting is used to produce an ornamental surface (for example a craggy surface resembling an electroerosion surface) only the adherence is worth determining in the bending test.

The protective effect of the film can also be evaluated with a test where sharp silicon carbide sand is poured on the test piece (SFS 3754). The test gives repeatable results despite its simplicity. The use of the results requires exact data on the thickness of the film in the test area, which is not always easy to measure.

A week old paint film is usually used for testing in the quality assurance of paints. The paint film is an ever changing organic coating, however, the physical and protective properties of which change over time. The same also applies to protective lacquers of the printed board, solder resist coatings and all other organic coatings.

Surface processes of mast structures

Painting and hot galvanising are suitable coating methods for corrosion protection of mast structures and other outdoor steel structures discussed in Section 6.2. Hot galvanising alone is not sufficient for corrosion protection which is why that too is painted. Figure 6.7 shows an example of the manufacturing process of these coatings.

The base material (steel) is cleaned in acid pickling bath when a hot dip galvanising process is used, and in the zinc epoxy process by blast cleaning (or grit blasting). Hot galvanising is done after the cleaning or in the paint alternative zinc epoxy painting. The layer rich in zinc gives steel the actual corrosion

protection (see Appendix 1, Section 1.2 *The electrochemical and galvanic voltage series of metals*).

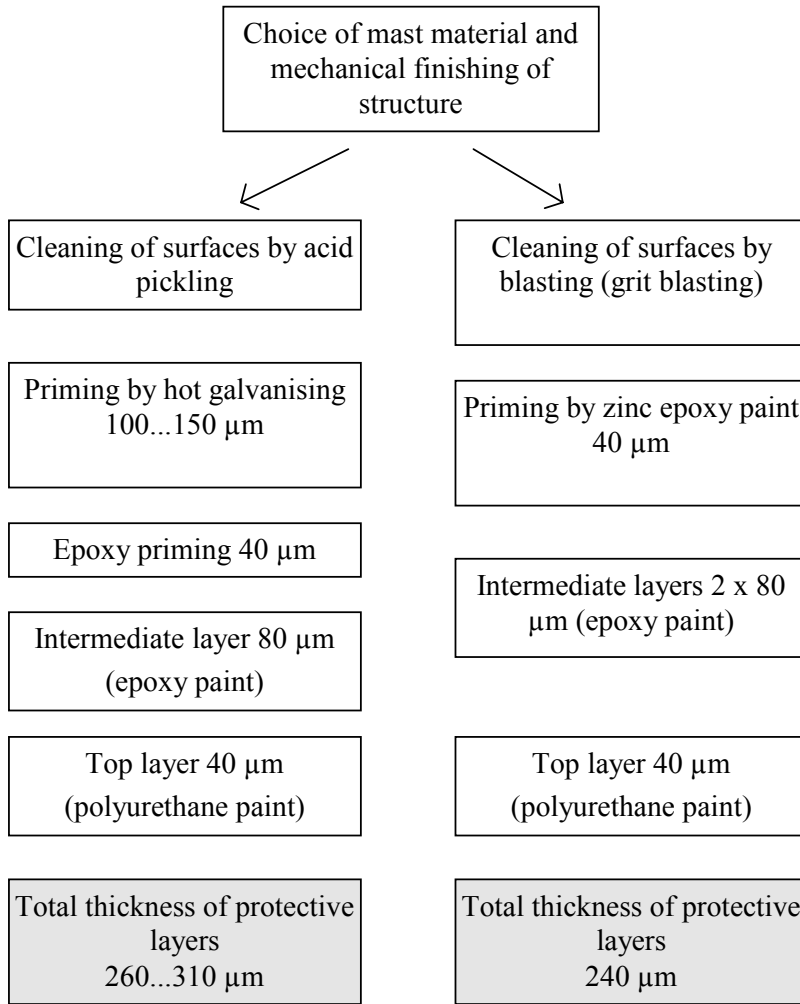


Figure 6.7. Coating alternatives for outdoor mast structures.

Since the durability of zinc in outdoor air is not very good, it must be protected by painting. The binder of the paint in touch with the zinc must be chosen so that it is resistant to the effect of the alkaline corrosion products of zinc and adheres well to the metal surface. The hot galvanized surface must in addition be roughened to provide enough of adhesive surface for the paint.

The binder of the intermediate layers must be chosen so that the intermediate layers adhere to the primer and to the top layer. The layer thickness is also increased by the intermediate layers to slow the penetration of water and corrosive compounds through the paint films, in other words to increase the protective effect of the layers.

The top layer should consist of a paint type that adheres well to the intermediate layer and tolerates solar UV radiation well. Since epoxy cannot tolerate sunlight, it must be protected with for example polyurethane paint, which binds well to the epoxy.

The thicknesses of the paint layers necessary for protection have been determined through practical experience and testing for reaching the desired protection time, usually 20...30 years.

A suitable standard for surface processing of outdoor steel structures is the following ISO 12944 standard series applicable to new and maintenance painting (covers also hot and spray galvanized surfaces) of steel structures more than 3 mm thick under climatic stress or submerged structures. The standard only covers air dry paint surfaces less than 2 mm thick. ISO 12944 classifies the durability of paint surfaces into three age categories, 2...5 years, 5...15 years and more than 15 years. Climatic stress is divided into six different corrosivity categories in ISO 12944-2, C1...C5-I and C5-M. Category C5-I, industrial climate and category C5-M maritime climate are the most stressful (see Table 5.5).

Categories of corrosivity of the atmosphere	Corrosivity of submerging stress
C1 very low	Im 1 submerging in fresh water
C2 low	Im 2 submersion in sea or brackish water
C3 medium	Im 3 sinking into the ground
C4 high	
C5-I very high (industry)	
C5-M very high (maritime)	

SFS-EN ISO 12944 fi/en 1998-11-30.

Paints and varnishes. Corrosion protection of steel structures by protective paint systems. Part 1: General introduction. 16 p.

Part 2: Classification of environments. 20 p.

Part 3: Design considerations. 30 p.

Part 4: Types of surface and surface preparation. 38 p.

Part 5: Protective paint systems. 59 p.

Part 6: Laboratory performance test methods. 26 p.

Part 7: Execution and supervision of paint work. 20 p.

Part 8: Development of specifications for new work and maintenance. 76 p.

The following publication gives a thorough practical demonstration of the properties and manufacture of metal coatings and surface processes.

Tunturi, P. & Tunturi, P. MET-publications 3-1999. Coating and surface processing of metals (in Finnish). Federation of Finnish Metal, Engineering and Electrotechnical Industries. 190 p. ISBN 951-817-696-5.

6.11 EMC and other seals

To guarantee EMC (electromagnetic compatibility) the resistance of all EMC contacts should remain sufficiently small throughout the life span of the product despite effects of various corrosion mechanisms.

The seams of different cases from small component cases to the outer shells of units and entire devices are typical EMC contacts. These are also used as EMC shields. The seams may be produced simply by pressing the pieces together mechanically, by soldering, by spot welding or the seams are realised by using various EMC seals. All these solutions have their own corrosion properties.

Another EMC contact type are various wire connections which are made by soldering, welding or with screws.

The third EMC contact type is the spring contacts of the EMC seals of chambers and rooms.

The basic problem with these various contacts is that different materials as to the galvanic (voltage) series are nearly always joined in them, which causes a corrosion tendency especially in polluted and humid conditions.

With regard to corrosion control, the EMC design should determine how well the electric contacts/joints should keep. When the resistance requirement for the joints is known the materials, coating and sealing techniques to be used can be decided. This applies to sealing sleeves, sealing masses, elastomers used as seals in covers/doors etc.

A lot of elastomer seals are used as EMC seals which are made conductive by mixing conductive materials in them (see next paragraph) or by weaving a jacket of metal thread on the elastomer core. These materials may prove problematic in the long run due to cracking and breaking. Thus, water may penetrate older cases.

One of the most important properties of elastomers is maintaining their flexibility, therefore both the material and its consistency should be considered when choosing the material. For instance, the amount of filler affects the

flexibility. A material containing more filler is always less flexible than a material with less filler. The filler may also react with external substances. The reactions always entail changes in the volume, which change the properties of the elastomer. An example of reactive filler is calcium carbonate, which is added to make the product cheaper, sometimes in excess. The fillers may also increase water absorption of the elastomer resulting in the elastomer becoming a water pump (instead of a seal) between the inside and the outside. That happens when water is absorbed from outside into the elastomer because of rain, for example, and then evaporated into the drier inside space.

The alkaline tolerance of some elastomers is weaker than others and these materials are not suitable for conditions with high humidity and where they come in contact with alkaline corrosion products, for example aluminium or zinc hydroxide. Of elastomers, silicone, urethane and acrylic/butadiene elastomers have the worst alkaline tolerance whereas various fluorine elastomers and elastomers resembling natural rubber have the best tolerance. [Schweitzer 1990].

In addition to ordinary metal platings, also conductive paints can be used for EMC protection (electrical sealing). For instance Precision Painting Anaheim, in California, provides paints for coating the device cases with paints containing copper or nickel. With these, a resistance of less than one ohm per square is reached on the surface when the thickness of the coating is about 50 μm .

[<http://www.precisionpainting.com/conduct.htm>]

6.12 Conductive plastics

Plastic can be made conductive by mixing conductive particles or fibres in it or by precipitating metal on the surface or by painting it with conductive paint. The plastic can also be conductive in itself, like polyacetylene or polyaniline.

To obtain conductivity with particle additives requires that they be added to the plastic in such quantities that the particles form conductive chains in the plastic, in other words the particles have to be in contact with one another. With particles, such as conductive soot (carbon) and metal flakes, the proportions may rise to 30% of the weight of the plastic. The mechanical properties of the plastic, such as flexibility and shock resistance begin to deteriorate rapidly after this percentage. With fibre-like substances such as 5...10 μm steel fibres only a content of about 10% is required, which does not change the mechanical properties of the plastic much. It is more common to use particle additives, since the qualities of conductive fibres, high price and the reduction in the recycling properties of the plastic greatly slow down the possibilities to increase their use.

With regard to corrosion, plastics including metal particles are the most problematic. Galvanic incompatibility of the metal particles determines the process of possible corrosion damage. When assessing the probabilities, the answer is usually found in the galvanic series of metals (see Appendix 1, Section 1.2 *The electrochemical and galvanic voltage series of metals*). The galvanic series of metals can also be used in the assessment of the corrosion risk of the surface of metal plated plastic or plastic painted with conductive paint.

The greatest weakness of naturally conductive plastics is their inferior mechanical properties. Conductive plastics may lose their electric properties also through oxidation/reduction reactions; for example polyaniline may change in this way. Conductive plastics can be compared to metals in relation to corrosion. For example polyaniline corresponds to silver in the quality grade and forms a galvanic corrosion pair with less noble metals. [Zipperling Kessler & Co, Ormecon™ Technical information].

6.13 Fire retardants

Fire retardants are used to slow down the burning and igniting of materials. In electronics, fire retardants have been used as additives on the circuit boards, cases and various seals as well as in the electrolyte of electrolytic capacitors.

The chlorinated and bromated substances of fire retardants may be problematic with regard to corrosion. When the material containing fire retardants, printed board or seal (elastomer) is in contact with metals, for example aluminium or galvanized support structure these contact surfaces react even in normal air humidity with the chlorine and bromine of the fire retardants. The zinc of the galvanized surface forms zinc chloride and zinc bromide with the fire retardant, these being hygroscopic salts form a saline electrolyte with humidity from the air, which then migrates into the material containing the fire retardant.

6.14 Use of corrosion inhibitors

Background

Vapour-phase inhibitors (VCI Volatile corrosion inhibitor, VPCI, VPI Vapour-phase corrosion inhibitor) are used to reduce corrosion on metal surfaces during transportation and storage of the electronics or, more rarely, during service or use of the devices, when there is humidity, oxygen or corrosive substances in the air.

The use of these is more widespread in the storage and transportation of various metal parts than in electronics. When using the inhibitor, it is crucial to have the protected target in a “tight” package in order to evaporate continuously enough protective substance (VCI) into the package environment and new VCI on surfaces all the time.

Vapour-phase corrosion inhibitors are solid chemicals, which evaporate and spread into the air space and adsorb on all surfaces, for example in an electronic device and form a film on the surface, which aims at slowing down corrosion. The inhibitor contains the actual inhibiting agent and the evaporating/vaporising agent, which transports the inhibiting agent onto the surfaces to be protected.

Inhibitors may also exist as solutions from which form they can evaporate into the surrounding space. The inhibitors act electrochemically by slowing down both anodic and cathodic corrosion reactions (or only one of these) [Rossi et al. 1999]. They can also isolate the water accumulating on the surfaces from the metal surface under the inhibitor and slow down corrosion caused by humidity. The advantage of a gaseous inhibitor compared to other protection techniques is its ability to penetrate in the smallest cracks and gaps in the coating etc. [Fiaud 1994, p. 2].

Corrosion inhibitors do not form an electrically isolating film on the connector contacts and will not cause short-circuiting in the conductor spacing on the isolator surfaces. Therefore, they can be used also in electronics provided that the choice of material is appropriate.

When using inhibitors [Menke 1997] one must ensure that

- the inhibitors protect all metals in the protected target
- a sufficient amount of the inhibitor actually reaches the protected surfaces in the initial phase (quick initial evaporation)
- a sufficient amount of inhibitor is available during the entire operation time (enough inhibitor must be released to the air space at all times)
- the carrier for the inhibitor (paper, plastic) functions as desired and does not for instance in humid conditions let corrosive compounds into the protected space
- inhibitor does not have an adverse effect on the connectors.

Inhibitors are supplied either as separate pieces (tablets, boxes, VCI foam) or as absorbed into the packaging materials (plastic film, felt) where the inhibitors gradually evaporate and travel to the protected surfaces through the air space. Previously, VCI was supplied mainly in powder form (in bags) or absorbed into

paper. The protective film will form already in one or two days in a closed space, or, according to some material manufacturers, in hours. In reality, the inhibitors cover all surfaces. Therefore, it must be ensured in the selection process that they do not have a negative effect on for example wooden or plastic surfaces.

Evaporating corrosion inhibitors can be used mainly in a closed space, for instance in transportation packages or as different wrappings around the transported item, since the inhibitor evaporates as gas and adsorbs onto surfaces which need continuously more of it in order to retain the protective effect. If there is airflow above the surface, the inhibitor will evaporate off the surfaces and lose its protective effect. This property also seems to reduce the possible negative effects when the parts are taken out of their packages and installed to the location of use. When the product is removed from the package protected with VCI, the VCI will evaporate even in a few hours from the surfaces [ZERUST 1999]. [Fiaud 1994] gives the affecting range of the inhibitors the numeric values of maximum 35 cm for DICHA and 2 m for CHC from the source to the protected target.

In transport packages there must not be sealed cover between inhibitor source and the surfaces to be protected. For instance there must not be a closed cabinet of electronics between electronic parts and the inhibitor source because the gas exchange may be very poor from outside to inside (look Section 2.6 *Corrosion prevention techniques, Minimisation of gas contacts*). Therefore in transport packages inhibitor sources should be both outside and inside the electronics. Situation will be a little better if the amount of inhibitors is larger than the minimum recommendation.

The operating time of inhibitors in a closed space may range from 1 to 10 years depending on the tightness. The operating time of the inhibitors is regulated for instance by using materials with low (10^{-5} ... 10^{-2} mm Hg) or high (10^{-2} ...100 mm Hg) vapour pressure, depending on the application. High vapour pressure evaporates the inhibitor fast and creates protective layer quickly. Low vapour pressure inhibitor evaporates the inhibitor slowly and can maintain it longer than high vapour pressure inhibitors.

If the vapour pressure is larger than the highest limit above then inhibitors may evaporate too fast and expire too soon. A lower vapour pressure than the lowest mentioned value above may evaporate inhibitors too slowly and then they cannot produce fast enough a protective layer [Aonuma & Tamai 1981].

Examples of substances with a great vapour pressure are cyclohexyl ammonium carbonate, diisopropylamine nitrite and guanidine carbonate. Materials of low vapour pressure are dicyclohexylamine nitrite, dicyclohexylamine chromate and hexamethylenetetramine [Aonuma & Tamai 1981].

It is important to ensure a sufficient amount of the inhibitor since too scarce amounts can even add to local corrosion [Fontana 1987], which is characteristic of inhibitors blocking anodic reactions. In tests and use it has been shown often that the amount of inhibitors recommended by their manufacturers are too low. Therefore the user of inhibitors has to find the right “dosage” by himself by tests and gathering practical experiences.

The effect of the amount of pollution in the air and on the protected surfaces is in a way the opposite to the use of too little inhibitor. If there is a lot of water and pollution the inhibitor will “wear off” quickly from the surfaces or its effect is not sufficient on the contaminated surface.

Inhibitors in transportation packages

The conditions of transportation, storage and installation of an electronic device are often worse than the conditions of production or use. The device does not generate heat during transportation, which would decrease the relative humidity compared to the conditions outside the device case. This is why the device or its parts should be protected and packaged to withstand the stresses occurring during transportation. The most ideal situation were to pack the device so that it is dry and free from the effects of air pollutants during the whole time of transportation and storage.

The combined effect of the humidity in air and pollution has the most significance with regard to corrosion. The fluctuations in the air temperature increase humidity. The transportation package usually consists of a mechanical cover, a plastic protective film and shock absorbing material. The plastic protective film reduces the ventilation inside the package but it does not prevent water vapour from penetrating to the inside. Drying substances (desiccants) can be used for moisture reduction. Corrosion inhibitors can be used to prevent at least to some extent the corrosive effects of the air pollution and humidity entering the package. The main problem is to keep the packages intact during the entire transportation and storage chain.

The protected product should be dry and free of solvents and other impurities. When using protective packaging materials the packaging should take place at

room temperature. The protective package should be sealed (not airtight) the access of water to the package must be blocked and the package should not be in contact with substances generating acid (moist wood or cardboard, sweat from hands etc.). Factors accelerating the release of the inhibitor substance (reducing the operating time of inhibitors) are long term exposure to temperatures exceeding 65°C and a chemically aggressive environment containing plenty of sulphur dioxide or salt (maritime transport).

When using VCI packaging materials made of paper, it should be ensured that the paper is halogen free (not for example salty), since humidity releases halogens that destroy the protective inhibitor film [Menke 1997].

Corrosion inhibitors may be mixed with the plastic film designated for transportation packages. When using such films, the amount of the inhibitor must be sufficient for the protected target. The problem with a homogeneous film is its symmetry; in other words it releases the inhibitor on both sides thus wasting half of the inhibitor. On the other hand, the film may let through water since if it were tight it could not release the inhibitor from the inside out either. The film should be gas tight in order not to let through water or oxygen onto the protected target. At the same time it should continuously evaporate new inhibitor to the protected target. Such a film may be manufactured using the three-layer structure where the inside and the outside surfaces are soft and chewy and the middle layer almost gas tight. The inhibitors are mixed with the inner layer. Such a construction makes the film mechanically sound, prevents water from seeping through and releases the inhibitor onto the surfaces of the protected device.

Multi-metal protection

Inhibitor materials are in principle selective, in other words they protect only certain types of metals and chemicals, for example against sulphuric compounds in the air. In more recent products, even chemicals with a wider effect or various chemicals combined have been used complemented with a desiccating agent.

The first product developed after World War II was DICHAN (dicyclohexylammonium nitrite), which only protects iron and aluminium. In DICHAN the vaporising agent is dicyclohexylamine and the actual inhibitor is nitrite.

The drawback with DICHAN is that it is slightly poisonous as other nitrates. Since then, more environmentally friendly materials have been developed that protect also copper and several other metals simultaneously. It is typical of the suppliers to offer an inhibitor separately for iron based metals, which will also

work for a number of other metals (for example zinc, lead, tin, nickel, chrome) but not for copper or aluminium.

An inhibitor of a certain manufacturer for non-ferrous metals can also be applied to aluminium, copper, brass and steel if it is completely galvanized. Multi-metal inhibitors are designed for all metals but they are not as effective on iron as the inhibitors specially designed for iron.

When using a corrosion inhibitor, the following items should be assessed:

- the sensitivity of the device in question to corrosion
- real environmental conditions (temperature, humidity, pollutants)
- adequacy of other action with regard to corrosion protection (transportation package, use of desiccant)
- protected targets and their materials and the choice of suitable inhibitors for them.

Table 6.4 lists the metals used in electronics. Because of the “selective” effect of inhibitors practical tests are needed to ascertain whether the materials in question are useful for the product of the company and whether the inhibitor acts as desired.

Table 6.4. Metals used in electronic products.

Part, component	Metals used in electronics
Cabinets, racks, springs, heat sinks	Aluminium, steel, brass, bronze, copper, coatings (zinc, nickel, copper etc.)
Printed wiring board	Copper, copper alloys, coatings (tin, tin-lead, gold)
Electrical contacts and groundings	Copper alloys, steel, aluminium, contact platings (gold, palladium, silver-palladium, silver, nickel, tin, tin-lead)
Connectors	Brass, beryllium-copper, Phosphor-bronze, chromium steel (stainless steel), contact platings
Switches and relays	Copper alloys, steels, chromium steel (stainless steel), contact platings
Passive and semiconductor components, microcircuits	Gold, copper alloys, nickel (barrier layer), silver, aluminium, kovar (nickel-steel alloy), tin-lead, wolfram

Adverse effects

The use of corrosion inhibitors may entail adverse effects such as corrosion of certain metals, decay of some plastic materials, deterioration of the isolation properties of the printed boards, formation of an obscuring film on the optical surfaces, discolouring of organic materials and formation of a thin isolating layer on the contact surfaces. The inhibitors affecting anodic reactions have a certain minimum amount. If dosed below this, they can add local corrosion instead of protecting from it [Fontana 1987].

In addition, DICHAH erodes copper, bronze and silver, is harmful to zinc and magnesium and has an adverse effect on health and the environment. Sodium nitrite inhibitor, which entails the same problems, is still used especially in applications requiring large amounts of inhibitor because it is cheap.

Some materials also carry health and environmental problems because of their cancer causing properties (for example older nitrite substances, DICHAH).

Since the inhibitor materials may cause corrosion in some metals the user should check prior to use that the inhibitor does not have such an adverse effect. In practice this can be done only by testing various inhibitors close to the actual conditions of transport and use and by using products to be protected and their parts and packaging materials as the test objects.

Table 6.5. Examples of inhibitor products.

Product	Method of use
Additive to latex for the coating of paper	Results in paper or cardboard with corrosion protection. Laboratory tests performed on a limited choice of metals. Manufacturer recommends laboratory or field tests on other materials.
Powder	Powder is blown to holes or other complex structures difficult to protect otherwise. Multiple metal protection up to two years, no need to remove powder prior to use of the device.
Spray	As in the above. Do not spray if the voltage is on in the electronics.
Capsule	Protection of electronics. Life span is valid if the air is changed at the most twice a day.
Stretch film, shrink-wrap, plastic film	For packaging devices or parts for transportation or storage. Plastic film can be processed antistatic in addition to inhibitor (used as bags for packaging component boards, see SFS-EN 100015-1).
Cell or foam sheet, blister foil	As in the above, also act as padding.
VCI cardboard packages	The package itself offers corrosion protection.
Coating material	Liquid polymer material containing inhibitor for protecting the component board. Is spread by spraying or with a brush. The resulting film can be removed with alcohol.
Grease	Grease containing corrosion inhibitor for protection of contacts.
Protective sheet	Sheet of material for protection of small devices (mobile telephone, laptop etc.).

Inhibitor products

Inhibitor materials are available for example as powders, bags, films (impregnated film/ semi-permeable film), capsules, etc. (Table 6.5). Capsules and tablets are the usual forms of material use (in closed or semi-closed cases, lockers etc.) and the treatment of packaging material with the inhibitor (plastic, stretch film, felt, paper, cardboard).

In some cases the inhibitor is combined to a water-absorbing material, for example CORTEC and [US Patent 5324448 see *Inhibitor patents*]. It is not always possible to use a desiccant, such as silica gel, together with the inhibitor since they adsorb not only water but also other gases, for instance VCI gases [Fiaud 1994, p. 1].

Manufacturers for materials listed in Table 6.5 are for example: Contract Chemicals Ltd, Corrosion Inhibitors Inc., Century Corrosion Technologies, Inc./Cortec Corporation, Daiwa Fine Chemicals, Grofit Plastics, EXCOR GmbH, Northern Technologies International Corporation Zerust™, Zerust Ltd and Senson.

Basic structure of inhibitors

VCIs are usually salts of a basic substance evaporating relatively quickly and a slowly evaporating acid [Fiaud 1994]. The most common basic materials are:

- Cyclohexylamine
- Dicyclohexylamine
- Guanidine.

The acids used with these are

- carbon acid (CO_3^{2-} ion)
- Nitrous acid (NO_2^- ion)
- Carboxyl acids (R-COO^- ions).

The most common actual inhibitor materials are [Fiaud 1994]:

Benzotriazole (BTA)

This organic substance is suited for the protection of copper and its alloys. The gas pressure of BTA is rather low, around 10^{-5} mm Hg (10^{-3} Pa) at 25°C, which means an initially slow but later long-term effect. BTA blocks the sulphidation of copper especially, in other words it offers good protection against H_2S and COS-gases. The effect of BTA weakens if there are plenty of chlorides present.

Dicyclohexylammonium nitrite (DICCHAN)

DICCHAN is used for protection of steels. It corrodes zinc and can be either inert or corrosive on aluminium and copper. It can be used as such or together with other VCI products. The gas pressure of DICCHAN in various temperatures is $7 \cdot 10^{-6}$ mmHg at -1°C, 10^{-4} mmHg at 21°C and $7 \cdot 10^{-3}$ mmHg at 60°C. DICCHAN is as poisonous as sodium nitrate.

Cyclohexylamine carbonate (CHC)

This material protects steel and various non-ferrous metals well but strongly corrodes copper and copper alloys. The gas pressure of CHC at various temperatures is: 0,4 mmHg at 25°C and 7,58 mmHg at 55°C, in other words much greater than that of DICHAN. The kindling point (flash point) of CHC is 49°C.

Contract Chemicals Ltd has manufactured a product of the latter: Cyclohexyl ammonium-N-cyclohexyl carbamate, which is a white crystalline substance. Its gas pressure is 0,4 mmHg at 25°C and 7,58 mmHg at 55°C and its kindling point is 49°C, in other words the same values as CHC. This product gives good protection on aluminium, cast iron, chrome, tin and its alloys and zinc, and some protection on copper, copper alloys, lead and soldering tin. The product is not recommended for magnesium.

As can be seen from the above, somewhat controversial data is given on CHC and other such substances, which emphasises the importance of inspecting in each application if the inhibitor material will act as desired.

Test methods and standards:

There are only a few standardised methods for testing the transportation packages in order to test the functionality of the corrosion inhibitors. The different operating methods and very varied chemical properties of the inhibitors make this testing difficult.

Federal Standard **FED-STD-101C**, Federal test method, standard test procedures for packaging materials. Method 4031, Corrosion inhibiting ability of V.C.I. vapors, procedures A and B. (March 13, 1980).

With this method the corrosion inhibiting ability of VCI-material is tested. Method A is meant for testing VCI-materials in crystalline or liquid state. Method B is used for testing products plated or impregnated with VCI-material. As corrosion indicator may act steel or some self selected metal in these tests.

Federal Standard **FED-STD-101C**, Federal test method standard test procedures for packaging materials. Method 3005, Contact corrosivity test of solid materials in flexible, rigid, or granular forms. (March 13, 1980).

This test is used to study if the packaging material causes corrosion on steel or aluminium surfaces in contact with the packaging material. This

testing principle can also be applied for testing whether the packaging material impregnated with corrosion inhibitor acts as corrosion protection or whether it causes corrosion on the surfaces to be studied.

For the user, the most practical way is to test the inhibitors for example in the company's own transportation packages and in their intended use. Connectors, circuit boards and also microcircuits and metal parts should be tested in order to check the various metal surfaces in a comprehensive way. The transportation packages and the products within should be tested at elevated temperatures ranging from 30...55°C and at high relative humidity of 60...98%, when the corrosion mechanisms correspond fairly well to those during transportation. If the testing air contains sulphuric compounds or chlorides the conditions correspond to reality even more. The inhibitor under study should be used according to the manufacturer's recommendations concerning application methods and quantity in the tests.

[Mercer 1994] describes the general testing technique for inhibitors in his article. The article mentions some ways of relatively simplified testing of VCI-products on metal samples. In tests one has to be conscious of the operation principle of VCI materials. They work only in closed spaces where is also a source of VCI material. Actually in tests where there may be a too large air volume or air change is too rapid, the concentration of VCI in air may become too low. But then if the inside structure of the device is clamshell or it contains cased parts, the distribution of inhibitor may be blocked out and protection remains low.

The error margin in the interpretation of the results is also great since the corrosion mechanisms and conditions have so many forms, the protection capacity of VCI materials is fairly limited with a positive effect on only a few metals. Wrong interpretations may also result from the fact that many packaging materials (wood, cardboard) emit at high humidity halogens, acids and other such corrosive substances which may reduce the effect of the inhibitor to nothing. Correspondingly some inhibitors evaporate so slowly that in quick tests the inhibitor does not have time to function [Kraemer 1997].

The [Jaeger 1997] reference describes how the QCM, Quartz Crystal Microbalance, method can be used for observing the functionality of corrosion inhibitors.

The following standards have specified some packaging materials with inhibitors. It is important to ensure with regard to humidity and corrosion protection that the materials used are resilient and tough enough mechanically and that they stop water from entering the devices. The material should tolerate

bending and stabs from sharp objects so that no holes or cracks would result during handling and transportation, which may be the case with aluminium foils.

MIL-I-46058C (1 July 1972). Insulating Compound, Electrical (for Coating Printed circuit Assemblies). U.S. Government Printing Office. Inactive 30 Nov 1998. 14 p.

MIL-I-46058C, Amendment 7 (14 September 1993). Insulating Compound, Electrical (for Coating Printed circuit Assemblies). Inactive 30 Nov 1998. 5 p.

MIL-B-22020-D (2 May 1990). Bags, transparent, flexible, sealable, volatile corrosion inhibitor treated. 11 p.

MIL-PRF-131J (26 August 1998). Barrier materials, watervaporproof, greaseproof, flexible, heat-sealable. 19 p.

MIL-PRF-3420G (11 September 1998). Packaging materials, volatile corrosion inhibitor treated, opaque. 16 p. (Used to protect steel)

MIL-PRF-22019D (31 August 1998). Barrier materials, transparent, flexible, sealable, volatile corrosion inhibitor treated. 16 p.

MIL-PRF-22191E (26 August 1998). Barrier materials, transparent, flexible, heat-sealable. 20 p.

MIL-PRF-81705D (3 September 1998). Barrier materials, flexible, electrostatic protective, heat-sealable. 27 p. (Replaces MIL-B-81705C).

Inhibitor patents

Some patents concerning electronics in particular have been published in the 1990s on corrosion inhibitors. The aim has been to improve the operating period of the inhibitor on the one hand, and to combine the inhibitor to moisture absorbing materials on the other (US patents) by drying the environment of the protected surface and covering the surfaces with a protective chemical. The Japanese patent JP 9031672A mentioned in the following applies to the use of Butynediol (2-butyne-1,4-diol) in the transportation of car parts.

US Patent 5324448. Combination dessiccant and vapor-corrosion inhibitor. June 28, 1994.

US Patent 5391322. Method for extending the service life of a vapor-corrosion inhibitor. February 21, 1995.

JP Patent 9031672A, Volatile corrosion inhibitor, February 4, 1997.

JP 9039907A. Packing method for metal sheet. February 10, 1997.

WO9749870A1. Anti-corrosive material. December 31, 1997.

The patent application (WO...) applies to multi-layer polyethylene film material where the outside protects mechanically and chemically and the inside has one or more layers impregnated with biocides or VCI or both in order to block the growth of microbes and corrosion.

US Patent 3836077: Apparatus protector, September 17, 1974

This patent applies to Zerust VCI-capsules, which can contain various inhibitor materials and which can be placed inside the device to be protected.

6.15 Gas absorbents

Materials, which absorb and chemically bind for example corrosive gases such as SO₂, H₂S and NO₂, can also be used to protect transportation packages and other closed spaces from corrosion [Kelly 1999]. These substances have been used to remove various gas residues from certain spaces. In transportation packages of electronics, a useful form is for instance SAP, Surface Active Paper, 3M™ Model 2101 Corrosion Control Absorber Patch by 3M. The material of 3M absorbs sulphur dioxide, hydrogen sulphide and carboxyl acid, among other things.

The material comes in rolls from which suitable pieces can be cut or ripped off for the packages.

[http://www.3m.com/ehpd/packaging/bags_PROD.html#patches].

This paper can protect various metals such as copper, tin, soldering tin, gold, nickel and brass. This means of protection is suited for all kinds of transportation packages, especially components where it is extremely important to maintain the soldering properties of the connecting wires. The effective time of use of the material depends on the tightness of the package, typical times range for six months to two years. If the packages leak the absorbing material becomes saturated before too long and loses its effect.

Instead of a gas absorbent seeped into paper capsules may also be used which contain for example silica mass impregnated with potassium permanganate for absorbing sulphuric compounds.

When using these materials it is important to study which gases and to what extent they absorb.

6.16 Removal of moisture from transportation packages

The reference [KOTEL 236] deals in general with materials of transportation packages and the mechanical, climatic, biological and static electricity tolerance requirements (see also SFS-EN100015-1 *Protection of components sensitive to static electricity* and IEC 61340-5-1 *Protection of electronic devices from electrostatic phenomena*). The limiting of the harmful effects of humidity and the resulting corrosion is one of the main qualities required of the packages. This section discusses moisture removal techniques.

Silica gel

Silica gel (silicon acid gel) is a water-adsorbing material, which at best adsorbs water more than 35% of its weight at relative humidity of 80%. It is the most common chemical used for removing moisture from transportation packages. Silica gel is made of sodium silicate and sulphuric acid. It is also known as amorphous silica, synthetic amorphous silica, amorphous silicon dioxide, (silica is colloid silicon dioxide, SiO_2).

Silica gel comes in porous granules. The specific weight is about $2,2 \text{ kg/dm}^3$. Despite its name silica gel is not a jelly (gel). Silica gel is sold and used in bags or boxes, which are sealed into airtight packages prior to use. Usually the silica gel boxes come with an indicator substance changing colour; for instance blue when dry and pink when wet [Silica gel FAQ 1999]. If the silica gel bags do not contain a humidity indicator other means should be used to verify that the material is dry prior to packaging. In a large room space, the silica gel bags will get wet in a few hours whereby they lose their ability to maintain dryness in the packages.

Silica gel granules are filled with micropores, which adsorb water, which goes through capillary condensation. (see Appendix 1, Section 3.8 *Condensation of water*). The ability of silica gel to retain water is based on the large internal area of these pores. The diameter of the pores in the granules is about 15 nanometres

[Silica Gel Desiccant Grade 1999] and the internal area about 600...700 m² per gram. Silica gel is chemically inactive, non-poisonous and the surface feels dry even when the gel is humid [Silica gel FAQ 1999].

The good properties of silica gel include the ability to absorb moisture until the saturation point is reached. Water is contained nearly permanently in silica gel, which is why the humidity levels of the air space can be maintained below a certain level and the absorbed humidity is not released back into the air space. If silica gel is placed into a free or too large air space it adsorbs water to the amount corresponding to the relative humidity of the air space and it will lose its operating ability within a few hours at humidity levels lower than these conditions.

The categories of equilibrium humidity of silica gel, in other words the greatest adsorbing amount of water as a function of the relative humidity of the air are stated in Table 6.6.

Table 6.6. Equilibrium humidity of silica gel and relative humidity of the air.

Relative humidity of air space (%)	10	20	40	60	80
Adsorbed water (weight%) at equilibrium	8	15	27	33	35

[Agm Container Controls, http://www.agmcontainer.com/silica_gel.htm, MIL-D-3516 Type II Grade H]

The amount of silica gel needed in packages of various sizes can be estimated based on Table 6.6. In practice, one must include the initial humidity of the adsorbent, the size of the air space, the initial humidity of the transportation package and the humidity seeping through the package during transportation. During long term transportations and storage the risk of moisture seeping into the packages is great and therefore a reasonable extra amount of adsorbent should be placed into the packages.

The advantage of silica gel is that it is reusable, in principle several times. The used humid material is dried in temperatures ranging from 120...150°C [Silica Gel Desiccant Grade 1999] and kept in an airtight package in order to prevent it from getting wet again before reuse.

Silica gel adsorbs not only water but also all condensing gases from the air, including oil. Therefore its properties during reuse may change as the pores gradually get blocked.

MIL-D-3464E (21 Apr 1987). Desiccants, activated, bagged, packaging use and static dehumidification. Type I, II & III. 21 p.

MIL-S-14374C (11 February 1983). Silica gel, iron free. 7 p. (Inactivated standard 23 June 1995).

Piechota, D. Humidity Control in Cases: Buffered Silica Gel versus Saturated Salt Solutions. WAAC Newsletter, Vol. 15, No. 1, Jan. 1992, pp. 19–21.

<http://palimpsest.stanford.edu/waac/wn/wn15/wn15-1/wn15-108.html>.

Other desiccants

Other adsorbents acting like silica gel include:

Molecular Sieve is the crystalline and porous form of zeolite, which is sodium, potassium or calcium aluminium silicate. It is the most effective and also most expensive of adsorbents. Zeolite adsorbs water effectively but it is also used as a gas filter and catalyst in its various forms. It can be made in such a way that it adsorbs especially water and no other substances. This property is based on the even size of its pores, which can be regulated. Other adsorbents have pores with varying sizes and are therefore not as selective. The adsorption of water is also quicker than with other substances and it also works in higher temperatures than other adsorbents.

<http://www.drjohn.demon.co.uk/index.html>

<http://www.gracedavison.com/pckdsfrm.htm>

<http://www.gracedavison.com/davhome.htm>.

Bentonite clay (Montmorillonite clay), which is a natural mineral containing water in the crystals (calcium aluminium silicate and sodium aluminium silicate [(Na,Ca_{0.5})_{0.33}(Al,Mg)₂Si₄O₁₀(OH)₂ nH₂O]) containing dozens of colloid silica minerals. Bentonite clay is the cheapest adsorbent for water removal. It is white, pink, light grey, light green or brown and will turn yellow when wet. The specific weight is about 2...2,7 kg/dm³. The internal area is about 74 m²/g.

<http://206.190.82.22/faq.htm>

<http://www.ssc.on.ca/mandm/montmor.htm>

http://www.jefo.ca/fiches_anglais/sodium_bentonite.html

<http://www.gov.sk.ca/enermine/facts/sembent.htm>

<http://202.112.29.88/kuang/mts1.html>.

Bentonite (montmorillonite) is also used as a mineral additive in some foodstuffs and cattle food, for wine clarification and for constructing water seals in earth construction. In painting technology, bentonite is used as an organically modified

gel to increase paint viscosity in order to prevent the heavy pigments from sinking to the bottom of the can.

The properties of bentonite when used as a desiccant are described in standard DIN 55473, Ausgabe:1997-12 Packhilfsmittel – Trockenmittelbeutel – Technische Lieferbedingungen. Suppliers include for example Chemische Fabriken Oker und Braunschweig AG.

In addition to silica gel, there are a number of other substances that can be used to absorb water, such as salts. Salts differ from silica gel concerning their capacity to retain water since in conditions of decreasing relative humidity of the air they desorb water and strive to maintain the relative humidity characteristic of the substance in the air space above the salt. [Appendix 1, Section 5 *Factors affecting the progress of corrosion* and Nordtest Remiss Nr 548-85 1987].

Alkali-metal partial salt of crosslinked poly(propenoic acid) is an alkaline salt of crosslinked polypropenoic acid. The crosslinking makes the substance nearly insoluble to water and the substance will absorb water and form a gel like mass [US Patent 5324448].

Alkali-metal poly(acrylate) is an alkaline polyacrylate, the most common linear sodium polyacrylate, which has been used as an additive in latexes for years. The desiccating properties of this substance are inferior unless it has been crosslinked to a polymer, in which case it will turn into a gelatinous mass when out into contact with water [US Patent 5324448].

Potassium poly(acrylate) is a linear sodium polyacrylate used in latexes [US Patent 5324448].

Partial sodium salt of crosslinked poly(propenoic acid) is the sodium salt of partially neutralised crosslinked polypropenoic acid which acts as in the above [US Patent 5324448].

Superabsorbents are substance that can absorb water even thousands of times their own weight. In this respect they thus exceed silica gel. These absorbents do not retain water as well as silica gel but release it slowly even in room temperature. In practice, superabsorbents maintain a certain humidity balance in a closed air space, which can be useful. These absorbents form a gelatinous mass with water, which can absorb a great deal of water. A typical application is babies' diapers where superabsorbents are as small polymer granules.

In addition to desiccants, gas absorbents such as active carbon capsules can also be inserted into the transportation packages. These adsorb the gases inside the package or gases penetrating the package. There are also oxygen-removing absorbents in use. Their aim is to prevent oxidation reactions, for instance in foodstuffs.

Transportation packages for components

The risk for exposure of the components to humidity during transportation is very great because of exposure to the outdoor air and large fluctuations in the temperature. Plastic materials always absorb some moisture. This can take place in a few days or weeks according to how high the relative humidity of the air and the temperature are. The seeping of moisture into the component packages during transportation and storage can cause serious difficulties in the soldering process since moisture in the component packages which usually occurs in liquid form in the micropores of the cases can make the cases explode or can result in microscopic cracks in them when taken to the soldering machine for soldering. This happens because the volume of water expands 1200 fold during vaporisation in soldering temperatures exceeding 200°C [Pecht 1995].

This is why dry packages for the prevention of moisture and corrosion are used especially in the semiconductor industry. They offer in principle good protection against climatic effects (standard JEP113-B). A desiccant and a humidity indicator are placed in the packages whereby the dryness of the inside air can be verified when opening the package.

In standards IEC 60286 and IEC 61760 are described the packages and the conditions which the surface mounted components (SMD) have to endure. See section IEC/IPC *Handling of components sensitive to moisture* (in the list Corrosion and humidity protection and material standards).

Vacuum package or dry nitrogen as protective gas?

The problem with vacuum/partial vacuum packages is the pressure difference between the outside and the inside, which force oxygen and moisture into the protected space with lower pressure than on the outside. Another problem area is keeping the inside sufficiently dry in order to prevent the condensation of water in low pressure. There is always some water in the components and on the surfaces of materials in the packaging phase [Appendix 1, Section 3.6 *Water solutions and electrolytes*]. The vacuuming of pressure and the dryness of the air space during the last handling phase determine how dry the insides of the

packages can become. It is difficult to remove the water adsorbed on the materials and the surfaces without heating. If water is left inside it will condense relatively easily since the volume of free space is relatively small in a partial vacuum package. The condensing water settles on the surfaces permitting possible oxygen to cause corrosion together with water and contamination of the surfaces.

When using dry protective gas, such as nitrogen, the protective gas fills the protected space and also effectively removes water from the surfaces since the relative humidity is low. Due to the protective gas there is no oxygen in the air space, which reduces corrosion significantly even with water on the metal surfaces [Fiaud 1994, p. 1]. If the pressure of the protective gas equals normal air pressure and the package is loose, no great pressure difference will be created between the inside and the outside of the package. Thus the exchange of gases between the outside and the inside also remains minimal compared to a corresponding partial vacuum package. Since the volume of the inside of the package is greater than in a partial vacuum package the amount of water possibly retained in the components and on the surfaces remains so minimal in relation to the available gas space that the relative humidity remains low and there is no condensation.

IPC (The Institute for Interconnecting and Packing Electronic Circuits) and JEDEC (Joint Electron Device Engineering Council) have published guidelines on how to define the sensitivity of microcircuits to humidity, how to handle the components prior to soldering and how to label components sensitive to humidity. In principle, these guidelines apply to non hermetic surface mounted semiconductor components (SMD), but they can be applied also to other components which can be expected to absorb moisture during storage and transportation and which are subjected to temperatures of nearly 200°C during the soldering process. These include ceramic surface mounted resistors and capacitors, which can absorb water.

By observing the guidelines of standard JEP124 the usability of packaged components can be ensured up to 12 months from the date of packaging. The internal humidity of the package must remain below 20% RH at a temperature of 30°C even after the guaranteed 12 months.

The requirements include

- MIL-PRF-81705D Type I package with water permeability of less than 31 $\mu\text{g}/\text{cm}^2/24\text{h}$ (0,02 $\text{g}/100 \text{in}^2/24 \text{h}$)

- MIL-D-3464E, Type II desiccant in the package
- MIL-I-8835A and MIL-P-116, Method II humidity indicator card
- ID-label for identifying the contents as components sensitive to humidity
- warning labels of components sensitive to humidity
- creating a partial vacuum in the package prior to sealing it.

Standard JESD22-A112-A presents a testing method for classification of components into categories by their sensitivity to humidity. The components are dried a minimum of 24 h at 125 C° before exposing them to humidity.

The testing conditions for components with unlimited storage time are 85°C/85% RH, 168 hours and for products that can tolerate a year of storage 85°C/60% RH, 168 h. The testing conditions for components sensitive to humidity which are allowed only 24 h in conditions 30°C/60% RH after the opening of the package and prior to soldering are 30°C/60% RH, 48/72 h.

The components must not be damaged in the soldering performed immediately after the above exposure.

The main standards concerning packages are listed below. For a more detailed list, see section IEC/IPC *Handling of components sensitive to moisture* (in the list Corrosion and humidity protection and material standards, pp. 213–216).

IEC 60286-3 (1997-12) Packaging of components for automatic handling – Part 3: Packaging of leadless components on continuous tapes. 37 p.

IEC 61760-2 (1998-02) Surface mounting technology – Part 2: Transportation and storage conditions of surface mounting devices (SMD) – Application guide. 9 p.

EIA/JEP124 (December 1995) Guidelines for the Packing, Handling and Repacking of Moisture-Sensitive Components. 14 p.

IPC/JEDEC J-STD-020A (April 1999) Moisture/Reflow Sensitivity Classification for Nonhermetic Solid State Surface Mount Devices. 21 p.

IPC/JEDEC J-STD-033 (May 1999) Standard for Handling, Packing, Shipping and Use of Moisture/Reflow Sensitive Surface Mount Devices. 20 p.

IPC-SM-786A (1995) Procedures for Characterizing and Handling of Moisture/Reflow Sensitive ICs.

JEP113-B (May 1999) Symbol and Labels for Moisture-Sensitive Devices. 6 p.

JESD22-A112-A (November 1995) Test Method A112-A, Moisture-Induced Stress Sensitivity for Plastic Surface Mount Devices. 12 p.

7. Application examples

7.1 Review targets

The review of estimating and developing the corrosion resistance of electronics starts by defining and outlining the aim of the review and after that by reviewing the environmental demands on the product, its physical structure and the entire production process including logistics and subcontracting and customer deliveries. Figure 7.1 shows a list of the review targets. A more detailed description of the entire review methodology and the contents of each header are presented in Appendix 3.

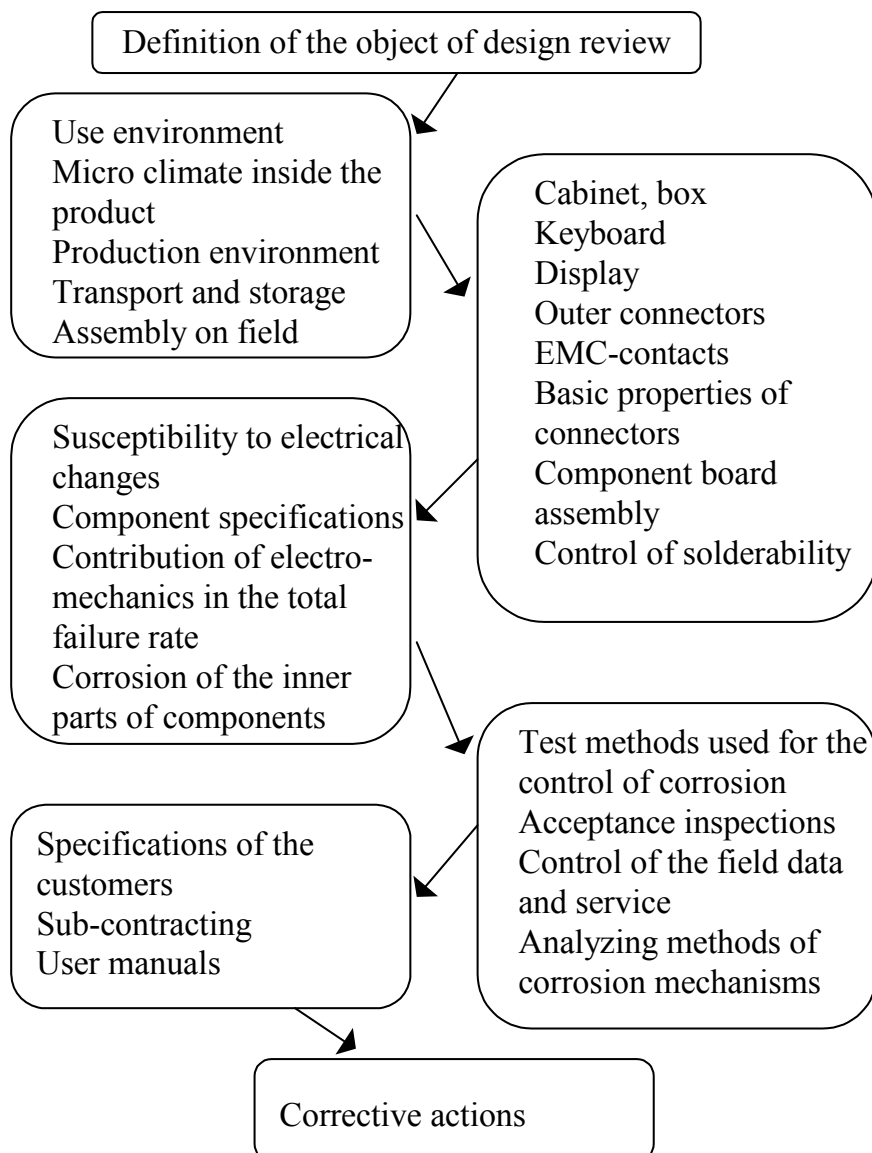


Figure 7.1. Review targets.

The outlining of the review target means agreeing on whether the entire design, production and logistic chain of the company or a single product family or, for example, a part of a specific product is processed.

The described review methodology (Appendix 3) deals with all sub-areas affecting corrosion resistance. The target determines the weight of each sub-area at hand. The review methodology presented in Appendix 3 is designed for use as a model when drafting the corrosion control procedure to be included in the own quality system of an electronics company. In practice, the reviewing is usually limited to smaller entities. When performing these partial reviews, it must always be checked that the corrective action actually removes errors and not only compensate for errors made somewhere else. Therefore, each partial review should contain at least a brief general review to include the crucial mistakes in the entire design–production–subcontracting–delivery chain.

A number of product reviews was performed in connection with this publication for developing the review methodology in Appendix 3. A procedure model was drafted for each product/company with suggestions for the necessary corrective action. The product families reviewed were elevator electronics, mobile telephone, frequency converter drive, and power supply.

These reviews led to the conclusion that the main part of the content of the review may be considered common to all products, but the detailed action performed as a result of the review are always unique even though their sphere could be the same as in some other product.

The following examples have described briefly the characteristics of each product with regard to corrosion resistance control. It is important to realise the wide basic homogeneity of the basic characteristics of these products too, namely:

- use of the products all over the globe
- homogeneity of external environmental conditions
- use of similar technology and components
- existence of similar subcontractor relations
- similarity of testing technology and quality control.

Environmental conditions and method of use

External or outdoor conditions and the basic stress caused by them are the same for all products. The content of this similarity is further enhanced by the fact that

most products are used nearly everywhere in the world. Since the method of use for the products differs and the final location of installation is most often indoors and the internal conditions of the device can be effectively influenced by the casing of the device, the environmental conditions are after all relatively individual for different products.

The biggest differences can be found in the method of use of the devices. Elevators are installed as fixed inside buildings and the machinery is spread around the house, mobile telephones travel with people, power supplies are usually installed inside another device and the frequency converter drive functions either as an independent device or as a part of a bigger unit.

Structure and components of a product

The basic materials of products starting from the circuit board and the main part of the components are very similar in all the product examples. Printed board materials are almost the same, although there are differences, too, multiple layer technique is common, surface mounting technology is found in all products, basic plating tin and gold are common in contacts and wiring patterns, liquid crystal technique is used for displays and membrane/film keyboards are seen. The main part of the microcircuits is encased in plastic and the power densities on component level are close to each other. At its densest, the density of the wiring patterns is nearly the same in various products.

The biggest differences are in the size of the product, case materials, case tightness and cooling techniques due to the differences in the total power levels.

Production process

Automatic assembly and surface mounting technology is used in the manufacture of all the reviewed products. Reflow or flow soldering is used as soldering techniques. The production facilities are relatively neat and air conditioning is common. The main differences are the series sizes in the realisation of the assembly. The share of manual labour is small in the large series of mobile telephones, but in elevator machinery, there is a lot of manual labour during the manufacturing and assembly. Due to the nature of serial work, lacquering is not used much even though it would be feasible because of the great wiring density to prevent operational problems due to humidity and contamination.

Subcontracting and transportations

Nearly all parts and components come from subcontractors to the manufacture of various products. Therefore, the problems caused by the transportation of these and due to corrosivity and humidity of the conditions are similar in the transportation, storage and soldering of printed boards, metal parts and components. Each component subcontractor and buyer have different practices in the specification of the transportation packages. In general, there is always room for improvement in the quality of the transportations and the transportation packages since the wetting of the transported materials and the soldering of the components cause problems.

One transportation problem in common is how to maintain sufficiently dry conditions inside the transportation packages/ or to use absorbents for corrosive materials or corrosion inhibitors. The significance of these becomes obvious in transportations and storages lasting more than a week, in maritime transportations and in tropical conditions.

There are major differences in the customer deliveries; some products are transported by air, some by road or railroad and some on ships. The storage times vary a great deal. Therefore, protection of the products with the transportation packages against the effects of humidity and corrosion is crucial with regard to the shape of the products at the acceptance point of the customer. In addition, installation and use practices are very different. The installation of elevators takes place in difficult construction conditions exposed to the effects of the weather, an frequency converter drive or power source may be exposed to more demanding conditions than what they were designed for and the user practices of mobile telephones are as varied as lifestyles themselves in different parts of the globe.

7.2 Elevator electronics

The specific features of elevator electronics are mainly due to the basic structure of elevators. The elevators are located on several floors in the buildings, which is why the electronics will have to be dispersed to various locations. There is electronics in both protected and unprotected spaces. The motor of the lift and its control are usually centred as one entity but all user instructions and panels are dispersed in the elevator and outside the elevator shaft. This results in a great number of wirings around the elevator shaft. The additional corrosive stress caused by the users and for example cleaning varies a great deal depending on the location of use of the elevator (apartment building, hotel, factory).

The installation of elevators to the location of use is problematic since the construction is most often started from the elevator shafts (wells) and the elevators are usually wanted to be operative at an early stage of the construction. This results in the machinery being exposed to the weather, construction dirt, water and dust.

In the review of elevator electronics, the electronic realisation itself, the consideration of the properties of the location of the parts and the setup of the installation have to be separately addressed due to the special characteristics discussed in the above. A great deal of attention should be paid on the greatly varying conditions that the wirings and the electronics are subjected to.

Another chapter in corrosion prevention is the organisation of the needed cooling for high power semiconductors when the aim is to maximise the cooling effect while minimising the airflow over the electronics to prevent contamination. All high power connections and connectors are also important review targets.

7.3 Frequency converter drive

The frequency converter drives discussed here were small devices of a few litres in size where the cooling was realised with free convection. The case is relatively open. Because of the small size, great packaging density and great power density of the power stages some of the electronics operates fairly warm. AC inverters can be placed relatively freely in various indoor spaces and even inside other devices.

Because of the cooling required by the great power level AC inverters are also exposed to airflow which makes the internal protection of the device an important review target. High temperature affects the ageing of isolation materials and joints, which is why the checking of the sizing of these in all high power targets is important. Power changes cause repeating thermal expansion, which affects the entire structure and all joints.

7.4 Power supply

The reviewed power supplies are designed as parts of larger device units. The power supplies are modules cooled by natural convection. The case is usually a sheet metal cover the structure of which can also be open. Power supplies can also form a separate power supply unit, which is a sizeable device cabinet.

The environment of a power supply is usually dry and warm due to the nature of use. Since the method of cooling of the customer devices is usually effective use of convection, some of the power supplies are directly exposed to the outside air of the host device. This can make the conditions very contaminating and corrosive.

High operation temperature usually keeps the power supplies dry but the heat affects the isolation materials and wiring connections causing decay, which is why these must be reviewed with care. The power load of the power supplies varies which results in great temperature changes, which accelerates the corrosion mechanisms.

7.5 Mobile telephone

The small size of a mobile telephone, large manufacturing series, large operation frequencies, great packaging density and transportation on people are the main factors causing the special features relevant to corrosion control of a mobile telephone. Many parts are mechanically weak due to the small size, which is why the durability of connector contacts is difficult to ensure, for example.

Mobile telephones are made relatively closed because they are continuously subjected to various chemicals or corrosive substances under human handling, changes in the temperature are common and the threat of wetting is great. Mobile telephones are also used outdoors but the secretions of the actual user and the risk of wetting damage is the greatest risks.

There are many important parts regarding corrosion control, the keyboards and displays containing many connections, the EMC seals and their contact areas, the surfacing process of the case, the dense wiring patterns of the printed board, the battery and connections for auxiliary devices. Optimisation of the tightness of the device case is problematic since on the one hand the case should be tight but removal of humidity on the inside should also be possible.

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IVF-publications

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Andersson, H., Lindblom, T., Lindgren, M. & Carlsson, P. **Silicone Contamination**. IVF Research Publication 98812.

The report evaluates the risk for silicone contamination of electronics using straightforward methods of analysis. The following areas are covered in the report: The relation between desorption and creeping of silicones in relation to the curing procedure. A method for controlled and reproducible contamination of surfaces with silicone. Limiting values for silicones to avoid contact and adhesion problems. Eight different silicone materials for electronic applications were analysed. The selection represents different preparation types, curing principles, and application areas. The desorption of low molecular siloxanes was analysed with gas chromatography/mass spectroscopy, gravimetric methods according to standards for clau for identification of condensed material on metals. Price SEK 7 200 (Approximately USD 950).

Tegehall, Per-Erik. **Cleanliness and Reliability**: Evaluation of Test Methods and the Impact of Contamination from Production Processes on the Reliability of Printed Circuit Board Assemblies. IVF Research Publication 96846, 1996.

The report presents results from an evaluation of various test methods for assessing the cleanliness of PCBs and PCB assemblies. These methods were used also for evaluating the cleanliness and reliability of PCBs and PCB assemblies produced by four PCB manufacturers and fourteen PCB assemblers using their ordinary production processes. Test boards specially developed for these evaluations with test patterns for measurement of surface insulation resistance between solder joints to soldered components are also described.

Tegehall, P.-E. **Evaluation of the Capability of Conformal Coatings to Prevent Degradation of Printed Circuit Assemblies in Harsh Environments**. Part 2. IVF Research Publication 96807, 1996.

The report presents the results from an evaluation of 15 conformal coatings capability to protect circuit assemblies in harsh environment. The conformal coatings were of different generic types. Also, the report gives a critical examination of environmental tests commonly used for the evaluation of the reliability of conformal coated assemblies. A test method

developed to simulate condensation of water is described. This test method combined with surface insulation resistance measurements was found to be a very useful tool for evaluating the sealing properties of an applied conformal coating. Price SEK 3 000 (Approximately USD 375).

Tegehall, P.-E. **Evaluation of the Capability of Conformal Coatings to Prevent Degradation of Printed Circuit Assemblies in Harsh Environments.** Part One. IVF Research Publication 93803, 1993.

Carlsson, P. **Solderability of Nickel/Gold Plated Printed Circuit Boards.** IVF Research Publication 98831.

The solderability of Ni/Au plated printed circuit boards has been studied extensively at IVF. The latest project has further addressed the reasons for bad solderability, and how to overcome these problems. A correlation between the surface quality of gold and poor solderability has been found. Plasma treatment and sulphuric acid cleaning change the surface properties and also has an effect on solderability. Results are presented for different soldering processes performed on PCBs from four different manufacturers. In addition, three different wetting balance methods for determining the solderability have been evaluated. Price SEK 10 000 (approx. USD 1250).

Environmental standards

See air corrosivity standards also in the next section *Dependability and corrosivity standards*.

IEC 60721-1 (1990-12).

Classification of environmental conditions – Part 1: **Environmental parameters and their severities**. 41 p.

Defines environmental parameters and a limited number of their severities within the range of conditions met by electrotechnical products when being transported, stored, installed and used.

IEC 60721-2-1 (2002-10).

Classification of environmental conditions. – Part 2: Environmental conditions appearing in nature. **Temperature and humidity**. 26 p.

Presents types of open-air climate in terms of temperature and humidity. Intended to be used as a part of the background material when selecting appropriate temperature and humidity severities for product applications.

IEC 60721-2-2 (1988-01).

Classification of environmental conditions. Part 2: Environmental conditions appearing in nature. **Precipitation and wind**. 21 p.

Presents fundamental properties, quantities for characterization and a classification of environmental conditions dependent on precipitation and wind, relevant for electrotechnical products. Defines the characteristics of precipitation and wind as background for the severities to which products are liable to be exposed during transportation, storage and use.

IEC 60721-2-3 (1987-12).

Classification of environmental conditions – Part 2: Environmental conditions appearing in nature. **Air pressure**. 7 p.

Indicates values of air pressure to which products are liable to be exposed during storage, transportation and use.

IEC 60721-2-4 (2002-10).

Classification of environmental conditions. Part 2: Environmental conditions appearing in nature. **Solar radiation and temperature**. 29 p.

Defines limiting severities of solar radiation to which products are liable to be exposed during transportation, storage and use.

IEC 61725 (1997-05).

Analytical expression for daily solar profiles. 13 p.

Provides a normative equation for analytically deriving a set of data points or a curve of irradiance versus time of day for a synthetic solar day.

IEC 60721-2-5 (1991-07).

Classification of environmental conditions – Part 2: Environmental conditions appearing in nature – Section 5: **Dust, sand, salt mist**. 35 p.

Presents characteristics of dust, sand and salt mist appearing in nature, and describes the influences from these environmental factors to which products are liable to be exposed during storage, transportation and use.

IEC 60721-2-6 (1990-12).

Classification of environmental conditions. Part 2: Environmental conditions appearing in nature. **Earthquake vibration and shock**. 22 p.

Deals with environmental conditions appearing in nature caused by earthquake vibration and shock.

IEC 60721-2-7 (1987-12).

Classification of environmental conditions. Part 2: Environmental conditions appearing in nature. **Fauna and flora**. 11 p.

Describes influences from fauna and flora to which products are liable to be exposed during storage, transportation and use.

IEC 60721-2-8 (1994-06).

Classification of environmental conditions – Part 2: Environmental conditions appearing in nature – Section 8: **Fire exposure**. 43 p.

Presents fundamental properties, quantities for characterization, and a description of environmental conditions in relation the occurrence, development and spread of fire within a building, and relevant to electrotechnical products exposed to fire during stationary use.

IEC 60721-3-0 (2002-10).

Classification of environmental conditions. Part 3: **Classification of groups of environmental parameters and their severities. Introduction.** 23 p.

Establishes classes of environmental parameters and their severities, covering the extreme (short-term) conditions to which a product may be subjected when being transported, installed, stored and used. Separate groups of classes are given for different product applications.

IEC 60721-3-1 (1997-02).

Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 1: **Storage.** 42 p.

Classifies groups of environmental parameters and their severities to which products together with their packaging, if any, are subjected when stored.

IEC 60721-3-2 (1997-03). 43 p.

Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 2: **Transportation.**

Defines the environmental conditions to which a product is subjected while being transported from one place to another after being made ready for dispatch from the manufacturing factory.

IEC 60721-3-3 (1994-12) and amendments 1 and 2.

Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 3: **Stationary use at weatherprotected locations.** 79 p. + 13 p. + 8 p.

Classifies groups of environmental parameters and their severities to which products are subjected when mounted for stationary use at weatherprotected locations.

IEC 60721-3-4 (1995-01) and amendment 1.

Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 4: **Stationary use at non-weatherprotected locations.** 53 p. + 8 p.

Classifies groups of environmental parameters and the severities to which a product may be exposed under use conditions, including periods of erection work, downtime, maintenance and repair, when mounted for stationary use at locations which are non-weatherprotected.

IEC 60721-3-5 (1997-03).

Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 5: **Ground vehicle installations**. 56 p.

Classifies the environmental conditions to which a product not forming part of the vehicle is subjected when installed in a ground vehicle. Such products are for example radios, communication systems, fare meters, and flow meters for liquids transported by the vehicle. Vehicles where products may be permanently or temporarily installed include road vehicles, rail vehicles, overland vehicles, handling and storage vehicles, and self-propelled machinery.

IEC 60721-3-6 (1987-04) and amendment 1 and 2.

Classification of environmental conditions. Part 3: Classification of groups of environmental parameters and their severities. Section 6: **Ship environment**. 25 p. + 3 p. + 8 p.

Classifies groups of environmental parameters and their severities to which a product is subjected when installed aboard a ship. Ships where products may be permanently or temporarily installed include ships propelled by mechanical means and ships not propelled by mechanical means.

IEC 60721-3-7 (2002-10).

Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 7: **Portable and non-stationary use**. 71 p.

Classifies groups of environmental parameters and their severities to which products are subjected during portable and non-stationary use.

IEC 60721-3-9 (1993-07) and amendment 1.

Classification of environmental conditions – Part 3: Classification of groups of environmental parameters and their severities – Section 9: **Microclimates inside products**. 21 p. + 3 p.

Defines classes of microclimatic conditions, to which components (basic parts, assemblies, built-in units) may be subjected inside products, and which are used under the climatic conditions classified in IEC 60721-3-3 and IEC 60721-3-4. Only air temperature and air humidity are taken into account.

IEC/TR 60721-4-0 (2002-08) Classification of environmental conditions – Part 4-0: Guidance for the correlation and transformation of the environmental condition classes of IEC 60721-3 to the environmental tests of IEC 60068 – Introduction. 37 p.

Dependability and corrosivity standards

IEC 60050-191 (1990-12) International Electrotechnical Vocabulary. Chapter 191: Dependability and quality of service.

IEC 60300-1 (2003-06) Dependability management – Part 1: Dependability management systems.

Describes the concepts and principles of dependability management systems. Identifies the generic processes in dependability for planning, resource allocation, control, and tailoring necessary to meet dependability objectives. Deals with the dependability performance issues in the product life-cycle phases concerning planning, design, measurements, analysis and improvement.

IEC 60300-3-1 (2003-01) Dependability management – Part 3: Application guide – Section 1: Analysis techniques for dependability: Guide on methodology.

This international standard gives a general overview of commonly used dependability analysis procedures. This guide is an introduction to the available methodology.

IEC 60300-3-2 (2004-11) Dependability management – Part 3: Application guide – Section 2: Collection of dependability data from the field.

Provides guidelines for the collection of data relating to reliability, maintainability, availability and maintenance support performance of items operating in the field. Explores the related topics of data analysis and presentation of results.

IEC 60300-3-4 (1996-08) Dependability management – Part 3: Application guide – Section 4: Guide to the specification of dependability requirements.

Gives guidance on specifying required dependability characteristics in product and equipment specifications, together with specifications of procedures and criteria for verification. Includes advice on specifying quantitative and qualitative reliability, maintainability and availability requirements.

IEC 60300-3-9 (1995-12) Dependability management – Part 3: Application guide – Section 9: Risk analysis of technological systems.

Provides guidelines for selecting and implementing risk analysis techniques. The objective of this standard is to ensure quality and consistency in the planning and execution of risk analyses and the presentation of results and conclusions.

IEC 56(Secretariat)353 18.10.1991 Requirements and guidelines for analysis of technological risks. This is a draft for IEC 60300-3-9. 29 p.

IEC 61160 (2006-02) Design review. 69 p.

This International Standard makes recommendations for the implementation of design review as a means of verifying that the design input requirements have been met and stimulating the improvement of the product's design. The intention is for it to be applied during the design and development phase of a product's life cycle.

ANSI/ISA-S71.01-1985 Environmental conditions for Process and Measurement and Control Systems: **Temperature and Humidity**. 22 p.

Establishes uniform classifications of temperature and humidity conditions for industrial process measurement and control systems. The classes of temperature and humidity conditions stated in this standard are suitable for use in activities related to process instrumentation, including design, manufacturing, sales, installation, test, use, and maintenance. The standard is compatible with IEC Publication 60654-1, 1979, Operating Conditions for Industrial Process Measurement and Control Equipment, Part 1: Temperature, Humidity, and Barometric Pressure.

ANSI/ISA-S71.04-1985 Environmental conditions for Process and Measurement and Control Systems: **Airborne Contaminants**. 18 p.

Classifies airborne contaminants that may affect process measurement and control instruments. This classification system provides a means of specifying the type and the concentration of airborne contaminants to which a specified instrument may be exposed. This standard is limited to airborne contaminants and biological influences only, covering contamination influences that affect industrial process measurement and control systems.

IEC 60654-1 (1993-03).

Industrial-process measurement and control equipment – Operating conditions – Part 1: **Climatic conditions**. 37 p.

Lists environmental climatic conditions e.g. air **temperature**, **humidity** and **air pressure** in specified locations to which land-based and offshore industrial-process measurement and control systems may be exposed during operation, during periods when they are installed but inactive and during storage or transportation.

IEC 60654-4 (1987-07). 31 p.

Operating conditions for industrial-process measurement and control equipment.
Part 4: **Corrosive and erosive influences**. 31 p.

Considers the corrosive and erosive industrial environment to which land-based and offshore industrial-process measurement and control systems or parts of systems may be exposed during operation, during periods when they are installed but inactive, during storage or transportation. Maintenance and repair conditions are not considered.

ISO 9223 (1992). Corrosion of metals and alloys – **Classification of corrosivity of atmospheres**. 13 p.

ISO 9224 (1992). Corrosion of metals and alloys – **Guiding values for the corrosivity categories**. 5 p.

ISO 9225 (1992). Corrosion of metals and alloys – Corrosivity of atmospheres – **Measurement of pollution**. 10 p.

ISO 9226 (1992). Corrosion of metals and alloys – Corrosivity of atmospheres – Determination of corrosion rate of standard specimens for the evaluation of corrosivity. 4 p.

MIL-HDBK-454A (2000). Standard General Requirements for Electronic Equipment. 156 p.

This handbook provides guidance and lessons learned in the selection of documentation for the design of electronic equipment.

SEMI F21-95, 18.9.1997.

Classification of Airborne Molecular Contaminant Levels in Clean Environments.

The purpose of this standard is to classify microelectronics clean environments with respect to their molecular (non-particulate) contaminant levels. This standard classification provides a consistent means of communicating acceptable contaminant levels of groups of specific airborne molecular contaminants. This standard classification is to be used in the specification of semiconductor clean environments (including process tool environments) and of contamination control and measurement equipment performance.

SFS-handbook 108. *Classification of environmental conditions and environmental testing*. FS-Käsikirja 108. 1989-07-01, **Ympäristöluokitus ja -testaus**. 77 p. (In Finnish)

Corrosion and moisture prevention and material standards

SFS-ISO 8044 (1989-08-22).

Corrosion of metals and alloys. Terms and definitions. Metallien ja metalliseosten korroosio. Termit ja määrittelyt (en fi fr). 18 p.

SFS-EN ISO 8502-6 (1999-10-04) (ISO 8502-6:2006).

Preparation of steel substrates before application of paints and related products. Tests for assessment of surface cleanliness. Part 6: Extraction of soluble contaminants for analysis. The Bresle method. 0 + 3 + 6 p.

SFS 3632 1977-03-14.

Paints and varnishes. Measurement of specular gloss. Maalit ja lakat. Kiillon mittaus. 7 p.

SFS 3644 1977-09-05.

Paints and varnishes. Determination of film thickness. Maalit ja lakat. Kalvon paksuuden määrittäminen. 12 p.

SFS 3754 1977-09-05.

Paints and varnishes. Determination of resistance to dry abrasion. Maalit ja lakat. Kulutuksenkestävyyden määrittäminen putoavalla hiekalla. 2 p.

SFS-EN 50173 1995-12-04.

Information technology. Generic cabling systems. Tietotekniikka. Yleiskaapelointijärjestelmät. 63 p.

BS EN 60352-3:1995 (IEC 60352-3:1993). Solderless connections. Solderless accessible insulation displacement connections. General requirements, test methods and practical guidance.

BS 7545:1991 (ISO 8407:1991). Method for removal of corrosion products from corrosion test specimens of metals and alloys. 12 p.

BS 5735:1979 (IEC 60426). Test methods for determining electrolytic corrosion with electrical insulating materials. 24 p.

BS 7195:1989. British Standard Guide for Prevention of corrosion of metals caused by vapours from organic materials. 16 p.

Metal coating standards

ASTM B488-01 (2006). Standard Specification for Electrodeposited Coatings of Gold for Engineering Uses. 8 p.

- 1.1 This specification covers requirements for electrodeposited gold coatings that contain not less than 99.00 mass% gold and that are used for engineering applications.
- 1.2 Specifically excluded from this specification are autocatalytic, immersion, and vapor deposited gold coatings.
- 1.3 Gold coatings conforming to this specification are employed for their corrosion and tarnish resistance (including resistance to fretting corrosion and catalytic polymerization), bondability, low and stable contact resistance, solderability, and infrared reflectivity. Several types of coatings, differing in gold purity and hardness, are covered by this specification.

ASTM B545-97 (2004)e1. Standard Specification for Electrodeposited Coatings of Tin. 8 p.

This specification covers the requirements for electrodeposited (electroplated) coatings of tin applied to metallic articles. Tin coatings are used to provide a low contact-resistance surface, to protect against corrosion, to facilitate soldering, to provide anti-galling properties, and to be a stopoff coating in the nitriding of high-strength steels.

ASTM B679-98 (2004). Standard Specification for Electrodeposited Coatings of Palladium for Engineering Use. 6 p.

- 1.1 Purity – This specification covers requirements for electrodeposited palladium coatings containing at least 99.7 mass% of palladium metal.
- 1.2 Properties – Palladium is the lightest and least noble of the platinum group metals. It has a specific gravity of 12.0, which is substantially less than gold (19.3) and platinum (21.5). This yields a greater volume or thickness of coating and, consequently, some saving of metal weight accompanied by a small sacrifice in corrosion resistance and reflectivity. The hardness range of electrodeposited palladium compares favorably with the other electroplated noble metals and their alloys.

ASTM B920-01. Standard Practice for Porosity in Gold and Palladium Alloy Coatings on Metal Substrates by Vapors of Sodium Hypochlorite Solution.

- 1.1 This test practice covers equipment and methods for revealing the porosity of gold and palladium coatings, particularly electrodeposits and clad metals used on electrical contacts.
- 1.2 This test practice is suitable for coatings containing gold or 75% by mass of palladium on substrates of copper, nickel, and their alloys, which are commonly used in electrical contacts.
- 1.3 A variety of full porosity testing methods is described in the literature. These porosity Test Methods are B 735, B 741, B 798, B 799, and B 809. An ASTM Guide to the selection of porosity tests for electrodeposits and related metallic coatings is available as Guide B 765.

ASTM B700-97 (2002). Electrodeposited Coatings of Silver for Engineering Use. 6 p.

- 1.1 This specification covers requirements for electrodeposited coatings of silver used for engineering purposes that may be mat, bright, or semibright and are not less than 98% silver purity.
- 1.2 Coatings of silver covered by this specification are usually employed for solderable surfaces, electrical contact characteristics, high electrical and thermal conductivity, thermocompression bonding, wear resistance of load-bearing surfaces, and special reflectivity.

ASTM B733-04. Standard Specification for Autocatalytic (Electroless) Nickel-Phosphorus Coatings on Metal. 13 p.

- 1.1 This specification covers requirements for autocatalytic (electroless) nickel-phosphorus coatings applied from aqueous solutions to metallic products for engineering (functional) uses.
- 1.2 The coatings are alloys of nickel and phosphorus produced by autocatalytic chemical reduction with hypophosphite. Because the deposited nickel alloy is a catalyst for the reaction, the process is self-sustaining. The chemical and physical properties of the deposit vary primarily with its phosphorus content and subsequent heat treatment. The chemical makeup of the plating solution and the use of the solution can affect the porosity and corrosion resistance of the deposit.

ASTM B765-03. Standard Guide for Selection of Porosity Tests for Electrodeposits and Related Metallic Coatings. 4 p.

This guide describes some of the available standard methods for the detection, identification, and measurement of porosity in electrodeposited and related metallic coatings and provides some laboratory-type evaluations and acceptances. This guide does not apply to coatings that are produced by thermal spraying, ion bombardment, sputtering, and other similar techniques where the coatings are applied in the form of discrete particles impacting on the substrate.

ASTM B798-95 (2005). Standard Test Method for Porosity in Gold or Palladium Coatings on Metal Substrates by Gel-Bulk Electrography. 6 p.

This test method covers equipment and techniques for determining porosity in noble metal coatings, particularly electrodeposits and clad metals used on electrical contacts.

ASTM B799-95 (2005). Standard Test Method for Porosity in Gold and Palladium Coatings by Sulfurous Acid/Sulfur-Dioxide Vapor. 4 p.

This test method covers equipment and methods for determining the porosity of gold and palladium coatings, particularly electrodeposits and clad metals used on electrical contacts.

ASTM B809-95. Standard Test Method for Porosity in Metallic Coatings by Humid Sulfur Vapor (“Flowers-of-Sulfur”). 5 p.

This standard covers equipment and test methods for determining the porosity of metallic coatings, where the pores penetrate down to a silver, copper, or copper-alloy substrate. This test method is suitable for coatings consisting of single or combined layers of any coating that does not significantly tarnish in a reduced sulfur atmosphere, such as gold, nickel, tin, tin-lead, and palladium, or their alloys.

ASTM B867-95 (2003). Standard Specification for Electrodeposited Coatings of Palladium-Nickel for Engineering Use. 9 p.

This specification covers requirements for electrodeposited palladium-nickel coatings containing between 70 and 95 mass% of palladium metal. Composite coatings consisting of palladium-nickel and a thin gold overplate for applications involving electrical contacts are also covered.

BS 1872:1984. Specification for electroplated coatings of tin. 12 p.

BS 3597:1984. Specification for electroplated coatings of 65/35 tin/nickel alloy. 12 p.

BS 6137:1982. Specification for electroplated coatings of tin/lead alloys. 12 p.

ISO 1456:2003. Metallic coatings – Electrodeposited coatings of nickel plus chromium and of copper plus nickel plus chromium. Ed. 3. 19 p.

ISO 1458:2002. Metallic coatings – Electrodeposited coatings of nickel. Ed. 3. 15 p.

ISO 2093:1986. Electroplated coatings of tin – Specification and test methods. Ed. 2. 8 p.

ISO 4523:1985. Metallic coatings – Electrodeposited gold and gold alloy coatings for engineering purposes. Ed. 1. 6 p.

ISO 4524-1:1985. Metallic coatings – Test methods for electrodeposited gold and gold alloy coatings – Part 1: Determination of coating thickness Ed. 1. 5 p.

ISO 4524-2:2000. Metallic coatings – Test methods for electrodeposited gold and gold alloy coatings – Part 2: Mixed flowing gas (MFG) environmental tests. Ed. 2. 31 p.

ISO 4524-3:1985. Metallic coatings – Test methods for electrodeposited gold and gold alloy coatings – Part 3: Electrographic tests for porosity. Ed. 1. 3 p.

ISO 4524-4:1985. Metallic coatings – Test methods for electrodeposited gold and gold alloy coatings – Part 4: Determination of gold content. Ed. 1. 2 p.

ISO 4524-5:1985. Metallic coatings – Test methods for electrodeposited gold and gold alloy coatings – Part 5: Adhesion tests. Ed. 1. 1 p.

ISO 4524-6:1988. Metallic coatings – Test methods for electrodeposited gold and gold alloy coatings – Part 6: Determination of the presence of residual salts. Ed. 1. 2 p.

ISO 4525:2003. Metallic coatings – Electroplated coatings of nickel plus chromium on plastics materials. Ed. 2. 15 p.

ISO 4526:2004. Metallic coatings – Electroplated coatings of nickel for engineering purposes. Ed. 2. 14 p.

ISO 10713:1992. Jewellery – Gold alloy coatings. Ed. 1. 3 p.

ISO 9453:2006. Soft solder alloys – Chemical compositions and forms. Ed. 2. 10 p.

ISO 9455-10:1998. Soft soldering fluxes – Test methods – Part 10: Flux efficacy tests, solder spread method. Ed. 1. 9 p.

JEDEC JP002 (2006). Current tin whisker theory and mitigation practices guideline. 22 p.

JEDEC JESD 22-A121 (2005). Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes. 25 p.

JEDEC JESD 201 (2006). Environmental Acceptance Requirements For Tin Whisker Susceptibility of Tin and Tin Alloy Surface Finishes. 19 p.

MIL-G-45204C (1983). Military specification, Gold plating, electrodeposited, (Cancelled 1998, replaced by AMS 2422). 18 p.

QQ-S-365D (1985). Federal specification, Silver plating, electrodeposited: general requirements for. 12 p.

QQ-N-290A (1971). Federal specification, Nickel plating (electrodeposited). 17 p.

SAE AMS 2422E. Plating, Gold. 2002 (SAE Society of Automotive Engineer).

This specification covers the engineering requirements for electrodeposition of gold and the properties of the deposit. This plating has been used typically to improve the solderability, electrical conductivity, corrosion resistance, performance, and appearance of electronic and electrical parts, but usage is not limited to such applications.

SAE AMS 2408H. Plating, Tin. 2003.

This specification covers the engineering requirements for electrodeposition of tin on metals and the properties of the deposit.

SAE AMS P81728. Plating, Tin-Lead (Electrodeposited). 1998.

This specification covers the requirements for electrodeposited tin-lead plating.

SAE AMS 2410. Plating, Silver Nickel Strike, High Bake. 2004.

This specification covers the engineering requirements for electrodeposition of silver on other metals, usually with a nickel strike between the basis metal and the silver, and the properties of the deposit.

SAE AMS 2412G. Plating, Silver Copper Strike, Low Bake. 1999.

This specification covers the engineering requirements for silver deposited on metal parts with a copper strike between the basis metal and the silver deposit.

ISO 248:2005. Rubbers, raw – Determination of volatile-matter content. 9 p.

ISO 248 specifies two methods, a hot-mill method and an oven method, for the determination of moisture and other volatile-matter content in raw rubbers. These methods are applicable to the determination of the volatile-matter content in the R-group of rubbers listed in ISO 1629 which are rubbers having an unsaturated carbon chain, for example, natural rubber and synthetic rubbers derived at least partly from diolefins.

ISO 4097:2000. 18 p.

Rubber, ethylene-propylene-diene (EPDM) – Evaluation procedure.

SFS 4446. 1979-12-31. 6 p.

Metallic coatings. Electroplated coatings of nickel. Metallien pinnoitteet. Sähkösaostetut nikkelpinnoitteet.

SFS-EN ISO 1461 fi/en 1999-08-23. 28 + 18 + 15 p.

Hot dip galvanized coatings on fabricated iron and steel articles. Specifications and test methods (ISO 1461:1999)

Teräs- ja valurautatuotteiden kuumasinkkipinnoitteet kappaletavaroille. Erittelyt ja koestusmenetelmät.

SFS-EN ISO 12944-1 fi/en 1998-11-30.

Paints and varnishes. Corrosion protection of steel structures by protective paint systems. Part 1: General introduction (ISO 12944-1:1998) Maalit ja lakat. Teräsrakenteiden korroosionesto suojamaaliyhdistelmillä. Osa 1: Yleistä. 16 p.

SFS-EN **ISO 12944-2** fi/en 1998-11-30.

Part 2: Classification of environments (ISO 12944-2:1998) Maalit ja lakat. Teräsrakenteiden korroosionesto suojamaaliyhdistelmillä. Osa 2: Ympäristöolosuhteiden luokittelu. 20 p.

Part 3: Design considerations (ISO 12944-3:1998). 30 p.

Part 4: Types of surface and surface preparation (ISO 12944-4:1998). 38 p.

Part 5: Protective paint systems (ISO 12944-5:1998). 59 p.

Part 6: Laboratory performance test methods (ISO 12944-6:1998). 26 p.

Part 7: Execution and supervision of paint work (ISO 12944-7:1998). 20 p.

Part 8: Development of specifications for new work and maintenance (ISO 12944-8:1998). 76 p.

SFS-EN **ISO 14713** fi/en 1999-08-23. 64 + 39 p.

Protection against corrosion of iron and steel in structures. Zinc and aluminium coatings. Guidelines (ISO 14713:1999)

Teräs- ja rautarakenteiden korroosionesto. Sinkki- ja alumiinipinnoitteet.

SFS-EN **22063** fi/en 1994-04-11. 24 p.

Metallic and other inorganic coatings. Thermal spraying. Zinc, aluminium and their alloys.

Metalliset ja muut epäorgaaniset pinnoitteet. Terminen ruiskutus. Sinkki, alumiini ja niiden seokset.

IEC/IPC handling of humidity sensitive components

IEC 60286-3 (1997-12). 37 p.

Packaging of components for automatic handling – Part 3: Packaging of leadless components on continuous tapes.

Relates to the tape packaging of electronic components without leads or with lead stumps which are intended to be connected to electronic circuits. Includes only those dimensions which are essential for the taping of components for the above-mentioned purposes.

IEC 60286-4 (1997-12). 23 p.

Packaging of components for automatic handling – Part 4: Stick magazines for electronic components encapsulated in packages of form E and G.

Intended to be used for storage of electronic components, for transport from the manufacturer to the customer and for in-house use in the manufacturing plant.

IEC 60286-5 (2003-10). 27 p.

Packaging of components for automatic handling – Part 5: Matrix trays.

Describes the common dimensions, tolerances and characteristics of the tray. It includes only those dimensions which are essential for the handling of the trays for the stated purpose and for placing or removing components from the trays.

IEC 60286-6 (2004-02). 27 p.

Packaging of components for automatic handling – Part 6: Bulk case packaging for surface mounting components.

Is applicable to bulk case packaging capable of containing surface mounting components. The bulk case is designed for transport and storage of components and the supply of components directly or by an appropriate feeder to the placement machine. The bulk case is attached to the automatic handling machine by means of a coupling interface.

IEC 61760-1 (2006-04). 30 p.

Surface mounting technology – Part 1: Standard method for the specification of surface mounting components (SMDs).

Gives a reference set of process conditions and related test conditions to be used when compiling component specifications of electronic components that are intended for usage in surface mount technology.

IEC 61760-2 (1998-02). 9 p.

Surface mounting technology – Part 2: Transportation and storage conditions of surface mounting devices (SMD) – Application guide.

Describes the transportation and storage conditions for surface mounting devices (SMDs) that are fulfilled in order to enable trouble free processing of surface mounting devices, both active and passive. The object of this International Standard is to ensure that users of SMDs receive and store products that can be further processed without prejudice to quality and reliability.

IPC/JEDEC J-STD-020A (April 1999). Moisture/Reflow Sensitivity Classification for Nonhermetic Solid State Surface Mount Devices. 21 p.

The purpose of this standard is to identify the classification level of nonhermetic solid state Surface Mount Devices (SMDs) that are sensitive to moisture-induced stress so that they can be properly packaged, stored, and handled to avoid subsequent thermal/mechanical damage during the assembly solder reflow attachment and/or repair operation. The classification procedure applies to all nonhermetic solid state Surface Mount Devices (SMDs) in packages which, because of absorbed moisture, could be sensitive to damage during solder reflow. The term SMD as used in this document means plastic encapsulated packages and other packages made with moisture-permeable materials. The categories are intended to be used by SMD producers to inform users (board assembly operations) of the level of moisture sensitivity of product devices, and by board assembly operations to ensure that proper handling precautions are applied to moisture/reflow sensitive devices.

IPC/JEDEC J-STD-033 (May 1999). Standard for Handling, Packing, Shipping and Use of Moisture/Reflow Sensitive Surface Mount Devices. 20 p.

The advent of surface mount devices (SMDs) introduced a new class of quality and reliability concerns regarding package cracks and delamination. This document describes the standardized levels of floor life exposure for moisture/reflow-sensitive SMDs along with the handling, packing and shipping requirements necessary to avoid moisture/reflow-related failures. Companion documents, J-STD-020, define the classification procedure and JEP113 define the labeling requirements.

Moisture from atmospheric humidity will enter permeable packaging materials by diffusion and preferentially collect at the dissimilar material interfaces. Assembly processes, used to solder SMDs to printed circuit boards (PCBs), will expose the entire package body to temperatures higher than 200°C. During solder reflow, the combination of rapid moisture expansion and materials mismatch can result in package cracking and/or delamination of critical interfaces within the package. The solder reflow processes of concern are convection, convection/IR, infrared (IR), vapor phase (VPR), and hot air rework tools. The use of assembly processes that immerse the component body in molten solder are not recommended for most SMD components. The purpose of this document is to provide SMD manufacturers and users with standardized methods for handling, packing, shipping, and use of moisture/reflow sensitive SMDs. These methods are provided to avoid damage from moisture absorption and exposure to solder reflow temperatures that can result in yield and reliability degradation. By using these procedures, safe and damage-free reflow can be achieved, with the dry packing process, providing a minimum shelf life capability in sealed dry-bags of 12 months from the seal date.

JEP113-B (May 1999). Symbol and Labels for Moisture-Sensitive Devices. 10 p.

Certain plastic surface-mount components are subject to permanent damage due to moisture-induced failures encountered during high-temperature surface-mount processing unless appropriate precautions are observed.

EIA/JEP124 (December 1995). Guidelines for the Packing, Handling and Repacking of Moisture-Sensitive Components. 14 p.

This publication establishes guidelines for the packing, handling and repacking of moisture-sensitive components. The guidelines are applicable to semiconductor manufacturers for the shipment of moisture-sensitive components and anyone else who handles these components prior to shipment of moisture-sensitive components to a distributor.

ANSI/IPC SM-786A (1995). Procedures for Characterizing and Handling of Moisture/Reflow Sensitive ICs.

The classification procedure applies to all integrated circuits in packages which, because of absorbed moisture, could be sensitive to damage during solder reflow. These ICs include plastic encapsulated packages and other packages made with moisture-permeable materials such as epoxies. The categories are intended to be used by IC producers to inform IC users

(board assembly operations) of the level of moisture sensitivity of product devices, and by board assembly operations to ensure that proper handling precautions are applied to moisture/reflow sensitive devices.

IPC/JPCA-4104 (May 1999). Specification for High Density Interconnect (HDI) and Microvia Materials. 100 p.

Covers the various conductive and dielectric materials that can be used for the fabrication of HDI and microvias. The 23 specification sheets included in IPC/JPCA-4104 give the qualification and conformance requirements such materials as photoimageable dielectric dry films and liquids, epoxy blends and coated foils. IPC/JPCA-4104 also includes six new test methods developed specifically for the testing of HDI and microvia materials.

Related documents for IPC/JPCA-4104:

IPC-6016. Qualification and Performance Specification for High Density Interconnect (HDI) Layers or Boards.

IPC-4101. Specification for Base Materials for Rigid and Multilayer Printed Boards.

Water absorption, water vapour and gas transmission of materials

ASTM-source: <http://www.astm.org/> <http://www.nssn.org/default.aspx>

ASTM E96/E96M-05.

Standard Test Methods for Water Vapor Transmission of Materials.

These test methods cover the determination of water vapor transmission (WVT) of materials through which the passage of water vapor may be of importance, such as paper, plastic films, other sheet materials, fiberboards, gypsum and plaster products, wood products, and plastics. The test methods are limited to specimens not over 1 1/4 in. (32 mm) in thickness except as provided in Section 9. Two basic methods, the Desiccant Method and the Water Method, are provided for the measurement of permeance, and two variations include service conditions with one side wetted and service conditions with low humidity on one side and high humidity on the other. Agreement should not be expected between results obtained by different methods. That method should be selected which more nearly approaches the conditions of use.

ASTM F1249-06.

Standard Test Method for Water Vapor Transmission Rate Through Plastic Film and Sheeting Using a Modulated Infrared Sensor.

This test method covers a procedure for determining the rate of water vapor transmission through flexible barrier materials. The method is applicable to sheets and films up to 3 mm (0.1 in.) in thickness, consisting of single or multilayer synthetic or natural polymers and foils, including coated materials. It provides for the determination of (1) water vapor transmission rate (WVTR), (2) the permeance of the film to water vapor, and (3) for homogeneous materials, water vapor permeability coefficient. Note 1 Values for water vapor permeance and water vapor permeability must be used with caution. The inverse relationship of WVTR to thickness and the direct relationship of WVTR to the partial pressure differential of water vapor may not always apply.

ASTM D1434-82 (2003).

Standard Test Method for Determining Gas Permeability Characteristics of Plastic Film and Sheeting.

This test method covers the estimation of the steady-state rate of transmission of a gas through plastics in the form of film, sheeting, laminates, and plastic-coated papers or fabrics. This test method provides for the determination of (1) gas transmission rate (GTR), (2) permeance, and, in the case of homogeneous materials, (3) permeability. Two procedures are provided: 1 Procedure M- Manometric. 2 Procedure V- Volumetric.

ASTM D3985-05.

Standard Test Method for Oxygen Gas Transmission Rate Through Plastic Film and Sheetting Using a Coulometric Sensor.

This test method covers a procedure for determination of the steady-state rate of transmission of oxygen gas through plastics in the form of film, sheeting, laminates, coextrusions, or plastic-coated papers or fabrics. It provides for the determination of (1) oxygen gas transmission rate (O₂GTR), (2) the permeance of the film to oxygen gas (P_{O₂}), and (3) oxygen permeability coefficient (P'_{O₂}) in the case of homogeneous materials.

ASTM D570-98 (2005).

Title: Standard Test Method for Water Absorption of Plastics.

This test method covers the determination of the relative rate of absorption of water by plastics when immersed. This test method is intended to apply to the testing of all types of plastics, including cast, hot-molded, and cold-molded resinous products, and both homogeneous and laminated plastics in rod and tube form and in sheets 0.13 mm (0.005 in.) or greater in thickness. Note ISO 62 is technically equivalent to this test method ASTM D570.

ISO 62:1999.

Plastics – Determination of water absorption, (gravimetric analysis, physical tests, plastics, tests, water absorption tests). 11 p.

ISO 535:1991.

Paper and board – Determination of water absorptiveness – Cobb method (paper, paperboards, tests, water absorption tests). 4 p.

ISO 811:1981.

Textile fabrics – Determination of resistance to water penetration – Hydrostatic pressure test.

ISO 2896:2001.

Rigid cellular plastics – Determination of water absorption. 11 p.

Packaging materials for transportation

DIN 55473, Ausgabe:1997-12 Packhilfsmittel – Trockenmittelbeutel – Technische Lieferbedingungen. (Bentonite).

DIN 55474, Ausgabe:1997-07 Packhilfsmittel – Trockenmittelbeutel – Anwendung, Berechnung der erforderlichen Anzahl Trockenmitteleinheiten.

DIN 55475, Ausgabe:1997-03 Packhilfsmittel – Klebestreifen aus Kraftpapier – Unverstärkt oder verstärkt, wasser – oder wärmeaktivierbar; Anforderungen und Prüfung.

MIL-B-22020-D (2 May 1990). Bags, transparent, flexible, sealable, volatile corrosion inhibitor treated. 11 p.

MIL-PRF-131J (26 August 1998). Barrier materials, watervaporproof, greaseproof, flexible, heat-sealable. 19 p.

MIL-PRF-3420G (11 September 1998). Packaging materials, volatile corrosion inhibitor treated, opaque. 16 p.

MIL-PRF-22019D (31 August 1998). Barrier materials, transparent, flexible, sealable, volatile corrosion inhibitor treated. 16 p.

MIL-PRF-22191E (26 August 1998). Barrier materials, transparent, flexible, heat-sealable. 20 p.

MIL-PRF-81705D (3 September 1998). Barrier materials, flexible, electrostatic protective, heat-sealable. (Replaces MIL-B-81705C). 27 p.

BS 1133-6.1:1991. Packaging code. Protection of metal surfaces against corrosion during transport and storage. Cleaning and drying of metal surfaces. 32 p.

BS 1133-6.2:1991. Packaging code. Protection of metal surfaces against corrosion during transport and storage. Temporary protectives and their application. 20 p.

BS 7541:1992. Specification for temporary protectives for the protection of metal surfaces against corrosion during transport and storage. 20 p.

BS 7195:1989. British Standard Guide for Prevention of corrosion of metals caused by vapours from organic materials. 16 p.

IEC/TS 61340-5-1 (1998-12). 157 p.

Electrostatics – Part 5-1: **Protection of electronic devices from electrostatic phenomena – General requirements.**

Specifies the general requirements for the protection of electrostatic discharge sensitive devices (ESDS) from electrostatic discharges and fields. It applies only to the manufacture and use of electronic devices. Gives information on how to design, use and control a protected area to ensure that electrostatic sensitive devices, having a withstand threshold voltage of 100 V (human body model) or higher, can be handled with a minimum risk of damage resulting from electrostatic phenomena.

Normal precautions given are applicable for areas with clean room types in excess of ISO 14644-1 class 5. Alternative precautions may be required in clean rooms of ISO 14644-1 class 5 or less if contamination is formed as a result of using the procedures specified in this technical report.

IEC/TS 61340-5-2 (1999-02).

Electrostatics – Part 5-2: **Protection of electronic devices from electrostatic phenomena – User guide.** 109 p.

Covers the protection from electrostatic discharge (ESD) damage of all electronic devices (components, assemblies and sub-assemblies) with voltage sensitivity of not lower than 100 V throughout their entire life. This is from the commencement of manufacture, through product assembly, product use and possible repair until the end of the product life. Is to be read in conjunction with IEC 61340-5-1.

SFS-EN 100015-1 (1993-03-15). **Basic specification. Protection of electrostatic sensitive devices. Part 1: General requirements.** 81 p.

Standard contains the European standard EN 100015-1: 1992 “Basic specification”. Protection of electrostatic sensitive devices. Part 1: General requirements.

Test method standards

Nordtest Remiss Nr 548-85 Calibration of instruments for measuring the relative humidity using saturated salt solutions, 1987. 31 p.

ASTM B117-03 Standard Practice for Operating Salt Spray (Fog) Apparatus. 10 p.

This practice describes the apparatus, procedure, and conditions required to create and maintain the salt spray (fog) test environment. This practice does not prescribe the type of test specimen or exposure periods to be used for a specific product, nor the interpretation to be given to the results.

ASTM B810-01a (2002).

Standard Test Method for Calibration of Atmospheric Corrosion Test Chambers by Change in Mass of Copper Coupons. 6 p.

- 1.1 This test method covers the calibration of atmospheric corrosion test chambers for electrical contacts that produce an adherent film of corrosion product on copper, such as a test comprised of a mixture of flowing gases that react with copper.
- 1.2 This test method is not applicable to tests where corrosion products may be removed from a copper surface during the test by fluids.
- 1.3 This test method is not applicable to tests where airborne solid or liquid material may be deposited on a copper surface during the test, as in a test which includes particulates suspended in the atmosphere.

ASTM B827-05 (2005).

Standard Practice for Conducting Mixed Flowing Gas (MFG) Environmental Tests. 9 p.

This practice provides for the required equipment and methods for gas, temperature, and humidity control which enable tests to be conducted in a reproducible manner. Reproducibility is measured through the use of control coupons whose corrosion films are evaluated by mass gain, coulometry, or by various electron and X-ray beam analysis techniques. Reproducibility can also be measured by in-situ corrosion rate monitors using electrical resistance or mass/ frequency change methods.

ASTM B845-97 (2003).

Standard Guide for Mixed Flowing Gas (MFG) Tests for Electrical Contacts. 11 p.

The techniques described in this guide pertain to mixed flowing gas (MFG) tests containing species that are applied to evaluate devices containing electrical contacts such as slip rings, separable connectors, electromechanical relays or switch contacts. These techniques may be relevant to other devices, but it is the responsibility of the user to determine suitability prior to testing.

ASTM D257-99 (2005).

Standard Test Methods for DC Resistance or Conductance of Insulating Materials. 18 p.

These test methods cover direct-current procedures for the determination of dc insulation resistance, volume resistance, volume resistivity, surface resistance, and surface resistivity of electrical insulating materials, or the corresponding conductances and conductivities. (Look IPC-9201)

ASTM G16-95 (2004).

Standard Guide for Applying Statistics to Analysis of Corrosion Data. 14 p.

This guide presents briefly some generally accepted methods of statistical analyses which are useful in the interpretation of corrosion test results. This guide does not cover detailed calculations and methods, but rather covers a range of approaches which have found application in corrosion testing. Only those statistical methods that have found wide acceptance in corrosion testing have been considered in this guide.

ASTM G48-03.

Standard Test Methods for Pitting and Crevice Corrosion Resistance of Stainless Steels and Related Alloys by Use of Ferric Chloride Solution. 11 p.

These test methods cover procedures for the determination of the resistance of stainless steels and related alloys to pitting and crevice corrosion (see Terminology G 15) when exposed to oxidizing chloride environments. Six procedures are described and identified as Methods A, B, C, D, E, and F.

1.1.1 *Method A* – Ferric chloride pitting test.

1.1.2 *Method B* – Ferric chloride crevice test.

1.1.3 *Method C* – Critical pitting temperature test for nickel-base and chromium-bearing alloys.

1.1.4 *Method D* – Critical crevice temperature test for nickel-base and chromium-bearing alloys.

1.1.5 *Method E* – Critical pitting temperature test for stainless steels.

1.1.6 *Method F* – Critical crevice temperature test for stainless steels.

ASTM G102-89 (2004).

Standard Practice for Calculation of Corrosion Rates and Related Information from Electrochemical Measurements. 7 p.

This practice is intended to provide guidance in converting the results of electrochemical measurements to rates of uniform corrosion. Calculation methods for converting corrosion current density values to either mass loss rates or average penetration rates are given for most engineering alloys. In addition, some guidelines for converting polarization resistance values to corrosion rates are provided.

ASTM D968-05.

Standard Test Methods for Abrasion Resistance of Organic Coatings by Falling Abrasive. 4 p.

These test methods cover the determination of the resistance of organic coatings to abrasion produced by abrasive falling onto coatings applied to a plane rigid surface, such as a metal or glass panel.

Sections: Method A-Falling Sand Abrasion Test

Method B-Falling Silicon Carbide Abrasion Test.

ASTM E1545-05.

Standard Test Method for Assignment of the Glass Transition Temperature by Thermomechanical Analysis. 4 p.

1.1 This test method describes procedures for the assignment of the glass transition temperature of materials on heating using thermomechanical measurements under prescribed experimental conditions.

1.2 This test method is applicable to amorphous or to partially crystalline materials that are sufficiently rigid below the glass transition to inhibit indentation by the sensing probe.

1.3 The normal operating temperature range is from 100 to 600°C. This temperature range may be extended depending upon the instrumentation used.

1.4 SI units are the standard.

1.5 This test method is related to ISO 11359-2. ISO 11359-2 additionally covers the determination of coefficient of linear thermal expansion not covered by this test method. This test method is related to IEC 61006 but uses a slower heating rate.

ASTM E1824-02.

Standard Test Method for Assignment of a Glass Transition Temperature Using Thermomechanical Analysis Under Tension. 3 p.

- 1.1 This test method covers a procedure for the assignment of a glass transition temperature of materials on heating using thermomechanical measurements under tension under prescribed experimental conditions.
- 1.2 This test method may be used as a complement to Test Method E 1545 and is applicable to amorphous or to partially crystalline materials in the form of films, fibers, wires, etc. that are sufficiently rigid to inhibit extension during loading at ambient temperature.
- 1.3 The generally applicable temperature range for this test method is – 100 to 600°C. This temperature range may be altered depending upon the instrumentation used.

DIN V 53160-1, Ausgabe:2002-10.

Bestimmung der Farblässigkeit von Gebrauchsgegenständen – Teil 1: Prüfung mit Speichelsimulanz.

DIN V 53160-2, Ausgabe:2002-10.

Bestimmung der Farblässigkeit von Gebrauchsgegenständen – Teil 2: Prüfung mit Schweißsimulanz.

IEC 60068-1 (1988-06).

Environmental testing – Part 1: General and guidance. 53 p.

Enumerates a series of environmental tests and appropriate severities, and prescribes various atmospheric conditions for measurements for the ability of specimens to perform under normal conditions of transportation, storage and operational use.

IEC 60068-2-1 (1990-05).

Environmental testing – Part 2: Tests. Test A: Cold. 43 p.

Concern cold tests on both non-heat-dissipating and heat-dissipating specimens.

IEC 60068-2-2 (1974-01).

Environmental testing – Part 2: Tests. Test B: Dry heat. 63 p.

Contains Test Ba: Dry heat for non-heat-dissipating specimen with sudden change of temperature; Test Bb: Dry heat for non-heat-dissipating specimen with gradual change of temperature; Test Bc: Dry heat for heat-dissipating specimen with sudden change of temperature; Test Bd: Dry heat for heat-dissipating specimen with gradual change of temperature.

Amendments am1 (1993-02) and am2 (1994-05).

IEC 60068-2-5 (1975-01).

Environmental testing – Part 2: Tests. Test Sa: Simulated solar radiation at ground level. 11 p.

Determines the thermal, mechanical, chemical, electrical, and other effects on equipment and components as a result of exposure to solar radiation at the surface of the earth.

IEC 60068-2-6 (1995-03).

Environmental testing – Part 2: Tests. Test Fc: Vibration (sinusoidal). 87 p.

Gives a method of test which provides a standard procedure to determine the ability of components, equipment and other articles to withstand specified severities of sinusoidal vibration.

IEC 60068-2-9 (1975-01).

Environmental testing – Part 2: Tests. Guidance for solar radiation testing. 34 p.

Describes methods of simulation designed to examine the effect of solar radiation on equipment and components at the surface of the earth. Should be used with IEC 68-2-5.

IEC 60068-2-9-am1 (1984-01). 5 p.

IEC 60068-2-9-am1 Corr.1 (1989-08). 1 p.

IEC 60068-2-10 (2005-06).

Environmental testing – Part 2-10: Tests – Test J and guidance: Mould growth. 49 p.

Provides a test method for determining the extent to which electrotechnical products support mould growth and how any mould growth may affect the

performance and other relevant properties of the product. Since mould growth conditions include high relative humidity, the test is applicable to electrotechnical products intended for transportation, storage and use under humid conditions over a period of some days at least.

IEC 60068-2-11 (1981-01).

Environmental testing – Part 2: Tests. Test Ka: Salt mist. 11 p.

Compares resistance to deterioration from salt mist between specimens of similar construction. May be used to evaluate the quality and the uniformity of protective coatings.

IEC 60068-2-13 (1983-01).

Environmental testing – Part 2: Tests. Test M: Low air pressure. 13 p.

Determines the ability of components, equipment and other articles to be stored, transported or used under low air pressure conditions.

IEC 60068-2-14 (1984-01).

Environmental testing – Part 2: Tests. Test N: Change of temperature. 29 p.

Determines the ability of components, equipment and other articles to withstand rapid changes of ambient temperature. The exposure times to accomplish this depend upon the nature of the specimen.

IEC 60068-2-17 (1994-07). (Look also IEC 60529).

Environmental testing – Part 2: Tests. Test Q: Sealing. 103 p.

Includes a number of tests which use different conditioning procedures appropriate for different application. The standard includes tests for air tightness, gas leakage (bubble test), liquid seepage, pressure rise, tracer gas with mass spectrometer, tracer gas with internal pressurization, immersion and bomb pressure.

IEC 60068-2-18 (2000-10).

Environmental testing – Part 2-18: Tests – Test R and guidance: Water. 75 p.

Provides methods of test applicable to products which, during transportation, storage or in service, may be subjected to falling drops, impacting water or immersion. The primary purpose of water tests is to verify the ability of enclosures, covers and seals to maintain components and equipment in good working order after and, when necessary, under a standardized dropfield or immersion in water. These tests are not corrosion

tests and should not be considered and used as such. The effects of a large temperature difference between the water and the specimen, such as increased water ingress resulting from pressure changes, as well as thermal shock, are not simulated. Established water tests in other standards are not intended to simulate natural rainfall and their quoted intensities are too high to be adopted for that purpose. Therefore, in addition to the high-intensity severities, Test R includes an artificial rain test based upon natural conditions but not taking into account high wind speeds generally associated with natural rain. Guidance is given on the applicability of the tests and the severities to be selected.

IEC 60068-2-21 (2006-06).

Environmental testing – Part 2-21: Tests – Test U: Robustness of terminations and integral mounting devices.

Applicable to all electrical and electronic components whose terminations or integral mounting devices are liable to be submitted to stresses during normal assembly or handling operations.

IEC 60068-2-30 (2005-08).

Environmental testing – Part 2-30: Tests – Test Db: Damp heat, cyclic (12 h + 12 h cycle). 27 p.

Determines the suitability of components, equipment or other articles for use, transportation and storage under conditions of high humidity – combined with cyclic temperature changes and, in general, producing condensation on the surface of the specimen. If the test is being used to verify the performance of a specimen whilst it is being transported or stored in packaging then the packaging will normally be fitted when the test conditions are being applied. For small, low mass specimens, it may be difficult to produce condensation on the surface of the specimen using this procedure; users should consider the use of an alternative procedure such as that given to IEC 60068-2-38. The main changes with respect to the previous edition are listed below: – editorial changes, – addition of normative references, – addition of guidance for temperature tolerances, – period for recovery has been extended.

IEC 60068-2-33 (1971-01).

Environmental testing – Part 2: Tests. Guidance on change of temperature tests. 13 p.

Gives guidance to designers and testing personnel on the specification and use of change of temperature tests. A change of temperature test is intended to determine the effect on the specimen of a change of temperature or a succession of changes of temperature.

IEC 60068-2-38 (1974-01).

Environmental testing – Part 2: Tests. Test Z/AD: Composite temperature/ humidity cyclic test. 20 p.

Applies to component-type specimens and is a test to determine in accelerated manner to the effects of high temperature, humidity and cold.

IEC 60068-2-39 (1976-01).

Environmental testing – Part 2: Tests. Test Z/AMD: Combined sequential cold, low air pressure, and damp heat test. 9 p.

Applies to aircraft components and equipment, partially to those installed in unheated or unpressurized conditions.

IEC 60068-2-40 (1976-01).

Environmental testing – Part 2: Tests. Test Z/AM: Combined cold/low air pressure tests. 17 p.

Applies to heat-dissipating and non-heat-dissipating specimens and is a test to determine the ability of components, equipment and other articles to be stored and used under simultaneous combination of low temperature and low air pressure.

IEC 60068-2-41 (1976-01).

Environmental testing – Part 2: Tests. Test Z/BM: Combined dry heat/low air pressure tests. 19 p.

Applies to heat-dissipating and non-heat-dissipating specimens and is a test to determine the ability of components, equipment and other articles to be stored and used under simultaneous combination of high temperature and low air pressure.

IEC 60068-2-42 (2003-05).

Environmental testing – Part 2-42: Tests – Test Kc: Sulphur dioxide test for contacts and connections. 15 p.

Provides an accelerated means of assessing the corrosive effect of atmospheres polluted with sulphur dioxide on contacts and connections.

IEC 60068-2-43 (2003-05).

Environmental testing – Part 2-43: Tests – Test Kd: Hydrogen sulphide test for contacts and connections. 14 p.

Provides accelerated means to assess the effects of the tarnishing of silver and silver alloys used for contacts and connections.

IEC 60068-2-45 (1980-01).

Environmental testing. Part 2: Tests. Test XA and guidance: Immersion in cleaning solvents. 20 p.

Applies to electronic components and other parts mounted on printed circuit boards which may be subjected to cleaning operations. Also gives information on test solvents and test temperatures. Amendment am1 (1993-02).

IEC 60068-2-46 (1982-01).

Environmental testing – Part 2: Tests. Guidance to Test Kd: Hydrogen sulphide test for contacts and connections. 23 p.

Gives guidance on the effect of hydrogen sulphide on electrical contacts and the significance of the test in IEC 60068-2-43 on the behaviour of contacts exposed to such atmospheres.

IEC 60068-2-48 (1982-01).

Environmental testing – Part 2: Tests. Guidance on the application of the tests of IEC 68 to simulate the effects of storage. 11 p.

In this guidance, the term “storage” describes the keeping of components, equipment or other articles for relatively long periods of time (ranging from some weeks to many years) in a non-operating mode.

IEC 60068-2-49 (1983-01).

Environmental testing – Part 2: Tests. Guidance on the application of the tests of IEC 68 to simulate the effects of storage. 11 p.

In this guidance, the term storage describes the keeping of components, equipment or other articles for relatively long periods of time (ranging from some weeks to many years) in a non-operating mode.

IEC 60068-2-50 (1983-01).

Environmental testing. Part 2: Tests. Tests Z/AFc: Combined cold/vibration (sinusoidal) tests for both heat-dissipating and non-heat-dissipating specimens. 21 p.

Combination of test Fc: Vibration (sinusoidal) and test A: Cold.

IEC 60068-2-51 (1983-01).

Environmental testing. Part 2: Tests. Tests Z/BFc: Combined dry heat/vibration (sinusoidal) tests for both heat-dissipating and non-heat-dissipating specimens. 21 p.

Combination of Test Fc: Vibration (sinusoidal) and Test B: Dry heat.

IEC 60068-2-52 (1996-02).

Environmental testing – Part 2: Tests. Test Kb: Salt mist, cyclic (sodium, chloride solution). 21 p.

Determines the suitability of components and equipment for use or exposure in a salt-laden atmosphere.

IEC 60068-2-53 (1984-12).

Environmental testing. Part 2: Tests. Guidance to Tests Z/AFc and Z/BFc: Combined temperature (cold and dry heat) and vibration (sinusoidal) tests. 10 p.

Gives guidance on the use of Tests Z/AFc and Z/BFc when testing components, equipment and other electrotechnical products.

IEC 60068-2-60 (1995-12).

Environmental testing – Part 2: Tests – Test Ke: Flowing mixed gas corrosion test. 41 p.

Determines the corrosive influence of operating and storage indoor environments on electrotechnical products components, equipment and materials, particularly contacts and connections, considered separately, integrated into a subassembly or assembled as a complete equipment.

IEC 60068-2-61 (1991-07).

Environmental testing – Part 2: Test methods – Test Z/ABDM: Climatic sequence. 33 p.

Specifies a ‘climatic sequence’ for products, primarily components, that is based on clause 7, and annex B of IEC 60068-1. Includes guidance for specification writers and those performing the test. Includes sequences Dry heat, Damp heat cyclic, Cold, Low air pressure, Damp heat cyclic.

IEC 60068-2-64 (1993-05).

Environmental testing – Part 2: Tests. Test Fh: Vibration, broad-band random (digital control) and guidance. 85 p.

Determines the ability to withstand specified severities of broad-band random vibration. Applies to specimens which may be subjected to vibration of stochastic nature by transportation or operational environments, for example in aircraft, space vehicles and land vehicles.

IEC 60068-2-66 (1994-06).

Environmental testing – Part 2: Tests. Test Cx: Damp heat, steady state (unsaturated pressurized vapour). 33 p.

Provides standard test procedure for the purpose of evaluating, in an accelerated manner, the resistance of small electrotechnical products, primarily non-hermetically sealed components (e.g. plastic encapsulation), to the deteriorative effect of damp heat. The test is not intended to evaluate external effects, such as corrosion and deformation. Test conditions are temperature 110, 120 or 130°C and relative humidity 85%. Test durations are 24, 48, 96, 192 or 408 hours.

IEC 60068-2-67 (1995-12).

Environmental testing – Part 2: Tests. Test Cy: Damp heat, steady state, accelerated test primarily intended for components. 17 p.

Provides standard test procedure for the purpose of evaluating, in an accelerated manner, the resistance of small electrotechnical products, primarily non-hermetically sealed components (e.g. plastic encapsulation), to the deteriorative effect of damp heat. The test is not intended to evaluate external effects, such as corrosion and deformation. Test conditions are temperature 85°C and relative humidity 85%. Test durations are 168, 504, 1000 or 2000 hours.

IEC 60068-2-68 (1994-08).

Environmental testing – Part 2: Tests. Test L: Dust and sand. 127 p.

Specifies test methods to determine the effects of dust and sand suspended in air, on electrotechnical products.

IEC 60068-2-69 (1995-12).

Environmental testing – Part 2: Tests – Test Te: Solderability testing of electronic components for surface mount technology by the wetting balance method. 43 p.

Describes two wetting balance methods. These methods determine quantitatively the solderability of terminations on surface mounted devices. The procedures describe the solder bath wetting balance method and the solder globuwetting balance method and are both applicable to components with metallic termination and metallized solder pads.

IEC 60068-2-70 (1995-12).

Environmental testing – Part 2: Tests – Test Xb: Abrasion of marking and letterings caused by rubbing of fingers and hands. 19 p.

Is intended to provide a standard method to determine the resistance of markings and letterings on flat or curved surfaces against abrasion as it may occur by manually operating actuators and keyboards. The method is also suitable to test the resistance against fluid contamination as it may occur under normal use.

IEC 60068-2-78 (2001-08).

Environmental testing – Part 2-78: Tests – Test Cab: Damp heat, steady state. 13 p.

Provides a test method for determining the suitability of electrotechnical products, components or equipment for transportation, storage and use under conditions of high humidity. The test is primarily intended to permit the observation of the effect of high humidity at constant temperature without condensation on the specimen over a prescribed period. This test provides a number of preferred severities of high temperature, high humidity and test duration. The test can be applied to both heat-dissipating and non-heat dissipating specimens. The test is applicable to small equipment or components as well as large equipment having complex interconnections with test equipment external to the chamber, requiring a set-up time which prevents the use of preheating and the maintenance of specified conditions during the installation period.

IEC 60068-3-1 (1974-01).

Environmental testing – Part 3: Background information – Section one: Cold and dry heat tests. 59 p.

IEC 60068-3-2 (1976-01).

Environmental testing – Part 3: Background information – Section Two: Combined temperature/low air pressure tests.

Gives background information for Test Z/AM and Z/BM.

IEC 60068-5-1 (1991-07).

Environmental testing – Part 5: Guide to drafting of test methods. General principles. 23 p.

Provides a framework for the drafting and presentation of test methods in Part 2 of IEC 60068 and guidance on its adaptation to particular situations.

IEC 60093 (1980-01).

Methods of test for volume resistivity and surface resistivity of solid electrical insulating materials. 44 p.

Gives test procedures and calculations for the determination of volume and surface resistivity. Establishes recommendations for: values of voltage and time of application; nature and geometry of electrodes temperature and humidity of atmosphere and test specimens; conditioning of test specimens.

IEC 60216 (2001-07).

Electrical insulating materials – Properties of thermal endurance – Part 1: Ageing procedures and evaluation of test results. 79 p.

Specifies the general ageing conditions and procedures to be used for deriving thermal endurance characteristics and gives guidance in using the detailed instructions and guidelines in the other parts of the standard. Simplified procedures are also given, with the conditions under which these procedures may be used.

IEC 60426 (2007-01).

Electrical insulating materials – Determination of electrolytic corrosion caused by insulating materials – Test methods. 26 p.

This standard determines the ability of insulating materials to produce electrolytic corrosion on metals being in contact with them under the influence of electric stress, high humidity and elevated temperature.

IEC 61006 (2004-01).

Electrical insulating materials – Methods of test for the determination of the glass transition temperature. 47 p.

Specifies procedures for test methods for the determination of the glass transition temperature of solid electrical insulating materials. They are applicable to amorphous materials or to partially crystalline materials containing amorphous regions which are stable and do not undergo decomposition or sublimation in the glass transition region. Changes from the first edition are as follows: – the standard has been completely revised from an editorial point of view and adapted to the state of the art; – a figure to demonstrate the dynamic mechanical analysis has been introduced.

IEC 61086-1 (2004-01).

Coatings for loaded printed wire boards (conformal coatings) – Part 1: Definitions, classification and general requirements. 13 p.

Gives the definitions, classification and general requirements for electrical insulating materials suitable for application as coatings for loaded printed wire boards (conformal coatings). This standard excludes requirements for compatibility between such coatings and printed wire boards, this characteristic being evaluated in individual applications. Surface modifiers are not classified as conformal coatings. They only provide a thin film that does not cure and has low mar resistance. They are excluded from this standard. Materials which conform to this standard meet established levels of performance. However, the selection of a material by a user for a specific application should be based on the actual requirements necessary for adequate performance in that application and not based on this standard alone. This edition includes the following significant technical changes from the previous edition: a) a Class 3 material for aerospace applications has been included; b) a new resin type (oligomeric blend material) has been added.

IEC 61086-2 (2004-02).

Coatings for loaded printed wire boards (conformal coatings) – Part 2: Methods of test. 37 p.

Gives the methods of test for electrical insulating materials suitable for application as coatings for loaded printed wire boards (conformal coatings). The tests are: visual assessment, properties after thermal cycling, resistance to organic liquids, coating removal, dissipation factor and permittivity, insulation resistance after damp heat, mould growth, shelf life,

flammability, tackiness, loss of volatile matter, thermal ageing, insulation resistance after salt mist, extreme altitude and temperature test, electric strength. In these methods the IPC Multipurpose test board pattern No. IPC-B-25 is used as test pattern.

IEC 61086-3-1 (2004-02).

Coatings for loaded printed wire boards (conformal coatings) – Part 3-1: Specifications for individual materials – Coatings for general purpose (Class 1), high reliability (Class 2) and aerospace (Class 3). 19 p.

Gives the property requirements for electrical insulating materials suitable for application as coatings for loaded printed wire boards (conformal coatings). Materials which conform to this specification meet established levels of performance. However, the selection of a material by a user for a specific application should be based on the actual requirements necessary for adequate performance in that application and not based on this specification alone. This edition includes the following significant technical changes from the previous edition: a) requirements for cleaning have been added; b) new properties based on modifications to IEC 61086-2 have been added; c) a Class 3 material for aerospace applications has been included.

IEC 60287-2-2 (1995-05).

Electric cables – Calculation of the current rating – Part 2: Thermal resistance – Section 2: A method for calculating reduction factors for groups of cables in free air, protected from solar radiation.

Is applicable to any type of cable and group running horizontally, provided that the cables are of equal diameter and emit equal losses. This publication supersedes IEC 61042.

IEC 60319 (1999-09). 39 p.

Presentation and specification of reliability data for electronic components

Describes the information needed for characterizing reliability and the detailed requirements for reporting reliability data.

IEC 60512-11-7 (2003-05). 9 p.

Connectors for electronic equipment – Tests and measurements – Part 11-7: Climatic tests – Test 11g: Flowing mixed gas corrosion test

Defines a standard test method to assess the effects of a controlled atmosphere polluted by gases at very low concentration on electrical contacts or connections.

IEC 60529 (2001-02). 91 p. (Look also IEC 60068-2-17)

Degrees of protection provided by enclosures (IP Code).

Applies to the classification of degrees of protection provided by enclosures for electrical equipment with a rated voltage not exceeding 72,5 kV. Has the status of a basic safety publication in accordance with IEC Guide 104.

IEC 61189-3 (1997-04). 105 p.

Test methods for electrical materials, interconnection structures and assemblies – Part 3: Test methods for interconnection structures (printed boards).

Provides a catalogue of test methods representing methodologies and procedures that can be applied to test materials used for manufacturing interconnection structures (printed boards) and assemblies. It mainly covers chemical, mechanical and electrical test methods.

IEC 61189-3-am1 (1999-07). Amendment 1. 33 p.

IEC 61300-2-30 (1995-06). 9 p

Fibre optic interconnecting devices and passive components – Basic test and measurement procedures – Part 2-30: Tests – Solar radiation.

IPC TM-650. Test Methods Manual. 1999.

Contains industry approved test techniques and procedures for chemical, mechanical, electrical, and environmental tests on all forms of printed boards and connectors. There have been 111 new or revised test methods added to IPC-TM-650 in the last two years./

<http://ipc.org/html/testmethods.htm/>

IPC-A-600E. Acceptability of Printed Boards. USA 1995. 113 p.

Contains visual illustrations of preferred, acceptable, and rejectable conditions for: plated through-holes; surface plating; solder coating; base materials; etching; conductors; mechanical processes; flexible and multilayer boards; bow/twist; flat cable and other conditions of printed wiring boards.

IPC-6011. Generic Performance Specification for Printed Boards. 10 p.

This specification establishes the general requirements and responsibilities for suppliers and users of printed boards. Describes quality and reliability

assurance requirements that must be met. For use with IPC-6012 through IPC-6018. Released July 1996.

IPC-6012. Qualification and Performance Specification for Rigid Printed Boards (With IPC-6011, Supersedes IPC-RB-276). 27 p.

This specification covers qualification and performance of rigid printed boards. The printed board may be single-sided, double-sided, with or without plated through-holes, multilayer with or without buried/blind vias and metal core boards. Covers finishes, plating, traces, holes/vias, electrical, mechanical and environmental requirements. For use with IPC-6011. Released July 1996.

IPC-6015. Qualification and Performance Specification for Organic Multichip Module (MCM-L) Mounting and Interconnecting Structures. 17 p.

This specification establishes the specific requirements for organic mounting structures used to interconnect chip components, which in combination form the completed functional organic single-chip module (SCM-L) or organic multichip module (MCM-L) assembly and the quality and reliability assurance requirements that must be met for their acquisition. For use with IPC-6011. Released February 1998.

IPC-9201. Surface Insulation Resistance Handbook, July 1996. 65 p.

This document is intended to cover the broad spectrum of temperature-humidity (TH) testing, associated terminology, and suggested techniques for proper testing. This Handbook covers the test methods used in the United States. (Look ASTM D257).

IPC-TR-476A. Electrochemical Migration: Electrochemically Induced Failures in Printed Wiring Boards and Assemblies, July 1995.

IPC-A-610B. Acceptability of Electronic Assemblies, USA December 1994 Includes Amendment 1, January 1996.

A must for all quality assurance departments, IPC-A-610B illustrates industry-accepted workmanship criteria through full-color photographs and schematic illustrations. The topics covered include component orientation and soldering criteria for through-hole, SMT and discrete wiring assemblies.

IPC-A-610C is valuable for all inspectors, operators and trainers; this visual guide provides each company with a clear representation of electronics acceptability criteria based on the consensus of industry experts. Revised November 2000. 134 p.

Related documents for IPC-A-610B:

EIA ANSI/J-STD-001D:2005. Requirements for Soldered Electrical and Electronic Assemblies.

This standard prescribes practices and requirements for the manufacture of soldered electrical and electronic assemblies. Historically, electronic assembly (soldering) standards contained a more comprehensive tutorial addressing principles and techniques. For a more complete understanding of this document's recommendations and requirements, one may use this document in conjunction with IPC-HDBK-001, IPC-A-610 and IPCHDBK-610.

ANSI/IPC PC-90-1990. General Requirements for Implementation of Statistical Process Control.

Desk Reference Manual DRM-SMT. IPC The Institute for Interconnecting and Packaging Electronic Circuits, Illinois 1998. 37 p. ISBN 1-580984-28-2.

ANSI/EIA-557-A-1995. Statistical Process Control Systems, ANSI approved May 10, 1995. 35 p.

EIA-557-1. Statistical Process Control Guidance for the selection of Critical Manufacturing Operations for Use in Implementing an SPC System for Passive Components.

CECC 00016, 1990.

Basic specification: Basic requirements for the use of Statistical Process Control (SPC) in the CECC system.

ISO 12302:1993.

Plain bearings – Quality characteristics – Statistical process control (SPC). 3 p.

EIA-625. Requirements of Handling Electrostatic-Discharge Sensitive (EEDS) Devices.

GR-63-CORE. (Issue 2, April 2002). NEBS Requirements, Physical protection, Telcordia Technologies, Generic Requirements. (Chapter 5.5 Airborne Contaminants Test Methods).

IPC-SS-615. Assembly Board Quality Evaluation Slide Set.

IPC-QE-615. Electronic Assembly Evaluation Handbook.

IPC-DRM-SMT. Surface Mount Solder Joint Evaluation Desk Reference Manual.

IPC-A-25. A Multipurpose 1 Sided Test Pattern.

Artwork for standard test boards as referenced in IPC-CC-830 and the newly released IPC-SM-840C. This is used primarily for surface insulation resistance testing. Price is for film or data. Available in film, electronically in Gerber and IPC-D-350 formats. If ordering Gerber or IPC-D-350, please specify the format. Revised February 1996.

IPC-SM-840C. Qualification and Performance of Permanent Solder Mask, January 1996. 52 p.

Streamlines solder mask classes into two classifications: H (high reliability) and T (telecommunications). IPC-SM-840C also integrates Bellcore requirements (class T) and provides minimum voltage breakdown, defines mask formulation latitude, adds new mask chemistries and more.

Related documents for IPC-SM-840C:

IPC J-STD-001D:2005. Requirements for Soldered Electrical and Electronic Assemblies.

IPC-J-STD-004A:2004. Requirements for soldering fluxes.

IPC-A-25. Multipurpose 1 & 2 Sided Test Pattern.

IPC-A-25.A Multipurpose 1 Sided Test Pattern.

IPC-A-600. Acceptability of Printed Boards.

IPC-6012. Qualification and Performance Specification for Rigid Printed Boards.

ISO 4611 (1987). Plastics – Determination of the effects of exposure to damp heat, water spray and salt mist. 7 p.

ISO 4623-1:2000. Paints and varnishes – Determination of resistance to filiform corrosion – Part 1: Steel substrates. Ed. 1. 7 p.

ISO 4623-2:2003. Paints and varnishes – Determination of resistance to filiform corrosion – Part 2: Aluminium substrates. Ed. 1. 6 p.

ISO 7384 (1986). Corrosion tests in artificial atmosphere – General requirements. 4 p.

ISO 8407: (1991). Corrosion of metals and alloys – Removal of corrosion products from corrosion test specimens. 7 p.

ISO 8565 (1992). Metals and alloys – Atmospheric corrosion testing – General requirements for field tests. 8 p.

ISO 9227: (2006). Corrosion tests in artificial atmospheres – Salt spray tests. 20 p.

Specifies the apparatus, the reagents and the procedure to be used in conducting the neutral salt spray (NSS), acetic acid salt spray (AASS) and copper-accelerated acetic acid salt spray (CASS) tests for assessment of the corrosion resistance of metallic materials, with or without permanent or temporary corrosion protection.

ISO 10062: (2006). Corrosion tests in artificial atmosphere at very low concentrations of polluting gas(es). 12 p.

Specifies tests which are intended to determine the influence of one or more flowing polluting gas(es) at volume fractions less than or equal to 0,000001 on test samples and/or articles of metals and alloys with or without corrosion protection under determined conditions of temperature and relative humidity. These tests apply to metals and their alloys, metallic coatings (anodic and cathodic), metals with conversion coatings, metals with anodic oxide coatings, and metals with organic coatings.

ISO 11359-2:1999. Plastics – Thermomechanical analysis (TMA) – Part 2: Determination of coefficient of linear thermal expansion and glass transition temperature. 10 p.

ISO 11907-1 (1998). Plastics – Smoke generation – Determination of the corrosivity of fire effluents – Part 1: Guidance. 6 p.

ISO 11907-2 (1995). Plastics – Smoke generation – Determination of the corrosivity of fire effluents – Part 2: Static method. 12 p.

ISO 11907-3 (1998). Plastics – Smoke generation – Determination of the corrosivity of fire effluents – Part 3: Dynamic decomposition method using a travelling furnace. 21 p.

ISO 11907-4 (1998). Plastics – Smoke generation – Determination of the corrosivity of fire effluents – Part 4: Dynamic decomposition method using a conical radiant heater. 22 p.

ISO 11997-1:2005. Paints and varnishes – Determination of resistance to cyclic corrosion conditions – Part 1: Wet (salt fog)/dry/humidity. 13 p.

ISO 11997-2:2000. Paints and varnishes – Determination of resistance to cyclic corrosion conditions – Part 2: Wet (salt fog)/dry/humidity/UV light. 5 p.

ISO 10062: 2006. Corrosion tests in artificial atmosphere at very low concentrations of polluting gas(es).

ISO 21207: 2004. Corrosion tests in artificial atmospheres – Accelerated corrosion tests involving alternate exposure to corrosion-promoting gases, neutral salt-spray and drying. 10 p.

MIL-STD-810F (2000). Environmental engineering considerations and laboratory tests.

SAE J2334. Laboratory Cyclic Corrosion Test (Cosmetic corrosion test). 2003.

The following test methods and guides are meant for testing non-hermetic component packages (package is usually plastic).

JESD22-A100-A (January 1989). Test Method A100-A Cycled Temperature Humidity Bias Life Test. 6 p.

The Cycled Temperature Humidity Bias Life Test is performed for the purpose of evaluating the reliability of non-hermetic packaged solid-state devices in humid environments. It employs conditions of temperature cycling, humidity, and bias which accelerate the penetration of moisture through the external protective material (enpsulant or seal) or along the interface between the external protective material and the metallic conductors which pass through it.

The test condition consists of a temperature, relative humidity, and duration used in conjunction with an electrical bias configuration specific to the device. Cycled temperature from 30°C to 65°C, humidity 90...98%, cycle time 12 hours, total test time 1008 hours.

EIA/JESD22-A101-B (April 1997). Test Method A101-B, Steady State Temperature Humidity Bias Life. 6 p.

The Steady-State Temperature Humidity Bias Life Test (85/85) is performed for the purpose of evaluating the reliability of non-hermetic packaged solid-state devices in humid environments. It employs conditions of temperature, humidity, and bias which accelerate the penetration of moisture through the external protective material (encapsulant or seal) or along the interface between the external protective material and the metallic conductors which pass through it. This revision enhances the ability to perform this test on a devices which cannot be biased to achieve very low power dissipation. Test conditions are 85°C/85% RH, test time 1 000 hours.

JESD22-A102-B (March 1991). Test Method A102-B Accelerated moisture resistance – unbiased autoclave. 3 p.

The test” is performed for the purpose of evaluating the moisture resistance of non-hermetic packaged solid state devices. It employs severe conditions of pressure, humidity and temperature that accelerate the penetration of moisture through the external protective material (encapsulant or seal) or along the interface between the external protective material and the metallic conductors that pass through it. This test is **destructive**; it may * be used for qualification, lot acceptance and as a product monitor. Test conditions are 121°C/100% RH, test times are 24 h, 48 h, 96 h, 168 h 240 h, 336 h.

JESD22-A110-B (February 1999). Test Method A110-B, Highly-Accelerated Temperature and Humidity Stress Test (HAST). JEDEC Solid State Technology Association. 11 p.

The test is performed for the purpose of evaluation the reliability of non-hermetic packaged solid-state devices in humid environments. It employs severe conditions of temperature, humidity, and bias which accelerate the penetration of moisture through the external protective material (encapsulant or seal) or along the interface between the external protective material and the metallic conductors which pass through it. The stress usually activates the same failure mechanisms as the “85/85” Steady-State Humidity Life Test (JEDEC Standard No. 22-A101-B) but in a much shorter time. Test conditions of HAST are 130°C/85% RH, 96 hours or 110°C/85% RH, 264 hours.

JESD22-A112-A (November 1995). Test Method A112-A, Moisture-Induced Stress Sensitivity for Plastic Surface Mount Devices. 12 p.

The purpose of this test method is to identify the potential classification level of plastic Surface Mount Devices (SMDs) that are sensitive to moisture-induced stress so that they can be properly packaged, stored, and handled to avoid subsequent mechanical damage during the assembly solder reflow attachment and/or repair operation. This test method may be used to determine what classification level should be used for initial reliability qualification. Test conditions of moisture chamber are 85°C/85% RH, 168 h, 85°C/60% RH, 168 h, and 30°C/60% RH, 6...192 h.

IPC/JEDEC J-STD-035 (May 1999). Acoustic Microscopy for Nonhermetic Encapsulated Electronic Components.

This method provides users with an acoustic microscopy process flow for detecting anomalies (delamination, cracks, mold component voids, etc.) nondestructively in plastic packages while achieving reproducibility.

Appendix 1

Fundamentals of corrosion and failure mechanisms

Fundamentals of corrosion and failure mechanisms

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1 Corrosion, water and humidity

1.1 Concept of acidity

The acidity of the water solutions has a great effect on what types of reactions take place on the liquid-metal boundary surfaces. On the other hand acidity can be used to describe the status of a metal surface in relation to corrosion. Is the status favourable to corrosion, corrosive, are any corrosion products that partially protect the surface forming on the surfaces (passive state) or is the state inert (immune state) with no metal corrosion.

The acidity or alkalinity of a solution is expressed as the concentration of hydrogen ions in it. The greater the concentration the more acid the solution. The usual way of expressing the hydrogen ion concentration is the pH value. The pH value of a solution is the inverse value of the logarithm C_{H^+} of the hydrogen ion concentration.

As a formula: $pH = -\log C_{H^+}$

The solution is acid if its pH is below 7 and alkaline when the pH exceeds 7. The pH of clean water is 7. Rainwater is usually slightly acid because some carbon dioxide is absorbed into it forming carbon acid with the water. The pH of dishwasher detergent exceeds 10; in other words the detergent solution is very alkaline. Even aluminium dissolves easily into water this alkaline.

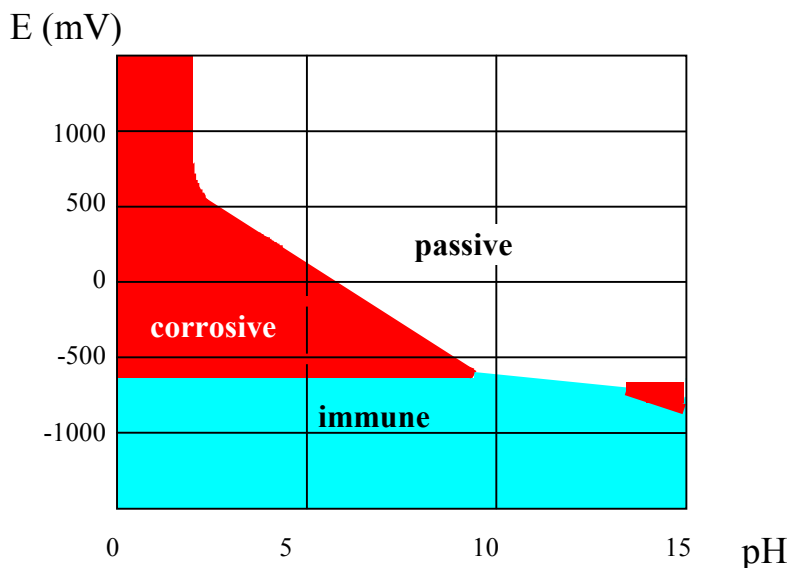


Figure 1.1. The simplified Pourbaix-diagram [Tunturi 1988].

The Pourbaix-diagram or the **pH-potential diagram** is the electrochemical balance chart of a metal (Figure 1.1). The point of zero potential is the potential of the hydrogen electrode with an agreed value of 0 V. The potential of the metal (corrosion reaction) is determined by comparison to this potential. When the potential is charted as a function of the pH of the measured solution, a Pourbaix-diagram results. If the chart is drawn up depicting only the corrosion of the metal (the metal reacts and corrodes), immunity (the metal does not react) and passive zones (the metal has reacted and reaction products protecting the metal have formed on the surface) the graph becomes more clear. For instance, by changing the potential of the metal with an outside voltage source the behaviour of the metal surface can be shifted from the corrosion zone to the passive or immune zone. This is used for example in the electric protection of natural gas pipes or ships (cathodic and anodic protection) [Mattsson 1996, pp. 95–103].

1.2 The electrochemical and galvanic voltage series of metals

The electrochemical voltage series of metals means the voltages of pure metals compared to standard hydrogen electrode. An electrochemical voltage series of metals is obtained when the potentials of various metals are compared in the same salt solution to the standard hydrogen electrode. The electrochemical voltage series classifies the “nobility” of flawless, clean metals completely free of oxide or passive layers [Chemical and electrochemical surface treatment, Part 1, p. 65, Kemiällinen ja sähkökemiällinen pintakäsittely. Osa 1]. Since some metals are nobler than others a voltage difference is created between them when they are put into the same solution. The ability of batteries to store and discharge electricity is based on this phenomenon. With regard to corrosion, this electrochemical voltage series is not interesting, because it does not describe the conditions in nature and the order of metals is different from the real metals and conditions.


The nobility order of real metals depends on the composition of metals, passivity of surface, and the solutions effective on surface among other things. In air on the surfaces of for example chrome steel ($\text{Cr} > 12\%$), chrome, aluminium and titan develop a passive layer (oxide) rapidly. Then their nobility order differs from that of pure metals.

The voltage series are called galvanic voltage series when actual metals which have been in touch with air and which are immersed in actual solutions, are measured and put into order of magnitude. The most commonly used galvanic voltage series is the sea water series. Seawater is a solution containing mainly NaCl, which is the most common and most harmful of all corrosive substances.

NaCl is also present in palm sweat, which means that every surface touched by human being contains salt, also.

Therefore, when estimating the differences in the nobility of various metals or their alloys, they should be immersed into the same liquid as they would be in actual corrosive conditions before it could be determined which of the metals is the most noble in the conditions at hand. The shaping of the metals and the differences in the compositions of the alloys as well as various surface treatments has an effect on the electrochemical potential. Therefore, different parts of the surface of the same metal may have different potentials. This heterogeneity increases sensitivity to corrosion in practical circumstances. Table 1.1 presents a galvanic voltage series of certain metals in seawater. The more positive the potential of the metal, the more noble the metal.

Table 1.1. Galvanic voltage series of metals in sea water 25 °C, pH 7,5, potential (mV) with regard to a standard hydrogen electrode.

Metal	Potential (mV)	Nobleness	
Gold	+420	Most noble	
Graphite	+200		
Silver	+190		
CrNi-steel 18/8, passive state	+90		
Nickel 99% Ni	+46		
Copper	+20		
Brass Ms63	(+13)		
Monel K	+12		
Titan	(-111)		
Tin 98% Sn	-260		
CrNi-steel 18/8, active state	-290		
Steel + hard chrome 50 µm	-291		
Lead 99,9% Pb	-310		
Steel	-460		
Cadmium anode metal	-490		
Aluminium 99,5% Al	-510		
Steel + zinc (cyanidic) 100 µm	-810		
Zinc 98,5% Zn	-860		
Magnesium	-1360		Most basic

Source: [Kemiallinen ja sähkökemiallinen pintakäsittely, Part 1, 1996, p. 65]

A galvanic cell is formed of metals immersed in a liquid, an electrolyte, since the less noble metal will act as the anode and the more noble as a cathode. Oxidation

(corrosion) will take place on the anode and reduction on the cathode (metal will accumulate on the surface). Thus, the less noble metal will corrode in the corrosion process.

It is easy to see from the voltage series what will happen when two different metals have contact with one another. Some metals will have two alternatives: the potential of the active state (corrosion state) and passive state. These metals are capable of forming a dense passive layer on their surface. Usually the oxide layer forming in air on the surface of the metal is considered the passive layer. In an active state, the metal will corrode. The active state will usually occur in narrow cracks, which gradually lose the oxygen, and therefore also the oxide layer of metal due to the effect of corrosive reactions. This cause to extensive local corrosion of the metal which is not easily detectable and therefore dangerous by nature (see Appendix 1, Section 2.6 *Crevice corrosion*).

Let us name as an example of conditions favourable to corrosion the fact, that the rusting of steel requires both water and oxygen simultaneously. An iron nail will not rust in conditions where relative humidity is less than 40% RH. Even though there is oxygen, corrosion will not set in because there is no condensed water on the surfaces where the corrosion process could take place. Correspondingly, a radiator will not get rusty on the inside even though it is made of carbon steel and it is full of water. There is water, but since it does not contain oxygen corrosion will not set in.

1.3 Corrosion in gases

An oxide layer is formed on the surface of a metal in air due to the effect of oxygen. Some metals, for example aluminium, have very dense oxide layers, which will protect the metal from further corrosion. Other metals, for example iron, have a porous oxide layer, which will not protect the metal. Tin and lead oxidise in relatively low temperatures, which is harmful for instance to the soldering properties of the conductors of the components. The decay of soldering tin (SnPb) in dry air is quite rapid already at 100°C, which limits significantly the life span of the products in hot conductor connections.

The corrosive gases in air cannot react much with a metal surface without the presence of water (humidity). For example aluminium tolerates very well absolutely dry sulphur dioxide. Gases start to react with metals only at elevated temperatures, >300°C. This explains in part why corrosion can be slow when the inside of the device is dry due to high temperatures of use. Even a small amount of humidity changes corrosive gases either into corrosive acids (sulphuric oxides, nitrogen oxides, acetic acid, chlorine gas) or bases/alkalines (ammonia, amines).

In addition, corrosive gases can add to each other's aggressiveness, for instance if the air simultaneously contains NO_x and SO_x and HCl, aqua regalis, which dissolves most materials, may form in the presence of water.

1.4 Absorption of water into materials

Different materials absorb water in different ways. In metals water appears as condensed water on the surfaces – as a layer of water where corrosion reactions take place. If the water does not react with the metal surface in any way but only adheres to it the phenomenon is known as adsorption. Adsorbed water will evaporate when the temperature rises. This is known as desorption.

Plastics usually absorb water 0...0,5% of their dry weight (epoxies 0,08...0,15%). Plastics based on pulp and polyamides (nylons) are an exception. Nylon PA6 can retain a maximum of 10% of water when immersed.

According to [Kosbar & Gelorome 1997] the most commonly used circuit board material in electronics, FR-4 absorbs water 0,3...2,2% of its weight. [Rudra & Jennings 1994, Vahter 1999] give FR-4 water absorption the value 0,85% at a temperature of 50°C and relative humidity of 60%.

Table 1.2. Absorption of water into two-component epoxy resin at 100 °C.

Time (h)	Water (weight%)
2	0,02...0,09
4	0,08...0,17
6	0,11...0,22
8	0,13...0,25

According to [Palmén 1990], table 1.2, two-component epoxy resin absorbs water about 0,1% of its weight at a temperature of 23°C and about 0,2% at a 100°C after immersion of eight hours.

Wooden materials, cardboards and paper can absorb water 10...30% of their weight if the relative humidity of the air exceeds 70%. The quantity of water absorbing into wood decreases slightly when the temperature is raised if the relative humidity of the air stays constant (Figure 1.2).

According to Figure 1.2 the amount of water absorbed into wood decreases drastically when the temperature is raised even if the relative humidity is held

constant. It is vital to realise that the amount of water absorbing into materials depends primarily on the relative humidity of the air (% RH) and not the absolute water content of the air (g/m^3). In higher temperatures some of the water absorbed into material stays in liquid form in the capillary cracks of the material and the main part is water vapour, which means that there is not as much room for water in the material as in lower temperatures.

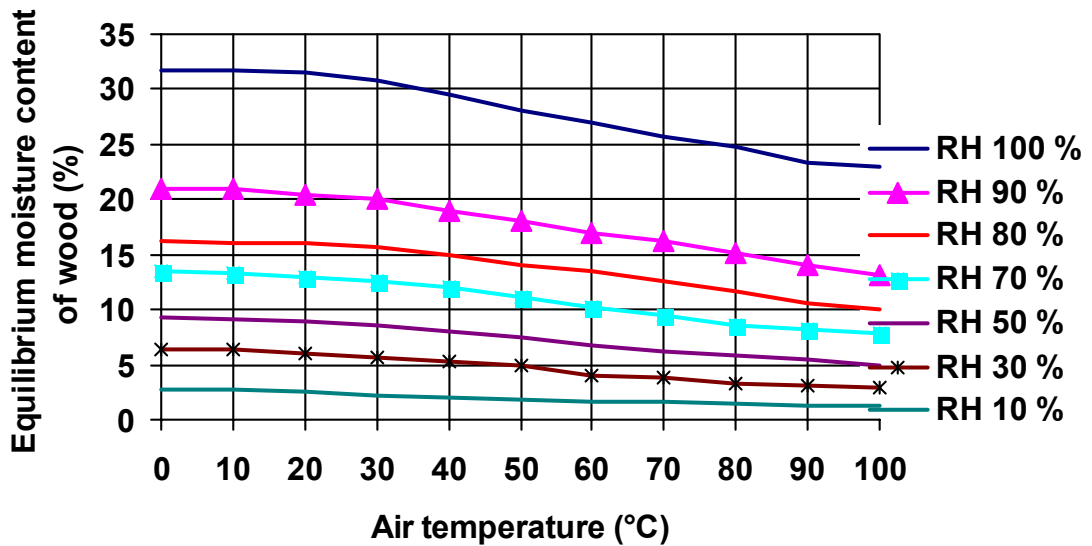


Figure 1.2. The equilibrium moisture content of wood as a function of relative humidity of the air (RH) and temperature [MET 17/80].

Cardboard materials absorb water about 15...20% of their weight if the relative humidity of the air is 100% near the room temperature. The quantity of water is almost independent of temperature in range 5...40 °C. At 50% RH water content is about 8% and at humidity 90% about 16% of the weight of cardboard [Paronen & Toroi 1959].

With regard to the absorption of water it is therefore important when for example products are packaged that the relative humidity of the packaging space is as low as possible. Then not much water will be retained in the packaging materials whatever the temperature. The absolute quantity of water in the air (g/m^3) mainly affects the accumulation of water through the airspace left in the package. If the air space is large compared to the size of the product and the packaging materials the relative humidity of the inside of the package will rise high when the temperature drops. This will result in the absorption of the humidity in the air spaces of the packages into the packaging materials and in extreme cases also condenses on the surfaces of the device and causes corrosion risk.

In the humidity testing it is important to ensure especially that the relative humidity of the air is as desired at all temperatures. If air at a lower temperature is heated into a higher temperature the relative humidity will decrease without exception and the humidity will no longer have the corrosive effect or the decaying effect on the isolations which is called for. The humidity test will then become a dry heat test with different fault mechanisms.

1.5 Absorption of water into plastics

The water vapour in the air absorbs quickly to nearly all plastic materials. Usually the absorption to plastics is 0...0,5% (epoxy 0,08...0,15%). Plastics based on pulp and polyamides (nylons) are an exception. Nylon PA6 can retain a maximum of 10% of water when immersed. If the plastic itself does not absorb much water, glass fibre curing will increase the absorption of water. If the plastic absorbs a lot of water (PA6 10%) the glass fibre curing will decrease the absorption of water [Törmälä et al. 1983]. Table 1.3 presents the figures for the water content of some plastics after they have exposed to humid air.

Printed board is usually made of glass enforced epoxy. Water may absorb to the board trough the edge among the glass fibers. This is rather theoretical possibility because the board is normally faultless (no unevenness, air bubbles, etc.), which ensures the tightness of the border between glass fibre and epoxy. The transmission of water into the board is almost impossible. At about 70% RH the wetting of epoxy starts. The water in the epoxy weakens the binding between glass fiber and epoxy, and may lead to breakdown of the laminate structure [Lfebre et al. 1991].

Table 1.3. Absorption of water from the air into plastics.

Plastic	Water content of plastic% (source 1)	Water content of plastic% (source 2)
phenol/formaldehyde/asbestos (bakelite)	0,1...0,3	0,1...0,5
urea/formaldehyde/alfa chemical pulp	0,4...1,3	0,4...0,8
melamine/formaldehyde/asbestos	0,1...0,3	0,08...0,14
epoxy		0,08...0,15
epoxy/glass fiber		0,05...0,20
unsaturated polyester plastic	0,2...0,3	0,06...0,28
unsaturated polyester plastic/woven glass cloth	0,1...1,0	0,05...0,50
cellulose acetate/butyrate	1,3...2,1	0,9...2,2
polystyrene	0,03...0,05	0,03...0,1
acrylonitrile/butadiene/styrene ABS	0,05...0,3	0,20...0,45
HD-polyethylene HDPE	< 0,01	0,01
polypropylene PP	0,1	0,01...0,03 (0,17 dipping) ⁵⁾
polymethyl methacrylate PMMA (plexiglass, perspex)		0,15
softened PVC	0,02	0,15...0,75
hard PVC	0,01	0,07...0,4
PA 6 (nylon 6)	2,5...3,0 3,5 ⁴⁾ (10 dipping)	
PA 6 (nylon 6)/ 30% glass fiber	2 ⁴⁾	
PA66 (nylon 66)	2,5...3,0 ~ 8 (dipping) ⁴⁾	1,1...1,5
PA66/30% glass fiber		1,8 ⁴⁾
PA66/35% glass fiber		0,9
PA 12 (nylon 12)	0,5...0,9; 0,19 ⁴⁾	0,25
PA12/30% glass fiber		0,07
polycarbonate PC		0,15...0,18
PC/10...40% glass fiber		0,07...0,20
PC/ABS blend	0,2 ³⁾	
Bayblend T45	0,7 (dipping) ³⁾	
polyacetal POM		0,22...0,25
polyester (satisfied) PETP		0,02
PETP/18% glass fiber		0,02
polyphenyleneoxide PPO	0,07	0,066
PPO/20...30% glass fiber		0,06
polytetrafluoroethylene PTFE (teflon)	0	0

¹⁾ [Pohjanpalo 1972]

²⁾ [Törmälä et al. 1983]

³⁾ Bayer Info

⁴⁾ Muovit konstruktioaerialina, INSKO 176-86, Finnish

⁵⁾ Hostalen PP Info

The testing method presented in standard ISO 62 Plastics – Determination of water absorption describes the speed of absorption of water very well. The testing times are only one or a couple of days. The material tested in these tests is usually a square piece of a plastic sheet of a thickness of either 1 mm or 2 mm. The side length of the sheet should be greater than 100 times the thickness of the sheet with at least heterogeneous materials (for example glass fibre cured epoxy sheet, printed board material). The test gives as the result the amount of water diffusing perpendicular to the surface of the sheet and it can be used for determining the diffusion coefficient in temperatures below the glass transition temperature of plastics.

ISO 62 has four absorption tests where the samples are dried before the test at a temperature of 50°C for 24 hours and weighed before and after the drying. Drying is repeated in 24 hour periods until the mass ceases to change more than 0,1 mg. The remaining mass is the initial mass of the sample (m_1):

Method 1

The samples are immersed first in distilled water at 23°C for 24 hours. The samples are weighed after the test (m_2) and the amount of absorbed water is calculated from the weight difference. The saturation humidity of the material can be obtained by repeating the immersion and the weighing after 24 h, 48 h, 96 h, 192 h, etc. until the change is at the most 0,1 mg when comparing to the previous but the last measurement (m_2). The change of mass is expressed as a percentage of the initial weight:

$$c = \frac{m_2 - m_1}{m_1} \times 100 \quad (1.1)$$

Method 2

The samples are immersed in distilled water at 100°C (boiling) for 30 minutes. The samples are weighed after the immersion (m_2). The saturation humidity can be obtained by repeating the immersion and the weighing after every 30 minutes until the change in the weight of the sample is at the most 0,1 mg.

Method 3

If it is known that the material contains substances that will dissolve in water, the samples are dried after the immersion tests in methods 1 and 2 as before the testing and their mass is weighed. If the mass obtained in this way (m_3) is smaller

than the initial mass after the drying the difference calculated from this will be regarded as the amount of matter dissolved into the water and it will be taken into consideration when calculating absorption according to equation (1.2).

$$c = \frac{m_2 - m_3}{m_1} \times 100 \quad (1.2)$$

Method 4

The samples are first placed in a space at 23°C and relative humidity of 50% for 24 hours after the drying and weighed thereafter (m_2). The saturation humidity of the material can be obtained by repeating the immersion and the weighing after 24 h, 48 h, 96 h, 192 h, etc. until the change in the weight of the sample is at the most 0,1 mg when comparing to the previous but the last measurement (m_2).

ISO 62 still advises to calculate the diffusion coefficients for water absorption of plastic materials based on the assumption that water absorption follows Fick's law at temperatures lower than the glass transition temperature of plastics.

The typical value of the diffusion coefficient at 23°C is about 10^{-6} mm²/s. Based on this a test sheet 1 mm thick obtains 70% of its saturation humidity in about 24 hours ($t_{70} = 10^5$ s) and the saturation humidity in less than a week. The diffusion coefficient is calculated from equation (1.3):

$$D = \frac{d^2}{\pi^2 t_{70}}, \quad (1.3)$$

where

D is diffusion coefficient of water in plastic (mm²/s)

d is thickness of test sheet (mm)

t_{70} is time (s), it takes for the humidity of the test sheet to rise to 70% of its saturation humidity.

When Fick's law was assumed to be valid the saturation humidity can be obtained from the 70% humidity measured based on the tests:

$$c_s = \frac{c_{70\%}}{0,7} \quad (1.4)$$

In order to obtain the necessary humidity and test time for calculation of the diffusion coefficient using the ISO 62 curve, a subjection (conditioning) time of a week at most is usually needed for the above methods 1...4.

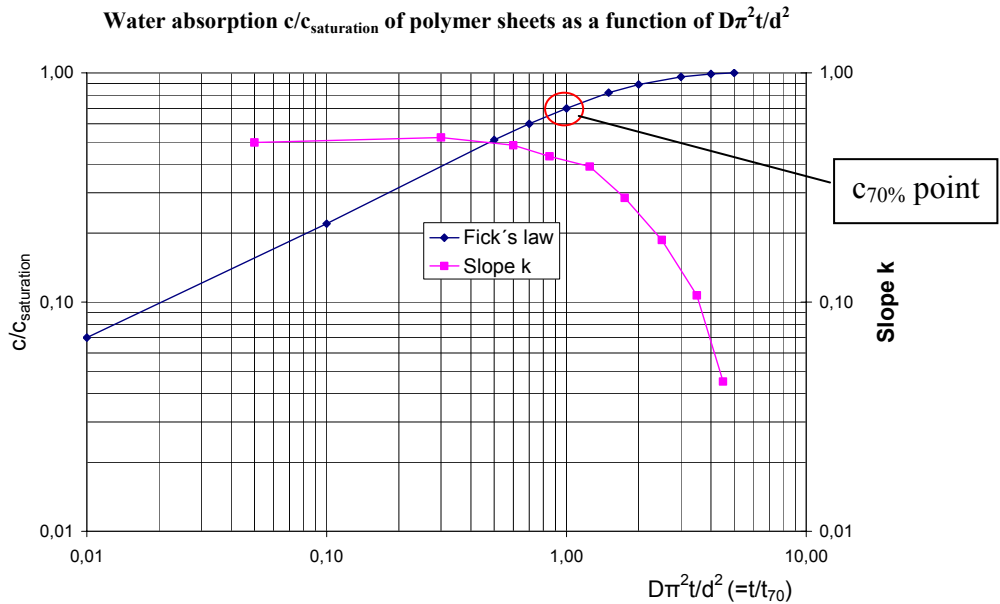


Figure 1.3. Water absorption according to Fick's law (ISO 62).

In Figure 1.3 it is given the theoretical water absorption of a sheet. Values are taken from the Table 1 of ISO 62, which gives the theoretical absorption according to the Fick's law. The time axis of Figure 1.3 is the relationship of the immersion time in water to the time, when absorption of water is 70% of its saturation value. In Figure 1.3 is the slope k of the absorption curve. The slope k is $\approx 0,50$, when $c \leq 0,51 \cdot c_s$, after this the slope is $< 0,5$.

1.6 Permeability of water vapour for materials

The permeability of water vapour for materials is an important property in electronics, especially in component packaging, devices designed as watertight and in all kinds of transportation packages.

Figure 1.3 shows the magnitudes of the water permeability of materials used for component cases. The articles of [Traeger 1976 and 1977, Schneider 1988, Palmén 1990] have addressed the suitability of non-metallic materials for hermetic packages of hybrid circuits. As can be deduced from the figure it only takes a few hours or weeks for water to penetrate a layer of plastic one millimetre thick.

Traeger's article gives the following equation (1.5) developed by Jonesin [1969] and Kassen [1974] for permeability of moisture for organic seals.

$$t = \frac{V \cdot L}{P \cdot A \cdot R \cdot T} \ln \left[\frac{p_o - p_1}{p_o - p_2} \right], \quad (1.5)$$

where

- t = time for obtaining partial pressure p_2 (s)
- V = free inside space of the case (cm^3)
- L = length of the diffusion route (cm)
- P = permeability of water for the sealing material ($\text{g}/(\text{cm} \cdot \text{s} \cdot \text{torr})$)
- A = cross section area of the seal (cm^2)
- R = gas constant ($3465 \text{ Torr cm}^3/\text{K g}_{\text{H}_2\text{O}}$)
- T = temperature (K)
- K = Kelvin
- p_o = partial pressure of water vapour in the outside space (torr)
- p_1 = partial pressure of water vapour in the initial state of the case (torr)
- p_2 = partial pressure of water vapour in the final state of the case (torr).

Equation (1.5) only gives the magnitude for permeability of moisture since the properties of the materials are usually not well known.

Really hermetic packages and seams can be made only of metals, glass and ceramic materials. The metal used as a case for a device can be porous and let water and air through like a sieve; for instance porous pressure cast aluminium is not watertight. Even good quality plastics always let a certain amount of water through. Despite permeability of water good plastic cases for components function well even in applications requiring a high degree of reliability.

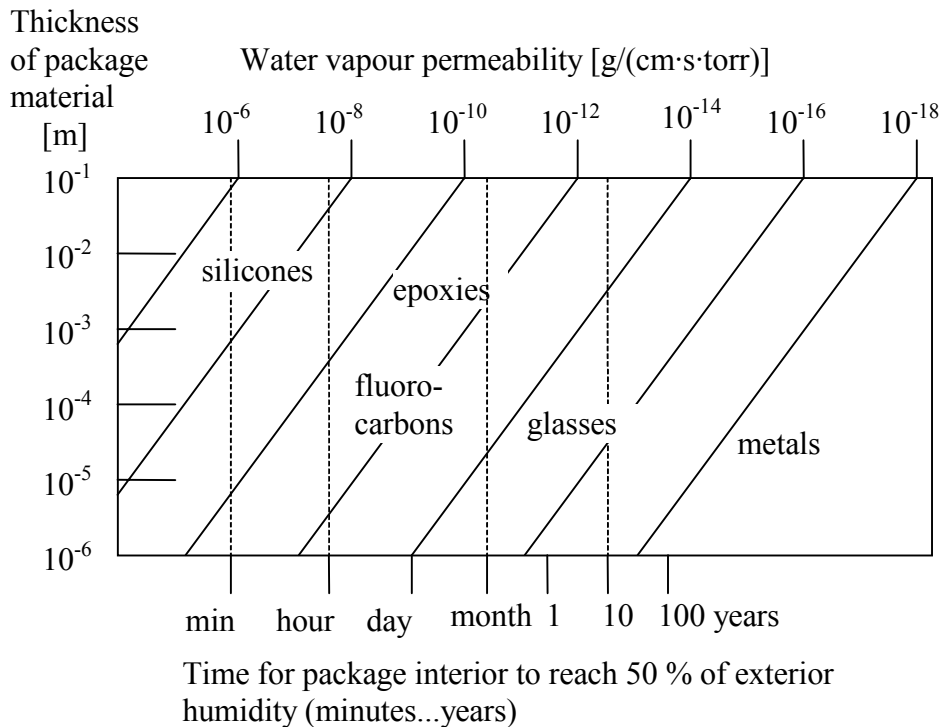


Figure 1.3. Permeability of water for case materials [Traeger 1976 and 1977, Schneider 1988].

The hermetic limit for cases has been considered $0,01 \text{ Pa cm}^3/\text{s}$ ($10^{-7} \text{ bar cm}^3/\text{s}$), which is not sufficient, however, since for instance at relative humidity of 80% RH in the environment, the humidity inside the case reaches the dew point temperature 0°C already in 100 days [Schneider 1988].

IEC 60068-2-17 classifies leaks into big and small ones using $1 \text{ Pa cm}^3/\text{s}$ ($10^{-5} \text{ bar cm}^3/\text{s}$) as the limit. The method Qk is used for testing of small leaks (hermetic cases) in the IEC standard. The method uses helium as the indicator gas. Helium leak can be detected with a mass spectrometer. The IEC testing requirements classify tightness of less than $0,1 \text{ cm}^3$ volumes into leaks between $10^{-1} \dots 10^{-5} \text{ Pa cm}^3/\text{s}$.

Plastics especially are used in all structural parts and components in electronics. In transportation packages, plastics are mainly used as protection from humidity and dirt. In this use a low permeability of water vapour is an important property. Table 1.4 shows permeability (transmission rate) data for water vapour and gases of some basic plastic materials. Please note that the permeability of water vapour does not depend on the pressure difference on each side of the film.

Table 1.4. Transmission rates of water vapour and oxygen [Plastics 1995].

Plastic material	Water vapour transmission rate (38°C, 90% RH)	Oxygen transmission rate (23°C, 0% RH)
	(g·mm/m ² day)	(cm ³ ·mm/m ² ·day atm)
polyvinylidene chloride (PVDC)	0,01 ... 0,08	0,0152 ... 0,2533
polychlorotrifluoroethylene (PCTFE)	0,015	4,458
polypropylene (oriented)	0,16	44,58
polypropylene	0,26	82,07
polyethylene terephthalate (oriented) (PET)	0,8	1,621
polyvinylchloride (PVC), rigid	0,88	3,141
nylon MXD6 (oriented)	1,1	0,2533
nylon 66	1,5	2,027
nylon 6	4,3	2,027
ethylene vinyl alcohol based materials (EVOH)	1,3 ... 3,4	0,0041 ... 0,0608
polyvinyl alcohol	750	0,0025
high nitrile resins	1,6	0,304
cellophane	137	0,4458

Source: [Plastics 1995] ref. Food Contact Polymeric Materials, review report. (ISSN 0889-3144) RARPA Technology Ltd, 1992.

The transfer of gases and vapour through film materials [Plastics, 1995 p. vi] takes place in three phases: dissolving into the material to be penetrated, diffusion of the dissolved components through the material as a result of differences in the concentrations and finally evaporation of the penetrated substances from the surface into the space on the other side of the material. The penetration of substances can be described with Fick's first law, according to which the volume (V) of the penetrating material (gas) is directly proportional to the area of the film (A), the difference in the partial pressure of gas on each side of the film (p) and time (t) and inversely proportional to the thickness of the film (s) if the film is homogeneous in the direction of penetration.

$$V = P \cdot \frac{A \cdot p \cdot t}{s} \quad (1.6)$$

The coefficient P, which represents Fick's first law in equation (1.6) is the permeability coefficient of the gas.

Fick's first law only applies to stable gases, which liquefy in temperatures and pressures far from normal conditions (for instance 0°C, 1 atm). Gases adhering to this kind of Henry's law include nitrogen, oxygen, argon and carbon dioxide (air).

Water vapour and acetone do not follow Henry's law since they concentrate and liquefy at usual temperatures and pressures. Therefore their permeability coefficient does not depend of the difference in the partial pressures of vapour over the film. Fick's first law for vapours is therefore presented in the following form:

$$W = VTR \cdot \frac{A \cdot t}{s} \quad (1.7)$$

Here the penetrated amount of matter (mass) equals W and VTR is the permeability for vapour (rate of penetration).

The unit for the permeability coefficient for gases is (cm³·mm)/(m²·days atm) and the unit of water vapour permeability is (g·mm)/(m² days).

The permeability coefficients for gases are generally measured in accordance with standards ASTM D1434 and ASTM D3985 and the permeability for vapour according to standards ASTM E96 and ASTM F1249.

The permeability coefficient for gas can be presented as equation $P = D \cdot S$, where D is the diffusion coefficient for gas and S is the dissolution coefficient of gas into the material to be penetrated. Both coefficients depend on the temperature and should therefore always be quoted with the measuring temperatures. The dissolution coefficient (S) usually increases with the temperature but in the case of easily condensing vapours such as sulphur dioxide and ammonia the dissolution coefficient diminishes when the temperature is raised.

The dissolution coefficient (S) for stable gases is proportional to the partial pressure of the gas. Therefore, the permeability coefficient of gas at constant pressure is independent of the pressure.

The permeability coefficient for vapours dissolving in small quantities, such as water vapour, in polyolephines can be proportional to the pressure difference on each side of the film. The pressure in which the measurement has been performed should always be quoted with easily dissolving vapours.

Adsorbed water may soften some materials, which increases the permeability of gases. On the other hand, the diffusion speed of water depends on the content of water vapour. This is why the relative humidity must be known in measurements of vapour permeability.

Stable gases do not usually react with plastic films; their permeability coefficient is inversely proportional to their molecular size. The permeability coefficient for other gases is strongly dependent on their condensation and tendency to combine with the film material in question. Vapours dissolving easily cause expansion of materials, which increases the permeability coefficient of vapours (and permeability).

The structure of polymer plastics has a substantial effect on permeability. The chemical reactions of gas and plastics can reduce permeability. Condensing the plastic and increasing its crystallisation reduce the permeability coefficient.

The additives in plastics also have an effect on the permeability of gases; softeners increase permeability since they “loosen” the structure of the plastic. Also fillers, especially when used in large quantities increase the porosity of the plastic and therefore the permeability of gases.

1.7 Relative humidity of air

Figure 1.4 shows graphs (Molliér diagram) depicting the dependency of the water content of air on the relative humidity and temperature. Each graph presents the values of relative humidity corresponding to certain absolute air humidity (absolute water content) in the air in different temperatures.

The values for absolute humidity (g/m^3) are given along the top edge, the relative humidity of the air on the left vertical axis (%) and the air temperature ($^{\circ}\text{C}$) on the horizontal axis at the bottom. The bottom horizontal axis also gives the dew point temperatures corresponding to a certain air water content, in other words the temperatures where the relative humidity of the air reaches 100% resulting in condensation.

The humidity graphs in the Figure 1.4 have been drawn using equation (1.8), which is valid in air pressure of 100 kPa [IEC 60721-2-1 Amendment 1, Appendix B].

$$\rho(t, \varphi) = 0,007932 \frac{273,16 \cdot e \cdot \varphi}{(t + 273,16) \cdot 100}, \quad (1.8)$$

where

- ρ is absolute air humidity (water content of the air) (g/m^3),
- e is the saturation water vapour partial pressure (Pa)
- φ is relative air humidity (%)
- t is air temperature ($^{\circ}\text{C}$).

The graphs in Figure 1.4 should be read as follows:

If the absolute air humidity (water content) corresponding to a relative air humidity of 80% at $14,5^{\circ}\text{C}$ is desired, the relative humidity is first pinpointed on the vertical axis and then the temperature $14,5^{\circ}\text{C}$ is looked up on the temperature scale from the horizontal axis. If the graph is now followed upwards from the crossing point, the absolute air humidity $10 \text{ g}/\text{m}^3$ can now be found on the scale at the top. The dew point temperature corresponding to a relative air humidity of 100% can be found at the location of the reading at the top by looking up the corresponding temperature directly on the bottom scale. The absolute air humidity (water content) of $10 \text{ g}/\text{m}^3$ gives here $11,5^{\circ}\text{C}$ as the dew point temperature.

When the same graph ($10 \text{ g}/\text{m}^3$) is followed down towards relative humidity of 50%, the corresponding temperature is about 23°C and 32°C for relative humidity of 30%. The relative humidity of 80% corresponds to the usual humidity of outside air and 50% the usual humidity of air indoors. The temperature difference between these points (80% and 50%) is only about $8,5^{\circ}\text{C}$ on the graph of $10 \text{ g}/\text{m}^3$. The raise of $8,5^{\circ}\text{C}$ on the temperature scale reflects the heating of air caused by an ordinary device or the change in the relative humidity of the air brought about by air entering the room space from the outside.

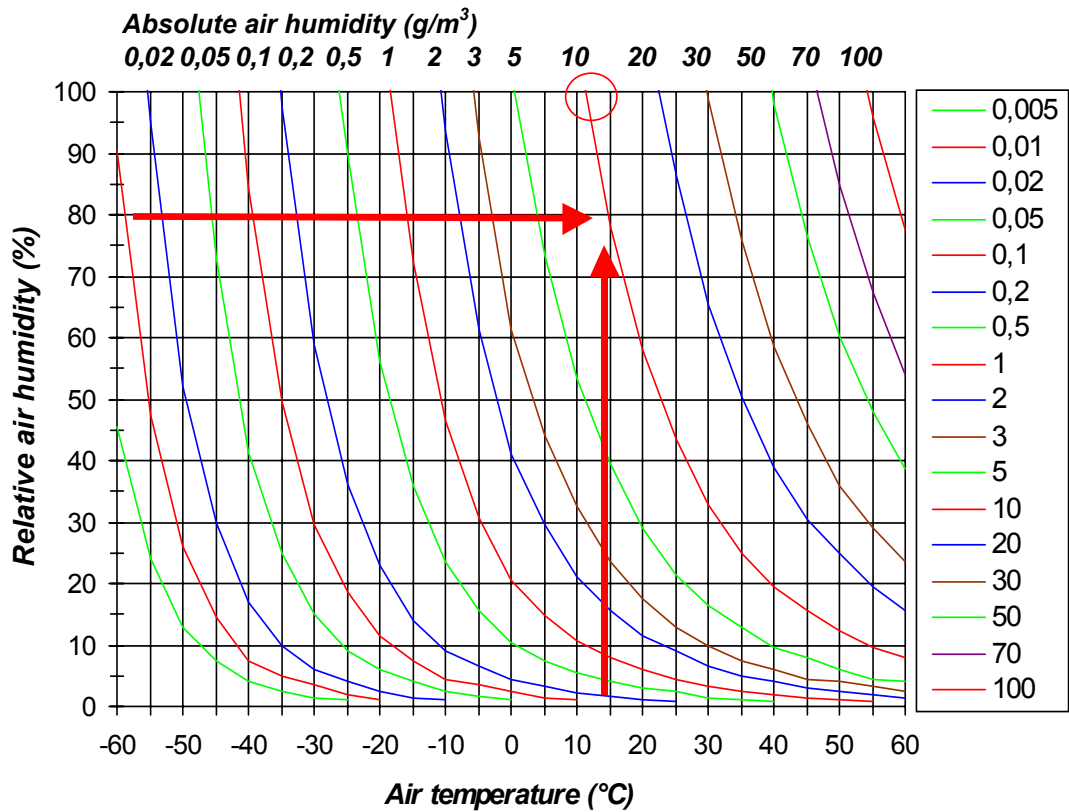


Figure 1.4. Relative air humidity as a function of absolute air humidity and temperature [IEC 60721-2-1, Amendment 1, Appendix B and SFS 5767, Appendix B].

It should be seen that in nature the measured maximum absolute amount of water in air has been in Bahrain 34 g/m^3 at $32 \text{ }^\circ\text{C}$. This corresponds relative humidity of 97% at that temperature. The reason to this is that in nature such conditions may occur only above warm water surface.

1.8 Condensation of moisture on the surfaces

Figure 1.5 presents a set of graphs depicting the temperature difference required for condensation between a metal surface and the air on various relative humidities and temperatures of the surrounding air. The graphs have been selected based on the data in Figure 1.4.

Figure 1.5 shows that at a relative humidity of 80%, condensation takes place on surfaces only $2\text{...}6^\circ\text{C}$ cooler than the air. At a relative humidity of 50% water condenses on surfaces $7\text{...}16^\circ\text{C}$ cooler than the air. Figure 1.5 also shows that no condensation will occur if the surfaces are even slightly warmer than the surrounding air.

Since corrosion accelerates considerably already at relative humidity exceeding 50% the surfaces of the insides of the device should be at least 10...20°C (or more) warmer than the environment. This limit the humidity of the air flowing across the surfaces to a maximum of 50% at all times.

The reduction of the humidity in the device is not completely linear. The temperature of the cooling air increases more than 10°C in only a few equipment when passing through. Therefore the relative humidity remains rather high. If outside air with a water content of 10 g/m³ is blown or vacuumed into the device at a reasonable speed (≈0,3 m/s), the surfaces in the vicinity of the entrance point will make contact with the outside air as it comes, with a relative humidity of nearly 80% since the air has had notime to warm up.

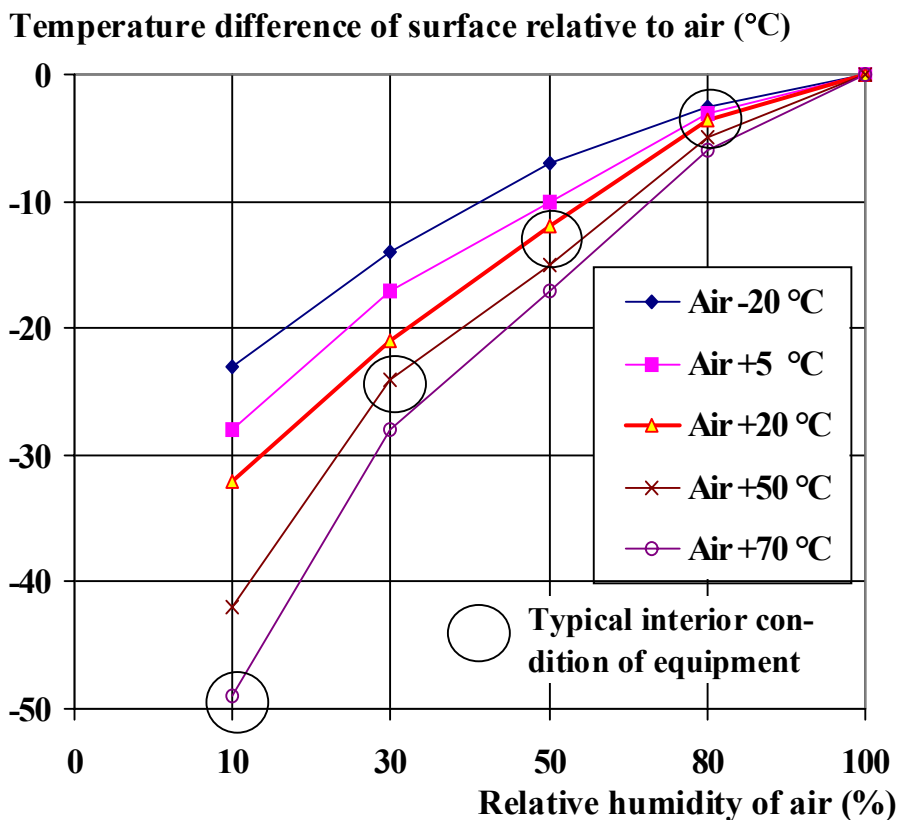


Figure 1.5. Temperature difference of the surface of the device relative to air when the dew point of the air is reached on the surface at various temperature and humidity values.

The incoming air also cools the structures in question. If the air hits targets that does not generate heat, such as connectors of the circuit board, the temperature and relative humidity of these will be almost the same as those of the incoming air, which will cause a relatively great corrosion risk. The risk of adverse effects of the humidity of the incoming air can be reduced by spreading the internal

temperatures more evenly to the inside structures (hot parts near the entrance points for the air) and on the other hand by minimising the blowing of outside air into the most sensitive areas (bare conductors and contacts).

Figure 1.5 shows circles around the most typical internal climates of a device: RH 10%/70°C, RH 30%/50°C, RH 50%/20°C and RH 80%/5°C.

It is usual in outdoor conditions for the thermal radiation of the night sky to be only 130...300 W/m² in clear weather, in other words the temperature of the sky is lower than the temperature of the surface of the earth. Therefore, the surfaces pointing towards the sky cool effectively since they radiate heat directly to the cold sky.

For example the temperature of a surface isolated from the earth may be -14°C, when the relative humidity of the air approaches 100% and the air temperature is 0°C. In these conditions, condensation of water and frosting takes place on all surfaces facing the sky [IEC 60721-2-4 **Solar radiation and temperature**, p. 13]. In metal structures that conduct heat well the cooling of the outside surface causes condensation even on the inner surfaces, which is the reason why water accumulates inside the device as well.

Table 1.5. Spectral energy distribution in the solar radiation test IEC 60068-2-5.

Spectral region	UV B	UV A	Visible radiation			Infrared
Bandwidth (µm)	0,28 ...0,32	0,32 ...0,40	0,40 ...0,52	0,52 ...0,64	0,64 ...0,78	0,78 ...3,00
Irradiance (W/m ²)	5	63	200	186	174	492

UV = ultraviolet (region B and region A)

In comparison let it be pointed out that on a clear morning in sunshine in the subtropical regions in cities the maximum value for solar radiation in the sky is about 700 W/m², which in theory corresponds to a surface temperature of 60°C on surfaces facing the sky. In the mountains the radiation during the morning reaches 1180 W/m². In standard IEC 60068-2-5 *Simulated solar radiation at ground level*, a test simulating solar radiation, the intensity distribution depicted in table 1.5 is used.

Thus, 6% of the radiation intensity in the test (1 120 W/m²) comes within the ultraviolet range, 50% in the range of visible light, and 44% in the range of thermal radiation. Corresponding data is available in standard IEC 61725 Analytical expression for daily solar profiles.

Theoretical surface temperatures on earth at night, outdoors, in dry or humid conditions have been calculated in Table 1.6 using equation (1.9) presented in IEC 60721-2-4.

$$T_0 = \left(\frac{A}{\sigma}\right)^{1/4}, \quad (1.9)$$

where

- T_0 is equilibrium temperature of the surface (K)
- σ is Stefan-Boltzmann's constant $5,67 \cdot 10^{-8} \text{ W}/(\text{m}^2 \text{ K}^4)$
- A is atmospheric radiation (W/m^2).

In practice, the surface temperatures are considerably higher than what would result from this equation due to the conductivity of heat, the surface emission coefficient, convection (wind) and the release of phase change heat during condensation of water.

Table 1.6. Theoretical temperatures of surfaces at ground level under clear night sky (°C) [IEC 60721-2-4, Figure 1].

Air temperature at a height of 2 m above ground level °C	Very dry air		Very humid air	
	Sky irradiance at night W/m ²	Theoretical temperature of surface °C	Sky irradiance at night W/m ²	Theoretical temperature of surface °C
30	296	-4
20	260	-13	323	+2
10	227	-21	270	-10
0	196	-31	220	-23
-10	168	-40	180	-36
-20	143	-49	148	-47
-30	123	-57	124	-57

In practice, the surfaces cool (radiate heat into the space) the more the greater the space angle, which shows the cold, sky looking from the surface in question. This is why vertical surfaces exposed to the sky also cool nearly as much as the horizontal surfaces. If the surface is obstructed by a structure or vegetation the temperature of which in practice equals the air temperature the surface will not

cool but remains in the temperature of the surrounding air since the surface “sees” only surfaces having the same temperature as the surrounding air. This explains the familiar phenomenon of the car windows staying clear under a shelter while they get frosted under the sky. This is as well the reason behind the effect of the gauze used as protection against frost for plants.

The heat of solar radiation may cause unexpected situations regarding condensation. If an equipment cabinet placed outdoors warms on one side in the sun, this may result in water evaporating from the warm side when air inside the device heats up. This raises the water content in the air, which may result in condensation on the cold side resulting in faster corrosion of the side in the shadow than of the side in the sun [Gellerstedt]. In a closed space, humidity always gathers on the coldest surfaces. This fact can be used in the design of devices by arranging an area colder than the other surfaces and gathering all the water where it causes the least harm.

1.9 Effect of temperature on the ventilation of the case

The changes in air temperature cause changes in the pressure of the air inside the device case, which results either in a drawing in or blowing out effect with the air in the case. The flow of air is relatively great even at ordinary changes of temperature if the case has openings.

In a closed space where the transfer of heat is minimal through the walls, the space equation of ideal gases is valid:

$$\frac{p_1 V_1}{T_1} = \frac{p_2 V_2}{T_2} = nR = \text{const} \quad (1.10)$$

where

- p is air pressure (Pa)
- V is air volume (m³)
- T is temperature (K)
- n is amount of matter mol (with water 1 mol = 0,018 kg)
- R is general gas constant = 8,314510 J/(mol·K).

The constant therefore depends only on the quantity of substance n. If the quantity is 1 mol, in other words

$$n = 1 \text{ mol}, pV/T = 1 \text{ mol} \cdot 8,314510 \text{ J}/(\text{mol} \cdot \text{K}) = 8,314510 \text{ J/K}.$$

In an isothermal change the temperature remains constant and $pV = nRT = \text{constant}$, in an isobaric change $V/T = nR/p = \text{constant}$ and in an isochoric change $p/T = nR/V = \text{constant}$.

Table 1.7. Air pressure and volume during changing of temperature.

Temperature °C	Air pressure when volume is constant kPa	Air volume when pressure is constant dm³
-10	89,8	0,898
0	93,2	0,932
10	96,6	0,966
20	100,0	1,000
40	106,8	1,068
60	113,7	1,137
80	120,5	1,205

According to the Table 1.7, a change of 10°C in the temperature starting from 20°C results in a change of 3,4% in the air pressure provided that the volume remains constant and similarly a 3,4% change in the volume if the pressure remains constant. A change of 30°C in the temperature already results in a 10% change in the pressure/volume. This corresponds to a normal range of fluctuation in the pressure of outdoor air, 92...108 kPa at sea level.

2 Corrosion types and failure mechanisms

2.1 Galvanic and bimetallic corrosion

Galvanic corrosion takes place if metals or conductive materials form a galvanic cell with an electrolyte. A galvanic cell has for example a metallic anode and cathode and the electrolyte enabling chemical reactions linking the anode and the cathode.

Galvanic cells are formed in the following situations [Mattsson 1996]:

- bimetallic cell (metal pair cell), where the anode and the cathode are different metals
- concentration cell, where the anode and the cathode are the same material but the concentrations of the substances participating in the reactions on the electrodes are different.
- thermo-galvanic cell, where the anode and the cathode are the same material and the consistency of the electrolyte is the same everywhere but the temperatures are different on each electrode.

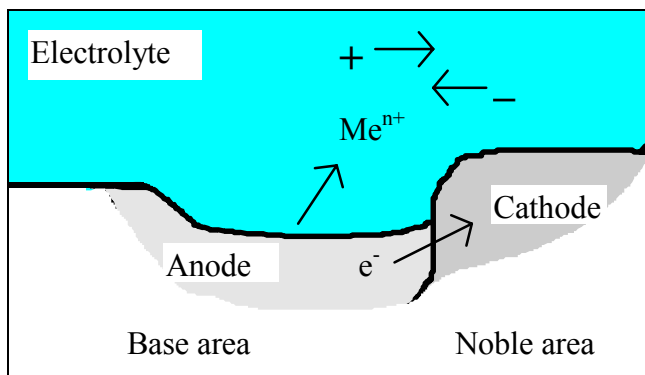


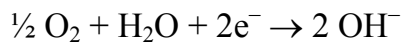
Figure 2.1. Short-circuited galvanic corrosion pair [Kemiällinen..., part I, 1996, p. 66].

Bimetallic corrosion (in a wider sense galvanic corrosion) takes place when two metals with different degrees of nobility are in electric contact with one another in **the same electrolyte**, in other words two different metals form a metal pair cell together with the electrolyte. The more noble material acts as the cathode and the less noble material as the anode. Oxidation takes place on the anode and reduction on the cathode. Bimetallic corrosion takes place also when a conductive material more noble or less noble than the metal is in contact with it, for example carbon, graphite or conductive plastic (see Appendix 1, Section 1.2

The electrochemical and galvanic voltage series of metals). Figure 2.1 shows the formation of bimetallic corrosion when two metals (short-circuited) are in contact with one another in the same electrolyte. In the anode reaction the metal oxidises, in other words a metal ion and free electrons are created.



In the cathode reaction, reduction takes place, in other words the oxygen usually dissolves into the electrolyte and hydroxyl ions are formed.



When these parts of metals of different degrees of nobility in contact with one another are immersed into the same electrolyte a short-circuited galvanic cell is formed. The galvanic cell has an anode, a cathode and the electrolyte. Electrochemical corrosion takes place in such a cell (pair); in other words the less noble material corrodes (Figure 2.2).

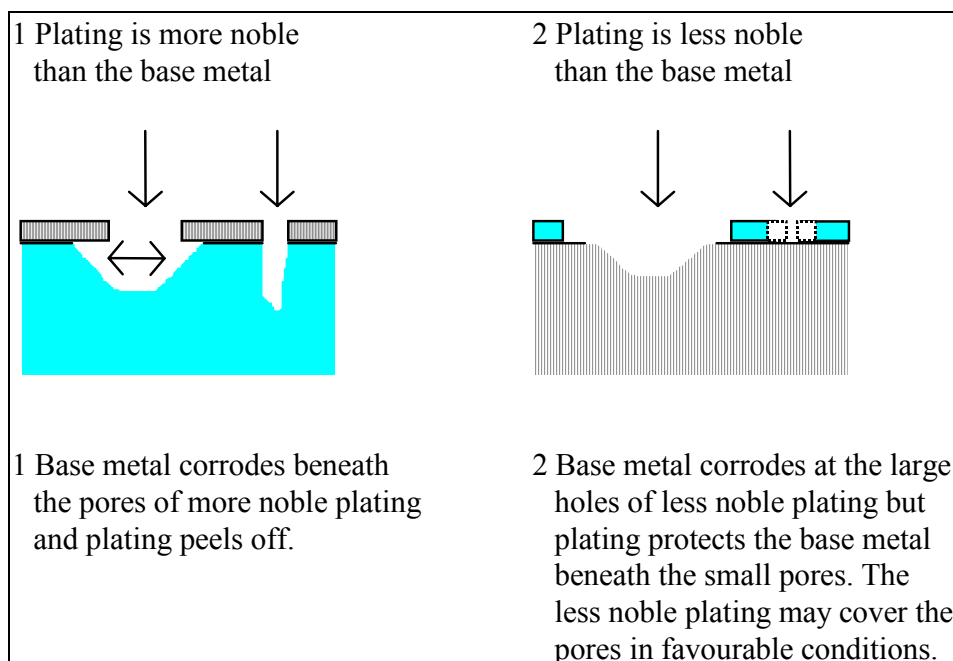


Figure 2.2. The effect of nobility of the plating on corrosion of metal.

In electronics the risk for galvanic corrosion is great since electric contacts are frequently needed in electronics. Due to technical issues, different materials have to be used in these and an electric contact established between them. The risk for galvanic corrosion is the greater the greater the difference of nobility of the materials measured with the galvanic series (see Appendix 1, Section 1.2 *The electrochemical and galvanic voltage series of metals*).

The most usual risk for galvanic corrosion in electronic devices is created when water condenses or drips on the surfaces of the parts and when water enters the capillary cracks between the surfaces.

Climatic corrosion takes place on the surfaces of metals where galvanic cells are formed due to the presence of water (anode and cathode regions) where water and the substances dissolved in it act as electrolytes. The concentration differences of the impurities on the surface and the variance in the consistency of the platings affect the chemical activity of these cells, the greater the differences the greater the corrosion risk.

Relative humidity of the air (see Appendix 1, Section 1.7 *Relative humidity of air*) has a strong effect on the speed of climatic corrosion. With various metals, the speed of corrosion accelerates strongly at values of about 60% of relative humidity, which is also called critical humidity. The amount of water on the metal surfaces is about the following according to [Mattsson, 1996 p. 80] and [Barton et al. 1974].

Description of conditions	Amount of water g/m²
– critical humidity in the air (about 60% RH)	0,01
– relative humidity of the air 100%	1
– when the surface is covered with dew	10
– when surface is wet from rain	100

Galvanic corrosion can be reduced by avoiding joints of metals with very different degrees of nobility by isolating the joined metals from one another and/or by preventing the access of water to the joining areas.

In plated structures bimetallic corrosion is in principle present as mechanisms depicted in Figure 2.2 where the faults in the plating of a noble and base metal behave in different ways. A plating more noble (for example chromium on steel) does not protect the base metal if there are faults in the plating but a plating less noble than the base metal “sacrifices itself” (for example zinc on steel) and protects the base metal relatively long even in fault spots from corrosion, see for example [Tunturi & Tunturi 1999, p. 8, figure 2.1] (see Appendix 1, Section 2.4 *Pore corrosion*).

2.2 Uniform corrosion

Uniform corrosion (uniform attack) is the most common form of corrosion. The material corrodes evenly on the entire surface. The anodic (corrosive) and cathodic (non-corrosive) areas change places continuously on the surface, which results in even corrosion of the material. The measure of uniform corrosion is the mean corrosion of the surface in micrometres per year.

2.3 Oxidation in gaseous environment

Oxidation is by definition a reaction, where the reacting substance gives away (donates) electrons. In anode reaction metal oxidizes, in other words creates metallic ions and free electrons. Therefore, solution of a metal during corrosion is also oxidation. In everyday terms, oxidation is the reaction of a substance with the oxygen in the air (burning, oxidation). In the air, an oxide layer is created on the surface of metals through a chemical reaction between the metal and the oxygen. The properties of this layer vary from metal to metal. The oxygen will not react much with the metal surface of noble metals (such as gold and platinum) in normal conditions and the oxide layer reminds more of a layer of adsorbed oxygen than an actual oxide layer.

Oxide layers can be classified into three types:

- porous such as the oxide layer of a tantalum,
- semi-dense such as the oxides of copper, iron and tin and
- dense, such as aluminium oxide.

With a dense layer, the oxidation will stop after the layer reaches a certain thickness, with a semi-dense layer the oxidation is continuously slowing and with porous layers the oxidation will continue until the metal has turned completely into an oxide.

2.4 Pore corrosion

The corrosion created at the microscopic pores, holes and faults of noble metal platings is called pore corrosion (see Figure 2.3). This corrosion is basically bimetallic corrosion where the less noble base metal corrodes and pushes the corrosion products towards the more noble plating and diffuses them on the surface. This is reason to the increase of contact resistance of e.g. gold plated contacts.

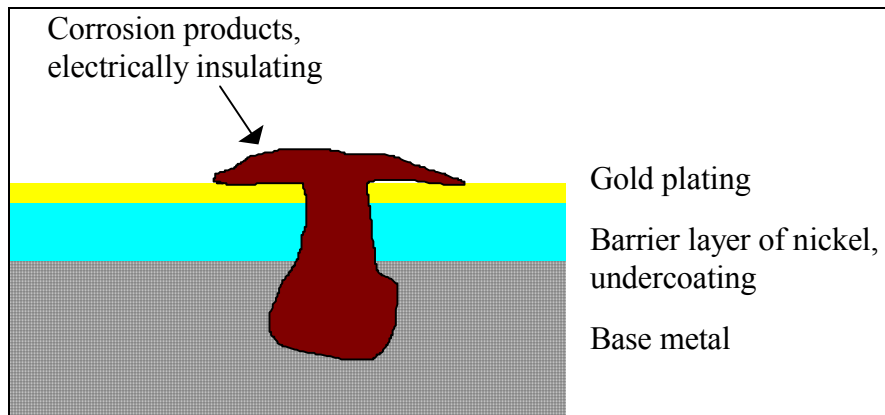


Figure 2.3. Pore corrosion on a contact [Henriksen et al. 1991].

Pore corrosion can also be seen on other noble metal platings such as silver and palladium. The risk for pore corrosion is great on platings less than 1 μm thick. The risk can effectively be limited by using a barrier layer of nickel under the gold.

Testing method IEC 60068-2-60 Test Ke: Flowing mixed gas corrosion test, Method 1 ($\text{H}_2\text{S} + \text{SO}_2$) is applicable to the pore corrosion tests of gold and palladium platings. A corresponding method is found in ASTM B799-95 Standard Test Method for Porosity in Gold and Palladium Coatings by Sulfurous Acid/Sulfur-Dioxide Vapor.

2.5 Pitting corrosion

Pitting corrosion is a local form of corrosion, which creates point or pit like indents on the surface of the metal. The anode is in the hole and cathode in the surrounding area usually. The surface seems full of holes although the main part of the surface remains nearly intact. In thin structures the corrosion may pierce the material very rapidly. Pitting corrosion is typical of metals the corrosion resistance of which is based on a protective passive layer on the surface in the conditions at hand. For example aluminium and stainless steel belong to such metals. Also noble coatings on a base material, for instance nickel coating on steel can create the conditions for pitting corrosion if the plating is damaged. The amount of pitting corrosion depends on the availability of sufficiently aggressive substances in the environment (for example stainless steel of type 304 corrodes in a neutral water solution containing Cl^- -ions and oxygen). Usually in outdoor conditions the spot corrosion of aluminium alloys stops gradually but if there is water staying on the surface containing chloride and oxygen the corrosion may proceed strongly.

2.6 Crevice corrosion

Crevice corrosion takes place in narrow cracks where the electrolytic solution cannot change with the same speed as elsewhere on the metallic surface. Cracks (spaces) of 0,025...0,1 mm are typically prone to crevice corrosion. Metals the corrosion resistance of which is based on the passive layer (see Pourbaix-diagram, Appendix 1, figure 1.1), are especially sensitive to crevice corrosion since an oxygen deficit forms in the narrow cracks and the metallic surface can no longer maintain its passive surface in these conditions. With the loss of the passive layer, the metal becomes anodic with regard to its surroundings.

2.7 Deposit corrosion

Deposit corrosion [Mattsson 1996 and Kemiällinen... 1996] means corrosion that develops under an impurity on a surface or near it (Figure 2.4). Deposit corrosion develops easily under for example humid coal dust, dirt from a road, clay, sand, leaves and in ships under the fouling growth. The access of air under the impurities is blocked with the help of water and an oxygen concentration cell (air element) is created on the spot in question.

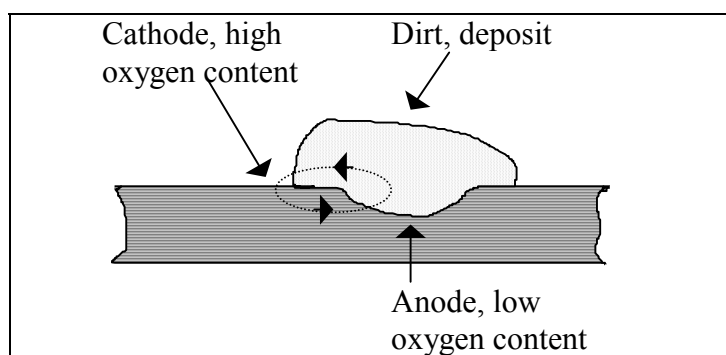


Figure 2.4. Formation of deposit corrosion [Mattsson 1996].

The occurrence of corrosion is caused by humidity, which is left between a dirt mass (fall-out) and the metal surface and stays there. Since the mobility of water is low in this gap corrosion develops as in crack corrosion. There is an area with low oxygen concentration underneath the dirt and an area with high oxygen content next to it; in other words the result is a corrosion cell the corroding anode of which is under the dirt mass and the cathode next to it.

A similar corrosion phenomenon may take place when wet glass fibre wool thermal isolation becomes in contact with a metal surface.

2.8 Dezincification and selective dissolution of tin

Dezincification of brass is a corrosion phenomenon where zinc dissolves away from the brass (selective corrosion, selective leaching) [Mattsson 1996 and Kemiällinen... Part1 1996]. Zinc loss takes place especially in brass where the zinc content is high. The granules with a high zinc content become anodic surfaces and granules with a high copper content become cathodic surfaces. The anodic surfaces corrode; in other words the zinc corrodes. The copper in the brass remains a porous mass with low mechanical strength. The phenomenon is seen in brass in contact with salt water or hot water. The phenomenon can be blocked by mixing arsenic (As) antimony (Sb), boron (B) or phosphor (P) with the brass.

Tin bronze also has corresponding selective dissolution of tin (tin loss) when the tin granules act as anodes being the less noble metal and corrode.

2.9 Filiform corrosion

Filiform corrosion is a corrosion type of a painted metal surface where corrosion progresses under the paint surface in filiform (wormlike) veins under the paint surface in random directions (filament formation) for instance when salt water comes in contact with the metal through a pore or hole in the paint. In the tests, filiform corrosion can be easily demonstrated for example on painted aluminium or steel surfaces in salt spray tests [Nakayama et al. 1998 and ISO 4623]. Crystalline salt may be found inside the dried bumps. Advanced filiform corrosion can in practice peel the paint off the metal in wide areas, which means that the filiform formations change into larger bumps.

2.10 Stress corrosion cracking and fatigue

Stress corrosion cracking can only occur if there is tensile stress on the surface of the metal and that the metal is at the same time subjected to a certain chemical. For instance moulded brass which is subjected to ammonia is prone to stress corrosion. A hemisphere for a clock can be named as an example. It can actually fall into pieces as a result of stress corrosion cracking even though it may appear entirely faultless.

Hydrogen embrittlement, a form of stress corrosion, must be considered when manufacturing electrolytic coatings. Since the cathode always develops some hydrogen which stays on the plating, a hydrogen removal heating must be performed on plated metal when needed in order to prevent migration of the

hydrogen from the plating to the base material where it can cause cracking. The removal of hydrogen is the last phase of the process especially in the manufacture of screws and other fixing devices. Hydrogen embrittlement can also be a result of corrosion of a metal in an acid solution!

Stress corrosion due to fatigue of the metal may occur in metal structures that are under continuous mechanical stress. In electronics, this is most significant in solder joints when the joint is subjected to great static forces due to different thermal expansion coefficients of the connector frame, metal conductors and the circuit board, for example.

When the temperature of the device fluctuates because of power (heat) peaks, switching the device on or off etc. a gradual break of the joint may occur if it has not been carefully dimensioned. This, in turn, will lead to an increase in the contact resistance and further in an increase of the temperature of the joint especially in high power contacts (> 1 A) even to the point of igniting the circuit board. The power needed for this is $1...2$ W/cm² and the ignition temperature of printed board is about 400°C. In a simulation carried out at Technical Research Centre of Finland, the temperature of the near vicinity of a solder joint on the printed board of FR 4 material was registered at over 500°C at 1 W power in the joint and at over 700°C in the hottest point. This corresponds to situations verified in some damage reviews of electronics.

2.11 Tensions on the plating

When plating metals with another metal using for example electrochemical methods, inherent residual tension will remain in the platings, which cause various faults depending on the scale of the tension and its location. Such platings are nickel, tin, tin-lead, nickel-gold, silver, zinc, chromating, etc.

The residual tension of a plating can be regulated by choice of the base material to be plated, choice of the plating bath, choice of the additives in the plating baths and by raising the temperature of the bath. The table 2.1 presents values for residual tension of some electrochemical coatings.

In chemical coating of metals the coating structures always contain residual tensions which can later result in cracking of the coating metal. Under tension metal becomes more reactive and therefore also more prone to corrosion than when not under tension. During the plating process, the precipitated metal also coprecipitates various impurities: additives from the bath, metallic and non metallic bath impurities, hydroxides of the precipitating metal and hydrogen gas

developing at the cathode. The coprecipitated impurities also have an effect on the electrical properties of the coating. The tension may be tensile stress or compressive stress depending on the precipitating metal. Tensile stress is considered more harmful because it reduces the resistance of the material to fatigue (subjects it to vibration damage). The tension in the platings can cause for instance several long whiskers to grow out of pure tin (see Appendix 1, Section 4.2 *Whiskers*).

Table 2.1. Inherent residual tensions of metallic platings [Dini 1993].

Plating	Tension MPa	Plating	Tension MPa
Cadmium, Cd	-3,4 ... -20,7	Cobalt, Co	138
Zinc, Zn	-6,9 ... -13,8	Iron, Fe	276
Silver, Ag	± 13,8	Palladium, Pa	413
Gold, Au	-3,4 ... 10,3	Chromium, Cr	413
Copper, Cu	13,8	Rhodium, Rh	689
Nickel, Ni	68,9		

Positive values stand for tensile and negative values for compressive stress.

2.12 Creep of corrosion products

Corrosion products can creep along metal surfaces. The external consequences of corrosion are the corrosion products, for example yellow/brown iron hydroxide (rust) on iron, white carbonate/hydroxide (white rust) on zinc and greenish carbonate/hydroxide (patina) on copper. Corrosion products precipitate somewhere in between the anodic and the cathodic areas where the corrosion current transports the ions dissolved into the electrolyte to react. Corrosion products dissolve in water and they can creep long distances from their place of origin with the solution. When the solution dries, they stay in a new place where they can start creeping again when a new water solution forms. Thus, typical ring-shaped figures form on the surface due to alternation of evaporating/wetting areas. The corrosion products forming in narrow cracks and pores also seem to burst out of their crack, which forms the impression that corrosion takes place in front of the crack. Electric fields and leakage currents accelerate the creep of corrosion products, which can quickly lead to short-circuits in devices with the electric power on (ref. migration in Section 2.13).

In electronics, the corrosion products of copper creep along gold and silver platings. The nickel used as an intermediate layer under the gold and silver

reduces the creep of corrosion products of copper. In very corrosive conditions with sulphur dioxide and chlorine, nickel corrodes and its corrosion products creep more than those of copper [Henriksen et al. 1991].

The creep of corrosion products can be demonstrated with humidity and heat tests and with mixed gas tests. IEC 60068-2-60 Method 3 (H₂S, NO₂, Cl₂), is applicable to the creep tests of corrosion products of gold platings.

2.13 Electrolytic corrosion and ion migration

Electrolytic corrosion and ion migration [Henriksen et al. 1991 and Schweigart 1999] (electrolytic migration) takes place for example on the printed board between the electric conductors when the conductors are linked by a material covered or impregnated by a hygroscopic electrolyte (see Appendix 1, Section 3.6 *Water solutions and electrolytes*). In electronics the existence of an ordinary voltage of 2...5 V between the conductors is enough to launch electrolysis and ion migration. The narrower the conductor spaces, the greater the field strength and the probability of ion migration. The conductor having a more positive voltage dissolves (corrodes) and the ions travel towards the more negative conductor. Electrolytic corrosion may break thin conductors and ion migration may cause short-circuits between the conductors where treelike conductive patterns form. On the cathode side the figures are usually metallic and on the anode side salts. The consistency and occurrence of the conductive substances varies according to the voltage and the impurity concentration on the surfaces. Contamination of the surfaces and gases from the air dissolving into the water on the surface, such as nitrogen and sulphuric compounds and carbon dioxide promote electrolytic corrosion and ion migration (see 4.4 *Electromigration*).

2.14 Fretting

When metal surfaces are in an abrasive motion against one another, fretting corrosion (abrasive corrosion, friction corrosion) takes place on all surface materials. Fretting can be caused for instance by strong vibration, heating caused by an electric current (switching the power on and off), electromechanical force caused by a high alternating current or the movement caused by fluctuations in the temperature of the environment due to different thermal expansion coefficients of materials.

Mechanical abrasion causes wear to the surfaces and loosens small particles from the metal surfaces which also corrode, in other words oxidise easily. A fretting motion can cause polymers catalytically of the gases in the air on palladium and

rhodium coatings. As a result, the contact resistance of the contact varies during motion and increases also permanently causing malfunctioning of the electronic device. In systems with contacts there is always some mechanical motion due to vibration or different thermal expansion coefficients of materials when the temperature changes. The differences in the thermal expansion coefficients have an effect especially in long circuit board connectors. If the contact system is flexible it can reduce abrasion [van Dijk & van Meijl 1996].

The extents of mechanical wear and corrosion of the surfaces depends on the materials, their hardness, compressive contact force, friction coefficient, amplitude and the speed of the motion. The amplitude of fretting motion can be 0,1...100 μm [Antler 1984]. The repetition frequency of the motion can be for example once in a few hours if thermal motion is the cause for fretting or a hundred Hertz when it is motion caused by mechanical vibration. At its most sensitive, fretting corrosion can double the contact resistance in tin plated connectors even after a couple thousand cycles and the resistance may become a hundred fold if there are 4...10 thousand cycles [van Dijk & van Meijl 1996 and Lees & Williams 1991]. A few hundred cycles is enough to raise the resistance to several ohms in certain cases!

Tin platings are especially sensitive to fretting corrosion since tin oxidises easily and is soft. Tin oxide is hard and brittle and penetrates the soft tin during fretting and increases thus the contact resistance. The oxides and other compounds forming at the contact point are weak electric conductors. The current in the contacts also has an impact on how harmful fretting corrosion becomes, since even in a somewhat corroded contact the plating material (for example tin) will melt or vaporise due to the heating caused by the current. Tin will melt at a voltage of 0,13 V and aluminium at 0,3 V over the contact surface [Braunovic 1989, Lee 1986, Kohlrausch 1900]. On very thin platings, fretting may expose the underlying metal or a hard plating may erode the opposite soft plating. Fretting corrosion takes place in all contacts, connectors, relays and switches that can be opened and where the contact surfaces glide in relation to one another. Even motion as small as 0,1 μm may cause corrosion. If the mechanical fretting can be removed, even soft platings such as tin can operate quite well at small currents and voltages [van Dijk & van Meijl 1996].

The change in the contact resistance of the connector caused by the fretting corrosion due to the change in the temperature can be estimated according to the reference [Malucci 1996, Vahter 1999], where a formula is presented for tin platings. According to the formula, the change in the resistance is proportional to

power 2,28 of the change in the temperature and the second power of the number of cycles.

$$\Delta R = k(\Delta T)^{2,28} C^2, \quad (2.1)$$

where

- ΔR is change in the resistance (m Ω)
- k is constant determined by experiment $2,36 \cdot 10^{-10}$ (m Ω /K^{2,28})
- ΔT is fluctuation range of temperature (K)
- C is number of fluctuations of temperature.

Robert D. Malucci has, when developing the formula, reached a conclusion that fretting corrosion mainly depends on the range of the changes in the temperature and not so much on the higher temperature that the contact might occasionally be subject to. Therefore, he has deduced that formula (2.2) derived from the equation (2.1) can be used when identifying a temperature fluctuation range and number of repetitions for the test corresponding to a certain condition of use:

$$C_2 = (\Delta T_1 / \Delta T_2)^{1,14} C_1, \quad (2.2)$$

where C_1 and C_2 are numbers of temperature changes in conditions 1 and 2; ΔT_1 and ΔT_2 are ranges of temperature changes in conditions 1 and 2.

If for example the daily change in the temperature is 25°C when using a connector for ten years and the test uses a temperature change of 100°C only 752 testing cycles are needed for a test corresponding to the conditions of use.

$$C_2 = C_1 (25/100)^{1,14} = 3650 \cdot 0,206 = 752 \quad (2.3)$$

The formula can also be used for comparing two conditions of use when evaluating the significance of fretting corrosion.

The sensitivity of the contacts of the device to fretting corrosion can easily be examined in an ordinary mechanical vibration test. In the test, the signal should be random noise set at a frequency range of for instance 10...150 Hz and at the same amplitude as when testing mechanical durability. During the test the occurrence of blackouts in the contacts is monitored, in other words the occurrence of malfunctions in the device. After the tests, the connectors are opened and inspected for signs of wear or change of colour in the contacts or the shell. Visual inspection of the connectors can also be linked to the temperature

change tests (life cycle tests). Thus, the information on whether fretting corrosion creates a significant failure mechanism for the device in question is obtained simultaneously. If the device has resonating areas during vibration, this can be the real cause behind the faults, which manifest themselves as fretting corrosion in the connectors even if the connectors are of good quality.

If the difference between the thermal expansion coefficients of for example the plastic in the frame of the connector and the metal of the contacts is about $40 \cdot 10^{-6}$ 1/K according to equation (2.4), the difference in the length ΔL at a temperature change of 100K (corresponds to temperature range -40...+60°C, for instance) is about 40 μm when the thickness of the connector frame is about 10 mm.

$$\Delta\alpha = \alpha_{plastics} - \alpha_{metal} \approx 40 \cdot 10^{-6} \quad (2.4)$$

$$\Delta L = \Delta\alpha \cdot \Delta T \cdot L, \quad (2.5)$$

where

- ΔL is difference in the change of length (mm)
- $\Delta\alpha$ is difference in the heat expansion coefficients (1/K)
- ΔT is change of temperature (K)
- L is length (mm).

The sensitivity of the contacts to fretting corrosion can be reduced by making the connector system flexible [van Dijk & van Meijl 1996], in other words such that no fretting takes place, by increasing the contact pressure [Braunovic 1989] or by lubricating the contact area [van Dijk & van Meijl 1996]. The increase in the contact pressure may increase wear if the impetuses are great and this is why it is not always a good means. Lubrication of the contacts may reduce corrosion but since it facilitates the gliding of the abrasive surfaces in relation to each other (reduces friction); it increases the fretting motion and in time will deteriorate the contact because of fretting corrosion.

2.15 Diffusion and corrosion of metals

Metallic materials and metal alloys consist of granules on the boundary surfaces of which atoms can migrate even at low temperatures. The boundary temperature is about 400°C, above which migration takes place mainly inside the granules. This diffusion phenomenon where different metals gradually mix with one another can be significant at temperatures of even less than 100°C. For example, diffusion between tin and copper takes place at such low temperatures.

Diffusion changes the consistency of the metals; in other words new phases of varying consistency are born. These are often fragile and mechanically weak. In extreme cases, extensive porosity may form under metal plating and the contact may also be lost in the end. Such combinations used in electronics are for example Al-Au, Au-Sn, Au-Pb, Au-Sn/Pb, Cu-Au, Cu-Pt and Pt-Ir. For instance, the link between soldering tin and gold is destroyed in five minutes at 120°C. This is why the gold platings to be soldered should be less than 0,5 µm thick in order to dissolve the gold fully into the soldering tin. An intermediate layer of nickel is used with copper metals to prevent the diffusion of copper. For example a nickel layer of 2...3 µm in between phosphorous bronze and 60Sn40Pb solder is enough to prevent the formation of phases between copper and tin [Dini 1993].

2.16 Intermetallic compounds

A layer of intermetallic compound is created at the joint of two metals because of diffusion. The layer joins the different metals to one another. In electronics, the formation of intermetallic compounds has great significance in joints, for example solder connections, where the copper of the wiring pattern diffuses into the soldering tin and the soldering tin diffuses into the copper whereby two layers of intermetallic compounds are formed. During soldering a thin layer of Cu₃Sn will form on the side of the copper and a thicker layer of Cu₆Sn₅ on the side of the tin [Vuorinen 2006]. The latter layer is more coarse and uneven by structure. The total thickness of the intermediate layers is typically 0,5...0,7 µm (...3 µm). The intermetallic compounds of copper and tin are crystalline and their quantity and structure depend on the soldering time and temperature. A short soldering time results in a layer of intermetallic compound with a fine structure, which improves the durability of the joint. A long time at a high temperature increases the granule size and the thickness of the intermediate layer. The durability of a thick layer of intermetallic compound is inferior to a thin layer. This is why soldering at as low temperatures as possible produces more durable connections.

The increase of the thickness of the intermetallic layer will continue even at usage temperatures of the electronics because of the low melting point of tin. This is the reason for some of the decay of the solder joints in use, for instance at temperatures of 80...120°C. This increase of the intermetallic layer (diffusion of copper into tin) has a great significance on the deterioration of the soldering properties of tin plated component leads during long storage even at room temperature since copper will diffuse on the tin layer and corrode on it and deteriorate the soldering properties

[SMT Terms and Definitions <http://www.smtnet.com/library/>].

The soldering of gold plated component leads may give a poorer result than leads plated with tin-lead because of the intermetallic compound formed by gold and tin. If the thickness of the gold layer exceeds 1,5 μm , the flux will not dissolve all gold from the plating, which results in an intermetallic layer containing a lot of gold and a possibility for an inferior solder connection. If the gold content of the solder exceeds 5% the intermetallic layer and the entire connection will be brittle. A gold plating of a thickness of about 0,5 μm will dissolve entirely into the solder (the gold content in the intermetallic layer will remain low) resulting in a durable connection provided the underlying metal (for example nickel) is not oxidised.

Nickel will form layers of intermetallic compounds much more slowly with tin than copper. This is why nickel is used as an intermediate layer (about 2...3 μm) between the gold and tin platings of component leads containing copper. Nickel will prevent effectively the diffusion of copper and zinc through the outer platings.

If too much phosphorus (P >10% of the weight) remains on the surface of the nickel in the electroless nickel plating process the soldering properties of the plating will deteriorate considerably. This may also affect the soldering properties of conductors where the base metal (brass, beryllium copper, bronze) has a layer of nickel on it first (barrier) and then a thin layer of gold or tin. When the outer layer dissolves into the solder it is impossible to obtain a good connection on a phosphorous nickel surface. The phosphorus of the nickel surface will diffuse in high temperatures (> 80°C) into the outer platings and this will result in poorer solder joints [Santangelo 1999 and Vuorinen 2006].

When using silver platings it is recommended to insert an intermediate layer of nickel between the copper alloys and the silver. If steel, zinc or zinc alloy is plated with silver, a layer of copper on these is recommended first and then nickel as an intermediate layer. The silver plating will adhere well on top of this [ASTM B700, <http://www.electroplating.com/> and Hoban 1997].

2.17 Microbiologically influenced corrosion

The term microbiological corrosion is used for corrosion affected by the presence of microbes and their activity on the biofilms on the surfaces of the materials. Microbiological corrosion (microbial corrosion or MIC microbiologically influenced corrosion) is active on all surfaces in contact with water, on metals as well as on other materials. It primarily affects non-metallic materials, such as wood, tapes, seals, paints, coatings, rubber, plastic etc. The active biological agents are bacteria, algae, mildew, fungi, lichen, moss and various micro-

organisms and their discharge. The chemicals originating from the above organisms corrode the surfaces underneath them together with the contamination caused by water and air.

[<http://www.meic.com/Newsletters/1999/Summer99.htm>].

Microbiological corrosion is local and becomes visible as various types of corrosion such as pitting, selective leaching, crevice corrosion, underdeposit corrosion and erosion corrosion.

Microbiological corrosion has the most effect in conditions where the surfaces are in constant contact with water either because of rain or condensation or on surfaces under water. Such conditions typically prevail at sea or in tropical environments.

[<http://www7330.nrlssc.navy.mil/html/biometal.html>].

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Microbiologically Induced Corrosion. May 1989.

2.18 Growth conditions for mould

In humid conditions, which are present especially during transportation and in tropical regions, the growth of mould fungi is a constant threat to the electronics and its packaging materials. The growth of mould fungi usually requires only enough humidity and a suitable temperature. Moulds receive nourishment also from the air but the presence of abundant organic matter naturally precipitates the growth. Mould is not the first factor to cause malfunctioning of the devices but it does affect at least the appearance of the devices since mould develops in organic materials, such as the transportation packages and the labelling stickers of the devices. [Viitanen & Ritschkoff 1990] describes mould and rot damage in buildings but the information on the conditions of mould development also apply to packages of electronics and other materials based on wood.

Mould grows on the surface of pine and spruce best when the relative humidity of the air exceeds 95% and the temperature is between +20...+40°C. The mould uses the wood for nourishment and rots it. The growth speed is clearly slowed down when the relative humidity drops below 90%. The lowest humidity to cause molding of the wood surfaces is about 80% RH. If the temperature exceeds 30°C, molding will begin already at 80% RH in six weeks. The growth at this point is microscopic and not yet visible to the naked eye. At temperatures below 20°C there is no detectable mould growth on the surface of the wood at less than 80% RH even after one year. At +5...+10°C visible mould only occurs at 96...98% RH during a twelve week incubation period, the water content of the wood is then 27...33%. The mould will become visible to the eye in about 5...6 weeks. At higher temperatures (+20...+40°C) molding of the wood takes place at relative humidity of 86...89% (water content of the wood being 16...18%) in about 4...9 weeks from the beginning of the wetting.

Mould can be detected under the microscope at an early stage. If the relative humidity exceeds 96%, mould growth will start immediately and become visible to the eye already in a few weeks. At relative humidity of 86...88% RH, the growth will start in about 3...4 weeks. Mould can grow slowly even at temperatures close to 0°C. At +50...+55°C temperatures the growth will stop and the fungal filaments will die. The mould spores die only at temperatures of 80...100°C. Long term relative humidity exceeding 80% is a great risk for mould development in wood materials at temperatures exceeding +10°C. At temperatures less than +5°C, the growth of mould requires a relative humidity of over 90% in the air.

On a clean wood surface, molding will start relatively gradually. Molding is obviously quicker also in the organic glues used for electronic labelling which can contain bone powder (protein) or pulp.

2.19 Effect of humidity and geometry on the insulation resistance of the printed board

One of the main failure mechanisms in the wiring patterns of printed boards is the reduction of the insulation resistance in between the conductors, in other words the increase of leakage currents caused by humidity and impurities. The changes of the insulation resistance in the surface structure of the printed board are affected in principle by the four sub-categories presented in Figure 2.5, where the values of the leakage currents also depend on the humidity in the environment and of the printed board itself [Hvims & Jørgensen 1998]. Naturally, the currents travelling on the surface also change because of the conductive impurities (such as salts) that accumulate on the surface and because of the various corrosion mechanisms.

The leakage current between two conductors travels on four routes (Figure 2.5). The current I_1 leaves one conductor (+) travelling through the protective coating to its surface and using the route provided by the impurities and water on the surface to pass through the protective coating to the other conductor (-).

Since the current I_1 passes through the protective coating twice, neither a thick layer of impurities on the surface nor water have a great effect on the strength of this current, in other words, the protective coating reduces significantly the effect of impurities and water on the leakage currents.

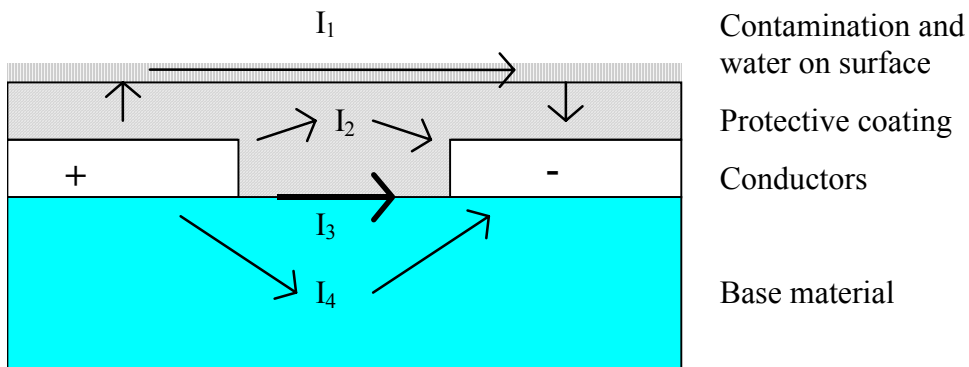


Figure 2.5. Travel routes for current between conductors of the printed board [Hvims & Jørgensen 1998].

If the protective coating is of water repellent material it reduces considerably the formation of a continuous film of water on the surface. Any holes or cracks in the coating have a negative effect on the protection and cause increasing leakage currents especially in humid conditions.

The current I_2 travels inside the protective coating to another wire (-). The quality, geometry and humidity content of the coating affect the strength of the current as do ionisation of the protective coating and fillers.

The current I_3 leaves one conductor (+) and travels on the boundary surface between the protective coating and the material of the circuit board on a route formed by impurities and water onto another conductor (-). The adhesion between the coating and the material of the printed board has an effect on whether cavities where water can accumulate because of the capillary effect form into this boundary surface. In the same way the adhesion between the protective coating and the metal conductors has an effect on whether cavities where water can accumulate because of the capillary effect form into this boundary surface.

Moisture repellent and chemically inactive coatings may have inferior adhesion qualities (silicon and some halogenised coatings, for example vinyl coating (PVC)). Therefore, a primer improving adhesion may be needed (ref. primer paint). When a protective coating is used, it is important to clean the surfaces thoroughly prior to coating them in order to retain the adhesion properties as intact as possible.

The current I_4 leaves one conductor (+) and travels through the material of the printed board to another conductor (-). The strength of the current mainly depends on the resistance of the printed board material and the water absorbed in it. Also various fillers of the printed board have an effect on the strength of the current.

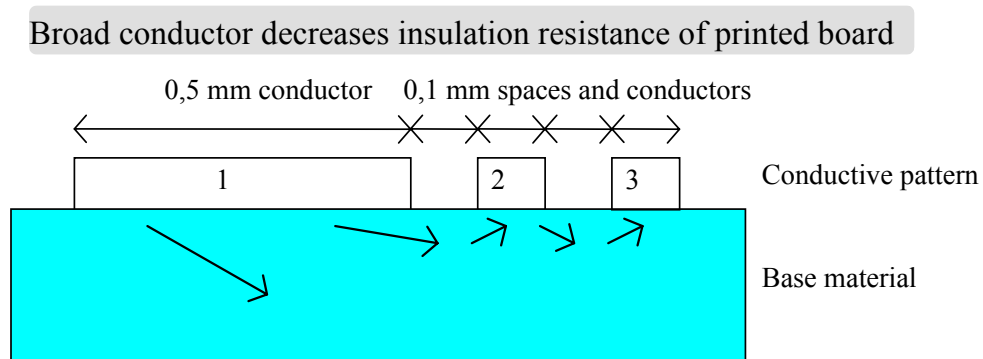


Figure 2.6. The width of the conductors in the printed board affects the insulation resistance.

In practice, the conductive patterns always have a great variety of conductor width and conductor spacing. It is useful to recognise the physical background in Figure 2.6 when designing and testing the conductive patterns and isolation resistances of a printed board.

The isolation resistance over isolation areas of equal width is not always the same since the areas of adjacent conductor zones have a great effect on it. The resistance between narrow conductors (2–3) is greater than between a narrow and a wide conductor (1–2) when the conductor spacing are equal.

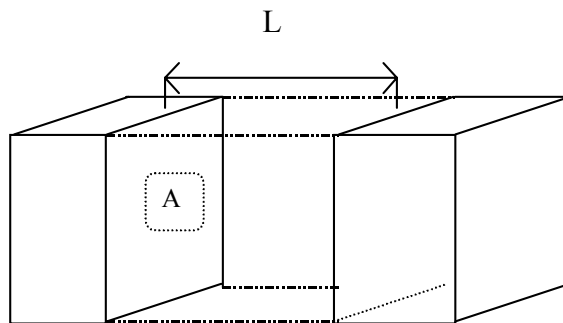


Figure 2.7. Insulation resistance between plane surfaces (A).

The insulation resistance between plane surfaces in Figure 2.7 is inversely proportional to the cross section according to equation (2.6).

$$R = \rho \cdot \frac{L}{A}, \quad (2.6)$$

where

- R is resistance between the plane surfaces (Ω)
- ρ is specific resistance of the insulation material (Ωm)
- L is distance between the plane surfaces (m)
- A is cross section of the plane surfaces (m^2).

The leakage current originating from wide conductors has a larger cross section to travel through the printed board material than thin conductors. The geometry of the conductors and the isolation zones determines the leakage current/insulation resistance corresponding to the travel route of the current I_4 in Figure 2.5. This geometric effect increasing the insulation resistance remains less, however, than the leakage current travelling on the surface if the conductor spacing is dirty and has a lot of water. Moreover, several humidity tests give a result whereby larger isolation resistances are obtained for narrow conductor

widths with narrower conductor spaces than in another wider pattern, especially on unprotected printed boards. In other words, the combination wide conductors and narrow conductor spacing is not as good as two narrow conductors in parallel with narrow conductor spacing. With regard to isolation, it would be best to use narrow conductors and wide conductor spacing.

If the metal conductors of the wiring pattern oxidise, as for example copper conductors as a result of temperature and humidity, this will complicate the flow of the current from one wire to another and increase the effective insulation resistance. The dense layer of oxide acts as a separate protective coating with weak conductivity on the conductors [Vahter 1999].

Fairly often the insulation resistance of a printed wiring pattern is tested using the IPC testing pattern. For example the test board IPC-A-25 Multipurpose 1 & 2 Sided Test Pattern (IPC B-25) described in standard IPC-SM-840C 25 is often used. The following standards contain extensive collection of measurement and testing methods for insulation and surface resistance (SIR surface insulation resistance).

ASTM D257-99 Standard Test Methods for DC Resistance or Conductance of Insulating Materials.

IEC 60093 Methods of test for volume resistivity and surface resistivity of solid electrical insulating materials.

IPC-9201 Surface Insulation Resistance Handbook.

The surface insulation resistance is determined with the help of the following equation using the surface resistivity ρ_p [see e.g. Nieminen 1999].

$$R_p = \rho_p \cdot \frac{L}{W}, \quad (2.7)$$

where

R_p is surface resistance (Ω) between two conductors

ρ_p is surface resistivity or square resistance (Ω/\square)

L is distance of conductors along the surface (m)

W is length of conductors along the surface (m).

When dealing with the insulation resistance of the wiring pattern of the printed board or the leakage currents between conductors it must be noted that the

surface resistance obtained from the measurements using the IPC testing pattern is not exactly the surface resistance in equation (2.7) but also includes the partial resistances of the rest of the printed board and coatings determined as in the above. The main part of the leakage currents usually travel along the surface of the printed board and on the boundary surfaces of the coatings which is why the resistance obtained in the IPC testing pattern measurements corresponds fairly well to the actual surface resistance. If a phenomenon during the testing alters the situation it is no longer a question of merely the surface resistance but of insulation resistance between the conductors which covers all factors.

Altogether at least the following factors have an effect on the leakage currents (insulation resistance) of the printed board. They should be taken into account in the circuit design and the interpretation of the testing results:

- geometry of the wiring pattern, in other words isolation spacing and conductor width
- metal particles left in the isolation spacing
- thickness of the protective coating
- specific resistances of the materials
- composition of the materials, impurities and additives
- conductive routes created by soiling of the surfaces and water
- absorption of water in the protective coating and the base materials
- adsorption of water into the boundary surfaces between materials (capillary adsorption)
- density of the protective coating and its adhesion to the surfaces
- corrosion/oxidation of the surfaces of the metal conductors.

In the conditions of use, when the voltage of the electronic device is switched off, the humidity of the device parts, for instance the printed boards, will settle at equilibrium determined by the outside air. If the level of humidity is high the base material of the printed board (and usually plastics) may become wet in such a way that initially there will be disturbances in trying to switch on the device until it has dried properly. The background for this phenomenon is in the change of the electric conductivity with the change of humidity and the change in the mobility of ions because of a raise in the temperature.

When a wet device is warmed in a dry environment the humidity of the printed boards begins to decrease resulting in a decrease of the leakage current caused by

the humidity. However, the mobility of ions (impurities of the surface and the material) increases when the device heats up, which increases the leakage current. The combined effect of these mechanisms may result in a short-term decrease of the insulation resistance of the material under the resistance of humid material when the device heats up. After warming and drying thoroughly the resistance returns to normal for dry material [Hvims & Jørgensen 1998].

As an example of humidity test results difficult to interpret the Figure 2.8 shows the result of [Vahter 1999]. Here the insulation resistance was measured in a wiring pattern of a printed board in a static humidity test at 85°C/85% RH about 496 h on uncoated printed boards and boards coated with a solder resist.

The combinations stated in Table 2.2 were among those used for conductor width and isolation spacing. The basic aim was to examine the effect of the conductor and isolation spacing and the solder resist on the insulation resistance of the printed board in order to estimate the effect of the surface phenomena on the malfunctions and corrosion sensitivity of the device.

Table 2.2. Conductor width and spacing in a humidity test [Vahter 1999].

Sample	Conductor *) width (mm)	Conductor spacing (mm)	Solder resist	Number of samples
E1	0,5	0,5	bare	5
E2	0,25	0,1	bare	5
J1	0,5	0,5	resist (JEP)	5
J2	0,25	0,1	resist (JEP)	5

*) The length of the wiring patterns was about 29 cm, and three conductors ran parallel. The middle conductor was in zero potential, the conductor on one side carried a voltage of +5 V_{dc} and the other one a voltage of -5 V_{dc}.

In Figure 2.8, the insulation resistance (surface resistance) of sample E2, bare wire pattern of 0,25/0,1 mm, increases throughout the humidity test. In principle, one could expect the resistance to decrease because of humidity and corrosion. This is not the case, however, but the increase of the resistance can be explained as follows. The insulation resistance (surface resistance) of the actual printed board base material is very large when dry and in this wiring pattern the measured insulation resistance of sample E2 was about 5000 MΩ initially. When the surface of the board gets wet at the beginning of the test the actual insulation resistance of the isolation material of the printed board does not have a great significance but the impurities and the layer of water on the surface determine the value of the insulation resistance which in this case is about 100 MΩ.

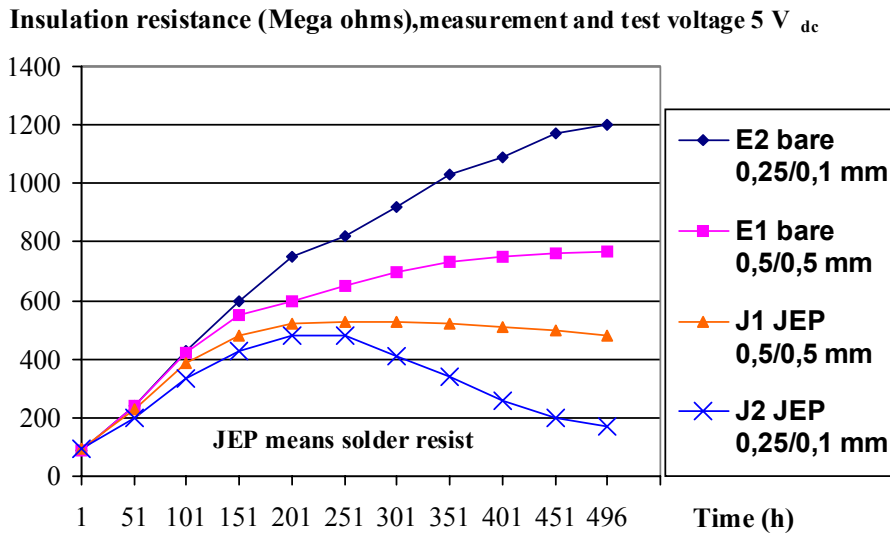


Figure 2.8. Change of the insulation resistance in a humidity test at 85 °C/85% RH on bare printed boards and boards coated with a solder resist JEP (each point represents an average of the measurements on five circuit boards) [Vahter 1999].

When time elapses in the test the impurities on the printed board material may evaporate, ions may be removed from the isolation spaces and copper conductors may oxidise. All of these make it more difficult for the current to travel from one conductor to another. In this case, the insulation resistance has risen to 1200 MΩ in 496 hours. Had the test been continued, the resistance would have started to decrease due to the possible motion of ions inside the base material because of humidity.

Sample E1, bare wire pattern of 0,5/0,5 mm, behaves in the same manner as sample E2, but the insulation resistance increases more slowly. In part, this slower growth of the resistance may be a result of a greater amount of impurities on the board than in sample E2. However, the greater width of the conductors has a considerable impact on the resistance in this case since the current has a wider route to travel on the surface as well as under the conductors.

On printed boards protected with a solder resist coating the routes for the current in the wiring pattern increase because of the addition of the solder resist and its boundary surfaces between the material of the printed board and the copper conductors, as can be seen in Figure 2.5 in the above.

Initially in the test, the insulation resistances of samples J1 and J2 coated with a solder resist are about 100 MΩ. During the test, the insulation resistance of

sample J2 0,25/0,1 rises initially but begins to decrease after about 220 hours reaching about 180 M Ω at 496 hours. In this case the water accumulating into the solder resist coating, the impurities in the coating and the boundary surfaces and the increase in the conductivity of the printed board together with the very narrow isolation space of 0,1 mm lower the resistance when the effects of the humidity progress. It is quite obvious that a thin solder resist deteriorates the isolation compared to a bare surface but if its adhesion is good it protects the underlying metal surfaces from corrosion and the effects of external contamination.

Why then is the resistance of sample J1 with a wider wire pattern greater than sample J2 with thinner wires? The reason for this is most likely the wider isolation space where the solder resist coating obstructs the passage of the current from one conductor to another and the decrease of the resistance now takes place more slowly than with a narrow conductor spacing. In this case also the transfer of current through the printed board base material itself is smaller than in the solder resist or on the surfaces.

As seen from this example, the value of the insulation resistance (surface resistance of the insulation material) of the wiring pattern of the printed board depends on several simultaneous factors the interpretation of which must be done carefully with emphasis on the occurrence of the various failure mechanisms. The cleanliness of the work is very significant in the performance of the tests as in the manufacture of circuit boards with regard to individual test results since the surface phenomena develop according to the impurities on the surfaces.

2.20 ESD-discharges and corrosion

Electrostatic discharges are a common problem in the production of electronics since the sensitivity of the components of high energy discharges is great and increases when the wiring density of the microcircuits becomes greater. ESD-pulses are typically several kilovolts or some tens of kilovolts. The build-up times of the pulses may be less than a nanosecond and the duration of the pulse is also about nanoseconds. This is why ESD disturbances travel in the devices as signals with a high frequency, 1...2 GHz. The wave impedances of the conductive routes and the properties of the surfaces have an effect on the passing of the signals. Because of the high frequency, ESD disturbances travel in the form of electromagnetic radiation between the structures (the structures act as the sending and receiving antennae) and in the form of current pulses along the surface.

The ESD pulse of great frequency travels in conductive areas mainly on the surfaces because of the skin effect. Therefore, the quality of the surfaces of the metallic wiring areas of the printed board and components has an effect on how the ESD disturbance travels and behaves inside the device.

Corrosion causes two types of failure mechanisms with regard to the travel of the ESD pulse [Franey 1999]:

- Corrosion increases the surface resistance of the metal areas and affects the insulation properties of the surface through changes in the dielectric constant for the surface.
- Corrosion creates discontinuities in the surface resistance of the metallic areas by disconnecting a well conducting metal surface.

Corrosion forms typically a layer of oxide or copper sulphate on copper. The resistance of these is initially pico or micro-ohms. The change in the capacitance has more effect on ESD, however, since the dielectric constant of oxides and sulphates is much greater than that of air. A capacitance is formed on the metal surface, which isolates and raises the voltage which the quick ESD pulse uses to discharge on the surface in question. The larger the discharge voltage, the higher the fault risk.

The discontinuities of the surface resistance of the metal areas are created in corroded spots. Since the ESD pulse travels on the surfaces of metals because of the skin effect these discontinuities reflect the power pulse back and forth which raises the amplitude and results in more failures than if the impedances of the conductive routes were well matched throughout the entire distance. Corrosion may therefore change the routes of the ESD pulses (earthing) and ruin a well-planned protection.

The described surface phenomena caused by corrosion and affecting the behaviour of high frequency ESD pulses reflect in the fault risk of the device considerably earlier than the usual contact faults, changes in the insulation resistance and corrosion through the conductors. This is why the increase in the packaging density requires better corrosion protection than earlier. The raise in the operation frequencies to exceed 1 GHz calls for better attention to the surface phenomena and corrosion from the designers.

2.21 Skin effect and corrosion

The usual frequencies in electronics fall in the range 1,0...2000 MHz. Also the main part of EMC/ESD problems in the devices occur in this frequency range. When the frequency increases the current concentrates on the surfaces of the wires/conductors due to the skin effect. This is why corrosion of metal surfaces

also affects the electrical functions of the device through the skin effect. Corrosion increases the resistance of metal surfaces, reduces their cross-sections and creates conductive routes between conductors. As a result, local discontinuities appear in the impedance of the conductors, which increases reflections in the travel routes of the currents and distorts the forms and phase angles of the signals. This can be seen as signal noise and slower dampening of quick disturbances, such as ESD pulses despite a solid grounding technique.

Direct current distributes evenly into a homogeneous wire but alternating current concentrates in the vicinity of the surface of conductive materials due to the skin effect when the frequency of the current is raised. The current concentrates on the half of the surface from where it is fed to the conductor or, in case of radiation on the half from where the radiation comes. Therefore, in coaxial cases, the current may concentrate on the outer or inner surfaces depending on the quality of the feed and connection.

The penetration depth of the current (δ) is used to express the skin effect [Ramo 1953, pp. 237–238]. The penetration depth (skin depth) means the depth calculated from the surface of the conductor where the frequency of the current has decreased to $1/e$ from the value on the surface ($e = 2,71828$). The formula 2.8 has been calculated for a flat conductor; however, it can be applied in practice for the calculation of the skin depth for any kind of a conductor.

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}, \quad (2.8)$$

where δ is penetration depth of the current (m)

π is 3,14159

f is frequency of the current (Hz)

μ is magnetic permeability of the material (H/m)

σ is conductivity of the material ($1/\Omega\text{m}$).

The decrease in the penetration depth of the current correspondingly increases the impedance of the conductors. The real part of the impedance, surface resistance R_s , is depicted by the equation:

$$R_s = \sqrt{\frac{\pi f \mu}{\sigma}}, \quad (2.9)$$

where R_s is surface resistance (Ω/\square).

The absolute value of the reactive part of the impedance of the material ($2\pi f \cdot L_i$) is the same as the real part R_s at all frequencies. Therefore, the phase angle of the impedance in the material is always 45° .

Table 2.3 shows some approximate value equations describing the penetration depth and surface resistance of some metals.

Diamagnetic metals, such as copper, aluminium, silver, brass and tin have a magnetic permeability of $4\pi \cdot 10^{-7}$ H/m.

Copper, for example, has a current penetration depth of about 20 μm at a frequency of 10 MHz and only 2 μm at 1000 MHz. Solder has a penetration depth of about 2,8 times that of copper. The surface resistances of copper are 0,8 $\text{m}\Omega/\square$ at 10 MHz and 8 $\text{m}\Omega/\square$ at 1000 MHz. Against this background, the corrosion of the surface of the wiring pattern used on the printed board begins to have a considerable impact on the damage caused by the skin effect at frequencies exceeding 100 MHz.

Table 2.3. Penetration depth of current and surface resistance of some diamagnetic metals as a function of frequency [Ramo & Whinnery 1953, p. 240].

Material	Conductivity, σ	Penetration depth, δ	Surface resistance, R_s
	$10^7/\Omega\text{m}$	m	$10^{-7}\Omega/\square$
Silver	6,17	$\frac{0,0642}{\sqrt{f}}$	$2,52 \cdot \sqrt{f}$
Copper	5,80	$\frac{0,0660}{\sqrt{f}}$	$2,61 \cdot \sqrt{f}$
Aluminium	3,72	$\frac{0,0826}{\sqrt{f}}$	$3,26 \cdot \sqrt{f}$
Brass	1,57	$\frac{0,127}{\sqrt{f}}$	$5,01 \cdot \sqrt{f}$
Solder tin	0,706	$\frac{0,185}{\sqrt{f}}$	$7,73 \cdot \sqrt{f}$

$$\mu = 4\pi \cdot 10^{-7} \text{ H/m}$$

2.22 Heat cracking phenomenon (popcorning)

One of the climatic problem areas related to soldering of electronics is for example the tendency of the plastic cases of components to absorb water during transportation and storage. Water can enter also at the boundary surface of the

component leads and the case. This can result in the components cracking (exploding, popcorning) when soldered exactly like popcorn, since the volume of water expands 1200 fold in the soldering temperature when it vaporises [Pecht 1995 and 1994]. The water in the various parts of an encased component can cause fractures and tear the parts of the component from one another, for example a piece of semiconductor from its base and from the case. The damage does not necessarily reach the surface of the case but can remain latent.

2.23 Testing of corrosivity of materials

Many materials used in electronics may contain substances, which are corrosive as such or after changing their composition. These substance releases may be gaseous, liquid or solid, and when the original material is in direct contact with some metal it may cause e.g. electrolytic corrosion (see Chapter 3.4).

Many chemical analysis methods are usable for evaluation of the corrosion risk of materials, but unfortunately they do not always show directly, if the substances found are risky or not. The researches should have an idea also, what kind of substances should be searched for. many times the amount of substances found are so tiny, that it is difficult to say if their is a real risk or not in practical use conditions.

The following simple test makes it possible to see, what is the corrosion risk level of the actual material. This test is independent of the quality of the corrosive substances; are they volatile or a more permanent part of the material. In this test the material under study is set in direct contact with copper plates, thereafter the sample is put in those environmental conditions needed, and after the conditioning the surfaces of the copper plates and the tested material are analysed to see if there are there any corrosion products.

This method is suitable for testing of all kind of materials e.g. construction, sealing, and filling compound. The test conditions may be high temperature and high relative humidity. If their exists corrosion in contact with copper surface, the corrosion products may be analysed, and it is possible to compare the composition of the corrosion products with the material composition. The test can be started with highly accelerated conditions to see rapidly, if their are any traces of corrosion. If such phenomena occur, the test conditions may be reduced towards the practical conditions, and if again the same corrosion is visible then the real risk for corrosion can be ensured.

The Figures 2.9 and 2.11 show two different ways how to put the material under study in contact with copper plates. It is important to connect a DC-voltage also between the elements to activate the electrolytic corrosion reactions on the anode and cathode. Also the migration of material will be visible.

Test conditions may be in start e.g. $T = 85\text{ }^{\circ}\text{C}$ and $\text{RH} = 85\%$, then it is possible to get corrosion reactions visible during some days or one week. The voltage may be 10...15 V. Of course some contact pressure is necessary to keep the parts together. If the application where the material is used has high voltages then a voltage near the actual application is feasible, because the high voltage is often the main reason for electrolytic corrosion and migration of materials.

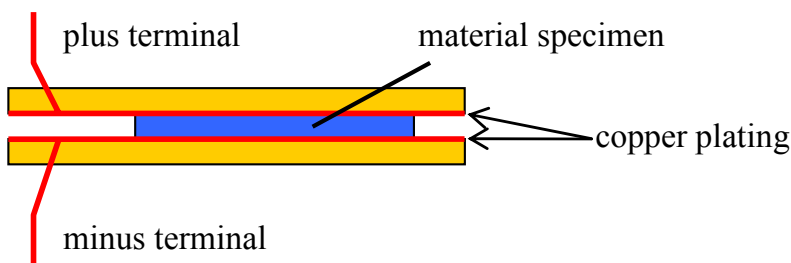


Figure 2.9. Testing of the corrosivity of material with two copper sheets.

The corrosion mechanism is electrolytic corrosion according to the Figure 2.10. At the plus terminal (anode) on the contact surfaces the copper diffuse to the test material and substances (ions) from the test material react with copper ions.

The analyses of plus and minus surfaces one can find the substances causing the actual corrosion. In Figure 2.9 the main corrosion takes place at the plus side of the material under test.

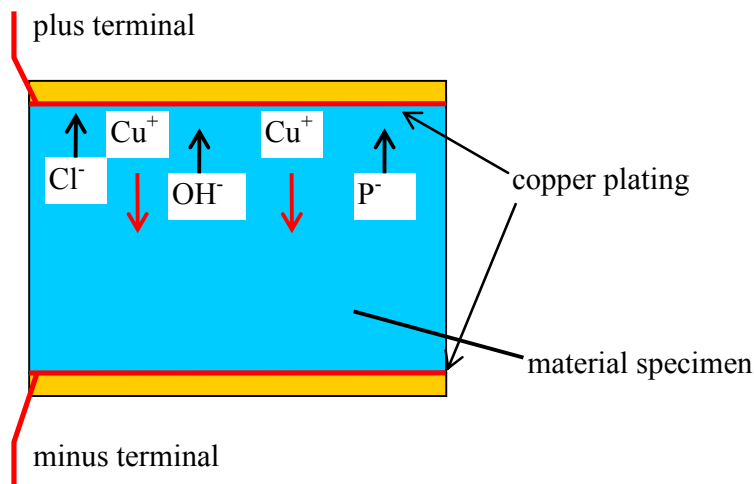


Figure 2.10. Testing of the corrosivity of material, most of the corrosion reactions take place near the plus terminal.

Analysis is easy because the surfaces are large. The visual inspection only may show the corrosivity level of the material. It should be ensured before the test that the copper surfaces are clean, and are not contaminated with corrosive substances. The test environment should be ensured, that it does not produce those corrosive substances, which are searched for.

In Figure 2.11 it is used a common test pattern that is used in insulation resistance measurements: IPC-9201 Surface Insulation Resistance Handbook / IPC-B-25A Multi-purpose Test Board.

In Figure 2.11 the material specimen is put on the test pattern. A more accurate analysis is needed with this test pattern, but it is possible to analyse accurately corrosion mechanisms those cases where material is in contact with printed board wiring. In this pattern both the migration of corrosion products and metal particles are visible.

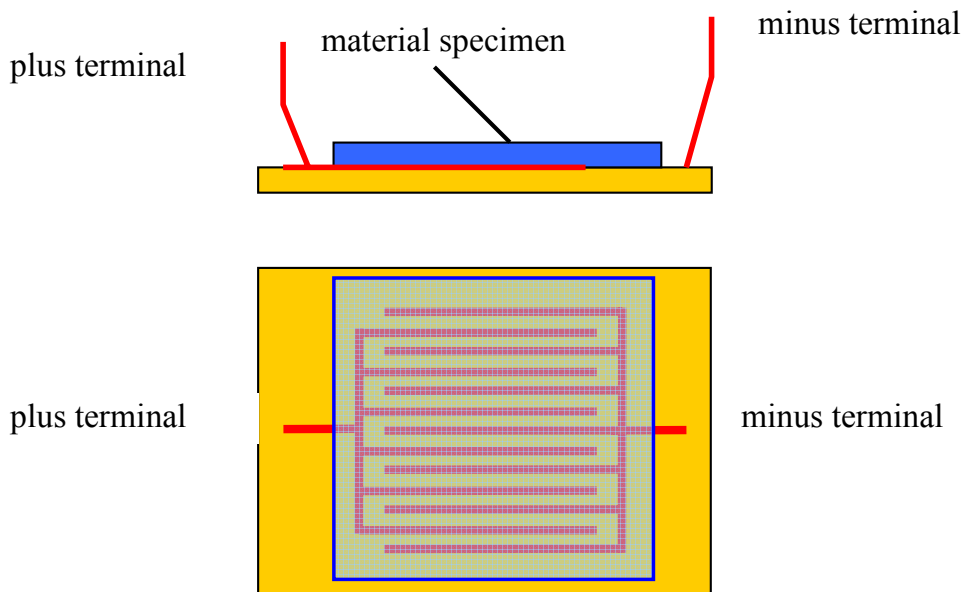


Figure 2.11. Testing of the corrosivity of material with one-sided IPC test pattern.

After conditioning in the test environment the material specimens and the copper surfaces are inspected visually. Documentation of the surfaces by photography is necessary as well as a more accurate analysis of the corrosion products.

The standard [IEC 60426] specifies test methods for determination of electrolytic corrosion caused by insulating materials.

Before making any decisive conclusions it is important to ensure that the corrosion products and the material specimen contain same substances. Suitable analysis methods are e.g. the following ones.

The composition of material under study can be analysed with X-ray fluorescence spectroscopy (XRF), which finds fluor and heavier substances.

The volatile organic compounds of the material may be found with gas chromatography. First the material sample is kept in closed ampoule at high temperature (e.g. 60 °C or 100 °C), thereafter the released compounds are analysed with mass spectroscopy (HS GC-MS headspace and gas chromatography).

3 Water solutions and surface tension

3.1 Ionisation

Atoms and molecules are electrically neutral elements of matter. When charged particles (electrons or protons) leave them as a result of chemical or physical reactions, the result is an ion. The charged particles leaving can also be ions!

Atom	Fe -> $\text{Fe}^{2+} + 2\text{e}^{-}$	iron
Molecule	$\text{CH}_3\text{COOH} \rightarrow \text{CH}_3\text{COO}^{-} + \text{H}^{+}$	acetic acid
Molecule	$\text{NaCl} \rightarrow \text{Na}^{+} + \text{Cl}^{-}$	salt (Cl^{-} = chloride)

Large organic molecules can ionise internally so that opposite charges are created at each end of the molecule. Such macro ions are usual in biological functions and can play a major part in microbiological corrosion (MIC microbiologically influenced corrosion).

In a corrosion reaction the ions dissolved in the electrolyte (solution) transfer the electric current. The ions do not have to originate from the corroding metal and indeed often they do not, but originate from the impurities accumulating on the surface. For example a saline solution already contains sodium and chloride ions. It is also a property of water that it ionises within itself to an extent.



Neutral clean water contains hydrogen ions 10^{-7} mol/dm^3 (pH = 7). The ionisation of water enables breaking it down with an electric current.

3.2 Condensation of vapour into liquid

Figure 3.1 shows a circle for a liquid molecule at the boundary surface of liquid and gas [Tommila 1965]. The molecules wholly inside the liquid are subject to equal cohesion forces from all directions from the neighbouring molecules if the molecule is in the middle of the liquid. In the picture on the left, R is the resultant of the cohesion forces affecting the molecule. A greater force from the liquid affects the molecule on the boundary surface than from the gas, and this results in surface tension in the liquid.

The shape of the surface also has an effect on the total values of the cohesion forces between liquid molecules on the boundary surface between liquid and gas. The area of the lower half of the circle (right hand picture 3.1) describes the

magnitude of the cohesion forces affecting a liquid molecule on a level surface. If the molecule is on a convex surface the cohesion force of the liquid molecules is smaller corresponding to the area marked in black in the right hand picture than on a level surface. The vapour pressure of liquid on a convex surface is greater than on a level surface, since the resultant of the cohesion force between the molecules is smaller towards the liquid. In the same way, the vapour pressure on a concave surface is smaller than on a level surface.

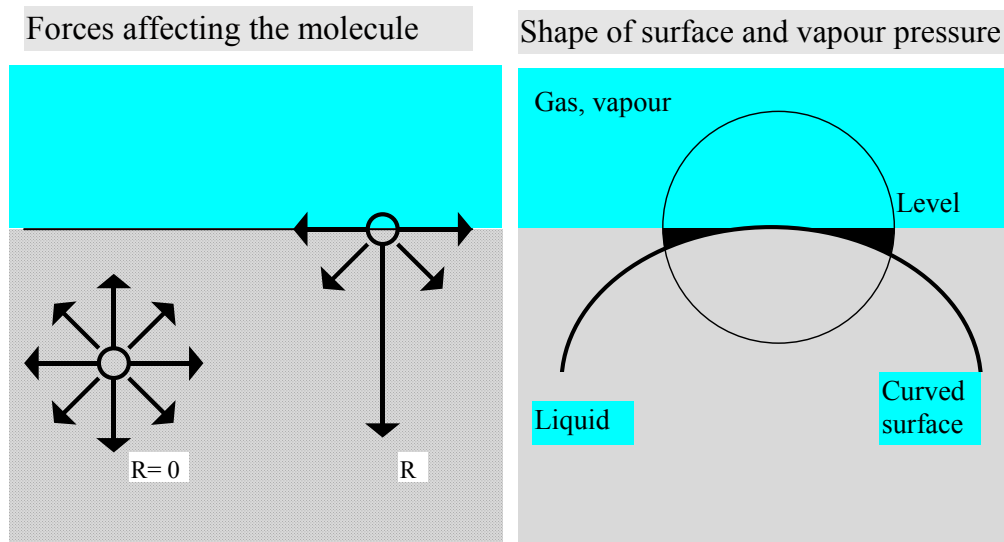


Figure 3.1. Molecular forces and the effect of a convex surface on the vapour pressure of the liquid.

Therefore, a molecule will come off the surface the more easily the more convex the boundary surface. It follows that the liquid drop (which is almost round) has a greater vapour pressure than a level liquid surface. Ordinarily, vapour pressure means the vapour pressure of a level surface.

The effect of a curved boundary surface on the vapour pressure becomes visible only in very small drops, a drop with a diameter of 1 μm the ratio of the vapour pressure to the vapour pressure of a level surface is only 1,0011 and in a drop of 10 nm 1,11. If the radius of the drop is 1 nm the ratio is already almost 3, in other words the vapour pressure of the drop is three times that of a level surface.

Therefore, small drops vaporise more easily than liquid on a level surface. This can be seen with water, which has a vapour pressure of around 100 kPa at boiling point. Water vapour cooled to just below the boiling point cannot condense into drops because the collisions brought about by the thermal motion of the molecules only create very small drops with a vapour pressure much larger than 100 kPa resulting in instant evaporation and over saturation of the vapour.

In order for the size of water drops to grow, the pressure in the surroundings must equal at least the vapour pressure of the drop. Therefore, drops suitable for condensation centres can only be born in strongly oversaturated vapour. In practice, the amount of oversaturation (vapour) needs to be four to fivefold in order to create viable condensation centres with a sufficient frequency.

When saturated vapour is led to a vessel, a layer of molecules will adsorb on the walls. Since the vapour pressure of the layer of molecules on the top is reduced because of adhesion from the wall material, more liquid condenses on the wall without interruption. This, in turn, promotes the condensation of for example water on solid surfaces.

If there is air (nitrogen) in the vapour, this prevents the landing of the vapour molecules on the wall and results in easily oversaturating the vapour because there is no condensation.

If there are dust particles in the vapour, liquid molecules will adsorb on their surface, which creates condensation centres. The vapour pressure of electrically charged drops is lower than of drops without a charge. Therefore, a drop will form around a water ion with less oversaturation than in unionised vapour. Dust and ionisation thus play a major role in the condensation of water for example in clouds and the formation of rain as well as inside the devices and in their vicinity.

As stated in the above, the vapour pressure is lower on a convex surface than on a level surface. Therefore, vapour pressure in capillary ducts is lower than normal and the liquid in them will not vaporise as easily as on convex and level surfaces. Thus, even thin layers of water remain as water in capillary conditions. It is thus understandable that corrosion in capillaries is much more severe than on open surfaces.

When heating a liquid it will easily overheat because the vapour pressure of the liquid on the surface of a small vapour bubble is lower because of a convex surface and no vapour bubbles can form. In other words, the vapour pressure of a vapour bubble in a liquid is greater than the vapour pressure of the liquid, which is why no matter is transferred from the liquid into the bubble. Impurities in the water and for example unevenness of the surface of the vessel speed up the start of the boiling since sharp corners or edges act as points of bubble formation.

3.3 Surface tension

Surface tension [Tommila 1965] is an intermolecular force in matter, which for instance contracts a liquid surface into a ball in zero gravity. Surface tension varies according to the quality of the liquid and the dissolved substances. Liquids, gases and solids each have their own surface tension which has an effect on the behaviour of boundary surfaces when in contact with one another and for example on the absorption of liquid into a porous solid.

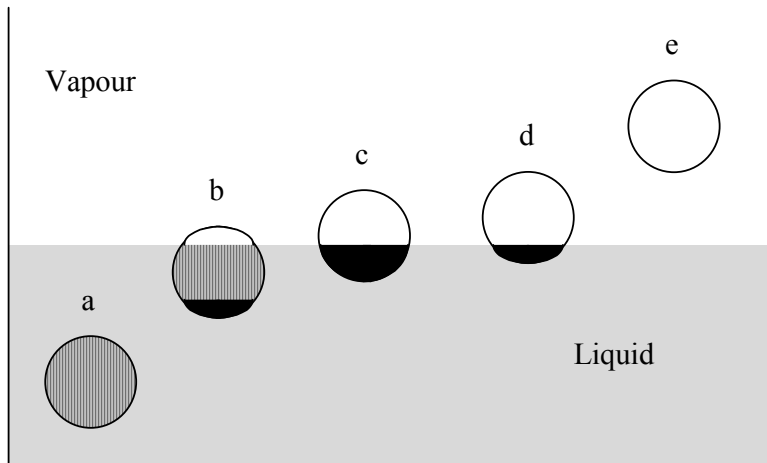


Figure 3.2. Emergence of surface tension [Tommila 1965].

There is a cohesion force between the molecules of solids, liquids and gases which decreases rapidly when the distance increases. It can be said that each molecule is surrounded by a sphere of influence the size and orientation of which depends on the location of the molecule in relation to other molecules.

The cohesion forces of other molecules towards a molecule inside a liquid cancel each other (location **a** in Figure 3.2). When the molecule moves from the centre to the boundary surface of the liquid and beyond that, the magnitude and direction of the force resultant affecting it change according to the darkened volumes in the figure (locations **a...e**).

Inside the liquid, in the sphere of influence, only the forces corresponding to the darkened space cancel each other out and the forces corresponding to the black areas remain active since the forces from above affecting the part reaching the gas space (vapour) are much smaller.

Thus the molecules on the surface are affected by a force directed into the liquid which is greatest for molecules exactly on the level of the surface. Above the liquid surface this force will gradually disappear (location **e**).

This resulting force creates a strained film on the surface of the liquid, which tries to shrink as much as possible. This property of the surface is the surface tension. A liquid drop in a free fall is drawn to a ball like shape due to surface tension. In reality, the drop will flatten out because of flow drag of the air.

Surface tension is a property of matter in solids, liquids and gases. Surface tension depends on the substances in contact, mixture ratios, temperature etc. The surface tension of water against air is $72,8 \cdot 10^{-3}$ N/m at 20°C. With organic substances, at room temperature it is about $20...30 \cdot 10^{-3}$ N/m. Surface tension against solid or another liquid will change because the forces from the other substance have an effect on the surface tension on the boundary surface. The surface tension of mercury at 15°C is $436 \cdot 10^{-3}$ N/m and of molten metals about $1\ 000 \cdot 10^{-3}$ N/m (for example, of Zn, $782 \cdot 10^{-3}$ N/m).

3.4 Surface tension equilibrium in the case of three phases

If a drop of liquid (C) is placed on liquid (B) with air (A) above, the situation may resemble that in Figure 3.3 [Tommila 1965]. Let us assume that liquid (C) is insoluble in liquid B. Then, three surface tensions affect the boundary line of the liquids and air and the following equation applies in the equilibrium:

$$\gamma_{AC} \cos \alpha + \gamma_{BC} \cos \beta = \gamma_{AB} \quad (3.1)$$

Since the cosine of an angle cannot exceed one an equilibrium is created only if

$$\gamma_{AC} + \gamma_{BC} > \gamma_{AB} \quad (3.2)$$

In this case the drop (C) settles in the form of a lens on the surface of liquid (B).

If

$$\gamma_{AC} + \gamma_{BC} < \gamma_{AB} \quad (3.3)$$

the liquid drop (C) will spread without limit on the surface.

If, for instance C is a complex carbon hydride and B is water, γ_{AC} is about 30, $\gamma_{AB} = 73$ and $\gamma_{BC} = 57$ (10^{-3} N/m). Thus, $\gamma_{AC} + \gamma_{BC} = 87$, which is $> \gamma_{AB}$ and carbon hydride C takes the form of a drop on the surface of the water. If C is an oleic acid, $\gamma_{AC} = 32$, $\gamma_{BC} = 16$ and $\gamma_{AC} + \gamma_{BC} = 48$ (10^{-3} N/m), which is much

smaller than $\gamma_{AB} = 73$, resulting in the oleic acid spreading on the surface of the water.

Surface tensions on the boundary of three substances

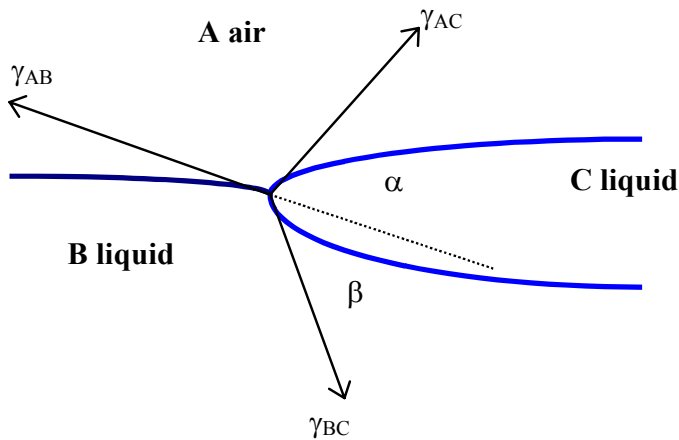


Figure 3.3. Surface tension equilibrium between liquids B and C and air A.

Also solids have their own surface tension. If there is a drop of liquid on a level surface, its form will be that of cases 1 and 2 in Figure 3.4 according to the ratio of the surface tensions of the material of the level surface and the liquid [Tommila 1965, Kalliorinne et al. 1990]. The surface tension between the solid substance and liquid C is parallel to the level surface because the surface does not bend. The shape of the liquid surface in a vessel, for instance in a capillary crevice is also presented in the picture. In case 1 the liquid wets the solid surface and rises along the surface of the vessel but when in case 2 the liquid settles into a drop it also strives to draw away (reject) from the solid surface of the vessel. In case 1 the adhesion forces of the liquid and the solid are greater than the cohesion forces of the liquid, whereas in case 2 the cohesion forces of the liquid are greater than the adhesion forces.

Now the angle of contact Θ is determined as follows:

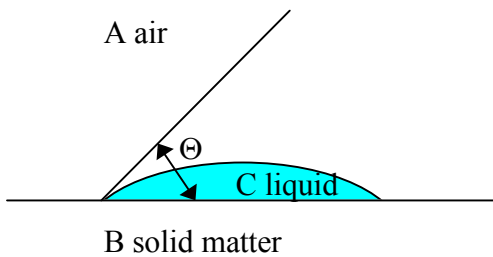
$$\gamma_{AC} \cos \Theta + \gamma_{BC} = \gamma_{AB}. \quad (3.4)$$

When the surface tension between the gas and the solid (γ_{AB}) is greater than between the liquid and the solid (γ_{BC}), $\cos \Theta$ is positive and Θ is smaller than 90° , in other words the situation is as in case 1, and the liquid drop will spread on the surface and wet it, in other words the boundary surface will strive to grow.

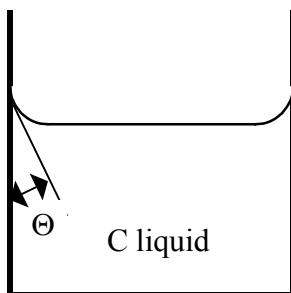
If the surface tension between liquid-solid (γ_{BC}) is greater than between gas-solid (γ_{AB}), Θ is between $90...180^\circ$ and the situation is as in case 2 where the liquid will not wet the solid surface, in other words the boundary surface between the liquid and the solid will strive to diminish and the liquid will contract.

Liquid on a solid surface

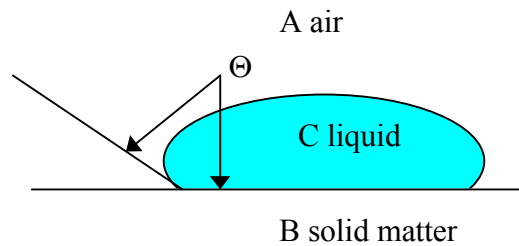
Case 1 $\gamma_{AB} > \gamma_{BC}$



Liquid C rises on walls



Case 2 $\gamma_{AB} < \gamma_{BC}$



Liquid C repels walls

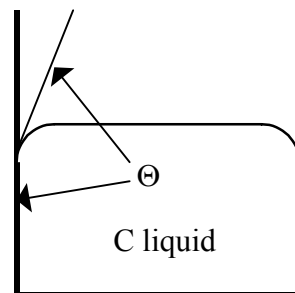


Figure 3.4. Liquid drop on a solid surface and corresponding liquid in a vessel [Tommila 1965].

When it is a question of a liquid and a gas (for example water and air), the contact angle of the liquid with a glass surface is usually zero ($\Theta = 0^\circ$) except with mercury, which has a contact angle of about 140° [Levine 1981, p. 326].

Liquids with a weak surface tension, such as alcohols often wet the surface better than water.

In the soldering of the printed boards the aim is always to have as good soldering properties as possible and therefore the situation in case 1. This information of the form of the boundary surface of the solder (solder tin-lead) and the metal to

be soldered is used in the visual inspection of the quality of the solder. If the form of the solder is as in case 1, it is probable that the entire solder connection is of good quality. If the form is as in case 2, it is probable that the solder connections are of inferior quality and the soldered surface has not been wetted well and the durability and functionality of the solder connection in use is likely to be inferior. To ensure the wetting of the soldering areas of the printed board and the leads of the components, the fluxes are chosen in the soldering process in such a way as to guarantee good wetting. In other words a weak surface tension between the soldering tin and the metal wetted by the flux is aimed at.

In case 1 in Figure 3.4, where the surface tension between the liquid and the solid is **weak**, in other words the common surface strives to grow, the liquid will rise in a narrow capillary duct. If the surface tension of the liquid is **great, as in the case of mercury**, the surface will go down in a narrow capillary duct.

It can be demonstrated that on a ball-shaped boundary surface between two substances (here air A and water C) the pressure difference of the substances can be obtained from the equation:

$$p^A - p^C = \frac{2\gamma}{R}, \quad (3.5)$$

where γ is the surface tension of the liquid against gas and R is the radius of the sphere in question [Levine 1981, p. 324, equation 13.9]. Calculated from equation (3.5) at 20°C the pressure difference at the boundary surface of water and air is 13 Pa, if the radius of the boundary surface is 1 cm and 1330 Pa, when R is 0,1 mm.

3.5 The capillary effect

The capillary effect means the travel of liquid (adsorption, rising) into narrow gaps (cracks) using the force of the surface tension of the liquid. A capillary gap is less than 0,5 mm between two surfaces or the inside of a narrow duct. Capillary gaps exist in practice also in all porous materials (blotting paper, textiles), where they are less than 0,1 mm.

Equation (3.5) can be used as a basis for measuring the surface tension of liquid-gas and liquid-liquid boundary surfaces with capillary ducts. The measurement is possible only if $\Theta = 0^\circ$, because the measuring of the wetting angle is difficult. In Figure 3.5 the angle is $\Theta > 0$, but since the tube is glass and the liquid is water, $\Theta = 0$, which makes it possible to measure the surface tension.

The liquid will rise into the capillary duct because the internal pressure of the liquid is smaller in the capillary duct with a concave liquid surface than the pressure of the gas above it. Since the pressure of the liquid outside the capillary equals the pressure of the gas above it, the pressure pushes the liquid into the capillary duct until the hydrostatic pressure of the liquid column equals the pressure difference in equation (3.5) between the liquid in the capillary and air.

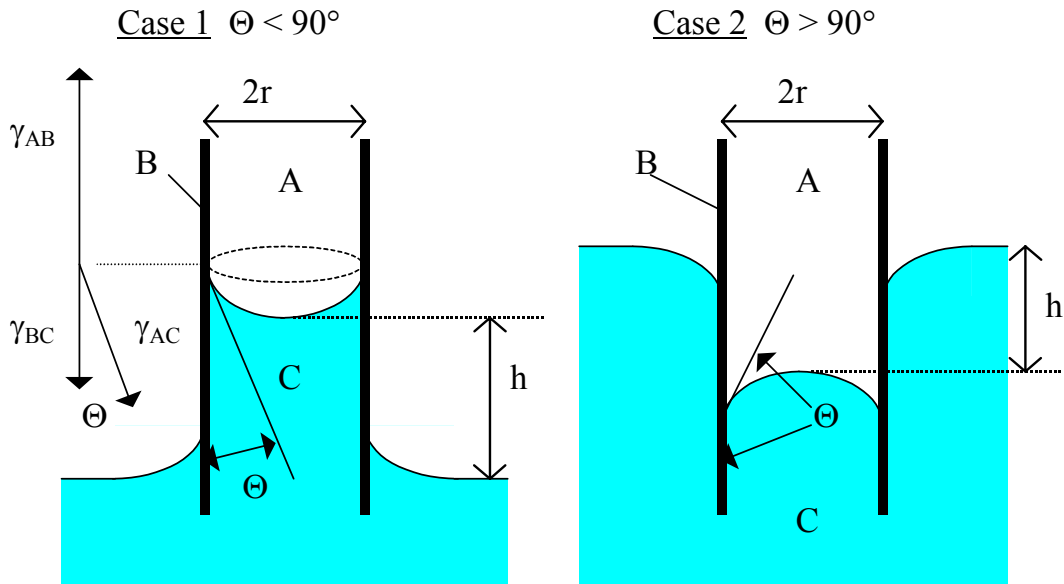


Figure 3.5. Behaviour of a liquid in a capillary duct.

The glass capillary duct in Figure 3.5 is assumed so narrow that the boundary surface of gas A and liquid C is round in which case equation (3.5) can be applied and the radius R of the sphere equals the radius r of the inside of the capillary duct. Because in this boundary surface liquid (water) glass $\Theta = 0^\circ$, as described in the above and the liquid-gas boundary surface is a hemisphere it can be shown that the liquid-gas surface tension γ_{AC} can be calculated from the equation:

$$\gamma_{AC} = \frac{(\rho_C - \rho_A)ghr}{2}, \quad (3.6)$$

in other words the pressure difference (equation 3.5) equals the hydrostatic pressure of a column of liquid with the height h deducted by the pressure corresponding to a gas column with the height of h .

ρ_A is air density, ρ_C is liquid density, g is acceleration of the earth's gravity, h is height of the liquid column in the capillary duct, r is inside radius of the capillary duct.

Equation (3.6) gives 15 cm as the rise of water in a glass capillary duct if the inside diameter of the duct is 0,2 mm and the air temperature is 20°C [Levine 1981, p. 326].

In case 1 in the above, where the liquid strives to travel along a solid surface (to wet it) the same liquid in a capillary duct rises in the duct the further the greater its own surface tension is.

The capillary effect takes place when for instance liquid is absorbed into a paper or cloth tissue. The crevices between the fibres act as capillary cracks drawing the liquid into them. If the cloth is waterproofed so that the wetting angle is between 90...180°, water will not soak into the cloth. Correspondingly, oily water absorbs into the feathers of birds because the wetting angle between the water and the feathers is less than 90°.

The use of surface active fluxes (substances reducing surface tension) in for instance detergents is based on this above quality. Dissolved in water they clean better. Surface active fluxes are used similarly in the soldering processes in electronics, where they reduce the surface tension of the surfaces to be soldered and clean them.

All kinds of narrow cracks/gaps (less than 0,5 mm between the surfaces) are always harmful with regard to corrosion of electronic devices. The capillary force draws liquids, which are often corrosive due to various impurities into the cracks. Since the vapour pressure of liquids in the capillaries is lower than in an open space, even thin layers of water remain in capillary conditions. Therefore, it is understandable that corrosion in the capillaries is much stronger than on open surfaces.

Surfaces rejecting water and aquatic solutions would be best with regard to corrosion properties of the surfaces. Then the aquatic solutions would not rise into the capillary cracks/gaps (less than 0,5 mm) and the risk of corrosion would be reduced. However, it is problematic to find surface materials that would function in this way in all conditions (for example ref. GORE-TEX®-materials).

3.6 Water solutions and electrolytes

A substance producing ions into a solution is an electrolyte. This results in the solution becoming conductive. An electrolyte dissolved into a certain solvent (for example water) is weak or strong according to whether the resulting solution is electrically a weak or a good conductive at reasonable electrolyte contents. Weak

electrolytes with water are for example ammonia NH_3 , carbon dioxide CO_2 and acetic acid CH_3COOH whereas sodium chloride NaCl , hydrochloric acid HCl and magnesium sulphate MgSO_4 are strong electrolytes.

Electrolytes can be grouped according to their structure [Levine 1981, 1978] into actual and potential electrolytes. An actual electrolyte carries ions in its pure form without a solvent. Most salts are actual electrolytes; in other words they conduct electricity. For example NaCl , CuSO_2 and MgS -crystals are formed of positive and negative ions. In their pure and liquid form, actual electrolytes are good electric conductives and potential electrolytes weak electric conductives.

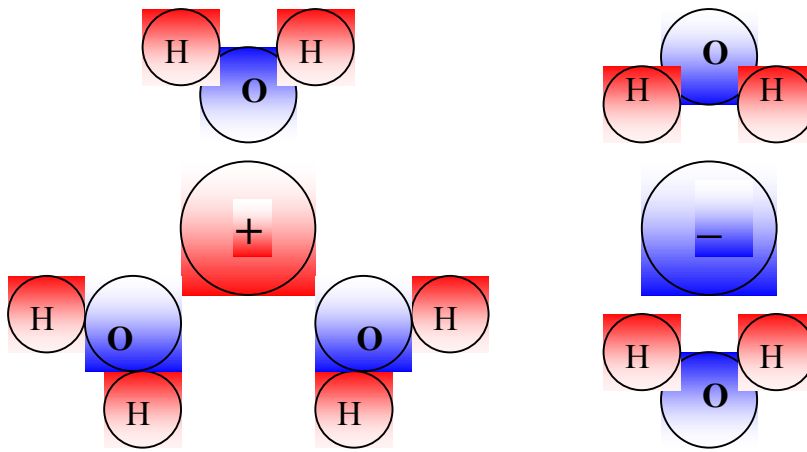


Figure 3.6. Hydration of ions in water, positive and negative ions.

When an ionic crystal dissolves into the solvent, the ions leave the crystalline structure and join the solvent as solvated ions. The term solvated means that a few molecules of the solvent surround each ion in the solution, which are bound to the ion by electrostatic gravity. This “stable” group formed by the ion and the molecules of the solvent moves in the solvent as one unit. Figure 3.6 presents solvated positive and negative ions. Because the solvent is water, these ions are called hydrated ions.

A potential electrolyte consists of uncharged particles in its pure form. When it dissolves into the solvent it reacts chemically with the solvent and forms ions.

For example acetic acid reacts with water:



resulting in H_3O^+ and acetate ions.

Hydrochloric acid HCl reacts with water:



resulting in H_3O^+ and chloride ions.

A strong electrolyte, such as hydrochloric acid has the equilibrium point heavily on the right side of the equation in the chloride ions. Weak acids, such as acetic acid, have the equilibrium point on the left side of the equation unless in very small concentrations.

Because the electrolytes bind molecules of the solvent, in the case of Figure 3.6 water, to themselves, this means that ions cannot travel in very thin layers of water (neither can corrosive current) because the water is bound to the ions and the formed groups cannot pass each other. Therefore, the water layer adsorbing to the surfaces must be about five molecule layers thick (about 10^{-9} m) before corrosion can develop to have any significance. This thickness of the water layer corresponds to the water layer adsorbing onto a metal surface when the relative humidity of the air next to the surface is 60...80% RH [Johansson 1995].

Table 3.1. Thickness of water layer on metal surface.

Relative humidity of the air (%)	Number of molecule layers H_2O
20	1
40	1,5...2
60	2...5
80	5...10

In practice, there is always a layer of water a few molecular layers thick on the surfaces of substances [Johansson 1995]. For instance the amounts of water in Table 3.1 have been measured on metals at various values of air humidity. This explains in part why corrosion speeds up considerably if the relative humidity of the air exceeds 60%.

3.7 Water solutions and surface tension

There are three typical categories of surface tension behaviour for dilute water solutions [Levine 1981, p. 333] when the electrolyte content of the solution is increased.

Type 1: The surface tension of water solutions of this type of electrolytes (Figure 3.7) increases slightly whenever the concentration of the solution increases. Most inorganic salts and saccharose behave in this way. The corrosion products of metals are mostly inorganic salts so they increase the surface tension of the water solution. The continuous slow increase of the surface tension is explained by the greater possibilities for interaction of the ions with opposite charges in the liquid than on the surface layers. Therefore, the ion concentration of the surface will decrease and the adsorption forces from the insides of the liquid towards the surface will increase which results in an increase in the surface tension of the solution.

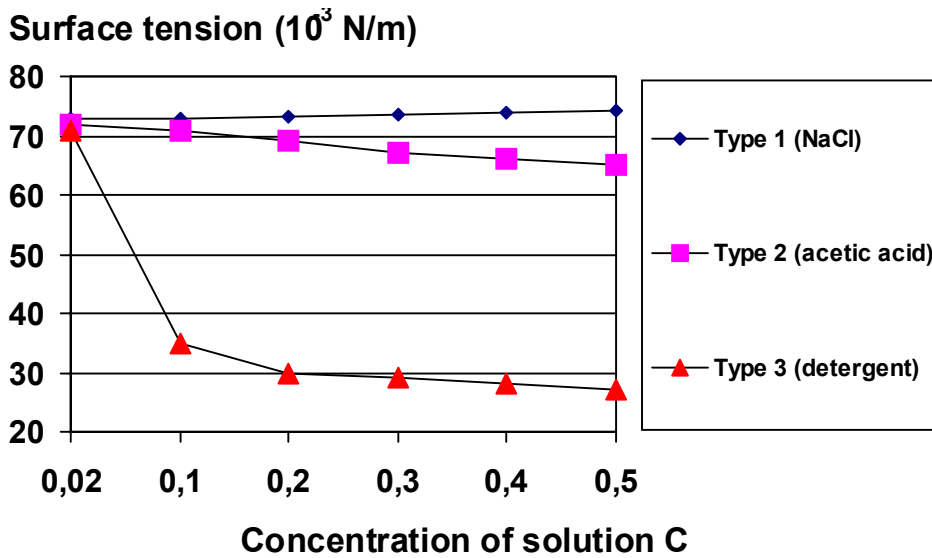


Figure 3.7. The effect of solution concentration on the surface tension of water [Tommila 1965, Levine 1981].

Type 2: The surface tension of water solutions of this type of electrolytes decreases relatively quickly when the concentration of the solution increases. Most organic substances soluble into water, such as acetic acid, belong to this category. Organic compounds soluble into water usually contain a polar part (such as an OH or COOH group) and a non-polar hydrocarbon part. Such ionised molecules collect on the surface layer of the liquid, where their polar parts point to and affect the polarised water molecules. The non-polar parts of these molecules are directed away from the water. This results in a reduction in the adsorption from the liquid to the surface resulting in a lower surface tension when the concentration of the water solution increases.

Type 3: The surface tension of water solutions of this type of electrolytes initially decreases very quickly and then reaches a steady level when the concentration of the solution increases. Electrolytes of this type adsorb strongly to boundary

surfaces (air-water). For example, the salts of organic acids with medium long molecule chains, in other words soaps and other surface active substances (for example pine soap and shampoos contain these). The sharp drop in the surface tension takes place at a certain critical electrolyte concentration.

Substances that reduce drastically the surface tension of liquid are called surface-active substances. For example ordinary detergents soluble in water are such. They clean dirt effectively from various surfaces.

Detergents reduce the surface tension by the help of surface-active substances (or tensides). With the help of detergents water penetrates easier between the cloth fibres and dirt particles. The other end of surface-active substance is hydrophobic and the other end hydrophilic. On the water surface the hydrophilic end penetrates into the water and hydrophobic into the air. Therefore the surface tension is reduced. When tenside meets a grease particle the hydrophobic end penetrates into the grease and the hydrophilic end into the water. Thus several tenside molecules cover a grease particle and remove it from the fibres of cloth [Haavisto et al. 1985].

Based on the above, it can be stated that the surface tension of a water solution will diminish the more the greater the electrolyte concentration on the surface of the liquid. The concentration of the electrolyte on the surface of the liquid is a property of matter, which can be used to affect the corrosion properties of surfaces.

3.8 Condensation of water

The condensation of water is the change of water vapour into a liquid on the surface of particles or uniform material (liquid or solid) when the relative humidity of the air reaches 100% (see Sections 1.5 and 1.6). This is not exactly true since condensation to the surface and vaporisation of water from the surfaces takes place continuously at all temperatures and air pressures. It depends on the conditions whether condensation or vaporisation prevails. The main factors regulating condensation are air pressure, partial pressure of water and temperature of the air and surfaces. Also the quality of the surfaces, particles in the air and the degree of contamination of the surfaces play a part in how strong condensation is (see Appendix 1, Section 3.2 *Condensation of vapour into liquid*).

The equilibrium between condensation and vaporisation depends in fact on the amount of thermal motion of the molecules in the substance. Water molecules move more slowly as liquid than as gas. The movement of the molecules

increases with temperature. The amount of water vapour in the air, temperature and pressure regulate the prevalence of condensation or vaporisation. Water vaporises both from the surfaces of liquid water and frozen water and correspondingly condenses into both these forms depending on the conditions.

The condensation of water is an exothermic reaction; in other words it releases heat to the amount charged into the water when it vaporises. If the underlying material conducts heat well, as for instance metals do, the released heat is quickly channelled away and the surface remains cool. If the metal is coated (painted) the conductivity of heat of the surface will diminish and condensation will slow down. Condensation is thus closely linked to the thermal conductivity of the underlying material.

If there are several heat channelling surfaces in the vicinity condensation is especially strong. This is the case for example in narrow cracks and capillaries. A structure with capillaries and metal surfaces against each other is the worst possible structure with regard to prevention of condensation.

3.9 Water repellent and permeable materials

When the surface tension between water and a solid material (γ_{BC}) is greater than the surface tension between gas and a solid material (γ_{AB}), the wetting angle Θ is between $90...180^\circ$ (Appendix 1, Section 3.4 *Surface tension equilibrium in the case of three phases*), which leaves water as drops on the surface of the solid material. The water will not spread or absorb easily into the material.

Water repellent materials are used for example in the manufacture of outdoor clothing textiles which must, on one hand, repel rain water and dirt but on the other hand be porous and let through human sweat and water vapour inside the clothing in order to keep the inside of the clothing dry unlike in waterproof raincoats. In outdoor clothing, the material should withstand reasonable outside water pressure in the form of heavy rain or a mechanical force, for instance when sitting on wet ground when the pressure caused by the sitting is about $0,2 \text{ kg/cm}^2$. An example of such a material is the material of W.L. Gore & Associates, Inc, GORE-TEX®, which has a water wetting angle of about 140° and water is mainly diffused through the fabric.

<http://www.gorefabrics.com/allweather/water.htm>

This material is made of polytetrafluoroethylene (TEFLON®) into a porous film where the size and the structure of the pores is chosen in a way that water is let

through only in diffusion [US Patent 4194041]. According to the patent brief the material absorbs water (is hydrophilic, water absorbent), lets it through molecule by molecule with the diffusion mechanism and then desorbs or evaporates the water from the other side where the relative humidity is lower than on the other side. Water vapour will pass through the film but liquid will not. The film is breathable and it filters substances with a larger molecule size. Thus, it is suitable for preventing water and dust from passing through the film. There is a large number of patents for this kind of materials and their manufacturing methods. A few of the basic patents are listed below. Other similar hydrophilic materials are for example Hypol® by W.R. Grace & Co and Nafion® by E. I. duPont de Nemours & Co [US Patent 4194041].

Materials such as GORE-TEX® are suitable for ventilation outlets of electronic devices where they stop splash water from getting in but enable the water vapour inside to get out making the device case “breathable”. In order for the breathing mechanism to operate properly, the temperature of the protected space must exceed the temperature in the environment at least a part of the time. The inside space will dry for as long as the partial pressure of water vapour on the inside is greater than on the outside.

Textiles are tested according to standard ISO 811:1981 Textile fabrics – Determination of resistance to water penetration – Hydrostatic pressure test.

Patents:

US Patent 4187390: Porous products and process therefore, Feb. 5 1980, Robert W. Gore, Delaware.

This invention provides a tetrafluoroethylene polymer in a porous form which has an amorphous content exceeding about 5% and which has a micro-structure characterized by nodes interconnected by fibrils. The material has high porosity and high strength. It can be used to produce all kinds of shaped articles such as films, tubes, rods, and continuous filaments. Laminations can be employed and impregnation and bonding can readily be used to produce a large variety of articles. Compressed articles of very high strength can also be produced from these porous forms

US Patent 4194041: Waterproof laminate, March 18, 1980, Robert W. Gore & Samuel B. Allen, Jr., Delaware.

A waterproof article for use in, for example, protective clothing. The article prevents liquid water from penetrating through to undergarments while at the same time permitting moisture vapour such as perspiration to pass out through the article. The article is thus both breathable and waterproof. The article is layered: a microporous hydrophobic outer layer which permits the passage of moisture vapour but resists penetration by liquid water at pressures up to about 345 Kn/m^2 ; a hydrophilic inner layer permitting the transfer of moisture vapour but preventing surface tension lowering agents such as those contained in perspiration and/or body oils from reaching the hydrophobic layer.

US Patent 5143783: Porous film of polytetrafluoroethylene and preparation thereof, Sept 1, 1992, Shimizu; Tetsuo, Osaka, Hosokawa; Kazutaka, Osaka, Japan.

A polytetrafluoroethylene porous film obtainable by applying an aqueous dispersion of emulsion polymerized polytetrafluoroethylene particles having an average minor particle size of 1 to 500 nm and an average aspect ratio of at least 10 on a substrate, drying the applied dispersion and optionally sintering the dried polytetrafluoroethylene particles on the substrate to obtain the polytetrafluoroethylene porous film, which has a uniform thin thickness.

US Patent 5869156: Porous products manufactured from polytetrafluoroethylene treated with a perfluoroether fluid and method of manufacturing such products, February 9, 1999, Hoo Young Chung, Minneapolis.

Porous materials suitable for a variety of uses including waterproof/breathable fabrics, air filters, liquid filters, liquid/liquid separation membranes, vascular grafts, mechanical seals, etc. which comprises an intimate combination of about 50 to 99.9 wt% polytetrafluoroethylene polymer and about 0.1 to 50 wt% of a fluorinated organic polymer which is liquid ambient conditions, such as the perfluoroether fluids, in the material has a microstructure characterized by nodes connected by fibrils.

4 Phenomena of metal surfaces

4.1 Dendrite

Copper either in its pure form or in alloys is often used as conductors in electronics. Copper may, if the conditions are favourable with enough humidity and voltage between the various parts, grow fir twig like dendrites between the parts. Dendrite is a metal crystal grown like a twig (fir twig pattern) that will grow for example on an energised component board between live copper conductors deteriorating the isolation between them even to the point of a short-circuit. Dendrites may be born on clean copper surfaces or as filaments branching out from the flaws in plating (e.g. holes in gold plating). High voltage accelerates growth of dendrites.

Dendrites are created through an electrolytic process on the surface of a printed board, for instance, with an ionic contamination and moisture. The cause for dendrites may be the composition of the solution in the coating process, reflow soldering or surplus flux residue on the printed board.

This method of dendrite formation emphasises the significance of cleanliness in the manufacture and handling of printed boards and also the need to protect the wiring pattern of the printed board from the immediate effects of humidity. Contamination from the air is difficult to avoid which is why dirt and electrolytes will always gradually accumulate on the boards (see electrolytes Appendix 1, Section 3.6 *Water solutions and electrolytes*) These together with moisture give rise to various corrosive phenomena.

Dendrites can also grow inside microcircuits where the same failure mechanism has been identified between the lead connections if moisture can seep into the case.

Also the lead containing glass seals of the outer conductors of hermetic components have shown lead-dendrites with some fluxes.

Dendrite crystallisation takes place inside metals when molten metal cools or when water crystallises into snow flakes. These phenomena should not be confused with the dendrites in between components, printed boards, wires and connector contacts.

4.2 Whiskers

Metals have property to grow filaments (whiskers) on their surfaces. These whiskers grow spontaneously as if one were pressing a toothpaste tube.

The length of the whiskers may be several millimeters. The whiskers may cause short circuits, which may momentarily disturb function of a equipment or even may cause a permanent failure into the electronic equipment.

The growth of the whiskers is most disturbing when pure tin plating is used. This is nowadays very important aspect because the [RoHS] directive of European Union forbids the use of tin-lead solders. The directive of European Union, [RoHS] concerning the restriction of the use of certain hazardous substances in electrical and electronic equipment limited from the June 2006 the use of such materials as lead (solder), mercury (batteries), cadmium (accumulator), hexavalent chromium (Cr₆, chrome plated aluminium and zinc, bright chromium plated decorations, keyboards and boxes), and halogenated fire retardants (printed wiring boards).

The internet pages in [<http://nepp.nasa.gov/whisker/>] contains plenty of relevant information about the whisker phenomena and guide for preventing whiskers. A similar phenomena has been seen on surfaces of cadmium Cd, indium In and zinc Zn [Galyon & Gedney 2004, Su et al. 2005].

Many components and structures are plated with pure tin in electronics. Pure tin tends to grow filaments on its surface (tin whisker). Such a whisker easily shortcuts the bare component conductors next to one another. A tin whisker can grow anywhere on a tin surface; its length is from 1...2 mm even to 4...10 mm and its thickness is 0,3...50 micrometres. A typical thickness is 1 µm.

For the devices a tin whisker is harmful because it creates random short-circuits between bare tin plated wires. The current needed for breaking the whisker is usually greater than 10 mA; sometimes even 50 mA is needed for burning the short cut. If the short cut does not receive enough current it may remain permanent.

A tin whisker is pure single crystalline tin, it will grow at random and it does not need moisture or voltage to grow and its growth does not depend on air pressure (also grows in vacuum). The reason to the growth of whiskers is the inner strain of the metal, which forces the metal atoms out of the surface.

A tin whisker may be straight, bent, crooked or divided, it may sometimes have openings and the outer surface may be grooved.

The growth of a tin whisker may start immediately after the manufacture of the tin plating or it may start growing years after the process.

The growth of tin whiskers is linked to tension in the following ways:

- tensions in the tin platings created during the manufacture (electrochemical coating leaves the most tension in the platings)
- pressure tension under a screw or a bolt
- bending or stretching of the surface after the plating
- scratches during the processing
- difference of the thermal expansion coefficients of the underlying material and of tin
- the birth of intermetallic layers between for example copper and tin Cu_6Sn_5
- corrosion may accelerate the growth of whiskers
- tin filaments are most easily created at a temperature of about $+50^\circ\text{C}$ (the recrystallization temperature of tin), the growth of the filaments ceases at temperature below -40°C and over $+140^\circ\text{C}$.

Clear tin platings seem to be more prone to the development of tin whiskers than platings with a matte surface.

Protective layers such as lacquer have been used to some extent on tin platings but the tin whiskers have been reported to grow through these [Woodrow & Ledbury, 2006].

JEDEC and IPC have published some standards for the control of tin whiskers:

JEDEC JP002 (2006) Current tin whisker theory and mitigation practices guideline.

JEDEC JESD 22-A121 (2005) Measuring Whisker Growth on Tin and Tin Alloy Surface Finishes.

JEDEC JESD 201 (2006) Environmental Acceptance Requirements For Tin Whisker Susceptibility of Tin and Tin Alloy Surface Finishes.

The current (1999) recommendation [Brusse 1998] for avoiding the risk of tin whiskers is first of all not to use pure tin in electronic platings. Using an alloy material, such as bismuth Bi, some underlay materials as nickel Ni, heat treatment, a thicker tin layer, etc. can mitigate the growth of tin whiskers. [JEDEC JP002].

4.3 Tin disease

Tin has two allotropes: the white metal, called beta-tin (β -tin), and a gray non-metallic powder known as alpha-tin (α -tin). At temperatures below 13,2°C the gray powder allotrope begins to show more stability than the white metal allotrope. As temperatures decrease below 13,2°C, the shift from the metallic allotrope to the gray non-metallic allotrope (α -tin) progresses, reaching a maximum at about -30°C. This phenomena is called the tin disease or tin pest. In electronics the tin disease does not exist often, because the tin disease in tin-lead solder starts only below minus 50 °C. The blend compounds of tin as lead, antimony, and bismuth decrease the risk for tin disease.

The use of tin-free solders [RoHS] increases the risk for tin disease, but it can be avoided by the use of the appropriate blend compounds.

The tin disease should be distinguished from the corrosion and oxidation of tin, which make the surface of tin gray. Look also [ASTM B545-97]

[Alan Bruzel, <http://dwb.unl.edu> and Bob Weintraub & E. J. Cohen <http://www.weizmann.ac.il/ICS/booklet/9/pdf/weintraub.pdf>].

4.4 Electromigration

Electromigration means the transfer of material in an electric conductor because of the current. Electromigration has become a significant failure mechanism in microcircuits with high-density aluminium and copper wiring. Electricity is the movement of electrons in materials. When the electrons move in the material, they also bombard the atoms of the material, which may be dislodged from their position in the crystal lattice. This is the case to a disturbing extent in the thin aluminium conductors of the microcircuits when the density of the current increases very greatly. The movement of atoms in a metal can create holes and breaks in the thin conductors or, on the other hand, atom clusters may be created into the conductor the internal pressure of which will result in a bulge in the metal conductor breaking the isolation layer on top of the metal revealing the metal like toothpaste coming out of a leaking tube.

[<http://www.research.ibm.com/research/press/micro.html>].

Electromigration is a significant failure mechanism already when the current in the aluminium conductors is about 1...5 mA and conductor widths are under 5 μm in other words, a very common situation in microcircuits. When conductor widths are more and more narrow then the electromigration is valid for all metals (ref. Appendix 1, Section 2.13 *Electrolytic corrosion and ion migration*).

5 Factors affecting the progress of corrosion

Corrosion reactions are electrochemical reactions taking place in a water solution. The water solution is created on a corroding surface when moisture in the air adsorbs and condenses on the surface. Impurities (salts) from the surface dissolve into the condensed layer of water, which makes the water solution into a conductive electrolyte. Thus, the requirements for corrosion are there.

The salts dissolved into the layer of water condensed on the surface and the relative humidity of the surrounding air determine if the water layers remains on the surface or if it dries. Ordinary salt, NaCl, which is all around us (for example sweat contains some salt), is one of the most harmful contaminants. The table below lists the relative humidity above saturated water solutions of different chlorides (salts) at the temperature of 25°C.

*Table 5.1. Relative humidity above saturated water solutions of metal chlorides in a closed space at the temperature of 25 °C *).*

Metal chloride	RH%
lead chloride	99
tin-lead solder chloride	96
tin chloride	77
sodium chloride	75
copper chloride	62
nickel chloride	59
iron chloride	52
aluminium chloride	48
magnesium chloride	33
zinc chloride	21

*) Saturated salt solutions were used in the calibration of instruments for measuring the relative humidity e.g. [Nordtest Remiss Nr 548-85 1987].

If the relative humidity in the environment is smaller than the relative humidity above the saturated solution the solution will dry and eventual corrosion will also stop. On the other hand, when the relative humidity of the environment increases, the dried salt immediately strives to return the saturated solution by absorbing moisture from the air. This is the case for example at night, when the air temperature drops and the relative humidity of the air increases.

Based on the table, it is understandable why corrosion tests are performed using relative humidity of 75% or 95%. These humidity values prevail in connection with chlorides that are abundant in nature (NaCl) and electronics (chlorides of

tin-lead solder). Accelerated tests corresponding fairly well to the real environmental conditions can be conducted with these humidities.

In corrosion reactions, the metal dissolves as positive ions on the anode or the corrosive area. When a positive ion is born, the metal is left with electrons, which are consumed, on the cathode or the non-corrosive area. In very acid conditions, hydrogen develops on the cathode in a water solution. In slightly alkaline and neutral conditions, which are more normal than strong acid conditions, water also disintegrates into hydroxyl ions instead of producing hydrogen, if oxygen is present. The hydroxyl ions react with the dissolved metal forming a corrosion product typical of metals, metal hydroxide. Thus, corrosion becomes visible.

Corrosion reactions thus always include the transfer of electrons from one molecule/atom to another. This transfer means the leaping of electrons over the potential barrier between the substances/spaces. The reactions of the cathode in neutral and alkaline conditions mean that the electrons leap over a potential barrier of about 0,4 V. This has significance when combining different metals. If the difference between the metals is less than 0,4 V in the galvanic voltage series the galvanic pair will not release enough energy for the electrons to bridge the cathodic potential barrier.

In corrosive reactions, the current will, travel in metals in the form of electrons and in a water solution in the form of ions. Ions collect or associate a layer of water molecules around them. This is due to the fact that water molecules are dipoles. In a water molecule, the negative end directs towards the positive metal ion (see Appendix 1, Section 3.6 *Water solutions and electrolytes*). This macro-ion requires a lot of space and moves much more slowly than a metal ion. This also means that a layer of at least a couple (about five) molecules of water must be adsorbed on the surface. This equals about one nanometre of water in order to start more rapid corrosion. The vapour pressure of this layer of a nanometre of water is however greater than the air pressures of the environment, so this layer is not constant but strives to dry quickly in an open space. Only a water layer of a micrometre is stable because its vapour pressure corresponds to a relative humidity of 100%.

The above bears simplified reference to the factors regulating the corrosion events. It must be remembered that the data is based on physical-chemical reactions measured in a controlled laboratory environment. In real conditions, the changes in the temperature, the presence of more than one substance in the solutions and mechanical stress influence the course of events by accelerating or decelerating the reactions. The basic knowledge behind corrosion must be mastered, however, since that determines the final result, experience then determines the time in which this is reached.

6 Contamination of the surfaces and air impurities

The dust from the air and the particles created by gas emissions [Burnett et al. 1992] are hygroscopic, water absorbent and conductive or become electrically conductive in humid conditions.

In addition to the air pollution causing corrosion in the metal parts, the fact that the substances on the surfaces become conductive can have an even faster effect. Then, the exposure of the contaminated surfaces to the surrounding humid air causes immediately great leakage currents between bare metal areas resulting in malfunctions in the devices. According to Burnett etc. a great number of failures was detected for example in computer equipment within a few hours in the United States in the early 1990s. The failures would often occur during a thunderstorm and they were interpreted as a result of a bolt of lightning or as earthing problems. Later, however it became obvious under closer study of the problem that the component boards in question were contaminated and the faults would occur when the relative humidity of the inside spaces exceeded 75% RH, in other words the failures were in no way related to EMC problems.

The contamination particles (dust etc.) contained a lot of sulphur wherever in the US the observations came from. Based on this, the contamination was deduced to originate mostly from “industrial polluting emissions”.

When analysing the particles they were grouped into large ones (more than 2,5 μm and into particles smaller than this, about 0,5 μm . The larger particles typically contained Fe, Ca, Si, Na, Cl and Al. They were assumed to be products of abrasion, such as mineral dust, textile dust, animals and plant fibres.

The small particles originated from burning or the change of gas particles in a free air space (for example the oxygenation of sulphur dioxide into various sulphates) The small particles contained SO_4^{2-} , NH_4^+ , NO_3^- , Pb and C [Walker 1980].

The main share of these particles originates from human activity [Finlayson-Pitts et al. 1986].

The small particles of less than 1 μm and containing water-soluble salts, such as sulphates originating from sulphur dioxide emissions were especially interesting. These are hygroscopic and absorb water in “critical air humidities” typical of them and make surface contamination conductive.

Small particles also travel to the insides through the ventilation systems and contaminate all surfaces, in other words also the insides of devices when room air is circulated in them, for instance for cooling purposes [Hinds 1982 and 1998].

The increase in the conductivity of the surfaces in electronics devices can be seen as two types of failures:

In high voltage applications the increase in conductivity causes occasional breakdowns which can result in the destruction of components. The electrical breakdowns leave traces on the boards so the reasons for the fault are detectable.

In applications with a lower voltage, for example in 5 V digital applications, the increase in conductivity gradually raises the leakage currents between the wires. The harmfulness of these depends on the sensitivity of the signal route in question to leakage currents. The increase in the conductivity is especially detectable in areas where the solder resist coating has holes or is too thin or altogether missing or where the conductor spacing of the components is very small. The problems are already visible in ordinary old microcircuits where the pitch between the terminals has generally been 2,54 mm.

The faults caused by increasing leakage currents may be random and hard to trace since there are no signs left of the faults, which could be detected, in electrical tests or in maintenance. In order to get to the root of the symptoms, as precise location of the faults as possible and careful analysis of the surfaces only can lead to the identification of the causes behind the failures.

The failures caused by impurities on the surfaces are more easily observed at high voltages when drier dust can also act as the discharge route.

The isolation resistances of the contaminated boards were measured between the wires. Based on this, the isolation resistance fell very sharply from the level of $10^{10} \Omega$ at relative humidity more than 60% RH and at a relative humidity of 80% was only about $< 10^6 \Omega$. When the contaminated dust was blown away with dry nitrogen gas, the isolation resistance at relative humidity below 60% was about $10^{11} \Omega$ and fell gradually to $>10^8 \Omega$ at 95% RH. Thus, the mere removal of dust improved the resistance a couple decades even at great humidity.

Burnett etc also studied what kinds of leakage currents or parasitic resistances between the conductors the 5 V CMOS circuits tolerated. According to the results, the resistance between the conductors can be 100 k Ω before the noise

margin of the output is exceeded and the logical state changed. In analog circuits the disturbance margin is more vague, the margin was determined at a resistance of about 1 M Ω between the input wires.

The testing of the contamination sensitivity of the surfaces on conductive substances is quite difficult, but an adequate method correlating fairly well with the industry is to spray a predetermined amount of saline solution on the boards and then to conduct electrical and humidity tests on them [Sandroff 1992]. The focus should be laid especially on the observation of the isolation resistances and leakage currents and the controlling of the malfunctions of the board in order to identify the emerging failures. The operation of the boards is monitored for a day or two, which gives the information on the number of failures occurring. If there is no experience of the tests lower saline concentrations should be the starting point and the amounts and testing periods should then be gradually increased in order to reach a clear failure limit in due time.

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Appendix 2

Quality requirements of the air

Quality requirements of the air

Finnish Meteorological Institute

[http://www.fmi.fi/ilmanlaatu/ilakaupu_10.html]

The amount and nature and altitude of emissions affect the air quality. In Finland as in other European Union countries the authorities issue regulations and guidelines on maximum emissions and altitudes (height of chimneys). Traffic emissions are controlled by exhaust fume regulations.

Council of the Finnish State Decision on the guidelines concerning air quality and sulphur fall-out was issued on June 19, 1996.

Table 1. Guidelines on air quality to prevent health hazards, Council of the Finnish State Decision, June 19, 1996.

Substance	Guideline value (20°C, 1 atm)	Statistical definition
Sulphur dioxide (SO ₂)	250 µg/m ³	99th percentage point of monthly hour values
	80 µg/m ³	second highest daily value of the month
Nitrogen dioxide (NO ₂)	150 µg/m ³	99th percentage point of monthly hour values
	70 µg/m ³	second highest daily value of the month
Carbon monoxide (CO)	20 mg/m ³	hourly average
	8 mg/m ³	8 hour average
Particles		
Total suspended particulates (TSP)	120 µg/m ³	98th percentage point of yearly day values
	50 µg/m ³	arithmetic annual average
Inhaled particles (PM ₁₀)	70 µg/m ³	second highest daily value of the month
Total amount of reeking sulphuric compounds (TRS)	10 µg/m ³ (in sulphur)	second highest daily value of the month, TRS is quoted in sulphur

Guidelines for prevention of vegetation effects

To prevent direct vegetation effects of air impurities in large agricultural and forest areas and areas significant for the preservation of nature, the guideline values for the annual average of nitrogen oxides, meaning the combined concentration of nitrogen oxide and nitrogen dioxide should not exceed $30 \mu\text{g}/\text{m}^3$ (20°C , 1 atm) calculated in nitrogen dioxide and the annual average for sulphur dioxide should not exceed $20 \mu\text{g}/\text{m}^3$ (20°C , 1 atm).

Guideline value for sulphur fall-out

To prevent the effects of air impurities in lake and forest ecosystems, the long term aim in Finnish forestry areas is to keep the yearly value of the sulphur fall-out below $0,3 \text{ g}/\text{m}^2$. This guideline value should be maintained through national and international effort.

Limit values and threshold values for air quality

The Council of the Finnish State issued a decision on the limit values and threshold values of air quality on 9th August 2001 no. 711. The aim of the decision is to implement the directives of the European Union on air quality.

Limit values for prevention of health hazards

The Council of the Finnish State decision issues limit values for nitrogen dioxide (NO_2), sulphur dioxide (SO_2), total particulate fall-out (TSP) and lead (Pb). The limit values coincide with the directive of EU except for lead, which has been issued a stricter limit value than in the directive based on the recommendation on air quality of the World Health Organization (WHO). The limit values apply to areas of habitation or human presence. The limit values define the maximum acceptable impurity contents of the air. The air protection authorities must make sure with all accessible means that these are not exceeded. If the limit value is exceeded the municipal or regional environmental centre must undertake action to improve the air quality. The member countries must report to the Commission of the EU on control of the limit values, transgressions of the limit values and on action to be undertaken to improve air quality in areas with repeated transgressions.

Table 2. Limit values for air quality, Council of State decision, 9.8.2001.

Substance	Limit value $\mu\text{g}/\text{m}^3$ (20°C, 1 atm)	Time for the calculation of mean value
Sulphur dioxide (SO ₂)	350	1 h
	125	24 h
Nitrogen dioxide (NO ₂)	200	1 h
	40	calendar year

Particulates, PM ₁₀ *)	50	24 h
	40	calendar year
Lead (Pb)	0,5	calendar year
Carbon monoxide (CO)	10 000	8 h
Benzene (C ₆ H ₆)	5	calendar year

*) PM₁₀ hengittävät hiukkaset, joiden aerodynaaminen halkaisija on alle 10 μm .

Threshold values for ozone in year 2010

To protect the health of people the threshold value of ozone is 120 $\mu\text{g}/\text{m}^3$, which is the highest daily 8 hour mean value. This may be exceeded 25 times during a year as a mean of three years.

To protect vegetation the threshold value is AOT40 18 000 $\mu\text{g}/\text{m}^3\text{h}$ as five years mean value.

See also: <http://www.epa.gov/p2/>

An Organizational Guide to Pollution Prevention. August 2001, U.S. Environmental Protection Agency (EPA), EPA/625/R-01/003. 158 p.

Appendix 3

Review methodology of the corrosion control

Review methodology of the corrosion control

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1 Corrosion control in electronics company

The reviews of electronics companies for corrosion control focus on environmental product demands, effects of production and transportation on corrosion behaviour and technical solutions of the products from component level to a finished product.

The review starts with definition of the environmental conditions during use, transport and production.

A major share of the reviews focuses on electromechanical solutions in various connectors, on the circuit board and in the terminals of the components. The functionality of the EMC contacts is also verified.

Another main aim is to solve the corrosion problems due to transport and subcontracting of the materials, components and the product.

If the company does not already practise a review methodology adapted to corrosion control, the establishment of such a method is a worthwhile aim when trying out the methodology presented here. The reviews should also lead to concrete actions to improve corrosion resistance. Any ideas concerning this should always be separately listed whenever presented during the review.

The ideas for corrective action should be addressed in a methodological way as presented at the end of this review methodology.

2 Verification procedure for corrosion resistance

The verification procedure for corrosion resistance design should be separately planned for each project and linked to the rest of the product development process. The nature and scope of each product development project and existing information on earlier products all have an effect on selecting the best way to carry out the verification.

Since the technical and logistic solutions concerning corrosion control have a large effect on the mechanics, platings, choice of components and the logistics of manufacture and acquisitions, the *first reviews* should be conducted already in the early *inventive and definition* phase and the early part of the planning. These preliminary reviews are meant for checking the general effects of the technical corrosion properties on the product and product development. It is important to agree on the organisation of the planning and the reviews of the results of

corrosion resistance planning and its effects on the product. The reviewing shall also be extended to subcontractors and suppliers of materials. At the same time, the aims of corrosion resistance planning as well as the quality and scope of the content are agreed and an initial plan formed about which tests and measurements will be used to support the verification.

In order to define the *agenda of the verification* and its methodology, a list is presented in the following on the issues that should be included in the reviews. The various issues should be addressed depending on the stage of the product development at which the review is conducted.

At the same time, the *nature of the verification target* should be kept in mind; in other words whether it is a question of a narrow component board level (plug-in unit) or an extensive system level verification or something in between. First, the method of conducting the verification in the case at hand is drafted, the accuracy of the verification is then defined and the applicable tests and, finally, measurements and the persons to be involved are selected.

It should be checked whether there is existing *earlier data on the design and testing* of the product in question and whether that data is still relevant in connection with the verification of a new planning project. The cost level of the verification and the risk level for accepting the product into production are set at this stage.

It is not the role of the verifier however; to design the product since the designer is in charge of the planning process and its result and also for the organisation of his work. The verifier helps the planning work to proceed towards the desired result.

General contents of the verification process

1 Definition of the verification target

Identification of the part of the product development to be verified, familiarisation with the identified target and its general aims. Both the designers and the verifiers of the products shall sufficiently familiarise themselves with the product in order to feasibly focus the content of the verification process itself in relation to the product development project and to gear it to the technically important targets.

2 Timeline for design reviews

The verification of corrosion resistance planning is started at the inventive and definition phase of a product or product development projects where the aims for the development work are set. The reviews are timed to coincide with the crucial phases of the project, such as goal setting, definition of the level for corrosion resistance, selection of material and component data, selection of planning principles, selection of the degrees of protection by enclosures (IP-code), use of tests and measurements, evaluation of the planning result and planning of the gathering of field data. It is important to time the reviews for sufficiently early phases in order to integrate the effects of the choices made on the various branches of product development as well as possible.

If possible, one should define the times and the content of the reviews to be conducted with the subcontractors as well.

3 Organisation

The persons to participate in the design process and the verification of corrosion resistance planning are agreed. The participants in the reviews held during various stages should include as appropriate the manager of the product development project, the project manager for corrosion resistance planning, the person responsible for quality and other designers and quality managers responsible for other areas of planning, such as electrical, mechanical, heat, EMC, logistics and environmental design.

Also persons responsible for the choice of components and materials should participate in the relevant reviews. The use of outside experts with a thorough knowledge of corrosion control or parts thereof is recommended especially for the review on the principles and testing methods of corrosion resistance planning.

If the product development has been divided to various organisational units or delegated in part to subcontractors, sufficient agreement should be reached on

how the information related to corrosion resistance planning (specifications) will be exchanged and possible reviews held. It is especially important to define the scope of each delivery that the organisational unit is in charge of. It is the task of the project manager to ensure that sufficient overlap is introduced in order to avoid gaps between two responsible units in crucial matters.

The staging of the work in corrosion resistance planning according to its content should be agreed in connection with the product reviews of the early stages in order to give each designer a complete enough picture of their tasks and responsibilities. The functionality of the border areas in this area must also be ensured by sufficient contacts between these persons in order to avoid “grey patches” or no man’s land in the design.

4 Reporting procedures

Documentation of the verification results is necessary for ensuring the chosen solutions, test results and the eventual corrective action. The verification reports should contain the matters reviewed as well as the various problems and their handling, corrective action with grounds for it and the results of the new reviews together with the contact information of the persons who carried out the verification process.

It is useful to have a logbook on the details of the design in corrosion resistance planning. The log assists in the gathering of experimental data. In addition, these notes should ensure that another designer could use them to deduce the reasons for certain solutions that have been adopted. This will also reduce the interference caused by a change of designer in the middle of the project.

Tests and the related measurements should be planned in advance. Solid advance planning reduces the risk of losing information because of testing mistakes and the need for second tests. Careful advance planning also reduces the work needed for documentation and analysis.

5 Planning of corrosion resistance

The procedure should be directed to at least the following areas in the actual verification of corrosion resistance planning:

- aims for corrosion resistance
- environmental tolerance, mechanics, thermal planning, EMC etc.
- aims for reliability, risk prone wiring patterns and components
- official regulations and standards applied by the company
- material and component information, (platings, failure mechanisms)
- basic technical anti-corrosion solutions
- transport logistics and corrosion resistance of products from subcontractors
- integration of measuring and testing needs in the design
- planning documents and logbooks, and backup copies of files.

In the planning, the focus is directed to the uniformity of the chosen basic solutions and the actual climatic conditions.

6 Analysis methods and measurements

The analysis methods used in corrosion and climatic tests provide real information on the device, which also corresponds fairly well to the conditions of use. The verification checks the qualitative and quantitative needs of the measurements and the planned analysis methods (visual inspection, microscopy, contact resistance and special resistance measurement, SEM, functional tests etc.) in relation to the product development task. The need of analyses must be recognised already in connection with the planning and the designer should define the targets for the testing and the ways of analysing corrosion and climatic effects in the tested products.

The verification of the analyses should include the following checkpoints:

- choice of analysis targets for obtaining useful information
- choice of analysis methods and technical accuracies
- possible measurements of platings, materials and component boards
- possible misinterpreting in the analysis results
- collection, recording and documentation of analysis results.

By preplanning the analyses and the measurements, easily occurring mistakes in the actual measurement situation can be reduced. It can also be ensured that the data for verification of the design will actually be obtained from the measurements. Preparation of studied measurement documentation prior to undertaking the measurement should provide some help here.

7 Testing

During testing the prototype of the product or the finished product is subjected to the desired stresses related to the environment and the usage situation. Basic testing can be carried out in laboratory conditions by using the device at normal or maximum loads. According to how much information is desired or needed, the device can also be subjected to the various extreme conditions encountered during its use. Typical tests related to corrosion resistance planning are static and dynamic humidity and heat tests and various chemical and gas tests. Mechanical vibration can also be used in the testing of corrosion properties. It is important to ensure in these tests that the product

- will function in various extreme conditions
- will not be damaged by the test conditions
- will not corrode excessively in the tests
- will function reliably throughout its planned operating span.

The stress level of the tests can also be increased stepwise to a level that will trigger a failure in the device. This is done to find out how far the failure limit is from the limits of the normal environmental specification. It is important with regard to the corrosion resistance planning as such to ensure that the corrosion protection qualities, tightness of the packaging, paint platings, connector platings etc. conform to the plan in the tests. At the same time, the conditions of the testing environment must also conform to the testing specifications.

The tests should measure actual corrosion and the parameters describing the electric functioning of the product, (malfunctions, contamination and corrosion of the surfaces etc.), in order to see how close to the design aims one is. Collection of information on mere functions/malfunctions from the tests may result in gross judgement errors when evaluating the functionality of the product. If the ingredients transmitted through the internal surfaces and casing of the device are not analysed, crucial information on the operability of the device in use will be lost. Correspondingly, the contact surfaces of the various connectors (contacts and shells) should be studied in the vibration tests for visible wear which could affect corrosion resistance.

In connection to the production one may use some simplified tests and especially the visual inspection to ensure the correct quality level of the most critical parts and deliveries from the subcontractors.

The testing plans and test results are studied during the verification and it is estimated if the tests are sufficient to describe the environmental stress of the product in question. The corrective action caused by eventual deficiencies is also checked together with the need to renew the tests.

8 Use of field data

The plans for the use of field data related to corrosion control are checked. Is there a plan for data collection and how will this be carried out? Has the service organisation been issued guidelines for recognising corrosion and for drawing up fault reports?

The field data on follow-up and faults is compared to the planning and test results. The reasons for possible differences are analysed, are the differences due to exceptional conditions, mistakes in the design, qualities of the components or the materials, transport logistics or changes in the construction of the device during production?

There is also feedback in the field data concerning the following areas: environmental conditions, mechanics, ergonomics, safety, human needs, EMC, electrical design and wear of materials. All these have an effect on the corrosion resistance design.

It is ascertained if there exists feedback documents, which are applicable also for solution of corrosion, related problems.

It is ascertained that the field experience is used in the following stage of product development and in the corrosion resistance design of new products.

9 Evaluation of planning and test results

In practice, a review should be arranged when the product development project is finished in order to verify the result. The results of the planning and testing of the device should be summarised in the review and compared to the previously set goals. All the aims in the planning are seldom achieved, partly due to technical reasons and partly because of various schedules, cost and other such limitations. On the other hand, only the products that have reached the customer from the production can yield relevant information on the behaviour of the product when put into use. It is worth paying attention to the feedback from the field related to for instance guarantee repairs, since only in this way can the designer obtain data on how feasible the planning has been in actual use conditions. He can thus develop his technical solutions.

The checkpoints during the final review should include among other things:

- achievement of the planning goals
- indications to change the objectives with regard to future needs
- feasibility of the design solutions for the product in question
- test results and the action resulting from them
- corrective action with regard to the product and planning of corrosion resistance
- collection and processing of feedback from the field
- recording of ideas related to planning and the product that open new possibilities for future needs

10 Relationship of verification to design goals

The verification normally centres on checking the application of the set aims and generally recognised design rules. The verification can be extended and the results of product development improved if the regular solutions are questioned and better means for improving the product qualities actively searched during the review.

The aims of product development should be evaluated when the planning progresses, then the design team may achieve even a better overall result concerning product quality than the original aims. Therefore, it would be useful to process these evaluations with the designers focusing on different planning areas.

It is an important part of product verification to assess the goal setting as such. The assessment addresses the aims for corrosion resistance, the degrees of protection by enclosures (IP-code), platings, power, temperatures, mechanics, materials, user conditions and testability. In addition, the effect of issues related to various environmental factors, ageing of materials, safety requirements, EMC limitations, ergonomics, energy conservation etc. on the aims of the planning is verified.

In order to recognise the stress level of the component boards and the components, the most failure sensitive platings, and components should be identified as well as the limitations and demands on the planning of any exceptional stress on them such as humidity, air pollution, overvoltage, changes in temperature, mechanical stress etc.

An example of a risk prone technique is the blowing of a great amount of air through an electronics cabinet, which can result in continuous contamination, high humidity and continuous changes in temperature. All of these accelerate various corrosion mechanisms.

3 Technical sub-areas of the review

Corrosion control in products is based on knowing the product characteristics, materials and the various environmental effects. The main environmental effects with regard to corrosion are humidity, heat, impurities in the air, the chemicals used during manufacture and use, and mechanical vibration. Figure 1 below outlines the factors to be addressed in the review.

Since corrosion effects are always a combination of various parallel effects and the effect on the product behaviour is often difficult to detect, the recognition of different failure mechanisms would be an important result of the review in addition to concrete suggestions for corrective actions.

Physically, one of the most important areas of corrosion control of an electronic product is to recognise the combined effect of temperature and air humidity on the degree of wetness and the resulting jump in the acceleration of corrosion even in mild climatic conditions. Especially running water or water condensing on the surfaces together with impurities in the air or on the surfaces greatly accelerate corrosion and generate bridges that conduct electricity between the wires.

The starting point of the review is to limit the entity to be reviewed. Therefore, the first task in limiting the review is to select and describe the actual target (product, production, user environments) and to characterise this in an understandable way in order to identify clearly the area of validity for the review when evaluating the results.

The review targets on an individual product and its design, manufacture, subcontracting, intermediate storage, transportation and customer use.

For all these targets, it is estimated what kinds of environmental (corrosive) effects occur and which means can be used to improve (optimise) corrosion resistance. The important thing in processing each detail is to assess the actual effect of eventual corrosion on the user properties of the product.

The review outline presented in the following is for intended reviewing of the electronics. It can be applied to all kind of electronic products.

Corrosion and climatic effects in electronics

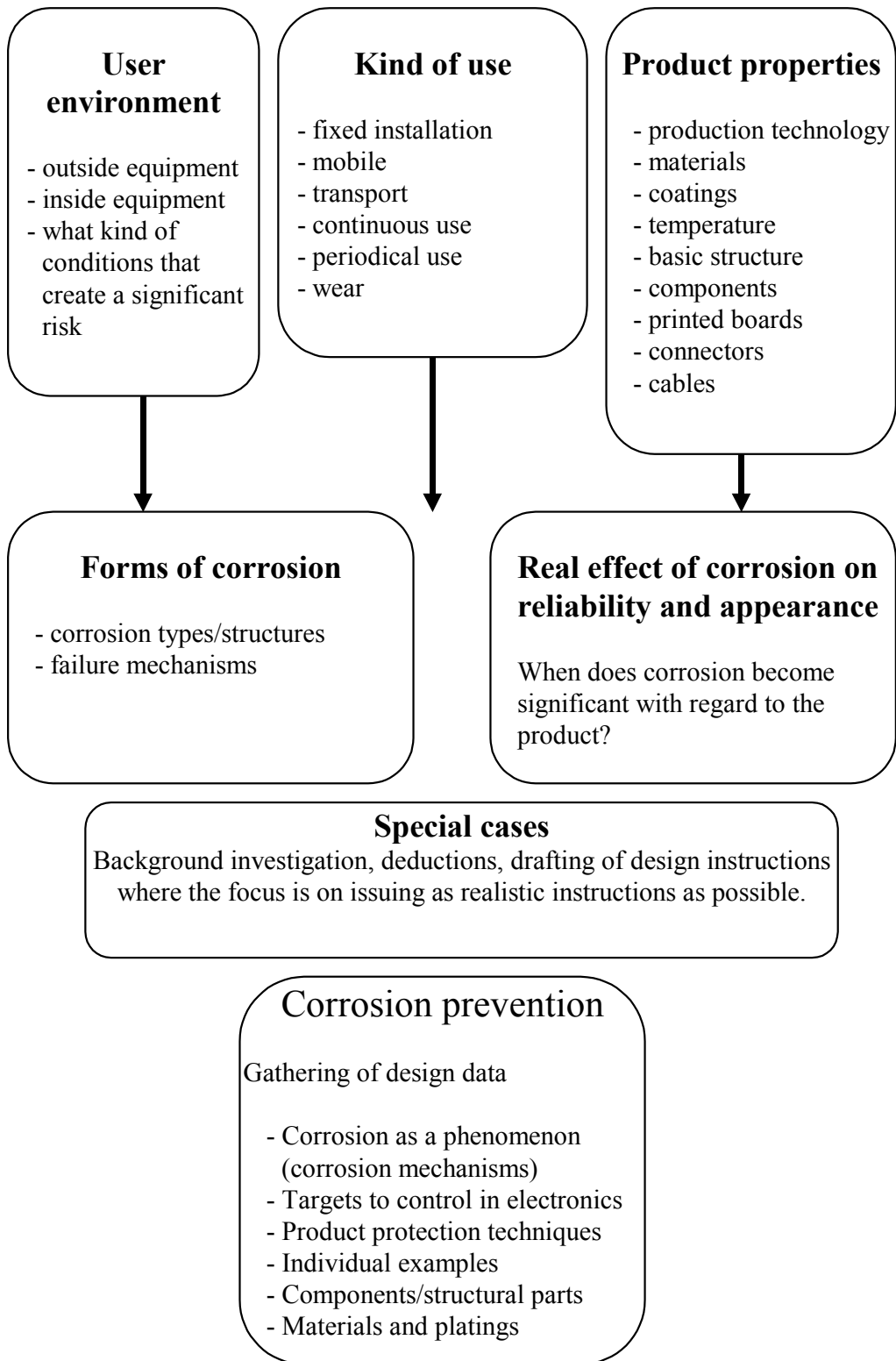


Figure 1. Areas of design review for corrosion control.

Please note that the **review is mainly limited to external parts outside of the components**. This is why, as a rule, only the property of the terminals (connecting wires) and protective casing of components is addressed here but for instance internal corrosion of the microcircuits is omitted.

The following areas are included in the review

- environmental effects
- details of the product structure based on corrosion sensitivity
- specifications of the product and its parts
- logistics in production, parts and product distribution chain.

The reviews always yield some ideas for action; the process for discussing these ideas is included in the suggestions below.

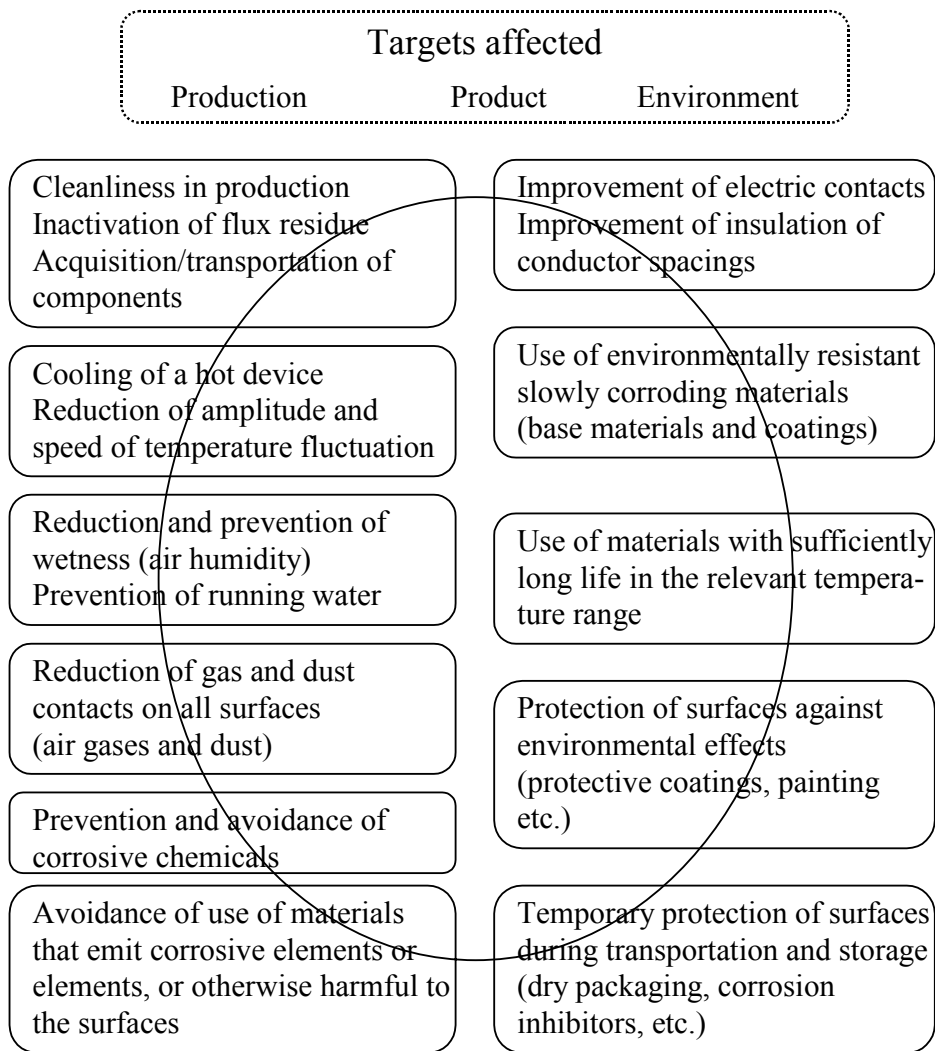


Figure 2. Principal physical means of corrosion control.

The principles for reducing corrosion risks presented in Figure 2 should be included in the reviews. Arguments for the choices to be made are looked for in the reviews, whether the product (structural means), the production methods and/or the use conditions are to be affected.

When considering any action, one must recognise the means and their physical effects on the product qualities, in this case especially corrosion resistance.

At the same time, care should be taken that the action in question does not deteriorate the electric or thermal resistance of a contact, for instance in such a way as to create EMC or thermal problems.

The responsible persons for the following areas should be included in the reviews as appropriate:

- sales
- acquisition of components and parts
- electri/thermal/mechanical/EMC design
- transport logistics and transport packaging design.

Corrosion control in the entire logistics chain

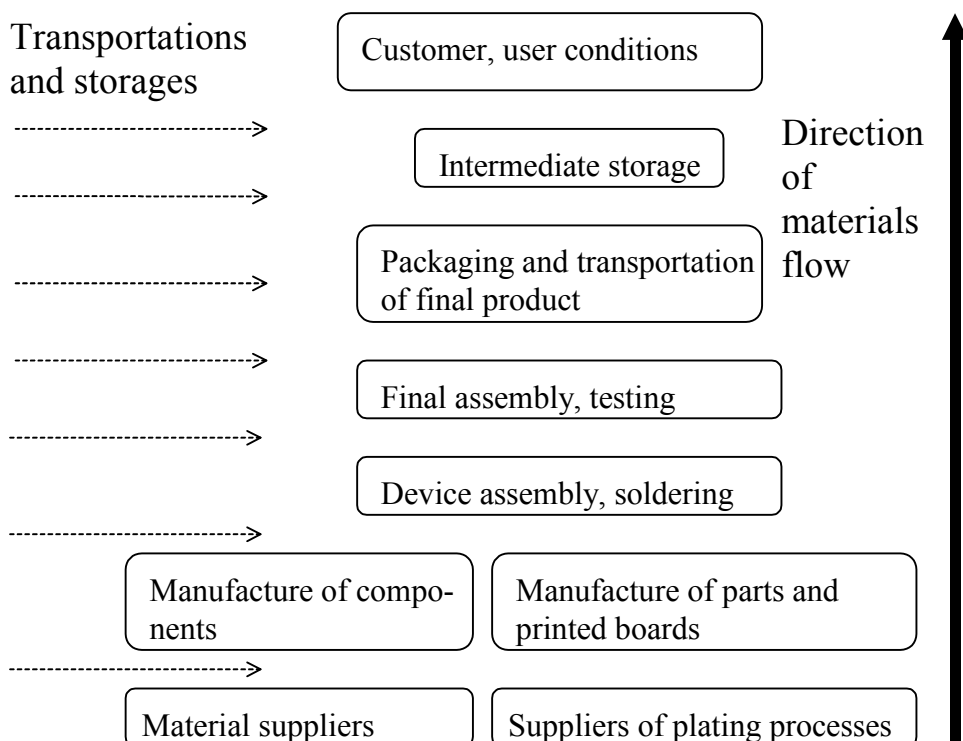


Figure 3. The entire logistics chain is involved in corrosion prevention.

Figure 3 presents a principal model of the logistics chain of manufacturing a device. It is important to extend the action also to subcontractors in corrosion prevention and the related review, since most of the surface plating and other materials processing affecting corrosion resistance is performed by the subcontractors.

The conditions during transportation are often out of control. Therefore, corrosion takes place easily during transportation and storage. This has an important effect on the soldering properties and the appearance of the product. The transportations between the various stages of manufacture of the individual product parts create obvious risks because of the uncontrollable climatic effects during the transportation. An ideal transport for all parts would be in dry conditions, which are protected from environmental pollution.

In some instances, the finished products are transported and put into intermediate storage in very inferior conditions. In such instances, careful packaging of the product (nitrogen gas or vacuum packing) is the only protective means.

4 design review method for electronics

4.1 Scope of the review target

The product or the product family to be reviewed is chosen and its characteristics described, such as

- users and geographical area including environmental conditions
- technical special characteristics and basic technology
- manner of use (portable, mobile)
- manner of production and subcontractor relations.

These are shaped into a general net of activity and an image is formed as to what happens where with regard to corrosion. It is crucial to recognise how the product is handled during subcontracting, production, transport and the customer's location of use and what type of stress with effect on corrosion occurs during these stages.

When limiting the target one should at first view corrosion on a scope as wide as possible since a technological, structural or operational change might suddenly create significant corrosion risks. When the general picture about matters related to corrosion has been formed, the main review can be limited strictly to an essential subsector.

During the review, one should create seamless co-operation between the electric, mechanical, thermal, and EMC planning groups. Those responsible for logistics and marketing should also be included in the reviews on corrosion control. Marketing may wish for solutions that are not technically feasible. If some of these groups perform changes only on their own terms, new corrosion risks are fairly easily created.

4.2 User environment

The external environmental conditions specification for the product is checked. The specification includes the environmental conditions during production, transport, storage and use. The environmental classifications defined by the International Electrotechnical Commission, IEC (IEC 60721 Classification of environmental conditions) may be used and eventually supplemented by product specifications.

The total stress created by the environment of the final product and the characteristics are studied including issues imported by human behaviour. The stresses directed to the outer shell of the electronics device are defined as thoroughly as possible:

- “Normal” user conditions taken automatically into account and
- “exceptional conditions” together with additional stress from humans/ animals“.

Electronics is used all over the world but it is possible to include some geographical specifications (alleviations/stricter specifications), since the production is also taking place in factories in various geographical locations.

More detailed specifications on both normal and exceptional conditions should be drawn up and checked on a regular basis.

The specification on the external environmental conditions of the product can be used both as customer specification and as the subcontractor specification concerning the manufacture of the external parts of the product.

Significant stress factors for corrosion are

- temperature and its fluctuations
- humidity, rain and freezing
- impurities in the air, gases and dust (including metal dust, pollen)
- biological effects in a humid environment, mildew, algae, microorganisms
- chemicals of animal husbandry, ammonia, pigsties, chicken coops, fisheries
- emissions of the process industry
- liquid and other such chemicals
- mechanical vibration.

Since the products will be used in all kinds of human activity, it is important to verify how the environmental specifications incorporate the typical conditions of various professions, which do not usually occur in urban conditions. For instance, the humidity and dust in earth construction, ammonia emissions of the byres in cattle husbandry, the sweating of a lumberjack or an athlete, emissions of the wet end of a pulp factory, ships, mines etc.

When drawing up and testing the environmental specifications, one should always check if condensation is allowed and taken into consideration in all its forms. Usually the devices with most corrosion have some time held water in

liquid form, which results in an increase by decades in the corrosion speed compared to dry conditions (RH < 40%).

4.3 Internal microclimate of the product

The internal condition specification for the product is reviewed using the external environmental specification as a basis. It is checked whether the specification includes the stress due to the functioning of the device itself or alleviations in the conditions. This enables verification of the tolerance for factual environmental stress required for the components. The packaging of the product protects the components on one hand and on the other increases the stress by increasing the use temperature, for instance.

The effect of the packaging structure of the product and of the used materials on the tightness of the product and on the quality of its internal climate and the effects of the occurrence of internal emissions (battery, plastics, glue etc.) are studied. It is also checked whether liquids, gases or dust find their way inside the product and accumulate there. It is also checked if the demands caused by this are included in the environmental specification.

As a part of the internal climate, it is checked whether the mechanical construction of the product and the quality of the surfaces allow easy condensation of water on the surfaces and capillary cracks. If this is the case, internal condensation and water accumulation into the cracks must be included in the definition of the internal microclimate of the product. This, in turn, affects the choice of platings, protection and materials.

Mechanical conditions should also be included in the internal climate of the product. For example vibration and bumps have a tendency to cause changes that promote corrosion in the platings and parts.

Therefore, when dealing with the internal conditions one should verify whether or not the risk for corrosion caused by the phenomena described in the above is accounted for.

4.4 Production environment

The environmental stress caused by the production environment is reviewed during all stages of the production in the final assembly as well as at the subcontractors' manufacturing the various parts.

The parts of the product are more sensitive to corrosion than the final product because the parts can be exposed without protection during transportation, storage and production. Corrosion is usually visible in the production in that soldering becomes difficult, as malfunctions or only as a visual deficiency. Various residues (dirt) remain on the surfaces of the product in the production as well as surface marks (scratches, dents) which may increase greatly the sensitivity to corrosion.

The printed boards of the product may have large contact areas (keyboard, EMC contacts, connectors) which may be already corroded because of transportation or storage conditions. Keeping these surfaces clean in every phase is important for the functionality of the final product.

The defined production conditions and the specifications for the loading and unloading docks during transportation as well as the intermediate storage conditions are checked.

Any corrosive chemicals, gases, dusts, air humidity and the general level of cleanliness in the production environment are inspected.

The solderability of printed wiring board may deteriorate during transport and storage but also during the soldering process itself some amount of corrosion develops on lands of printed wiring board. In a multiphase soldering process high temperature and/or solder fluxes corrode lands. This happens if components are assembled in many separate phases between successive soldering on both sides of printed wiring board, where lands are bare to make possible soldering in the next phase of the process (Look Section 4.13 *Soldering and corrosion*).

Soldering process remains various residues from e.g. fluxes, which are meant to help solderability. It should be inspected that there is not on component boards too much ionic electricity conducting debris and the residues of fluxes do not later cause corrosion problems, especially if no-clean soldering process is used.

During production, grease and other such impurities are easily left on the surfaces if the products are handled with bare hands. Creams and perfumes, which may contain silicon, are especially harmful, since silicon makes soldering more difficult and reduces the adhesion of protective platings to the surfaces to be protected. (IPC-A-610B Acceptability of Electronic Assemblies, USA December 1994, January 1996, pp. 5–6).

The actual production processes, such as assembly of components and soldering, may also leave corrosive residue on the products (for example oil from the assembly machine and flux residue from soldering). It is checked if the effects of these have been attended to in the planning. Such residue may also increase corrosion.

Mechanical stress, blows, torsion and vibration may cause microscopic cracks in the printed boards (surface mounted components) which may become manifest only gradually when the corrosion through the cracks begins to take effect. Correspondingly, the various platings may become scratched for various reasons, which facilitates the start of corrosion. Therefore, a part of the prevention of the effects of corrosion is to avoid too great mechanical stress.

The methods applied in the production, the purity in the handling of the parts and the possibilities to damage the various contacts and connectors mechanically are checked. For example, is there a need to open and close some connectors several times although the specification for connectors would allow only a couple of openings/closings? The evaluation of these details helps in locating the risks for promoting corrosion and other harmful effects during product assembly.

The above issues are addressed in the reviews and the suitability of the handling procedures assessed and alterations to them discussed.

4.5 Transportation and storage

The transportation of the components and parts needed in the manufacture of the product always involve a great risk for all kinds of environmental climatic and other effects such as heat and cold, changes in temperature, wetness, dust, exposure to sea-air and mechanical damage.

During container and sea transportations, there is always a great risk for the transport pallets (wafters) to be subjected to dripping salt water and relative humidity of close to 100%. Air transportation entails great changes in temperature, humidity and air pressure.

There are clear corrosion risks in the transportation of the finished product to the customer already during the packaging at the factory and the assembly of transport cases. Correspondingly, the handling of the packages, the drying method of wet packages and storage in unstable conditions at the receiving end can damage the product and launch visible corrosion.

The basic problem in packaging technology is to find a method that avoids sealing a great deal of moisture in the package (product package, transport pallet) with the air and the packaging materials. Water will condense on the surfaces, especially metallic ones, in cooler transportation temperatures. This is apt to cause corrosion and mildew growth for instance in adhesive labels. One means is to use breathing packaging, another means is to use vacuum or protective gas packaging and a third means is to use water absorbent substances (silica gel) in a sufficiently tight product transportation package.

The basic problem is to transport the parts and the final product packaged in such a way as to keep the surfaces of the product dry and clean despite external stress. The problem is to avoid wetting of the product parts due to condensing water during some part of the transportation of the product. Condensation accelerates corrosion to such an extent that even a couple of hours of wetness can ruin the product or make soldering significantly more difficult.

If the products are not packaged protectively for example for short distance transportation from one factory to another, the transportation should take place quickly from and to sheltered loading docks in covered trucks. It should be made sure that the cargo does not remain in the car overnight or over the weekend and become exposed to the effects of humidity.

Also the storage methods for the components and parts and the allowed storage times need to be verified. This includes checking the dates of manufacture on the incoming supplies in order to avoid outdated merchandise.

During the review, the demands on the transportation and storage procedures and conditions and on the turnover of materials are inspected.

4.6 Case structures

Depending on the manner of use the outer case (shell, cabinet) may become exposed to various chemicals. Portable devices can be carried inside the clothes where humidity may be considerable, especially in a warm climate and during exercise.

The design of the tightness of the case is inspected during the review; is the case an open, breathable or sealed structure? A half open breathing structure is probably feasible. It is possible to estimate the incoming residue based on the openness/tightness of the case and deduce from this what kind of protection is needed for the inner structures. What kinds of openings are permitted?

It is always possible that water condenses on the outside and inner surfaces of the case or on other parts at some point during the life cycle of the product. Condensation takes place most easily on bare metal surfaces and capillary cracks, in other words in points generally prone to corrode. A bare metal surface may cool (but also warm up) faster than a painted surface which isolates heat slightly. The coat of paint may also absorb some moisture, which leads to slower wetting than on a bare metallic surface.

Capillary gaps (cracks) collect water, which does not come out very easily. Since there are always some impurities on the surfaces and in the air, such as salts, the condensing water travels to the gaps easily and stays there.

The water collecting properties of the above structures are checked together with the sensitivity of the outer case to corrosion and UV light. In addition, the sensitivity of the structures and the outer shell to substances that are left on the surfaces as a result of human activity are checked.

It is checked how the frame structure supports the inner parts, whether its movement causes repeated stress and torsion to the joints and the connectors, for instance. Does the frame structure maintain to a sufficient degree the contact pressure of large EMC contact areas?

Does the frame structure tolerate mechanical vibration for example in vehicle installation? Does this mode of use cause extra friction and stress on the various contact surfaces and connectors?

Are possible seals elastic even after five years?

Can the thermal expansion due to thermal fluctuation cause friction in the structures and the contacts and result in abrasive corrosion in the connectors. Are the thermal expansion factors of the various materials close enough to one another (case, frame, EMC seals, printed boards)?

4.7 Keyboard

The keyboard is in contact with the user for much of the time and it is also a component that wears, its internal structures and outer shell wear down and deteriorate due to mechanical stress alone. The keyboard also forms a major part of the packaging structure (its outer shell). Therefore, the same chemicals as the rest of the outer shell affect it.

The ageing properties of the outer shell of the keyboard are checked with consideration to permeability of moisture or running water. The permanence of markings is also considered. Is the material mechanically and chemically durable and can it withstand the effects of ultraviolet (UV) light?

Can excretions from skin and skin creams creep inside the keyboard where they may corrode contacts or prevent the mechanical function of keyboard? Do these materials have some harmful effect on materials of keyboards?

The tightness of the keyboard compared to the rest of the package is checked. Are the joining seams as desired? Can water collect inside the keyboard or around it due to the capillary effect?

The corrosion and wear of the keyboard contacts in use increase contact resistance and leakage currents. Are the platings compatible in the different contact halves? Do they last throughout the desired life cycle?

How the keyboard is repaired? Is it possible to clean it mechanically or with detergents, is there any guidance for service organisation?

4.8 Display

The display is basically a relatively well protected and stable part in the packaging structure of the product.

The tightness of the display itself and its sensitivity to the effects of humidity and to the collection of water inside should be checked. If water gets inside the device (condensation, accident) does it absorb to the display itself or the external connectors of the display?

The connector of the display to the printed board may be opened. Its corrosion resistance follows that of other corresponding connectors. Sometimes the terminal density of the connector may be too high; a risk for shortcuts between the conductors may arise from metal migration or conductive dirt and other particles.

How the display is cleaned? Is there any instruction for use and service? If some liquid detergent is used it may deteriorate the display.

4.9 External contacts

Various connectors for auxiliary devices etc. can form external contacts of the product.

In connectors that can be opened and closed, the corrosion problems are related to mechanical wear of the platings. The compatibility of the metal platings of the two connector halves also has an effect on the progress of corrosion. Therefore, resistance to wear and materials that function well mechanically/electrically are crucial for the operability of the connections.

The basic problem for all of these is the sensitivity to dirt due to the activity of the users themselves and to the access of outside air directly to the contact surfaces. This can be avoided for instance by designing the contacts in such a way as to prevent the user from touching the most sensitive contacts.

The antenna, battery or the SIM card contacts of a mobile phone are not usually opened. In these, slow corrosion may be dominant. This can be temporarily remedied by opening and closing the connectors a couple of times.

The wear resistance of the platings, the stability of the electrical operations, the mechanical flexibility of eventual spring contacts, enough latitude (in order to prevent the excess reduction of a contact surface due to a minor fault in the position) and the chemical inactivity of the surfaces are issues that help in the control of the corrosion sensitivity. It is also checked, if the joining mechanism of the contacts is such that it prevents damage to the contact areas in normal use.

The external contacts also form partial openings on the outside surface of the device. These have significance to the ventilation of the parts inside and in case of accidental wetting.

4.10 EMC and corrosion

The electromagnetic compatibility (EMC) properties of equipment may be deteriorated if conductors, contacts, shield covers and metallic coatings meant for EMC protection are gradually corroded during use and storage.

Reasons for deterioration of EMC properties base on increase of contact resistance and decrease of insulation resistance. In high frequency circuits (about 1 GHz) EMC problems may increase because of skin effect phenomena, which concentrates current on surfaces of electric conductors. Thus even very tiny corrosion, which changes surface resistance and capacitance cause reflection of

e.g. high frequency ESD pulses from these discontinuation points (ESD is electrostatic discharge).

An electronics device may have large contact areas for EMC (electromagnetic compatibility) protection where different materials are set against one another, such as various metals (Al, Cu, Ag, Au, Sn, Zn, Fe), printed board platings, conductive paints etc.

The demands on contact resistance (resistance/contact area/length) set by the EMC designers are inspected. The verification of the adequacy of the material qualities is based on this: compatibility of the materials, resistances, corrosion sensitivity and the retaining of elasticity of elastic materials, for instance.

When EMC seals are used, it should be checked that the design of the contact surfaces/areas is such that no water can be retained in between the surfaces or that at least the central area remains dry in all conditions.

If the parts are transported to another factory after the manufacture of the EMC seals, the transportation package of the parts and the handling instructions are checked in order to prevent the seals from damage or corrosion during these stages.

As the EMC contacts are not usually opened, they are not subject to mechanical wear. Corrosion can take place slowly because of a relatively closed space. It is checked, whether capillary gaps/cracks where dirt and water may accumulate remain between the surfaces. If different materials are in contact with one another, more corrosion occurs than when identical materials are used.

If the EMC-contact resistance should be milliohms for the contact points and material containing Al or Cu is used against an Au plating, there is an increased risk of the weakening of protection due to galvanic corrosion.

It is checked if the EMC protection is continuous, in other words if sufficiently large cracks remain even after design to offset the significance of the actual EMC contacts.

The fixed seals of the equipment case shall be inspected. The opening and corrosion of these seals may change them into slot antennas, which deteriorate the EMC properties.

4.11 Basic properties of connector contacts

The mechanical design of the connectors, of material choice and platings together determine how sensitive a joint is to corrosion, or how much and how quickly the electrical resistance of the joint will increase. Heavy contact pressure reduces the early effects of corrosion, a chemically inactive gold plating will not corrode but a thin precious metal plating ($< 1 \mu\text{m}$) is always porous allowing relatively easy corrosion of the non precious metals underneath (Cu, Ni). Small contacts and contact pressures are problematic because a very small fault in the plating of the contact point may cause loss of the signal route because of minor corrosion. The opening and closing of connectors wear down the surfaces and can temporarily lower the resistance but wear also accelerates corrosion and brings about faults in the joint more quickly.

The following basic details are checked on the connectors

Based on the size of the current and voltage, it is checked if the contact is a low signal contact ($I < 100 \text{ mA}$ and $U < 1 \text{ V}$) or a contact with a stronger signal. In contacts with a low signal, very minor corrosion products on the surfaces may cause contact disturbances, since no electrical spark-over takes place on the contact surfaces as in contacts with stronger currents and voltage.

Plating materials are chosen on the basis of the environmental conditions, contact current, contact forces and times of openings/ closings. In practice, only plating materials such as Au, Ag and AgPd are feasible in contacts with a low-level signal. Of these, Ag materials corrode rather easily, whereby the selection narrows. Platings with Ag and Ni are feasible for stronger voltages since the current/voltage passes through thinner oxidation and other corrosion films. A Sn-coated connector functions well (is resistant to corrosive conditions, has a soft gas-proof contact point), if the contact pressure is sufficiently high and the connector is not opened more than a few times.

The hardness of the surface and its evenness has an effect on the wear-resistance. Relatively hard plating is more wear-resistant but the contact surface remains smaller than with soft platings. Soft plating is feasible for connectors not regularly opened. The contact quality is better than with hard platings. Soft plating is pliable and can form an almost gas-tight contact, which corrodes more slowly than worn hard plating.

The basic properties of platings are:

- composition of the plating material
- composition of the intermediate layer, if any
- composition of the base material
- thicknesses and evenness of layers
- hardness of the plating layers
- porosity of the plating
- adhesion of the surface (adhesion of the layers on the base)
- roughness of the surface.

The basic problem of the use of very thin layers of plating is their inferior mechanical durability and the porosity of the plating. Thin plating in electronics connectors is of a thickness of less than one micrometre.

The manner of processing metallic platings and the finishing of the plating (polishing, lubrication, inactivation) can have a drastic effect on the corrosion of the plating. In connectors that are opened, lubrication is sometimes used to reduce friction and to protect the connecting point. The measuring and definition of these properties can usually only be based on corrosion resistance tests and user experience.

The spring properties of the spring contacts should be adequate (sufficient contact pressure, long life). Brass will give in and not maintain the spring force in use. Even a couple of connecting times may cause permanent disfigurement. Therefore, a spring made of Beryllium Copper (BeCu) or Phosphorous Bronze (SnCu) and designed for a large enough spring motion will ensure sufficient contact pressure throughout the life cycle of the product.

Too much bend of the contact springs during use may in some cases cause problems because the bending limit of the spring material is exceeded or because of cracking of the hard plating of the spring. For example, a testing method for the viscosity of nickel plating on steel is given in standard SFS 4446, Appendix C on electrically precipitated nickel platings. The minimum requirement is that the plating can stand a stretch of 8% without breaking. According to the standard, the test is performed on a nickel plating of a thickness of 25 µm. Such a stretch is formed on a contact if the bending radius is too small. Bending tests suitable for electronics components which can also be applied on the testing of coated wires or keys are given in standard IEC 60068-2-21 (1999-01) Environmental testing – Part 2-21: Tests – Test U: Robustness of terminations and integral mounting devices.

The number of connecting times sets limitations on the choice of thickness and hardness of the platings. Thicker and harder contacts must be used in continuously opened contacts and the surface pressure must not be too high. Softer platings and possibly greater surface pressure may be used in contacts opened only occasionally, whereby the contact point is gas-tight and will not corrode so easily.

Fretting, which means an abrasive motion of the contact surfaces against one another may, in some contact structures, cause corrosion of the contact point (fretting corrosion, abrasive corrosion, friction corrosion). Mechanical fretting motion extracts metal particles from the surfaces and may create polymers of the gases in the air catalytically with e.g. palladium compounds. Tin platings are especially sensitive to fretting corrosion since tin oxidises quickly and is soft. The conductivity of the oxides and other compounds forming in the contact points is not good. On very thin or soft platings fretting may expose the underlying metal or hard plating may fret through the opposite soft plating.

The mechanical fretting motion of the contacts usually results from mechanical vibration, the electromechanical force caused by strong alternative currents and the changes in the ambient temperature. The amplitude of the movement may extend from a couple of micrometres to a hundred micrometres.

In the review, the (structural) sensitivity of the connectors to mechanical abrasion is checked. The probable frequencies and amplitudes of vibration, temperature fluctuations and electromechanical forces are checked and the materials and the contact pressures used with the platings ascertained.

The location of the connector contacts in the shell and the design of the shell should be decided in such a way that small errors in the position when joining the connectors will not damage (bend etc.) the connector. A wide enough flexing margin for the connector contacts should also be ensured in order to avoid permanent disfigurement to the contacts due to joining.

The required isolation resistance and maximum voltage limit the wire gaps. The risk of shortcutting in wire gaps of less than 0,2 mm is great since already relatively small loose particles (for example metallic particles) can cause a shortcut. Also the risk of migration of metal and corrosion products across the isolation gaps grows considerably.

The size of the connection and separating force can be used as an indicator of the feasibility of the mechanical structure of the entire connector structure. The

connection and separating forces of a connector vary according to the number of contacts and the spring properties. Very great forces usually cause mechanical damage to the connecting surfaces and the frame structures and make joining difficult. On the other hand, small forces may cause opening of the connectors during mechanical vibration.

The mechanical durability, stability and sufficiently low resistance of high current connector contacts should be addressed since even a slight increase in the resistance of a bad contact results easily in a major loss of power (heating) in the contact. For instance, the loss of power with resistance of 10 mΩ is 10 mW at a current of 1 A, 1 W at a current of 10 A and 4 W at a current of 20 A. A power of one watt will heat the surroundings to such a degree that the ignition risk of the printed board and other isolation materials is great.

The mechanical support of connector back wiring shall be inspected to avoid effects of pull, bending and vibration. At the same time it shall be inspected that condensation or dropping water cannot reach through wiring the contact area and other parts of connectors.

4.12 Component board entity

The printed boards of the product may be constructed with dense conductive/wiring patterns and the product may include both solderable and pressure joints and contacts. Especially EMC protection needs large contact areas and varying materials are used for these. The compatibility of the various materials is checked.

The most critical phase is the manufacturing of the printed board, where too small conductor spacing, impurities and unsuccessful metal platings and solder resist coatings cause problems because of corrosion. The circuit board should be dry prior to packaging for transportation in order to avoid corrosion during transport.

Corrosion can take place already in the transportation package before the assembling and soldering of the components and later during use. The quality assurance of the printed board platings and of general cleanness play a crucial role.

In respect of corroding, maintenance of cleanness during component assembling and the selection of a flux material in the soldering which will not cause corrosion problems later have a crucial role.

Are stickers (adhesive labels) or marker colours used on the component boards that leave corrosive or otherwise harmful residue on the surfaces (e.g. chlorides from marker colours)?

Apart from reducing the risk of condensation solder resist and lacquer primarily protects the metal layers and conductor spacing mechanically and from direct contact with water. Is the wiring pattern protected to a sufficient degree against mechanical stress and effects of humidity? Do the metal plating and solder resist coating suffice or should thicker protective lacquers be used at certain points?

A natural capillary gap occurs between the components and the printed board when the component rests against the printed board. If bare conductors are routed underneath the component the water possibly seeping into this capillary gap can cause corrosion of the conductors and component terminals. Therefore, it is best to protect the wiring pattern with a solder resist or with lacquer. Very dense wiring (flip-chip) requires isolation mass underneath the component to fill the empty conductor spacing and gaps.

When using mildly activated flux (RMA-flux) in the soldering process, the flux residue is not usually washed off. Such residue is usually harmless, but in difficult environmental conditions with occasional seepage of moisture on the surfaces, a heavier accumulation of flux residue for instance on the edges of the board or in some grooves cause moderate corrosion. Therefore, a quality criterion for the soldering process of a printed board could be to ensure that such residue is not left on the boards.

4.13 Soldering and corrosion

The maintenance of the soldering properties of the components and the printed boards is the most important corrosion-related problem in the production and transportation.

In the review it is checked how the soldering properties of the components and the printed boards have been ensured and how the components are transported and handled in the various stages of the production process. The existing specifications for the terminals of the components and the printed board platings are checked.

Due to various production-related reasons, the terminals of the components are sometimes plated with tin alloys, sometimes with silver alloys and sometimes with gold. Usually the platings are inexpensive and therefore also easily

oxidising and corrosive in use, since the price of the components as well as various technical reasons in production limit the choice of the plating. These platings can be used provided that the transportation and storage conditions are good enough and of a short duration.

Tin and silver alloys are always covered with a thin layer of metal oxide or other corrosion products, which results in slight deterioration in their soldering properties. Gold platings are often marginally thin ($< 0,3 \mu\text{m}$), which makes them vulnerable to humidity and long term storage or scratches. If the corrosion is slight, the soldering problems can be remedied with mildly activated fluxes, but at times component batches with poor soldering qualities are encountered.

The solder lands of printed wiring boards are protected conventionally with solder (HASL plating). The solderability of lands decreases gradually because of corrosion. The new organic solderability maintaining platings (OSP) allow use of more dense wiring patterns and some better solderability than solder platings.

The solderability of printed wiring board may deteriorate also during the soldering process itself because some amount of corrosion develops on lands of printed wiring board. In a multiphase soldering process high temperature and/or solder fluxes corrode lands. This happens when components are assembled in many separate phases between successive soldering on both sides of printed wiring board, where lands are bare to make possible soldering in the next phase of the process. To avoid such problems in multiphase soldering process the function of soldering lands, platings, solder and fluxes shall be inspected.

The plastic packages of components usually absorb some water (less than 0,15% of their weight) already in the first few days. If for example the packages of the microcircuits are too damp, even explosions in the soldering may take place. These result in damage and microscopic cracks to the components that let in air. Has the dryness of the components been ensured?

Because of the above, the transportation and storage times of components and printed boards should be limited, the dryness of the transportation packages ensured, the soiling (touching) of components during use avoided, the use of sufficiently good platings in the terminals ensured etc.

4.14 Sensitivity to electrical changes

The disturbance sensitivity of the device concerning the increase of resistance in the signal routes and power feed connecting points is checked in connection with

the electrical design. The aim is to obtain data on how large resistance changes can be allowed in the different conductor routes without disturbance to the operation of the device (keyboard, display, outside connections). This helps in deducing to what extent corrosion may be allowed in the different joints.

Correspondingly, it is checked how small isolation resistances and maximum voltages can be allowed in various parts of the component board between conductors. This helps in estimating the effect of conductivity of the humidity and corrosion products on the operation of the product.

EMC-contacts are evaluated for how good the electrical contact has to be, in other words, how strong EMC dampening is required in each part.

4.15 Component specifications

Various specifications of components, printed boards, platings, etc. are checked for eventual obscurities in the definitions, when the essential parts aiming at corrosion control are included. These include the plating of all structural parts and material demands also in subcontracting.

Do the specifications include the internal conditions of the device to a sufficient degree? Are the structural demands of the mechanics and the platings specified to a sufficient degree?

4.16 Share of electromechanics in failure frequency

As a part of the reliability study of the product, the share of electromechanics in the overall failure frequency of the product should be checked. This share can be considerable if there are many different joints and miniature structuring is used in all possible parts.

If parts have been customised for an individual product, the fault risk may be increased or decreased. If e.g. connector has bad design (mechanics, soldering properties, platings) or the manufacturing quality changes too much then such part may deteriorate reliability. If by customised design all properties of connector are optimised so that compatibility with other parts is good and corrosion resistance is good too, reliability may be better than by using standard components.

4.17 Corrosion of components

Using the corrosion risk, the components can be divided into the following categories. The dominant failure mechanisms in each category should be studied with the component manufacturers in the last instance. During the review, it is studied which groups or individual components in one's own application belong to the group most risk prone to corrosion. Then, appropriate action concerning the component specifications, acquisition directions, component use and testing is identified.

The device (equipment) manufacturer can influence the corrosion of the components mainly by softening the microclimate in the device. The main factor in reducing corrosion is to avoid too high humidity and temperature in the microenvironment in the device both during use and standby. In coastal and sea climates the salt chloride content in the air may become an important factor, as well as polluted or dusty factory or natural conditions.

Component type	Typical corrosion problems
Solder connections	Decay of material with time and especially at high temperatures. Creation of mechanically weak alloys during the soldering process. Mechanical fatigue due to differences in the heat expansion factors. Cold solder connections because of dirt, corrosion and materials. Small contact area of high current contacts.
Pressure connections	Pressure joints of wires for mate pins, connector terminals etc. are internally gas tight especially in the contact point if carefully completed. If the joint remains loose due to worn tools, wrong wire diameters, size of the connector or other such mistakes, the risk for corrosion of the joint becomes relatively great. Also vibration during use quickly ages loose and mechanically too weak joints.
Connectors	The device connectors usually have an open structure, which means that particles in the air have access to the contacts. A good connector shell offers relatively good protection, however. In outside structures, the tightness of the structure and the corrosion resistance of the platings have a crucial role. Fretting is a typical failure mechanism, mostly affected by mechanical design and choice of materials as well as platings.
Membrane switches	The seeping of water into the inner structures of the switch through the seams or the film structures, corrosion of the contact area. Mechanical wear and ageing of film materials.

Switches, toggle, lever, rotary	Mostly have an open structure whereby the corrosion risk for metal surfaces is as in the connectors. If the contact area is protected, gas corrosion and water do not matter. Mechanical wear of the keys and possible sparking (arcing) increase corrosion.
Keyboards	Keyboards are in direct contact with users, which increases risks for problems because of various accidents and chemicals. Failure mechanisms are the same as in other switches.
Printed boards	<p>The density of the conductive pattern of printed board, protective coatings used, and the residual impurity effect how sensitive a printed board is on corrosion reactions because of humidity and contamination. Weakly adhered protective coatings in humid conditions increase the corrosion because of moisture.</p> <p>The plating of plated-through holes (vias) of a printed board is difficult. Therefore it may happen that the tin plating does not reach the inner surfaces. Then the corrosion of not plated copper is probable.</p>
Relays, contactors	Mostly have an open structure such as switches, corrosion of relay switches due to mechanical wear, electric load, air pollution and humidity combined. Contact disturbances caused by vibration.
LCD displays (liquid crystal displays)	Structures may be semi-tight; seepage of water to the inside should be prevented. External connector wires with small insulation gaps increase the risk of corrosion and leakage.
Microcircuits	<p>Microcircuits are usually encased in plastic, which protects the surface of the semiconductor if well made. In the long run impurities in the case, corrosion of the wiring and migration of semiconductor impurities and metal result in failures in the semiconductor and its metallization. Hermetic metal and ceramic cases are the most resistant to humid conditions.</p> <p>A typical corrosion phenomena on microcircuits is the corrosion of outer conductors. The plating or the conductor itself may corrode, this may produce dendrites, which creep on the package between the conductors and may cause leakage or short circuits.</p>
Power semi-conductors	Faults in high intensity semiconductors are mostly due to high currents and errors in their manufacturing. The packages are often metal or heat-resistant plastic. Therefore, the packages are usually relatively tight and outside conditions have little effect (except heat).

<p>RCL-components (resistors, capacitors, inductors)</p>	<p>RCL-components are usually encased in plastic or painted (resistors). Gradual seepage of moisture to the inside increases faults through corrosion.</p> <p>In surface mounted devices, high soldering temperature may cause microscopic cracks to the surfaces.</p> <p>Ceramic chip capacitors are sensitive to mechanical (and thermal) stress, which may cause microscopic cracks in the inside parts and promote corrosion, which brings out the breaks.</p>
<p>Electrolytic capacitors</p>	<p>Electrolytic capacitors are in part self-repairing; in other words a local fault may become fixed on its own. In wet types, the drying of the electrolyte reduces the capacitance. The cases are usually tight to preserve the electrolyte, which means that no water, or air from the outside has access. In dry electrolytic capacitors current peaks may cause gradually progressing decay. Explosion due to an excess current is a risk to be considered when using large capacitors.</p>
<p>Seals</p>	<p>The seals of electronic boxes may release corrosive gas or liquid phase compounds at high temperature (> 40 °C). The problems may arise if the box is tight when there is little change of air inside the box. Therefore it is useful to make sure that the sealing materials do not release any corrosive compounds.</p>
<p>Filling compound</p>	<p>The filling compounds are used to protect the electronics and to improve the heat transfer properties of a product. These materials are in contact with the conductors and components. Therefore they may increase the corrosion risk. For example the filling compounds contain fire retardant materials often, and these compounds may contain corrosive compounds and water. The contact with the conductors at high voltage increases future the corrosion risk. The clearance between the filling compound and printed board may act as a route for moisture, which increases risks for corrosion.</p>

4.18 Testing methods in corrosion control

The testing and measurement methods for ensuring the corrosion properties and corrosion resistance of the product employed in product development; acceptance checks and production are reviewed. It is checked if these are appropriate and sufficient for the examination of the corrosion properties.

Do the used tests include a quick test for obtaining preliminary information on for example the sensitivity of a circuit solution to the effects of corrosion (humidity)?

Does analysed information exist on the sensitivity of the product to resistance changes in the joints and wiring and isolation gaps (sensitivity to corrosion, leakage currents) and has this information been checked with the electrical planning.

Which environmental tests of the design phase are used and how are they applied? Are humidity and corrosion tests in use, do they include the fluctuations in the temperature and the humidity, have condensations and the capillary effect been studied? Has the effect of vibration on the connectors and the contact surfaces been studied? Is reliability testing performed in an elevated temperature?

Are any of the used tests in principle unsuitable for testing of corrosion resistance of the product in question? What is the value of these?

Are type tests based on accepted environmental specifications performed at the start of a product series and later in connection with eventual changes?

Is it possible to perform production testing and possible environmental tests as a part of the production?

4.19 Acceptance inspections

The main focus in the acceptance inspections should be on the monitoring of faults due to transportation and on the quantities of the correct products. The condition of the packages is checked as well as the appearance, moisture damages, quality of the surfaces and the electrical properties of the parts and the components as appropriate.

The packaging dates of the component packages (if original packages) should be recorded in order to verify the age of the goods coming in from the various suppliers and to trace the reasons for possible soldering problems and fluctuations in the quality of the terminals and other platings.

It is checked whether the results of the acceptance inspection of components and parts are forwarded to the designers in a suitable form in order to give the designers a clear picture of the real quality of the components and parts and for the necessary corrections to the component specifications and the design of the product in question.

4.20 Management of field data and service

In the review it is checked if there exists a method for the collection of field data concerning corrosion and the consideration of corrosion as a fault phenomenon and what kind of a method it is?

What kind of information can be extracted from the field data feedback? Does the data contain information on the nature of the faults, the cleanness of the immediate surroundings of the device, the environmental conditions at the time of the fault, exceptional situations, such as water damage, storm or thunder at the time of the incident, was the product transported or otherwise handled in an exceptional way?

Has the service organisation for the device been issued directions for expressing the nature of the faults also in faults resulting from corrosion? Does the service pay attention in general to the background data of the failures and is the information given to the manufacturer of the device?

Have the results of the possible acceptance inspections conducted by the customer (large customers) been used especially to check the damage during the transportation stage, which is always risky. Is there an agreement with the large customers on receiving feedback data and is this data transmitted to the designers?

Could a method be developed for collecting feedback also from the end users of the product?

Does the feedback data from the service and the customers go directly to product development in a usable form and is the feedback from the field used for developing the next product generations?

Does a form for failure data exist with which one could collect usable data from service concerning corrosion failures?

The feedback forms for identifying corrosion should contain at least the following basic information:

- What was the condition of equipment when it came for service? Is it opened, is it cleaned or has someone tried to repair it, is it transported carefully packaged or is it deteriorated during transport?
- What is the appearance of equipment? Are there visible failures on surfaces, is it contaminated or covered by foreign materials inside and outside, is

colour changed somewhere, is dust or liquid on surfaces, is it exploded, is it burned (fired), does it smell burned? Is there any broken wires or conductors? Is there corrosion on conductors or are components clearly damaged? Does connectors have worn or otherwise changed platings.

- In what kind of situation the failure came out? What was temperature, was there storm or otherwise abnormal weather, high humidity, dusty, gases, water damage, fire?, Is equipment or package wetted?
- How the failure came out? Equipment functioned abnormally, finished totally, was there abnormal voices, are failures long term and repeating, are failures increasing? How the equipment is used after the first failures?

It shall be prepared methodology for such failed devices where service cannot find no failures at all. Has a guide given for service organisation how to manage equipment “non failed in service” that service would not damage the traces of original failures?

If among equipment is plenty of “non failed in service” devices one may suspect problems with gradual corrosion, bad thermal design and/or problems with EMC-design. There may be some component failure also, software failure, or simply bad electrical design.

Latent failures should be researched carefully by using good analyse methods to find out the real reasons for failures. It is important to research accurately component boards, connectors and keyboards to find out the failures when one suspects that corrosion, effects of humidity or contamination may be reason for failures.

4.21 Analysis method for corrosion failures

It is checked, whether sufficient directions for the analysis of the faulty devices returned from the field exist in order to verify the possible role of corrosion in the failures.

The most important aim of the analysis is to find out the actual reasons for the faults, which requires careful recording of the relevant traces and background study of the events.

It is ascertained whether the analysis method includes:

- guidance for the recognition of corrosion and the use of comprehensible methods and terms in the initial identification of faults

- directions for the packaging of a faulty part and its transportation to failure analysis
- directions against cleaning the product and touching the surfaces before the analyses have been completed
- careful handling of the product after fault detection, corrosion faults are often contact faults which may disappear if the connectors are opened and the switches moved
- the acquisition and recording of the background information for the fault before the fault analysis (time, place, conditions, exceptional circumstances)
- visual check starting from the external parts and proceeding gradually to the inner parts, photographing is a good way to document the occurrence and distribution of corrosion, dust and water marks
- functional tests to verify the failure and its nature
- recognition of possible shortcuts in the conductor spacing
- identification of loose contacts, weak mechanical structures
- condition of the connector surfaces, possible signs of corrosion, in the last instance a microscope is needed with a 10...20 magnification.
- analysis methods for the composition of visible corrosion products
- comparison of specifications and the faulty product to ascertain whether the faulty parts have been made according to specifications.

4.22 Customer specifications

If a large share of the products is delivered to a large customer, they can have some general requirements for the product. It is checked if these include demands related to corrosion and environmental tolerance and if these demands deviate from the company's practice in a more demanding direction.

4.23 Subcontractor relations

In subcontracting it is checked whether corrosion resistance has been included in the product specifications presented to the subcontractor and if the packaging, transportation and processing methods and cleanness have been sufficiently considered. Do the methods of the subcontractor correspond to the above demands in the company's own production? Is the subcontractor aware of the significance of corrosion protection? Are the production process and the employed work and quality assurance methods of the subcontractor such that the

result may be expected to meet the desired quality standards regarding corrosion resistance?

In corrosion protection, various surface treatments hold a key position. The surface treatment processes are usually difficult to control. Therefore, the level of procedures for verifying the constancy of a certain process should be defined. The actual quality standards for the materials and parts to be acquired should be considered and formulated in such a way that the designer, the subcontractor, the company's own production and the company's customer could discuss the plating issues on equal terms.

Since the true quality of the plating depends on the content of the process, the acquisition specification for platings should be developed in co-operation with the subcontractors to include the necessary information on the methods and parameters for finishing the plating in question.

It is not necessary to specify other than some nominal values for the plating to the subcontractors (plating firms, metal and plastic parts). The information on the final aim, for example global durability, in a person's pocket, life cycle five years can be left out. The subcontractor will then try to interpret the specification he has received from his own starting points and try to optimise his own production process. The product designers or subcontractors may not have common knowledge on how the parts should be coated in order that the end product operates in the best possible manner.

Various platings are also mixed for different reasons. The main reason is smoothness of production, (for example easy soldering properties), but durability in field conditions is left in the background since no proper grip over it exists.

4.24 User instructions

In order to avoid the worst user mistakes the product instruction reviews should focus on whether the instructions contain certain warnings of conditions increasing the corrosion risk.

The instructions could also include information on prevention of wetness and limitations on the use of various liquids and chemicals in the cleaning of the device. Attention should also be paid to the use in outdoor conditions and in outdoor activities in general, where wetness (moisture close to the skin) and sunlight (UV-light) typically create corrosion.

4.25 Processing method for suggestions for action

There are several important action targets in a product in respect of corrosion sensitivity. The suggestions for action concerning these are grouped according to the structure of the review. If possible, the suggestions are processed as follows:

PROCESSING OF SUGGESTIONS FOR ACTION

Listing of **suggestions** from each sub-sector as they emerge

Reasons for the action are recorded, **why** it should be performed

Introduction into the underlying **failure mechanisms** in order to evaluate the means to remedy the situation

Focusing of the **content of the action** and its manner of execution

The manufacturer estimates the technical and economical **feasibility** of the action

The manufacturer defines and **executes** the final action

Appendix 4
Corrosion glossary

Corrosion glossary

This glossary contains terms in English and in Finnish.

The following sources, which have been used in the creation of this glossary, have vocabulary on corrosion and air quality.

Some common abbreviations for quantities and their counterparts in the SI system are listed at the end of this glossary.

SFS-ISO 8044 (1989-08-22, 1. ed.).

Corrosion of metals and alloys. Terms and definitions. Metallien ja metalliseosten korroosio. Termit ja määrittelyt (en fi fr). 18 p.

SFS 5348 (1987-09-21, 2. ed.).

Quantities and units. Moisture. Suureet ja yksiköt. Kosteus. 3 p.

ASTM E673-03.

Standard Terminology Relating to Surface Analysis. 10 p.

The definitions listed apply to (a) Auger electron spectroscopy (AES), (b) X-ray photoelectron spectroscopy (XPS), (c) ion-scattering spectroscopy (ISS), (d) secondary ion mass spectrometry (SIMS), and (e) energetic ion analysis (EIA).

EPA United States Environmental Protection Agency. **Terms of Environment.** <http://www.epa.gov/OCEPATERMS/index.html>.

InterCorr International, Inc. **Glossary of Corrosion Related Terms.** <http://www.corrosionsource.com/handbook/glossary/>.

Goosey, Martin, T. **Plastics for Electronics.** 1986. Elsevier Applied Science Publishers. London. ISBN 0-85334-338-1. (Lasisiirtymälämpötila). 380 p.

OK International. **Glossary of Terms. Soldering and fume extraction definitions.** <http://www.okinternational.com/>.

UNEP Solvents Technical Options Committee. **UNEP STOC: Glossary.** (It covers scientific, technical and other fields). <http://www.protonique.com/unepstoc/stocfile/glossary.htm>.

Vornamo, H. **Ilmansuojelun ja yhdyskuntailmatutkimuksen perusteet.** Kunnallinen terveydenhoitoyhdistys. Painoprint Oy. 1975. Helsinki. 151 p.

Term	Meaning
<i>Absolute humidity</i> Absoluuttinen kosteus, höyryn osatiheys	The ratio between the vapour mass and total volume [SFS 5348]. For example the mass of water vapour in the air per volume unit (g/m ³).
<i>Absorb</i> Absorboida	To absorb, to retain. E.g. gas absorption into active carbon (see <i>adsorb</i>).
<i>Absorbent</i> Absorbentti	Substance, e.g. blotter paper, which absorbs another substance.
<i>Absorption</i> Absorptio	The seeping of a substance into another substance (absorbent). E.g. gas seeps (absorbs) into liquid or a solid substance or a liquid absorbs into a solid substance.
<i>Acetic acid</i> Etikkahappo	Acetic acid is an organic acid produced in nature by the metabolism of acetic acid bacteria. The acid can also be manufactured synthetically (for example silicone resins curing with moisture release acetic acid during the curing reaction).
<i>Acidic, acid</i> Hapan	Solution with a pH below 7, see <i>pH value</i>
<i>Activated carbon</i> Aktiivihiili	A porous carbon material with good adsorption properties. Activated carbon is porous carbon with an exceptionally large internal area, around 400...1 600 m ² /g and a pore volume of more than 30 cm ³ /100 g. The area aimed at is more than 1 000 m ² /g. The pore diameters are around 0,2...10 000 nm, pores of less than 2 nm are frequent as well as pores of 25...5 000 nm. There is an abundance of micropores diameters of less than 2 nm and of 25...5 000 nm called macro-pores. Medium-size meso-pores of 2...25 nm are the least frequent in typical activated carbon. Activated carbon is basically water repellent; it adsorbs organic and other non-polar gaseous and liquid substances. Activated carbon comes as powder, granules or pellets [Henning & Degel 1990]. http://www.activated-carbon.com/solrec2.html
<i>Adhesion</i> Adheesio	Adhesion is the traction between two surfaces, which may consist of valence forces (chemical adhesion), interlocking mechanisms (mechanical adhesion), van der Waals forces or combinations thereof. http://palimpsest.stanford.edu/don/dt/dt0042.html

<i>Adiabatic</i> Adiabaattinen	A thermotechnical process where the temperature changes without transfer of thermal energy into the system or out of it. Adiabatic heating takes place for instance when air pressure is increased in a thermally insulated space.
<i>Adsorb</i> Adsorboida	To suck inside, bind on the surface. Usually used in connection with surface chemical phenomena (see <i>absorb</i>).
<i>Adsorbate</i> Adsorbaatti	A substance adsorbed on the surface of another substance.
<i>Adsorbent</i> Adsorbentti	An adsorbing substance binding another substance to its surface.
<i>Adsorption</i> Adsorptio	The adhesion of liquid or gas particles to the surface of a solid substance. The surface forces of the solid substance bind other substances on the surface. A substance with small particles (for example fine sand dust) adsorbs better than a substance with coarser particles. Adsorption is greatest in low temperatures. A substance with heavy molecular weight adsorbs to the surfaces more easily than a substance with low molecular weight.
<i>Advection</i> Advektio	In meteorology, advection means horizontal movement of an air mass. For instance, warm advection means the horizontal movement of a warm air mass to replace a colder air mass. Correspondingly, the movement of a humid air mass to a drier area or inversely, the movement of a dry mass to a more humid area. www.booty.demon.co.uk/metinfo/glossary.htm http://www.booty.demon.co.uk/tthkfaq.htm
<i>Aerosol, gas dispersoid</i> Aerosoli	The mixture of gas (for example air) and the liquid droplets (mist) or solid particles (smoke) completely blended in it (lat. aero = air, solu'tum = dissolved). http://www.edu.fi/oppimateriaalit/ymparistotietous/sanasto/sanasto.htm
<i>Aerosol particle</i> Aerosolihiukkanen	Solid particles or drops completely blended in gas, usually air. Coarse particles are usually a product of mechanical processes; fine particles are created from gases, chemical reactions or from condensation due to dropping of temperature.
<i>Agglomeration</i> Agglomeroituminen, kasaantuminen	The increase in size of particles, for example rain drops in collisions or by joining other particles.
<i>Air impurity,</i>	Substances not belonging to the basic composition of clean

<i>pollutant</i> Ilman epäpuhtaus	air or a part deviating from the normal composition.
<i>Alkaline</i> Emäksinen	A solution with a pH exceeding 7, see <i>pH value</i>
<i>Aluminium zincified</i> Alusinkitty	Thin steel plate with a plating of 55% Al and 45% Zn
<i>Ammonia</i> Ammoniakki	NH ₃ ; corrodes all copper alloys.
<i>Ammonium</i> Ammonium, ammonium-ioni	NH ₄ ⁺ ; corrodes all copper alloys..
<i>Anodic oxidation</i> Anodisointi, anodinen oksidointi	A method where the surface of a piece is oxidised in a suitable solution with electric current. Both AC and DC current can be used.
<i>Anodic protection</i> Anodinen suojaus	In anodic protection the object to be protected is made positive relative to the auxiliary anode with the aid of external current source. This brings the potential of protected object to passive area. (See also <i>cathodic protection</i>)
<i>Atmospheric corrosion</i> Ilmastollinen korroosio	Corrosion of materials due to the effect of substances in the air such as oxygen, water, salt and sulphuric compounds and temperature and solar radiation. In a wider sense a part of microbiological corrosion can be included which takes place through substances and microbes spreading in the air.
<i>Atom</i> Atomi	The smallest structural particle of a substance which can be verified with chemical methods. Consists of a positive nucleus and a curtain of electrons surrounding the nucleus.
<i>Barrier layer</i> Välikerros	A separate barrier layer is used under the metal plating (Au, Sn, Ag) of wires, contacts and connectors. The purpose of the barrier layer is to block the diffusion of the components (copper, zinc) of the base metal alloy through the pores of the upmost plating. The barrier layer also improves the adhesion of the plating and evens the base. Nickel is often used as material for the barrier layer.
<i>Bentonite clay</i> Bentoniitti-savi	Bentonite clay (montmorillonite clay) is a natural mineral (calcium aluminium silicate) containing crystalline water and dozens of colloidal silica minerals. It is the cheapest adsorbent for removal of water. It is also used as a mineral additive in some foodstuffs, animal fodder, for clarifying wine and in land construction for building water insulations.

	In paint technology bentonite is used as an organically modified gel used to increase the viscosity of the paint in order to prevent the heavy pigments from sinking to the bottom of the can.
<i>Bimetallic corrosion</i> Metalliparikorroosio	Bimetallic corrosion arises due to the action of a bimetallic cell, i.e. galvanic cell, where two different metals are in contact with each other. This is probably one of the most common corrosion mechanisms in electronics. See Appendix 1, Section 2.1 <i>Galvanic and bimetallic corrosion</i> .
<i>Biocide</i> Biosidi	A substance blocking microbial growth chemically or biologically. Stops the growth of bacteria, fungi (mildew fungi), algae and various spores. E.g. ozone and chlorine also function as biocides. Biocides are used widely from foodstuffs and drinking water to the promotion of preservation of all kinds of materials. Biocides are used to prevent jellification in the water flow systems in the industry, for example in paper mills. Also used in cutting coolants in engineering industry. Some biocides cause irritation to the eyes and respiratory organs and they are also powerful allergens.
<i>Capillary phenomenon</i> Kapillaari-ilmiö	The travel of liquid (absorption, rising) into narrow gaps (cracks) caused by the surface tension of the liquid. A capillary gap (crack) is a space of less than 1 mm in between two surfaces or a hole or the inside of a narrow duct.
<i>Catalyst</i> Katalysaattori	A substance that affects a chemical reaction without changing itself.
<i>Cathodic protection</i> Katodinen suojaus	In cathodic protection the object to be protected is made negative relative to the auxiliary anode (soluble or inert) with the aid of external current source. This brings the potential of protected object to immunity area. An alternative way for cathodic protection is use of sacrificial anodes in water. E.g. putting zinc-anodes in contact with engine protects outboard engine. Zinc is less noble than materials of engine and forms a sacrificial anode (galvanic anode).(See also <i>anodic protection and Pourbaix diagram</i>)
<i>Chloride</i> Kloridi	Chloride Cl^- ; chloride-ion corrodes most metals. Usually the precipitation value only is presented for chlorides since the salt exists in the air mainly as NaCl particles and not as gaseous chloride Cl_2 .

<i>Chlorine</i> Kloori	Chlorine (Cl ₂) itself is rarely a pollutant in nature except near paper and pulp mills. In humid conditions, chlorine quickly disintegrates into hypochlorite and chloride. Hypochlorite is a strong oxidant. Chlorine corrodes most metals even in small quantities. Chlorine has a strong synergistic effect with hydrogen sulphide (H ₂ S) since both sulphuric acid and hydrochloric acid are created in its presence. Chlorides have the ability to penetrate protective oxides of metals and increase their corrosion.
<i>Chromating</i> Kromatointi	The transformation of the surface of certain metals, for example Al and Zn to be more corrosion resistant by letting a solution with chromates react with the surface. This creates an electrically conductive layer of metal chromates on the surface.
<i>Cohesion</i> Koheesio	The internal attraction power of a substance. The force that draws the atoms of a substance to one another.
<i>Colloid</i> Kolloidi	A substance finely dispersed in liquid or gas (water, milk etc.). (Advances in Colloid and Interface Science)
<i>Concentration</i> Pitoisuus	For example, the concentration of foreign substances in the air is expressed either as mass per volume unit ($\mu\text{g}/\text{m}^3$) or as volume ratio mm^3/m^3 or cm^3/m^3 .
<i>Condensation</i> Kondensaatio	E.g. humidity in the air becomes liquid water, condenses, when the temperature drops.
<i>Contamination</i> Kontaminaatio	The accumulation of solid and liquid impurities on the surface of another substance. Also oxidation and other chemical reactions produce new compounds which can be regarded as contamination on the surfaces of materials. Also microbiological phenomena cause contamination of the surfaces. Also air impurities, in other words substances foreign in clean air (gases, dust), are called air contamination (water vapour is not included in air contamination).
<i>Convection</i> Konvektio	The flow of an intermediate agent. Transfer of heat through or with an intermediate agent, for example air. The intermediate agent can be liquid, gas or solid. Free or natural convection means the transfer of heat with an airflow streaming past the surfaces emitting heat. The convection is caused by the uplift created by the differences in temperature. Forced convection means a flow of air created with a fan for transferring heat.

<i>Coprecipitation</i> Kerasaostus	Coprecipitation means the precipitation of another substance together with the actual precipitating substance for example during the plating process. This can take place unintentionally (precipitating impurities) or with intent, as in the precipitation of diamond dust in a nickel matrix when manufacturing diamond tools, for example a diamond disc.
<i>Corrosion</i> Korroosio	Destruction of a substance through various chemical reactions. Corrosion of metals is the oxidation of metal atoms into ions (see <i>oxidation</i>). The most commonly known corrosion reaction is the rusting of iron and steel. Similar processes take place in other metals as well and also in non-metallic materials such as plastic, concrete and ceramics.
<i>Creep of corrosion products</i> Korroosio- tuotteiden ryömiminen	A failure mechanism typical of gold platings is the creeping of corrosion products along the surface in conditions where the air is humid and contains H ₂ S, NO ₂ or Cl ₂ gases. Salts of various metals are typical creeping corrosion products. They are also hygroscopic and promote the accumulation of water to the corrosion areas.
<i>Crevice corrosion</i> Rakokorroosio	A form of corrosion where the corrosion takes place in a narrow gap or crack. See also <i>deposit corrosion</i> , <i>filiform corrosion</i> and <i>pitting corrosion</i> .
<i>Deposit, fall-out, dust fall</i> Laskeuma	The fall of fine particle substance (mass exceeding 10 µg) in air to the ground due to gravity. The measurement is performed with a collector set at a specific height. The unit is mg/(m ² ·h) or mg/(m ² ·day).
<i>Deposit corrosion</i> Piilokorroosio (saostuma- korroosio)	Deposit corrosion is corrosion that develops under or near a surface impurity because of lack of oxygen. For example, deposit corrosion easily develops under moist clay, dirt from a road and fouling growth in ships.
<i>Depth of penetration, skin depth</i> Tunkeutumissyvyys	The depth in the skin effect phenomenon at which the density of the current is 1/e (e = 2,71828) of the density of the current on the surface in a good planar electric conductor.
<i>Dew point</i> Kastepistelämpötila	Temperature where the relative humidity of the air is 100%.
<i>Dezincification</i> Sinkinkato	See selective corrosion.

<i>Diffusion</i> Diffuusio	The spreading of a substance (solid, liquid, gas) to another substance by blending. The diffusion mechanism strives at spreading the substance evenly to another substance. Diffusion also means the random transfer of substance atoms and molecules in the substance. Energy can also spread through diffusion.
<i>Dispersion</i> Dispersio	The dilution of an impurity through diffusion or turbulence.
<i>Durable water repellent, DWR</i> Vettä hylkivä materiaali	Material on the surface of which the wetting angle Θ of water is 90...180°. If the surface tension (γ_{BC}) between a liquid and a solid is greater than surface tension (γ_{AB}) between a gas and a solid, Θ is between 90...180°. For example GORETEX® fabrics have a wetting angle of 140°, which means that water is left on the surface as drops and will not penetrate easily.
<i>Dust</i> Pöly	Solid particles in air with a diameter of approximately 1...150 μm . See IEC 60721-2-5, Annex A. The solid particles may contain almost any materials (most commonly coal dust, soot). Dust collected on the surfaces is also called deposit.
DWR	See durable water repellent.
<i>Electrochemical series</i> Sähkökemiallinen jännitesarja	The electrochemical series of metals means the voltages of pure metals in relation to a standard hydrogen electrode. The electrochemical series is obtained when the voltages of different metals are measured in a similar saline solution in relation to a standard hydrogen electrode. The electrochemical series classifies the “nobility” of flawless, clean metals completely devoid of oxide or passive layers (see <i>galvanic series</i>).
<i>Electroless plating</i> Kemiallinen pinnoitus, virraton pinnoitus	A plating method where another metal precipitates on the metal surface from a solution either due to the combined effect of the base metal and the precipitating substance or solely due to the dissolution of the base metal. For example copper plating of an iron nail in a copper salt solution is electroless plating.
<i>Electrolyte</i> Elektrolyytti	A real electrolyte is a substance with ions in its pure form without a solvent. Therefore a substance producing ions into a solution is an electrolyte which is seen as changes in the conductivity of the substance. Usually the term electrolyte refers to a solution formed by a solvent (for example water) and an electrolyte dissolved into it (e.g. salt). An electrolyte

	dissolved in a certain solution (e.g. water) is strong or weak according to whether the resulting solution conducts electricity well or not at reasonable electrolyte contents.
<i>Electrolytic corrosion</i> Elektrolyyttinen korroosio	Electrolytic corrosion is created in the electrical conductors when they are linked together by a material containing an electrolyte (e.g. salt) and there is a voltage between the conductors. The conductor in a higher potential gradually dissolves (corrodes) and can eventually break. See <i>ionic migration</i> .
<i>Electromagnetic compatibility, EMC</i> Sähkömagneettinen yhteensopivuus	Electromagnetic compatibility, meaning that the device may not create too much electromagnetic disturbance emissions to disturb other devices and, on the other hand, the device must function even if there is a reasonable amount of electromagnetic disturbance or utility signals of other devices (for example signals from radio telephones).
<i>Electromigration</i> Elektromigraatio	The travel of metal atoms in an electric conductor caused by the electric current in the conductor. The electrons advancing in the conductor bombard the atoms, which move from one place to another. This results in local thinning of the conductor and the accumulation of metal at another location. This is a typical failure mechanism of high-density microcircuits with aluminium wiring especially.
<i>Emission</i> Emissio, päästö	The discharge of gas or particles into the air (meteorology).
<i>Erosion corrosion</i> <i>Impingement attack</i> Eroosiokorroosio	A phenomenon created by extremely rapid travel of a corrosive solution over the surface. Corrosion is accelerated since the quick motion of fluid replaces the fluid on the surface and keeps the surface clean from eventually protective corrosion products. The gas bubbles of the fluid increase the corrosion rate.
<i>Filiform corrosion, filament formation</i> Lankamainen korroosio	A corrosion type of painted metal surfaces where corrosion progresses as threadlike formations under the paint surface in random directions. The formations are visible as threadlike or local bumps on the painted surface. In tests, filiform corrosion can be demonstrated for example on painted aluminium or steel surfaces in salt spray tests where the formations may contain crystallised salt grains.
<i>Fretting</i> Hiertyminen	Abrasive motion of surfaces against one another. Results in surface shaping on metal surfaces and loss of metal particles affected by surface pressure, smoothness of the surface, hardness of the surface materials. Fretting may result from mechanical vibration of fluctuation caused by changes in

	temperature. Fretting may cause corrosion of the surfaces for example in connectors (fretting corrosion). The fretting motion in electronics connectors varies from a micrometre to a couple of tens of micrometres.
<i>Fretting corrosion</i> Hiertymiskorroosio	Corrosion of the contact point of opposite surfaces caused by fretting (fretting corrosion, abrasive corrosion, friction corrosion). Mechanical fretting motion dislocates metal particles, which corrode easily. The oxides and other compounds forming in the contact point often have low conductivity. Moreover, fretting may create polymers catalytically from the gases present in air for example on palladium surfaces.
<i>Galvanic series</i> Galvaaninen jännitesarja	The galvanic series of metals means the relation of the metal voltages to a standard hydrogen electrode when the voltages of real metals are measured in real solution in for example seawater at a certain temperature. The galvanic series describes the differences in the nobility of the metals. The galvanic voltage series only applies in the measuring conditions in question (see <i>electrochemical series</i>). Metals with very different degrees of nobility corrode easily when in contact with one another.
<i>Gas, vapour</i> Kaasu	A state of substance where the molecules are separate from one another. Many corrosive substances travel long distances in gaseous state (SO ₂ , NO _x).
<i>Getter</i> Getteri-materiaali	Substances suitable for removing gaseous waste used for removing for example nitrogen impurities such as water, oxygen, hydrogen, carbon dioxide etc. Getter materials usually operate in high temperatures exceeding 200°C. There are getters for room temperature as well, Zr-V-Fe, for instance. Typical use of getter is the manufacture of vacuum picture tubes where gas residue is removed from the tube by inductively heating the getter material placed inside the tube [http://www.getters.com/]. In the semiconductor industry getter materials are used for example in the sputtering process to remove unwanted particles from the chamber where the metallization of the microcircuit is conducted.
<i>Glass transition temperature</i> Lasittumis- lämpötila	The glass transition temperature T _g of plastics is the temperature where a cooling amorphous plastic cures into a glass-like, brittle and tough substance. The properties of the plastic, for example the thermal expansion coefficient undergo a radical change in the process. This temperature

	should not be exceeded in use. If the temperature is raised above the glass transition temperature the plastic softens and acts like a viscous fluid or rubber. The glass transition temperature for polystyrene is about +100°C, for PVC + 81°C, for nylon 66 +50°C, for polyethylene (HDPE) -100°C and for PTFE -147°C [Goosey 1986, p. 28]. The measuring methods include for example differential scanning calorimetry DSC. See also ISO 11359-2, IEC 61006, ASTM E1545 and ASTM E1824.
HASL, <i>Hot air solder levelling</i> HASL-juotepinnoite	HASL coating is a solder coating of the soldering areas of a printed board. The board is dipped into the solder (e.g. wave soldering) and the surplus solder is removed by blowing hot air.
<i>Heat cracking</i> <i>Popcorning</i> Lämpöpaukahtelu	Popcorning or popping takes place when soldering wetted components. The water inside the components vaporises in the soldering temperature (about 230°C) and expands about 1200 fold and tears explosively the inner structures of the component. http://www.calce.umd.edu/general/demos/defects/defects/ppcrack.html
<i>Hot galvanized, hot-dip zinc coated</i> Kuumasinkitys	A method for plating steel with zinc by immersing it into molten zinc.
<i>Humidity of solid material, w,</i> Kosteuspitoisuus, (kiinteän aineen)	The ratio of the mass of water in a solid substance and the total mass [SFS 5348].
<i>Hydrochloric acid</i> Suolahappo (kloorivetyhappo)	HCl.
<i>Hydrogen sulphide</i> Rikkivety	H ₂ S; corrodes silver at all air humidity levels and all copper alloys.
<i>Hydrophilic</i> Hydrofiilinen	Water “favouring” (wetting) substance, which expands and forms a colloidal solution in water. For example gum arabic is hydrophilic.
<i>Hydrophobic</i> Hydrofobinen	Water repellent material.
<i>Hygroscopic</i> Hygroskooppinen	Water retaining and absorbing material. For example table salt, calcium chloride, alcohols such as glycerol, propylene glycol and sorbitol and sulphuric acid are hygroscopic. They absorb water from the air and bind it chemically.

<p><i>Inert material</i> Inertti materiaali</p>	<p>Here in meaning: Naturally corrosion resistant stable material, which corrodes very slowly in normal environmental conditions.</p> <p>In certain conditions, a chemically passive or stable material is inert. For instance, nitrogen is an odourless, colourless and <u>inert</u> gas usually in N₂ molecules. Also noble gases such as helium are inert gases. Of plastics, for example polypropylene and teflon are inert. Waste is stable (inert) if no biological, physical or chemical changes take place (e.g. glass, mineral soil).</p>
<p><i>Inherent corrosion resistance</i> Luontainen korroosion-sietoisuus</p>	<p>Property of a substance, component or device making it naturally corrosion resistant without any further action in certain environmental conditions.</p> <p>For instance, nearly inert matter and hermetic cases are naturally corrosion resistant. On the device level, the control of the tightness of the case, the airflow and of the temperature may make the device naturally corrosion resistant.</p>
<p><i>Insulation resistance</i> Eristysresistanssi</p>	<p>The resistance between two electric conductors supposed to be isolated from one another. Insulation resistance is measured with certain direct voltage corresponding to the conditions of the user application in question (see <i>resistivity</i>).</p>
<p><i>Intermetallic compound</i> Välimetalli</p>	<p>Intermetallic compound is a metal alloy created on the contact surface of metals when metals diffuse into one another. Intermetallic compounds are created for example during soldering when gold and copper diffuse into the soldering tin and, on the other hand, when soldering tin diffuses into the copper and possibly into the gold plating on it. Intermetallic compounds are usually brittle and crack easily. During soldering the amount of intermetallic compound grows logarithmically when the soldering time, the temperature and the thickness of the platings of the wires under soldering increase.</p>
<p><i>Ion</i> Ioni</p>	<p>An electrically charged particle in the size range of an atom or a molecule (e.g. metal ion in a water solution, hydrogen ion).</p>

<i>Ionic migration, electrochemical migration</i> Ionien vaeltaminen	Ionic migration means the transfer of ions from one electric conductor to another when there exists voltage between conductors. The migration requires humidity for the creation of the ions and for the travelling path. Migrating ions lower the insulation resistance and can eventually cause shortcuts between the conductors. See <i>electrolytic corrosion</i> .
<i>IP code, International protection</i> IP-suojausluokka, IP-koodi	International Protection means the protection classification of enclosures for electronic equipment defined in IEC-60529. The classification covers tightness ranging from open and direct contact protected to dust/water tight structures.
<i>Microbiologically influenced corrosion, MIC, microbial corrosion</i> Mikrobiologinen korroosio	Corrosion affected by the presence and activity of microbes on the biofilms on the surfaces of materials. Microbiological corrosion affects all surfaces in contact with water; metals as well as other materials. Bacteria, mildew, fungi, lichen and moss and various fauna and their discharges act as the biological agents.
<i>Micro-organism, microbe</i> Mikro-organismi	Bacteria, fungi, algae, protozoa, viruses, and their dormant states (spores).
<i>Molecule</i> Molekyyli	A particle of matter formed by several bonded atoms.
<i>Molecular sieve</i> Molekyyliseula	Crystalline and porous form of zeolite, which is sodium, potassium or calcium aluminium silicate Most effective and most expensive of adsorbents.
<i>Montmorillonite clay</i> Montmorilloniittisavi	See bentonite clay. The name derives from its discovery in 1847 in Montmorillon in France. http://www.ssc.on.ca/mandm/montmor.htm
<i>Nitric acid</i> Typpihappo (sievesi)	HNO ₃ . The salts of nitric acid are nitrates.
<i>Nitrogen dioxide</i> Typpidioksidi	Nitrogen dioxide NO ₂ and nitrogen monoxide NO are nitrogen oxides. Nitrogen oxides are often depicted with the sign NO _x since for example burning reactions produce various nitrogen oxides of which NO ₂ only accounts for 5...10%. In the air, the amount of nitrogen dioxide is usually about half of all nitrogen oxides. Nitrogen dioxide corrodes some metals, such as copper and brass. Nitrogen dioxide coupled with sulphur dioxide corrodes various materials. Together with chlorine it corrodes even gold.

<i>Nitrous acid</i> Typpihapoke	Nitrous acid is a water solution with NO_2^- ions. The salts of nitrous acid are nitrites.
<i>No-clean flux</i> Pesemätön juoksute	A flux used in soldering which need not be cleaned off the printed board due to its chemical inertia. The relatively low corrosivity of the flux makes it possible to leave it on the printed board after the soldering.
<i>Odour threshold</i> Hajuraja	The lowest level of content of an air impurity detectable by human senses and causing an odour characteristic of the impurity.
<i>Organic solderability preservatives, OSP</i> Orgaaniset juottuvuuden säilyttävät pinnoitteet	Organic materials used to maintain the solderability of the soldering areas of the printed board during transportation and the multi-phase soldering process. OSP coatings replace the traditional tin-lead plating in the soldering areas.
<i>Oxidation</i> Hapettuminen	Reaction, where the positive charges in a substance grow or the negative charges diminish (the substance donors electrons). Oxidation takes place for example in the anodic region where the metal ionises when it donors electrons (becomes oxidized into ions, see <i>corrosion</i>).
<i>Ozone</i> Otsoni	Allotropic form of oxygen (O_3), created by the effect of ultraviolet light from the oxygen in the air. Ozone is a strong oxidant and therefore also corrosive.
<i>Painting</i> Maalaus	Covering of a surface with organic substances, for example solvent-, powder- and latex painting.
<i>Particulate</i> Hiukkasjakoiset ainekset	Air impurity consisting of liquid drops and solid particles.
<i>Passive layer</i> Passiivikerros	A layer or reaction produce often forming on metal surfaces in air preventing further corrosion of the metal.
<i>Patina</i> Patina	The name of the greenish corrosion product of copper, copper carbonate/hydroxide.
<i>Permeability coefficient</i> Läpäisykerroin, läpäisevyyskerroin	Coefficient P in Fick's first law ($V = P (A p t)/s$), which gives the permeability of gas in a material film at a certain pressure difference (p) over the film. Fick's first law only applies to stable gases, which do not condense near the actual pressure or temperature (see <i>vapour transmission rate</i>).

<i>pH value</i> pH-arvo	A figure giving the degree of acidity of a solution. The pH-value is the counter value of the logarithm of the hydrogen ion content in the solution. In neutral water the pH-value is 7 and therefore the content of hydrogen ions is 10^{-7} mol/dm ³ .
<i>Phosphating</i> Fosfatointi	A method whereby a protective metal phosphate layer is precipitated on a metal. Several methods with iron phosphating and zinc phosphating as most common. Phosphating also improves the adhesion of organic coatings.
<i>Pitting corrosion,</i> <i>pit corrosion,</i> <i>pitting</i> Pistekorroosio, kuoppakorroosio, pistesyöpyminen	A local form of corrosion with quick appearance of only deep holes to the surface with most of the surface nearly intact. Pitting corrosion is common in its various forms with all metals and their alloys (see <i>uniform corrosion</i>).
<i>Plating</i> Pinnoitus	Surfacing of one material with another. For example, chemical and electrochemical plating.
<i>Pollutant</i>	See air impurity
<i>Popcorning</i>	See heat cracking
<i>Pore corrosion</i> Huokoskorroosio	Pore corrosion is typically the corrosion at microscopic holes, pores and flaws of noble metal plating. The corrosion is typically bimetallic corrosion where the less noble base metal corrodes and pushes the corrosion products towards the nobler surface layer and then spreads them along the surface.
<i>Pourbaix diagram</i> Pourbaix- diagrammi	The Pourbaix-diagram or the pH-potential diagram is the electrochemical balance chart of a metal. This describes the state of metal surface (corrosive, passive, immune). (see Appendix 1, Figure 1.1)
<i>Powder painting</i> Pulverimaalaus	Painting method where the paint is in powder form and is spread with an electric field between the gun and the surface. The paint is “fried” onto the surface at an elevated temperature.
<i>Relative humidity,</i> φ, Suhteellinen kosteus, suhteellinen höyryosuus	The ratio of the molar share of dry water vapour to the maximum molar share of dry water vapour that a gas can contain, in other words that ratio of the partial pressure of vapour to the saturation pressure in the said temperature [SFS 5348]. For example the amount of water contained in air as a percentage of the maximum amount of water possible in the said temperature and pressure.

<i>Resistivity</i> Ominaisresistanssi	Characteristic resistance of material, the unit is Ωm .
<i>Salt</i> Suola	The reaction product of an alkali and an acid.
SAP	See Surface Active Paper
<i>Selective corrosion,</i> <i>selective leaching</i> Valikoiva korroosio	A corrosion phenomenon where some components of a metal alloy corrode/dissolve, for instance dezincification of brass and tin leaching of tin bronze.
<i>Selective dissolution of tin</i> Tinakato	See selective corrosion.
<i>Silica gel</i> Silikageeli, piihappogeeli	Silica gel (silicon acid gel) is a water absorbing material, which at best absorbs water more than 35% of its weight if the relative humidity of the air is 80%. It is the best-known chemical used to absorb humidity in transportation packages. Silica gel is made of sodium silicate and sulphuric acid. It is available as amorphous powder, glasslike pieces, moisture gels and crystalline. Also known as amorphous silica, synthetic amorphous silica, amorphous silicon dioxide.
<i>Silicon</i> Pii	Silicon is an element (Si) the most common chemical compound of which is quartz, (SiO_2). The most common organic silicon compounds are various silicon.
<i>Silicone</i> Silikoni, polysiloksaani	A group of organic polymer silicon compounds which can come as gas, liquid or solid depending on the length of the polymer chains. Silicone resins are used in electronics (silica resin) and silicone rubber as high temperature insulators (200°C). Silicone resins are also used in the manufacture of lacquers and paints. Silicone oils are colourless water-repellent fluids used as additives in creams, paper and textiles. Silicone oil creeps along the surfaces and can spread on electric contacts and form an isolating film.
SIR	See Surface Insulation Resistance
<i>Skin effect</i> Virranahto	The pinching of current on a surface of an electric wire takes place when the signal frequency is raised. The phenomenon becomes significant in the frequency range of over one megahertz. Skin effect on the conductive metal surfaces of electronic components and printed boards increases the harmful effects of corrosion since corrosion increases the surface resistance and causes discontinuities on the surface. At great frequencies of over 100 MHz the skin effect enhances the disturbances caused by only slight corrosion.

<i>Smog</i> Fotokemiallinen sumu	Air pollution created by photochemical oxidisation of an impurity. Causes tear discharge, plant lesions and a pungent smell characteristic of ozone.
<i>Solder resist, solder mask</i> Juotteenesto-pinnoite, JEP	A temporary or permanent protection material which aims at preventing the adhesion of solder and impurities to areas outside the actual soldering areas. Solder resist is also used to prevent dendrite growth in the wiring pattern of the printed board (IPC-SM-840C).
<i>Solid phase</i> Kiinteä olomuoto	A phase of a substance. Silicon dioxide and most metals are typical solid phase substances at 23°C.
<i>Solution</i> Liuos	Liquid and the substances dissolved in liquid form a solution, for example saline solution, sulphuric acid solution.
<i>Soot</i> Chimney soot Noki	Carbon dust often originating from imperfect burning on cars, heating plants etc. In practice, the term soot covers all suspended solid particles in the air (see <i>dust</i>). Soot adsorbs water and other air pollutants and promotes bimetallic corrosion.
<i>Stress corrosion cracking</i> Jännityskorroosio	Stress corrosion (stress corrosion cracking, cracking or break caused by stress corrosion) is a corrosion phenomenon which is created by the combined effect of corrosive chemicals and tension of metal or by the hydrogen absorbed into the metal. The metal will crack because of stress corrosion before reaching its structural stress limit.
<i>Sublimate</i> Härmistyä, sublimoitua	The transformation of a substance directly from gaseous form to solid form. For example, transformation of water to a solid form at low temperature.
<i>Sulphur dioxide</i> Rikkidioksidi	SO ₂ ; corrodes all metals except noble metals.
<i>Sulphuric acid</i> Rikkihappo	H ₂ SO ₄
<i>Surface active</i> Pinta-aktiivinen	Substances that greatly reduce the surface tension of liquid are surface-active substances. These are for example ordinary water-soluble detergents, which remove dirt effectively from various surfaces.
<i>Surface Active Paper, SAP</i> Pinta-aktiivinen paperi	Paper soaked with gas absorbing material.
<i>Surface Insulation Resistance, SIR</i>	The resistance between two parallel metal conductors on a surface. In practice the surface resistance alone cannot be

Pinnan eristysresistanssi	stated because it is always a combination of the resistivity of the surface and of the inside of the material and of geometry (ref. insulation resistance).
<i>Surface resistance</i> Pinnan resistiivisyys	Surface resistivity or square resistance of the surface of material, the unit is ohm per square (Ω/\square).
<i>Surface tension</i> Pintajännitys	Force between the molecules of a substance contracting the surface of liquid and making a liquid drop form into a ball in zero gravity. The force of surface tension varies according to the quality of the liquid and the dissolved substances. Liquids, gases and solids each have their own surface tension, which affects the behaviour of surfaces touching one another and for instance the absorption of liquid into a porous substance.
<i>Suspended matter, – particles</i> Leijuma	Content of impurities characterising fine particles floating in air (mass less than 10 μg , no obvious falling velocity). The unit is $\mu\text{g}/\text{m}^3$.
<i>Suspension</i> Suspensio	Mixture of a solid and a liquid.
<i>Thermal expansion factor, coefficient</i> Lämpölaajenemis-kerroin	A relative value showing the expansion of material within a range of changes in the temperature.
<i>Time of wetness</i> TOW Kastumisaika	In ISO 9223 the time of wetness is defined as the time the metal surface is covered by adsorptive and/or liquid films of corrosive electrolyte, e.g. water and substances dissolved in it. In classification of climates, the time of wetness is defined as the times when the relative humidity of the air is $> 80\%$ and the temperature is $> 0^\circ\text{C}$.
<i>Tin whisker</i> Tinasäie (tinaviiksi, tinakarva)	A tin whisker is a filament similar to a hair growing from a pure tin plating which may cause short-circuiting between parallel wires or surfaces. The growth of tin whiskers depends on the internal tensions of the tin plating and the purity of the tin.
TOW	See time of wetness
<i>Underdeposit corrosion</i> Pinnoitteen alle syöpyminen	Conditions prevailing under most surfaces and accelerating corrosion and resulting in corrosion of the basic material under the plating (see <i>passive layer</i>).

<i>Uniform corrosion</i> Yleinen korroosio	A form of corrosion where corrosion progresses evenly and simultaneously on all surfaces of a substance (see <i>pitting corrosion</i>).
<i>van der Waals forces</i> van der Waalsin voimat	Weak electrical interactive forces which exists between molecules and bonds them to one another. The forces are physical attraction and repulsion forces forming the cohesion forces of liquids and molecular crystals. The forces are a product of dipole-dipole and in part dipole induced dipole (dispersion) interactions. However, even non-polar molecules and atoms have a weak mutual cohesion. Van der Waals forces only have effect within a relatively short distance and the force is inversely proportional to the seventh power of the intermolecular distances. These forces have an important part in the adhesion mechanism. http://palimpsest.stanford.edu/don/dt/dt3669.html
<i>Vapour transmission rate</i> Höyryn läpäisevyys	Permeability of water vapour of e.g. a film, which does not depend on the pressure difference over the film. Vapour permeability is the coefficient VTR in the modified Fick's first law $W = VTR (A t)/s$, where W is the amount of vapour passing through the film (see <i>permeability coefficient</i>).
<i>White rust, wet storage stain</i> Valkoruoste	In humid conditions a hot galvanized plate may develop white rust, porous – powdery corrosion product which is zinc carbonate/hydroxide.
<i>Wicking</i> Kapillaarinen imeytyminen	Wicking is absorption of liquid along the fibres (threads) of base material (e.g. printed board).
<i>Zeolite</i> Zeoliitti	See molecular sieve
<i>Zinc coating, galvanization</i> Sinkitys	General term for plating with zinc, see <i>aluminium zincified</i> .

Quantity conversions from the Anglo-Saxon system to the SI system

Old Anglo-Saxon units are still frequent in the literature. The following presents some quantities used for describing air quality and other properties of the air. It is not recommended to use the old units. It is however, important to know the correct equivalents in the SI system.

International System of Units (SI): The modern metric system.

<http://physics.nist.gov/cuu/index.html>

Mass and pressure

psi = pounds (pressure) per square inch

1 lb = 16 oz = 0,45359244 kg (lb = pound)

1 lb = 16 oz 1 oz = 28,35 g (oz = ounce)

(the troy ounce is used for noble metals = 31,10 g)

1 psi = 0,453592 kp/in² = 0,453592 kp/ 6,4516 cm² = 0,07031 kp/cm²

1 kp/cm² = 735,56 torr = 0,980665 bar

15 psi = 1,055 kp/cm², 1 atm = 760 torr = 760 mm Hg = 1013,25 mb

1 bar = 100 kN/m² = 100 kPa (Pa = Pascal)

Length and layer thickness

in = inch, 1 in = 25,4 mm, 1 mils = 1 in /1000 = 25,4 μm

1 Å = Ångström = 10⁻¹⁰ m, 1 nm = 10⁻⁹ m

micron = micrometre = 1 μm = 0,001 mm

Volume and volume ratio

1 cm³ = 1 mL millilitre, 1 mm³ = 1 μL microlitre

ppm (parts per million) = 10⁻⁶ = 1 cm³/m³

ppb (parts per billion) = 10⁻⁹ in the United States (volume/volume 1 mm³/m³).

The abbreviation ppb should not be used to avoid confusion, since billion equals 10¹² in England and elsewhere.

In England billion = million million and in the United States thousand million.

The abbreviations ppm and ppb should only be used to express concentration (mass ratio) but they have been occasionally used for volume ratios.

The following conversions for gas concentrations (mass ratio in air) can prove useful:

SO ₂	1 μg/m ³ = 0,38 mm ³ /m ³	1 ppm SO ₂ ≈ 2630 μg SO ₂ /m ³
H ₂ S	1 μg/m ³ = 0,71 mm ³ /m ³	1 ppm H ₂ S ≈ 1410 μg H ₂ S/m ³
NH ₃	1 μg/m ³ = 1,43 mm ³ /m ³	1 ppm NH ₃ ≈ 700 μg NH ₃ /m ³
NO ₂	1 μg/m ³ = 0,53 mm ³ /m ³	1 ppm NO ₂ ≈ 1880 μg NO ₂ /m ³
Cl ₂	1 μg/m ³ = 0,34 mm ³ /m ³	1 ppm Cl ₂ ≈ 2940 μg Cl ₂ /m ³

Directory

Directory

Some used Internet addresses are listed in the beginning of this directory.

See also the contents on pages 6..8 and Appendix 1 Fundamentals of corrosion and failure mechanisms and Appendix 3 Review methodology of the corrosion control, and Appendix 4 Corrosion glossary.

Patents and standards in Internet

Delphion / Thomson Corporation <http://www.delphion.com/>

Patentti- ja rekisterihallitus. <http://www.prh.fi/>

ANSI American National Standards Institute. <http://web.ansi.org/>

ASTM American Society for Testing and Materials.

<http://www.astm.org/>

BSI British Standards. <http://www.bsi-global.com/>

CENELEC European committee for electrotechnical standardization.
<http://www.cenelec.org/Cenelec/Homepage.htm>

DIN Deutsches Institut für Normung e.V. <http://www2.din.de/>

EIA Electronic Industries Alliance. <http://www.eia.org/>

IEC International Electrotechnical Commission

<http://www.iec.ch/index.html>

IEEE The Institute of Electrical and Electronics Engineers.
<http://standards.ieee.org/>

IPC – Association Connecting Electronics Industries <http://www.ipc.org/>

ISA International Society for Measurement and Control. <http://www.isa.org/>

ISO International Organization for Standardization. <http://www.iso.ch/>

JEDEC Solid State Technology Association (Is the semiconductor engineering standardization body of the Electronic Industries Alliance (EIA)).

<http://www.jedec.org/>

SAE Society of Automotive Industry. <http://www.sae.org/>

SESKO Suomen Sähköteknillinen Standardisoimisyhdistys SESKO r.y.
<http://www.sesko.fi/>

SFS Suomen Standardisoimisliitto. <http://www.sfs.fi/>

US Patent and Trademark Office. <http://www.uspto.gov/>

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Title Corrosion and climatic effects in electronics		
Abstract <p>Corrosion control in electronics and know-how concerning various protection methods have become an important field of design since electronics is increasingly used as integrated into different devices in highly corrosive conditions. On the other hand, the increase of the packaging density of electronics has resulted in electronics that is sensitive to the corrosive effects of the environment even in milder conditions.</p> <p>The project charted the mechanisms through which the climate, other environmental factors, contamination, the way of use of the device and its structure as well as the manufacturing process affect the corroding and faults of the electronics. A method was developed for solving these problems by which both the experienced and the beginning designer can check the feasibility of the applied corrosion protection technique and foresee possible corrosion problems in the structure of the device as well as find new approaches for solving them.</p> <p>The report also presents an evaluation method for the corrosive effect of the usage environment. In addition, various types of corrosion and protection against them are described, corrosion analysis and measurement methods introduced and testing methods used for quality assurance regarding corrosion discussed. Comprehensive lists of standards and literature concerning corrosion and climatic effects are appended to the report.</p> <p>This report is available in English and in Finnish (VTT Publications 623, http://virtual.vtt.fi/inf/pdf/publications/2007/P623.pdf).</p>		
ISBN 978-951-38-6991-5 (soft back ed.) 978-951-38-6992-2 (URL: http://www.vtt.fi/publications/index.jsp)		
Series title and ISSN VTT Publications 1235-0621 (soft back ed.) 1455-0849 (URL: http://www.vtt.fi/publications/index.jsp)		Project number
Date February 2007	Language English	Pages 242 p. + app. 173 p.
Name of project Corrosion and climatic effects in electronics (KORSU)		Commissioned by VTT Technical Research Centre of Finland, Finnish Funding Agency for Technology and Innovation (Tekes), ABB Industry Ltd, Technology Department, Benefon Ltd, Efore Ltd, Kone Elevators Ltd, Nokia Mobile Phones Ltd.
Keywords corrosion, electronics, electronic equipment, design, verification, atmosphere, climate, moisture, humidity, pollution, quality, quality control, temperature, corrosive gas, measurement, tests, environmental tests, Finland		Publisher VTT P.O.Box 1000, FI-02044 VTT, Finland Phone internat. +358 20 722 4404 Fax +358 20 722 4374

This publication "Corrosion and Climatic Effects in Electronics" is designed as an aid in electronics design and its quality assurance. The publication discusses the problems caused by corrosion and climatic stress on electronic devices, the nature of corrosion and the ways of controlling corrosion in an enterprise that use subcontracting. Corrosion control is linked here to the quality system of the company whereby a general review methodology is designed for identifying the factors affecting corrosion in the company activity and in the use of a product in the customer environment.

Know-how concerning environmental stress factors such as heat, humidity, contamination and air impurities as well as corrosion risks and phenomena caused by human and organic activity and the prevention methods for these corroding effects belong to corrosion control. This publication guides the user in identifying the means to tackle certain corrosion and environmental problems and in developing the design methods of the company in such a way that corrosion and climatic effects are considered on a wide enough scale throughout the activity.

The project was carried out under the heading "Corrosion and Climatic Effects in Electronics" as a part of the Finnish Funding Agency for Technology and Innovation (Tekes) research programme "Electronics for the information society-ETX", which was launched in 1997. The project was carried out at VTT in co-operation with Tekes, ABB Industry Ltd Technology Department, Benefon Ltd, Efore Ltd, Kone Elevators Ltd and Nokia Mobile Phones Ltd and Tampere University of Technology, Microelectronics.

Julkaisu on saatavana

VTT
PL 1000
02044 VTT
Puh. 020 722 4404
Faksi 020 722 4374

Publikationen distribueras av

VTT
PB 1000
02044 VTT
Tel. 020 722 4404
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This publication is available from

VTT
P.O. Box 1000
FI-02044 VTT, Finland
Phone internat. + 358 20 722 4404
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