2077

VTT RESEARCH NOTES

V T T T I E D O T T E I T A

Plant life management (XVO)
Report 1999

TECHNICAL RESEARCH CENTRE OF FINLAND

ESPOO 2001

VTT TIEDOTTEITA – MEDDELANDEN – RESEARCH NOTES 2077

Plant life management (XVO)
Report 1999

Edited by

Jussi Solin

VTT Manufacturing Technology

TECHNICAL RESEARCH CENTRE OF FINLAND
ESPOO 2001

ISBN 951–38–5786–7 (nid.)
ISSN 1235–0605 (nid.)

ISBN 951–38–5787–5 (URL: http://www.inf.vtt.fi/pdf/)
ISSN 1455–0865 (URL: http://www.inf.vtt.fi/pdf/)

JULKAISIJA – UTGIVARE – PUBLISHER

Valtion teknillinen tutkimuskeskus (VTT), Vuorimiehentie 5, PL 2000, 02044 VTT
puh. vaihde (09) 4561, faksi (09) 456 4374

Statens tekniska forskningscentral (VTT), Bergsmansvägen 5, PB 2000, 02044 VTT
tel. växel (09) 4561, fax (09) 456 4374

Technical Research Centre of Finland (VTT), Vuorimiehentie 5, P.O.Box 2000, FIN–02044 VTT,
Finland, phone international + 358 9 4561, fax + 358 9 456 4374

VTT Valmistustekniikka, Voimalaitosten materiaalitekniikka, Kemistintie 3, PL 1704, 02044 VTT
puh. vaihde (09) 4561, faksi (09) 456 7002

VTT Tillverkningsteknik, Material och strukturell integritet, Kemistvägen 3, PB 1704, 02044 VTT
tel. växel (09) 4561, fax (09) 456 7002

VTT Manufacturing Technology, Materials and Structural Integrity, Kemistintie 3, P.O.Box 1704,
FIN–02044 VTT, Finland
phone international +358 9 4561, Fax +358 9 456 7002

Otamedia Oy, Espoo 2001

Solin, Jussi (ed.). Plant life management (XVO). Report 1999. Espoo 2001, Technical Research Centre of Finland, VTT Tiedotteita – Meddelanden – Research Notes 2077. 68 p. + app. 3 p.

Keywords industrial plants, nuclear power plants, life tests, energy production, life (durability), aging (metallurgy), management, cracking, inspection, reliability, service life, pressure bearing components

Abstract

Experimental and analytical research is being carried out in an industrially oriented project dealing with on estimating and managing lifetime of critical structural components in energy industry. The research topics included systematic component lifetime management, lifetime of pressure bearing components, piping vibrations and integrity management, management of materials ageing, non-destructive inspection, water chemistry, oxide films and their role in service reliability and build-up of activity levels, stress corrosion cracking in Inconel welds, irradiation assisted stress corrosion cracking of core components, development of crack growth testing methods as well as the mechanisms of environmentally assisted cracking.

The main results of the first project year are summarised in this report.

Preface

The current project on plant life management - or “Rakenteellisen käyttöiän hallinta” in Finnish - was started in 1999 for four years. The first phase, referred as “project year 1999”, was started in May 1999 and ended in April 2000. This report describes the main activities during this period. The contributing authors and participating organizations are listed in acknowledgements.

The aim of providing scientifically verified, but still practical tools for plant life management was known to be ambitious and during the first year this challenge has been a subject for long discussions.

To be safe, we need to find and use correct models on ageing mechanisms, but simplification is also needed for bringing the results into practice. Within this project, some subprojects generate totally new knowledge on ageing. On the other hand, simplification is expected especially for the first subproject dealing with the lifetime management. To put it together, a motto is proposed for this project:

“Life is short and information endless.
We must learn to simplify,
but not to the point of falsification.”
Aldous Huxley

Finally, open communication between the researchers and utility staff has been essential to guide the work and to obtain a balanced combination of research and problem solving activities. Hopefully this leads to appropriate information for optimization of inspection intervals, reduction of maintenance costs, enhancement of operability and extension of plant lives in the participating and other industries.

Contents

Abstract ... 3

Preface ... 4

1. Introduction ... 7

2. Lifetime management of materials and structures in nuclear power plants ... 8
   - 2.1 Systematic component lifetime management ... 8
   - 2.2 Planning of repairs ... 11
     - 2.2.1 Subproject activities in 1999 ... 11

3. Lifetime of pressure bearing components ... 12
   - 3.1 Piping vibrations management ... 12
     - 3.1.1 Subproject activities in 1999 ... 12
     - 3.1.2 Literature study on updating FE models with modal data ... 14
     - 3.1.3 Development of the random vibration module for the FPIPE program ... 16
     - 3.1.4 Studies for the pilot piping ... 17
   - 3.2 Development of a program system for piping integrity assessment ... 23
     - 3.2.1 Subproject activities in 1999 ... 23
     - 3.2.2 Description of the target program system ... 23
     - 3.2.3 Improvements in the data base ... 25
   - 3.3 Management of materials ageing ... 29
     - 3.3.1 Subproject activities in 1999 ... 30
     - 3.3.2 Irradiation embrittlement, recovery and re-embrittlement ... 30
     - 3.3.3 Thermal ageing of cast stabilised austenitic stainless steel ... 33
   - 3.4 Non-destructive monitoring of structural integrity ... 38
     - 3.4.1 Subproject activities in 1999 ... 38
     - 3.4.2 Development of a mechanised scanner for ultrasonic inspection ... 38
     - 3.4.3 Capabilities and qualification of NDT-techniques ... 39
     - 3.4.4 Plans for year 2000 ... 40

4. Effects of environment on component service reliability ... 41
   - 4.1 Water chemistry, service reliability and activity levels ... 41
     - 4.1.1 Subproject activities in 1999 ... 41
     - 4.1.2 Correlation of water chemistry, oxide films properties, activity build-up and material behaviour in VVER and BWR conditions ... 41
     - 4.1.3 Stability of oxide films during the shut-down process of a VVER plant ... 43

4.1.4 Correlation of oxide films properties and environmentally assisted stress corrosion cracking (EAC) in BWR conditions.............................. 44
4.1.5 Influence of deposited oxides on the material behaviour of secondary side components in a VVER plant 45
4.1.6 Plans for year 2000.. 46
4.2 Stress corrosion cracking in Inconel welds.. 47
4.2.1 Subproject activities in 1999 47
4.2.2 Relevant crack growth mechanism 48
4.2.3 Crack growth rate tests.. 50
4.2.4 Plans for year 2000.. 55
4.3 Mechanisms of environmentally assisted cracking 55
4.3.1 Subproject activities in 1999 55
4.4 Irradiation assisted stress corrosion cracking of core components.................. 56
4.4.1 Subproject activities in 1999 57
4.4.2 IASCC in PWR reactor conditions.. 57
4.4.3 Development of crack growth testing methods....................................... 60

5. Summary 63

Acknowledgements... 66

References.. 67

Appendix

1. Introduction

The Finnish nuclear power plants have operated for more than 20 years. No significant outages have occurred due to materials or structural integrity problems. All four units, two BWR's at TVO Olkiluoto plant and two VVER's at Fortum Loviisa plant, have continuously achieved excellent usage factors. Naturally, the utilities are very much interested to be able to continue this record and efficient operation long in future.

The fact that the Finnish nuclear reactors have performed so well is a good proof of high expertise, effective operation and successful preventive maintenance. However, concerns on long term availability motivate continuous investments to maintain the excellent usage factors and to be able to continue operation long in future. Research on critical components' ageing, structural integrity and lifetime management belongs to that investment. The current project "Rakenteellisen käyttöiän hallinta" is supposed to carry out essential parts of this utility driven research.

To keep the project in focus, the work plan was based on current and anticipated challenges of the Finnish nuclear power plants. However, technology transfer across the industry sectors was also a target. The nuclear industry may benefit of adopting approaches tested in other industry. On the other hand, part of the advances in conceptual solutions, materials science and other generic technology shall be transferable to other capital intensive industry sectors where avoiding of unplanned outages is equally important.

The partial public funding received from the National Technology Agency (Tekes) underlines the interest to a broadened application basis. In practice, much of this is achieved through separate spin-off projects.

This report describes the main activities and achievements during the first project year.

2. Lifetime management of materials and structures in nuclear power plants

2.1 Systematic component lifetime management

Many power and process industries are currently developing preventive maintenance and plant life management systems for their own use. Consideration of plant specific design and integrity problems support use of tailored programs and/or data bases for plant life management. The final applications will be developed on plant type, utility, plant or system level. However, common features can be included in the systems.

The project - as a whole - deals with systematic component lifetime management, piping vibrations and integrity, NDE, materials ageing, interactions of coolant and materials, environmentally assisted cracking and ageing of reactor internals.

The aim of this subproject is to define, how the results should be applied in practice. It is necessary but not sufficient to advance knowledge on the relevant ageing mechanisms and their impact on the selected components. The parallel disciplines shall also be integrated such that quantitative assessments on remaining safe life and failure risks are possible.

Quantitative safety assessments can only be achieved through probabilistic approaches. For that purpose correct models on ageing mechanisms and the influencing factors are needed, but well-founded simplifications are also necessary. Another point is user friendliness. If the utility staff is supposed to input a huge amount of data and knowledge in the system, it need to be compatible with the existing data management systems. The additional work shall be minimised.

Although similar needs exist at many production plants in energy and process industries, the plant life management systems - or at least their applications - need to be tailored for the utility needs. One possibility is to utilise modularity in a similar way as in the development of a program system for piping integrity assessment described in chapter 3.2.

Figure 1 shows a general scheme of component lifetime management followed in the current project. The subproject organisation is also based on this model.

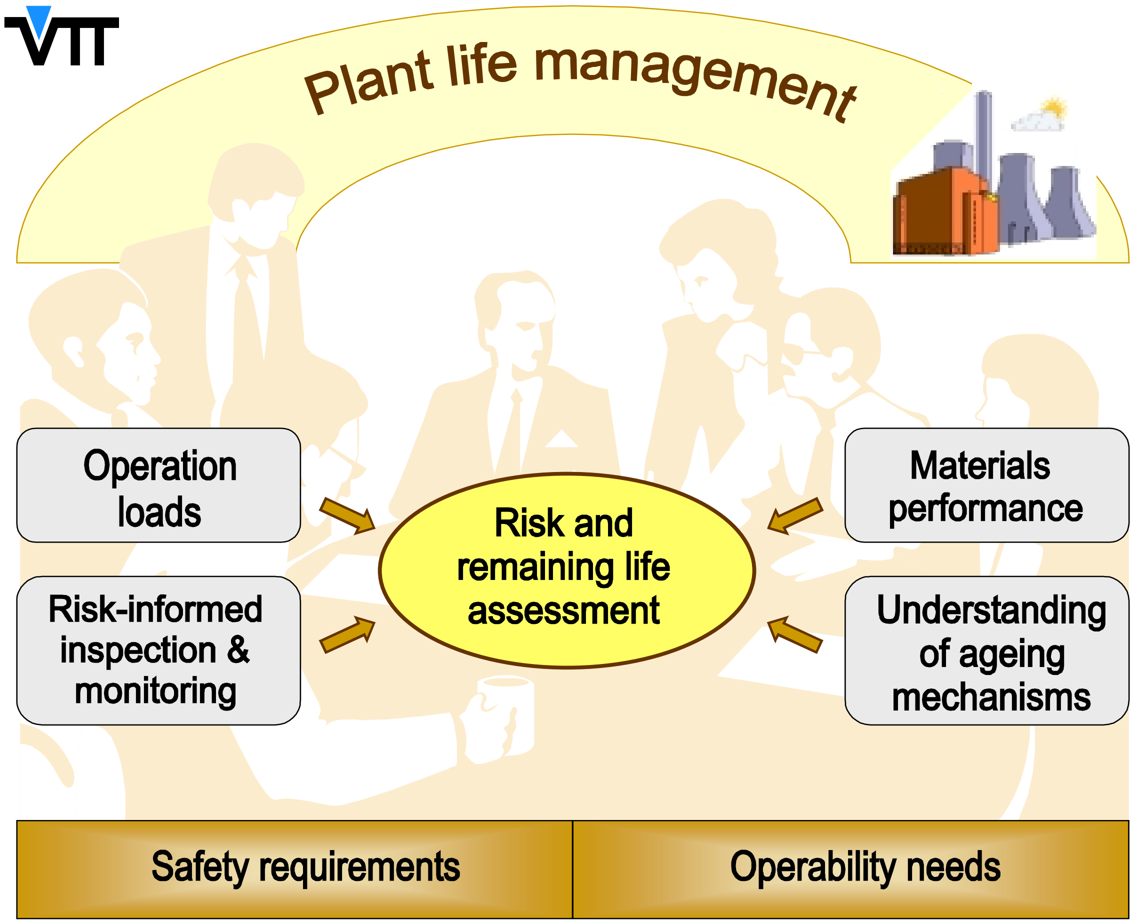


Figure 1. Elements of systematic component lifetime management.

Systematic component lifetime management serves two parallel needs. The safety requirements set a mandatory basis for all operations. Operability needs originate from economical interests and market restrains.

The topics to be considered are outlined in Table 1. Knowledge is needed on

- relevant ageing mechanisms and their impact on the selected components,
- materials performance in the process environment and subjected to the operational loads,
- operational loads[1] in normal steady state operation and in transients, and
- condition of the materials and components.

---

[1] "Loads" appear in a generalised meaning here. All mechanical, thermal, chemical and other stressors are included.

Table 1. Topics to be considered for component lifetime management.

Ageing mechanisms	**Materials performance**
• Material degradation - irradiation embrittlement - thermomechanical ageing - fatigue (LCF, HCF, thermal f.) - creep • Surface reactions - metal-oxide-coolant interaction - general and local corrosion - erosion, wear, fretting - crack initiation • Crack growth - fatigue crack growth; · thermal- & corrosion fatigue - stress corrosion cracking; · TGSCC, IGSCC, IASCC	• Composition, strength • Fracture toughness • Irradiation embrittlement • Thermal ageing • Fatigue - low cycle, high cycle fatigue - thermal fatigue - corrosion fatigue • Stress corrosion cracking - intergranular (IGSCC) - transgranular (TGSCC) - irradiation assisted (IASCC) • Corrosion, erosion, wear • Creep
Condition monitoring	**Operational loads**
• Non-destructive testing - risk informed inspection - crack detection - crack sizing • Material condition monitoring - surveillance testing - ageing measurement by NDT • Monitoring of operation - water chemistry monitoring - oxides and contamination - temperature transients	• Steady state operation - pressure and thermal loads - vibration • Transients - start-up, shut-down - thermal stratification - water hammer - abnormal transients • Environmental loads - irradiation doses - coolant chemistry - corrosion potential

2.2 Planning of repairs

Development of a platform for planning and analysing of repair welding specifications for safety critical structures was included in the original project plans, but this task was postponed in an early phase due to availability and prioritisation of resources. However, late in 1999 it was decided to include a literature survey concentrating on novel improvement and repair technologies potentially suitable for reactor internals.

2.2.1 Subproject activities in 1999

The goal of this subproject is to survey the state-of-the-art the newest repair and improvement methods for nuclear power plant components. Possibilities to a remote controlling of the applied processes reduce the radiation exposures of the workers, too.

In 1999 this subproject contained the following task:

- A literature study was started to clarify the state of the art in development of methods for repair welding and improvement processes for better resistance against fatigue and stress corrosion of nuclear power plant components.

The survey (Pelli, 2000) was aimed to find out the applicability of the following methods:

- YAG laser welding,
- laser shock peening,
- water jet peening, and
- ultrasonic impact peening.

YAG laser welding provides an excellent possibility to a remote controlled repair process and it can be used in narrow places because the power can be transmitted through an optical fibre. The power source and the control board can be more than 200 meters away from the repaired part.

Both laser shock and water jet peening have been applied in practice for the residual stress state improvements for reactor internals. They are clean methods because no additional material is needed. Experimental data shows that the use of them can transform the former tensile residual stresses on the surface into a compressive stress and then prevent stress corrosion failures.

This task was initiated late in 1999 and completed during the year 2000 (Pelli, 2000).

3. Lifetime of pressure bearing components

3.1 Piping vibrations management

The dynamic behaviour of the supports and other details described in the design documents may significantly differ from the current condition of the piping. This aspect is particularly important when considering the applicability and generalisation of the project results.

The main goal of this subproject is to develop a method to obtain a system to monitor piping vibrations and associated phenomena like stress cycles and fatigue. The aim is to obtain relevant and adequate information with only a very limited amount of vibration sensors. This should be possible in case the condition monitoring system is complemented with either a directly coupled computational model or with frequency dependent influence matrices and/or functions. Influence matrices and/or functions are obtained by use of computational models and will give direct vibration related stress results without reanalysis of the structure.

Making an adequate model to describe the dynamic behaviour of a piping system is complicated. The dynamic behaviour of the supports and other details described in the design documents often differ significantly from the actual piping. Special purpose programs and several tuning iterations may be necessary to accurately tune the models to the actual piping. The approach to come to such a model is shown in Fig. 2.

3.1.1 Subproject activities in 1999

The chosen systematic approach to be used in this project is illustrated in Fig. 3. A project team is formed and experts from the industry participate actively in the work. In the year 1999 this subproject included the following tasks:

- A literature study was performed to investigate the state of the art in the development of methods to update FE models with help of experimental data. This is called modal analysis.
- A computational module for random vibration analysis was developed and implemented in the special purpose finite element program FPIPE. The program has been developed by FEMdata Oy and is widely used in Finnish industry.
- A pilot study was started to develop and verify a combined analysis system consisting of experimental vibration measurements, modelling and analyses.

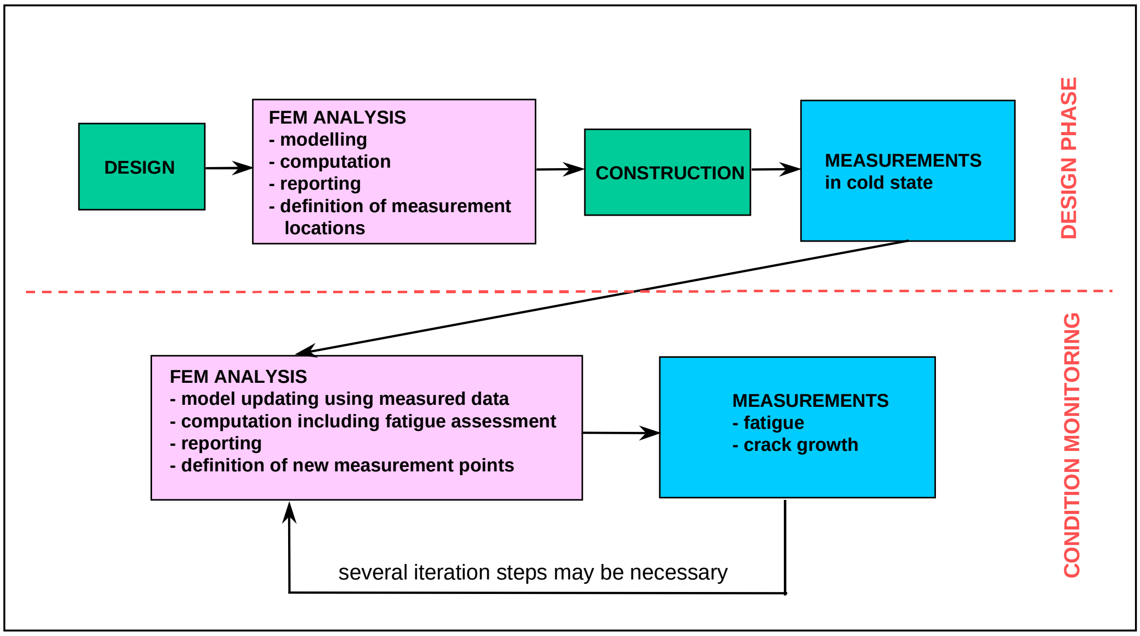


Figure 2. The adopted approach to come to an adequate model to describe the dynamic behaviour of a piping system.

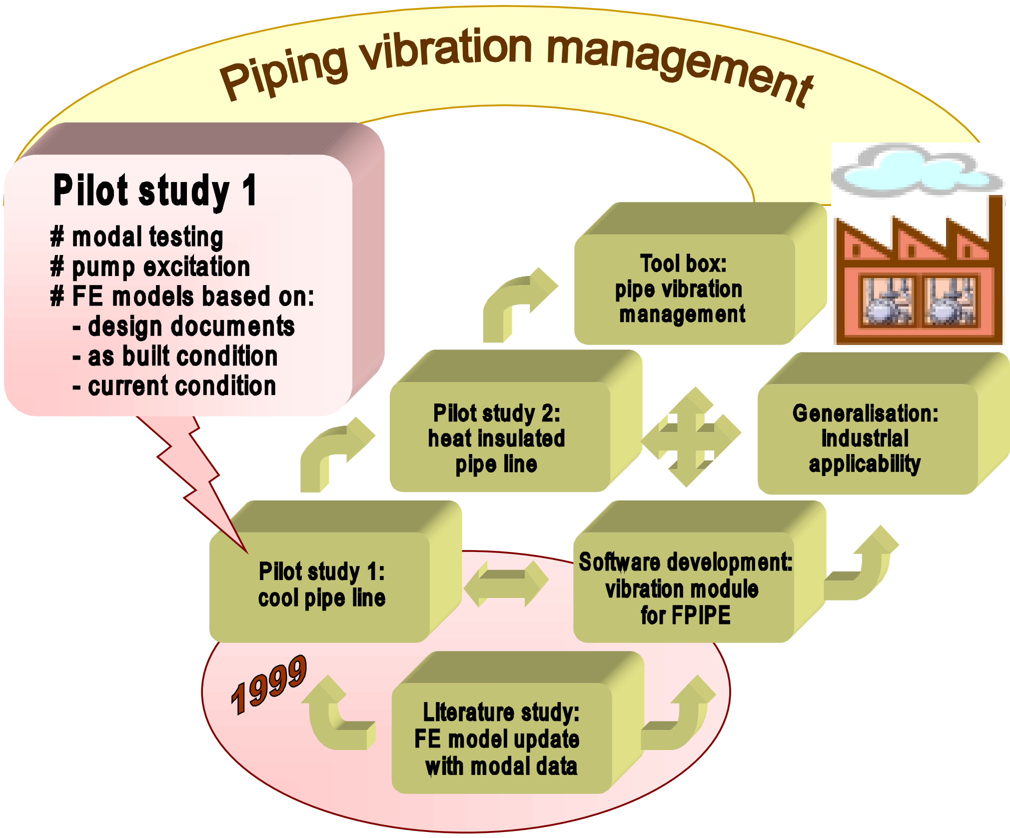


Figure 3. The general project plan for developing a piping vibrations monitoring system and the scope of the first phase during the project year 1999.

3.1.2 Literature study on updating FE models with modal data

The dynamic behaviour of a structure can be assessed using either analytical predictions or experimental measurements. Both are based on the assumption that vibration characteristics of a system within a given frequency range can be described by a mathematical model with a limited number of co-ordinates and modes. The analytical predictions are usually done using the finite element (FE) method. The experimental evaluations are normally performed by modal testing and analysis of the test results.

Generally it is believed that experimental data is more reliable, because it contains the contributions of all features really existing in the system. However, it is difficult and expensive to obtain comprehensive experimental data with a reasonable effort and in a reasonable time. Therefore the most efficient and still reliable approaches combine theoretical computations and experiments. They use measurements to validate and update the analytical model. Development of suitable methods to update FE models with experimental data is a key element of the current subproject.

The routes to perform theoretical and experimental vibration analyses are outlined in Fig. 4. According to Ewins, the first step of a theoretical analysis is to generate a *spatial model* describing the physical characteristics of the structure in terms of mass, stiffness and damping properties. Using the spatial model, structural vibration modes are defined. As a result a *modal model* is obtained, consisting of natural frequencies, corresponding vibration mode shapes and modal damping factors. Finally, the structural behaviour under a given excitation is assessed and a *response model* is obtained. On the other hand, experimental vibration analysis starts from the measured response and aims to obtain a mathematical description of the dynamical or vibration behaviour of a structure through modal testing (Ewins, 1986).

A simple comparison of experimental and computational results may give an impression of whether the correspondence is good or not, but it does not give any guidance on how the computational model should be updated. To enable a more valuable comparison, a few criteria have been proposed in literature. Allemang & Brown (1983) have presented a Modal Assurance Criterion (MAC)

$$MAC_{ij} = \frac{\left[\{\phi_i\}^T \{\phi_j\}^*\right]^2}{\{\phi_i\}^T \{\phi_i\}^* \{\phi j\}^T \{\phi_i\}^*} \tag{1}$$

where $\{\phi\}$ is a measured or predicted eigenvector. The value of MAC varies between 0 and 1. A higher MAC value indicates a better correlation between the measured and computed responses.

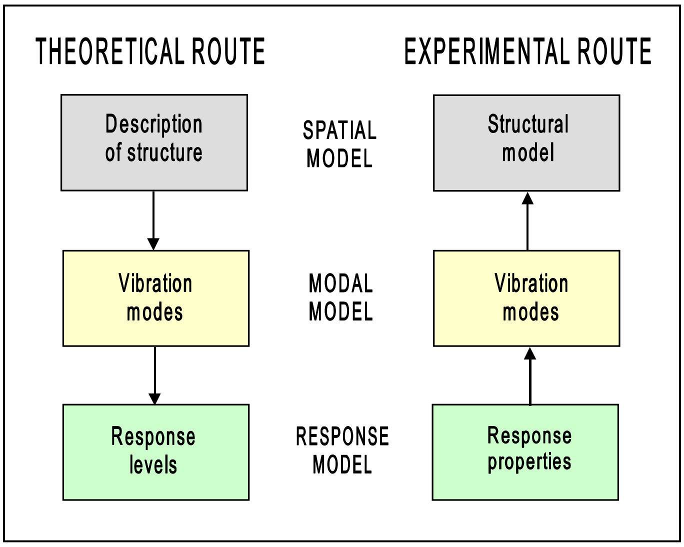


Figure 4. Different routes of vibration analysis (Ewins, 1986).

A separate report (Talja et al., 2000) briefly discusses the following criteria:

- The Coordinate Modal Assurance Criterion is a correlation indicator corresponding to a given common coordinate between the models.
- Frequency function overlays utilise visual plots of measured and predicted response functions against each other.
- Sensitivity based methods construct a sensitivity matrix of partial derivatives of the target modal parameters for an iterative procedure.
- The methods based on frequency function (FRF) and correction factors for each finite element are considered very promising for our purposes.

The frequency function based method for updating the FE model

An example of FRF based methods has been presented by Lin and Ewins (1990). Up to three correction factors per finite element are first allocated: one for mass matrix, one for stiffness matrix and one for damping matrix, if damping is included in the analysis. The values of these correction factors are iterated until the difference between the measured and predicted response functions is minimised at a number of selected frequency points. The following main benefits are associated to this method:

- The measured FRF data can be directly used without any modal analysis.
- This method can be applied even to structures with non-modal behaviour due to high damping or high modal density.
- Statistical methods can be used to solve the problem.

3.1.3 Development of the random vibration module for the FPIPE program

FEMdata Oy has developed a set of special purpose finite element (FEM) programs, which are widely used in Finnish industry. The FPIPE program is used for analysing the behaviour and strength of pipes. Due to its commercial availability, wide use and suitability for the purpose, FPIPE was selected as a key element to be used in the integrated piping vibration monitoring system.

Within the current project, a computational module for random vibration analysis has been implemented in the FPIPE program system. The plan is to test and verify the module through the pilot studies and other analyses within this project. The VTT staff performs the verification analyses, the industrial partners in the project bring in their needs and advice as target users of the software, and finally, the software improvements will be realised by FEMdata Oy.

Assumed excitation

Using the developed random vibration analysis module one may consider loading defined as power spectrum densities (PSD). Such loading is typically caused by natural phenomena like earthquakes, wind, waves or turbulent flow. Another common example is loading of moving vehicles caused by the ground surface roughness.

The excitation process is assumed to be stationary and ergodic[2] and its mean value is assumed to be zero. This means that the excitation is constant in a statistical meaning and that its mean value over time is zero. The excitation process is defined in a frequency plane using spectral densities (power spectra, PSD).

The loading may consist of several force or acceleration excitations at support points. One force excitation may consist of several nodal point loads. The correlation between the excitations is defined using cross spectrum densities.

Analysis and application

After the calculation of eigenvalues and eigenmodes, the random vibration analysis is performed as a superimposition of eigenmodes. As a result, the RMS response of the structure is obtained. It is expressed as effective displacement, force, moment and stress

---

[2] An ergodic process is always stationary, but all stationary processes are not ergodic. Ergodic is defined as follows: Any average obtained with respect to time along any member of the ensemble is exactly equal to the corresponding average across the ensemble at an arbitrary time.

values and some statistical characteristics of the response. If desired, also auto and cross spectrum densities of the response components can be computed.

The user manual of the module contains a description of the input data and the theory behind the computation. Additionally, information on the program development and a couple of application examples are included.

Depending on the results of the testing and verification work at VTT, some updating of the module may prove necessary. After that the module can be taken into production use.

3.1.4 Studies for the pilot piping

A first pilot study was started to develop and verify a combined analysis system consisting of experimental vibration measurements, modelling and analyses. The following tasks were included in this study:

- Selection of a piping system suitable for both in service and off service experiments and for modelling without unnecessary complexity.
- Modal testing to characterise the dynamic behaviour of the piping. Both operational and natural mode shapes were obtained through measurements by acceleration transducers.
- The excitation in the piping caused by the piston pump was assessed by an acoustic analysis software which has been earlier used as a design tool for compressor piping systems at the Neste Oil refinery.
- FE models of the piping were generated based solely on the data from the design documents. Therefore, the results simulate the vibration behaviour that would be predicted during a design project.
- The results obtained by the first FE models were compared to the experimental results and the sensitivity of the results to different assumptions and simplifications was evaluated.

The aim is that new models with gradually increased amount of knowledge on the actual piping condition will be generated in the next phase of the project. Furthermore, a second case study, including elevated temperature and damping effects caused by thermal insulation of the piping, is planned before the developed vibration monitoring approach can be recommended for general purposes.

This pilot study will also provide some new information and answers to the important questions: How reliable are the CAE-models used for design? How should one combine and compare the results of field measurements to those given by the CAE-model?

Description of the pilot piping

A part of the auxiliary feed water system piping at Olkiluoto 1 unit was chosen as the object for this pilot study. The main reason for this selection was a good suitability for the experiments that were performed both during operation and in a standstill condition.

During normal operation, the auxiliary feed water system is not in use except for the periodically performed tests lasting for five minutes each month. The expected - and measured - vibration amplitudes were so small that no integrity problems are anticipated due to this vibration.

The part of the piping system being under consideration is located on the outside of the containment between the containment penetration and the auxiliary feed water system pumps. The pumps are 3 piston plunger pumps running at a frequency of 4 Hz. The pipeline has a total length of about 40 meters and it has two major branches. There are 17 different kind of supports and three different actuators.

This pipeline is made from DN 100 stainless steel pipe. The design pressure, which is effective during the use of the pump, is 90 bar and the design temperature is 100 C. However, the piping is filled with water that does not exceed the room temperature during any anticipated transient. This means that the piping is not insulated and that temperature is not an issue.

Modal testing

Modal testing was performed to experimentally characterise the dynamic behaviour of the piping. The mode shapes and associated frequencies were determined both during operation and in standstill condition. Thus, both operational and natural mode shapes were obtained.

The following equipment and software was used for the measurements and for the vibration animations:

- Acceleration transducers: Bruel&Kjaer type 4371 and Wilcoxon Recearch
- Hammer: 1.68 Kg
- Charge amplifiers: Bruel&Kjaer
- Recorder: Sony 16 channel DAT- recorder

- Dual channel FFT spectrum analyser AND AD-3525
- ADCNV File conversion program
- Animo for DOS and Animo for Windows

Operational mode shapes

During the short operation periods of the auxiliary feed water system, 16 acceleration signals were recorded. However, altogether 29 points had to be measured in several directions to record the behaviour of the complete piping system with a sufficient accuracy. This means that five measurement sessions were needed. A time span of five months had to be allocated for this task.

One vibration signal, being the same signal for all measurements, was chosen as the reference signal. Because the behaviour of this reference point was similar in all measurements, this was considered to a valid procedure.

With help of the frequency dependent phase relation between the reference signal and the other signals it was possible to produce animations of the complete pipe for any single frequency. The most significant frequencies were selected based on the maximum amplitudes in the piping and animations were made for these frequencies.

Natural mode shapes

The operational mode shapes are resulting from the reciprocating pump induced excitation, which is active during the whole operation period.

The natural mode shapes are excited with hammer impacts causing short time impulses with more or less uniform energy input over the significant frequency band. The mode shapes themselves are then recorded but the data immediately after the impulses are neglected. The data after the direct influence of the excitation has become negligible are used to determine the modes and associated frequencies. This is done in a similar way as described above for operational modes. Only the modes belonging to natural frequencies are resulting from these measurements.

Assessment of piston pump excitation

Neste Engineering has recently taken into use an acoustics analyse software PULS for the design of compressor piping filled with gas. The pilot study offered a good possibility to examine, how this approach would work, when analysing piping systems for liquids. The difficulties one will meet in defining an acoustic excitation in such cases are an issue of interest.

The pipe lines in energy and process industry contain plenty of reciprocating compressors. They cause a remarkable acoustic excitation in the piping. The accuracy of the analyses performed in the design phase should be assessed. But in practice, it is quite impossible to go to the field after a design project and stop the compressor for measurements, just to find out how successful one has been with the design tool.

Discussion on the excitation analysis

The pumping system considered contains a reciprocating pump and chambers. The purpose of the chambers is to cut off the harmful high or low frequencies and dampen the pulsation. In this case, the task was to define the forces that cause the vibration.

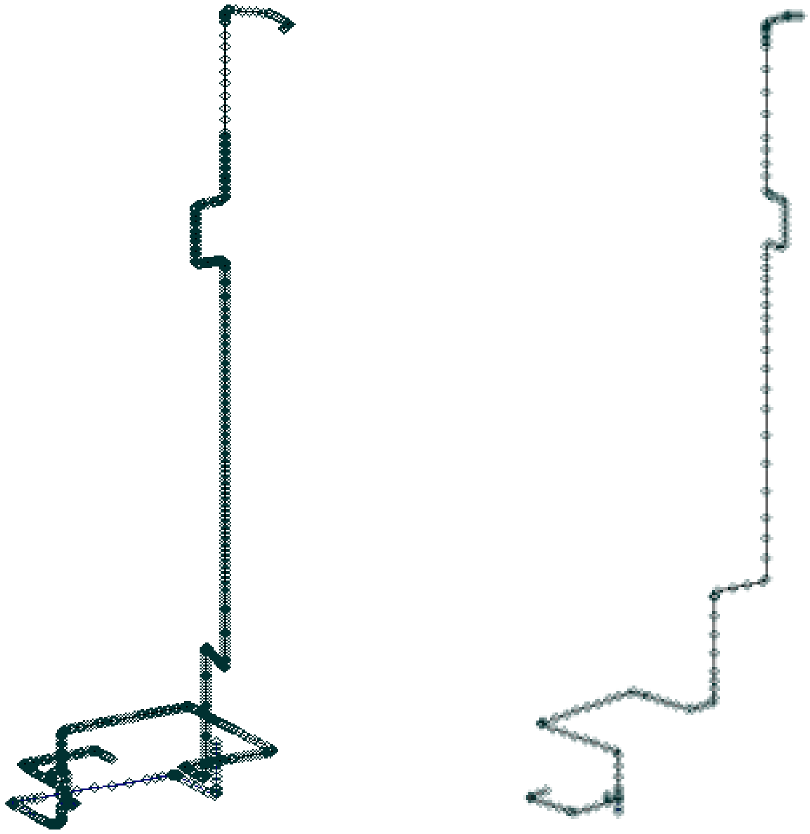
The most difficult thing with regard to the modelling was to find out the volumes of the chambers. After a small research it turned out that there are three possibilities to define the volume. To be sure, it was necessary to calculate the volume in three different ways and then compare the results. The comparison of results showed that the shaking force can vary even 30%, but the pulsation pressure response seems to be quite the same.

Later, when the acoustic and mechanical systems are coupled together and the mechanical response analysis is done, we have a chance to compare the results of on site measurements and those generated with the model. This will probably show how important the chamber volume is in real life. The second interesting result will be the ratio of the model results compared to field measurements. So far, much of the work has been getting acquainted with the difficulties in the modelling and learning what kind of basic data one should have to create a digital acoustic model of this kind.

FE analyses for eigenmodes using models based on the design documents

Different FE models of the pilot piping have been generated. So far, the models are based solely on the data obtained from the design documents. In the first ‘A’ model (Fig. 5a) also the branch lines were modelled. In the second ‘B’ model (Fig. 5b) the elements corresponding to the branch lines were replaced with spring constants calculated from a FE model. In addition, some other revisions were included. The latest model B2 has fewer elements and better-tuned support spring constants than the earlier ones.

Different ways to describe stiffness of the supports were compared. The first analyses using model A1 were performed with rigid piping supports. In model B1 the rigid supports were replaced with roughly estimated spring constants. These spring constants were calculated based on tables of solutions for simply supported beams.

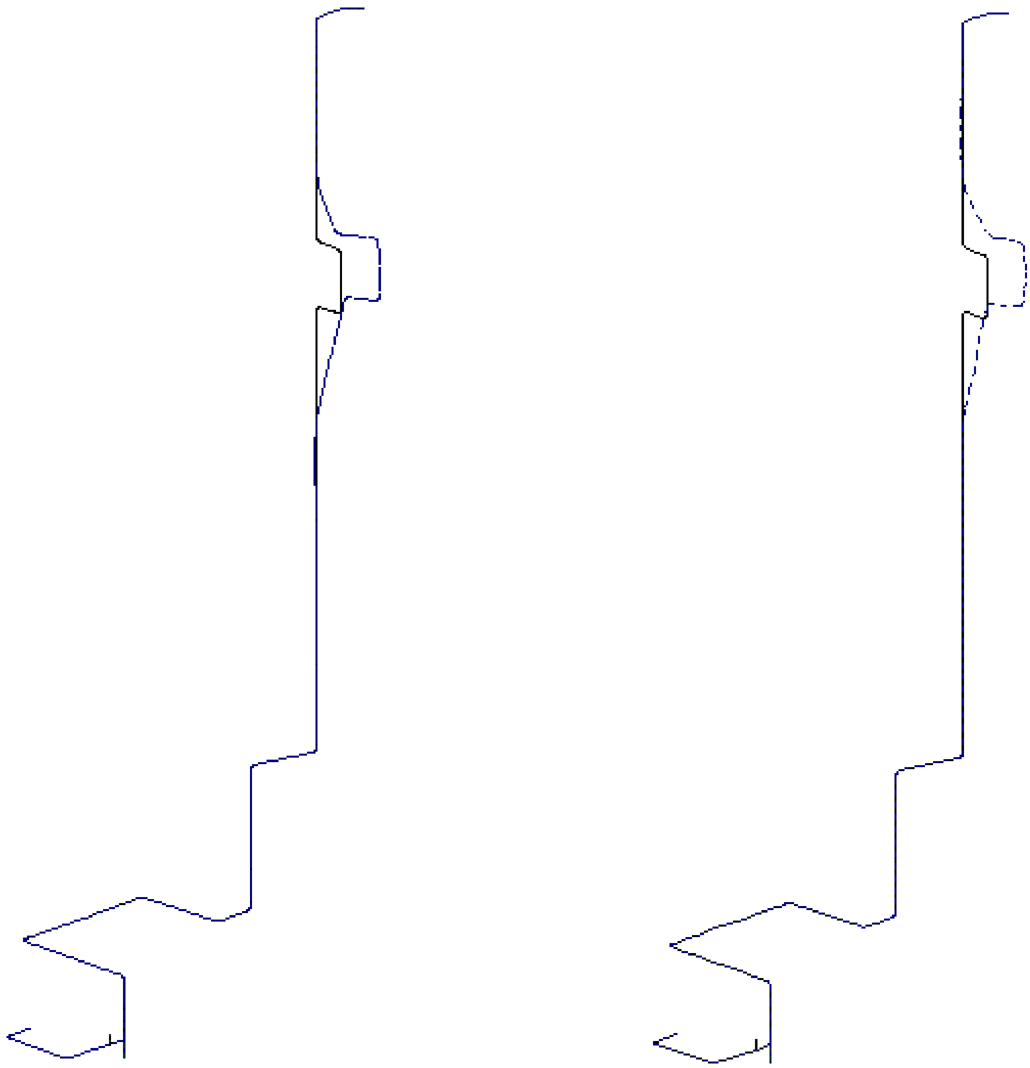


a) b)

Figure 5. Two models of the pilot piping, a) the original model with branch lines and b) a model without branch lines. Note that also the projection angles are different.

Models A1 and B1 were the first models compared with the experimental results. The FE analysis results gave several more eigenmodes than the experimental results. In FE analyses, natural frequencies lower than the lowest experimentally measured one were also found. Some of these could be neglected due to friction. They should disappear also in further refined models based on the real properties of the piping and supports. Despite the simplifications, clearly similar eigenmodes were found. This comparison also showed that one of the critical aspects in FE models is, how accurately the piping supports are modelled.

An example of the FE analysis is given in Fig. 6. The first eigenmodes of the models A1 and B2 are shown. With the rigid piping supports (A1) the frequency is 5,77 Hz and with roughly estimated spring constants (B2) the frequency is 8,65 Hz.



a) b)

Figure 6. The first eigenmodes of the pilot piping as obtained by FE analysis. a) The model A1 with the rigid piping supports at 5,77 Hz and b) the model B2 with roughly estimated spring constants at 8,65 Hz.

During the second project year the analyses for the first pilot piping will be completed and the second pilot study with the insulated piping system will be started.

3.2 Development of a program system for piping integrity assessment

Among many other companies, TVO is currently developing a piping lifetime management system for their own use. Consideration of plant specific design and integrity problems support use of tailored programs and/or data bases. The final applications will be plant type, utility or plant specific. However, common features can be included in the systems.

3.2.1 Subproject activities in 1999

Some general modules to be included in the TVO system are developed in this project. Integrity assessment of pipes containing crack-like defects was the topic for this subproject in 1999. The following tasks were included:

- Updates and improvements in the search capabilities of the relational data bases which contain the description and information on the piping systems.
- Visualisation and definition of the crack data.
- Information transfer capability between FPIPE and the data base.
- Outlines for development of treatment of loads.

3.2.2 Description of the target program system

A comprehensive program system for integrity assessment of piping is the target of TVO. The target program system as a whole and the parts which are considered in this subproject are shown in Fig. 7.

For safety reasons, cracks are searched by NDT in the periodic in-service inspections. If an indication can be considered as a crack, its influence in piping integrity need to be assessed during the same outage period. Therefore, the program system shall be suitable for very fast analyses of pipes containing cracks.

To be really practical, such a program system should not only support the calculations but also provide an effective platform for data management. One possibility is to connect the analysis programs to a data base, which contains all information needed to build computational models of the piping under consideration.

When ready the system will consist of the following modules:

1. Several relational databases containing all information related to the structures under consideration. This forms a hierarchic description of the piping components and includes files for geometry, materials, contents, loading, stresses, etc. The databases will be edited through associated user interfaces.
2. A database containing the reports related to the structures under consideration.
3. Interface modules which connect the databases and the analysis modules. The preferred interface is a neutral file that can be used as a batch input file to the analysis modules
4. Commercially available analysis modules to perform flow, thermal, fatigue, fracture mechanical and/or other structural analyses.
5. With user interfaces equipped databases for analysis results. They will contain all resulting significant information such as stresses, displacements etc.
6. Tailor made analysis modules to perform post processing of previously obtained results. These could be, for example, fatigue monitoring, crack growth monitoring or specifications for in-service inspection.

The basic purpose of the system is to perform piping stress analyses according to given load spectra, followed by a fatigue and fracture mechanical analysis. Thus the remaining lifetime can be estimated and the need for improving, maintaining or monitoring actions can be specified. The loading spectra shall be user definable.

The system will be built up of stand-alone programs. These modules can be separately used for their own purposes already before the system is completed as a whole. As far as possible, commercially available programs will be used. For special purposes, new programs will be developed.

At the present, the integrity of piping components containing crack-like flaws can be assessed using the MASI-PIPE program system, which has been earlier developed at VTT in co-operation with TVO. The MASI program is capable to estimate crack growth due to fatigue or stress corrosion cracking. It utilizes appropriate fracture mechanical models depending on the stress intensity factor value or its variation during a loading cycle. A weight-function based program VTTSIF is included for stress intensity factor value computations. The acceptability of a found or postulated crack can be judged using a program module, which is based on the rules presented in the ASME XI code.

One important feature of the whole system will be the opportunity for information change between different programs. For example, stress analysis for the piping is best performed by a special purpose FE program, e.g. FPIPE. The capability for direct use of the results in the stress intensity factor computations is especially valuable, because the local stress distributions at the location of a flaw are needed for the crack analysis.

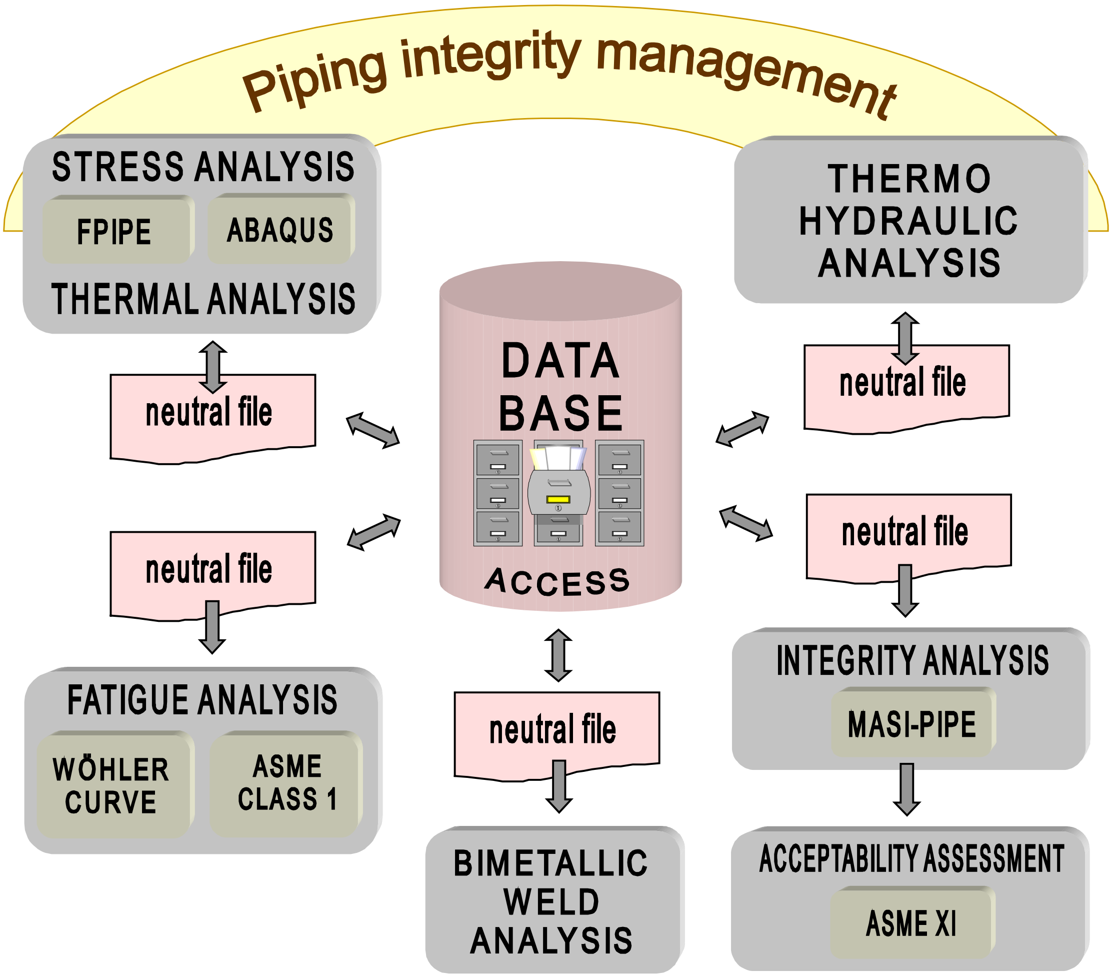


Figure 7. The target program system for piping integrity management at TVO.

3.2.3 Improvements in the data base

The piping data base has been earlier developed at TVO. Extensions and improvements to it were introduced in 1999 within this project. One of the most important achievements was the addition of more convenient search and navigating capabilities within the data base. Additionally, the material and piping data bases were updated from ACCESS version 2 to ACCESS 2000. This change required rather extensive revisions in the search commands, because the version 2 commands are no more supported, but it will significantly extend the usability of the data bases.

The nodal data and search possibilities according system, piping, element or nodal point selection are visualised in Fig. 8. Fig. 9 shows element data and visualisation of the piping. Further visualisation possibilities of an isometric view of the piping with a zooming capability are presented in Fig. 10.

One of the main challenges for the development is how to deal with the loads. A system is being developed for systematic consideration of the loading cases and loading case combinations. Both the treatment of loading input data to a finite element analysis program and the storing of relevant stress analysis results shall be covered.

At present, the user interface of the piping database has capabilities for transferring the geometrical data to a FEM program. The interface module for transferring geometrical data as an input file to the FPIPE program can be started after choosing a system, piping or an isometric element. Together with Mr. Torkkeli of FEMdata, a plan was prepared for creating capabilities to transfer further data to FPIPE, especially for definition of the loading.

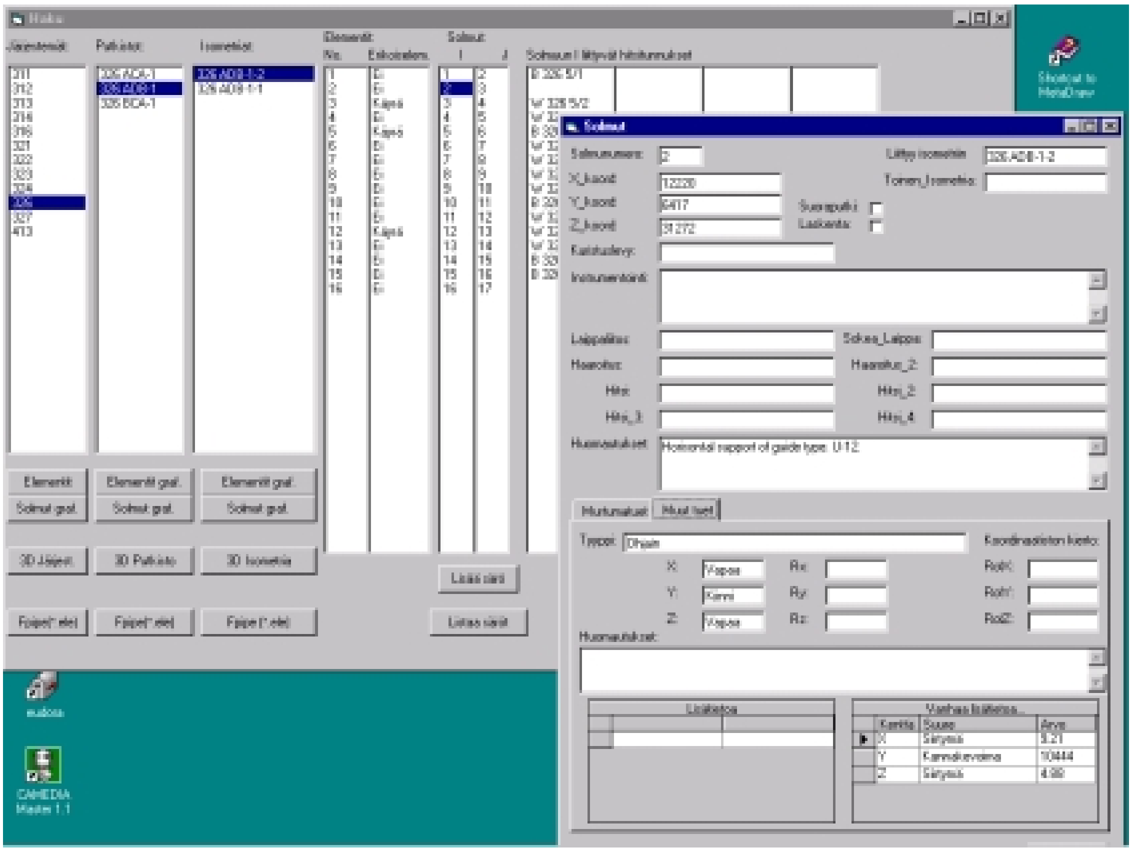


Figure 8. Searching of nodal data from the data base.

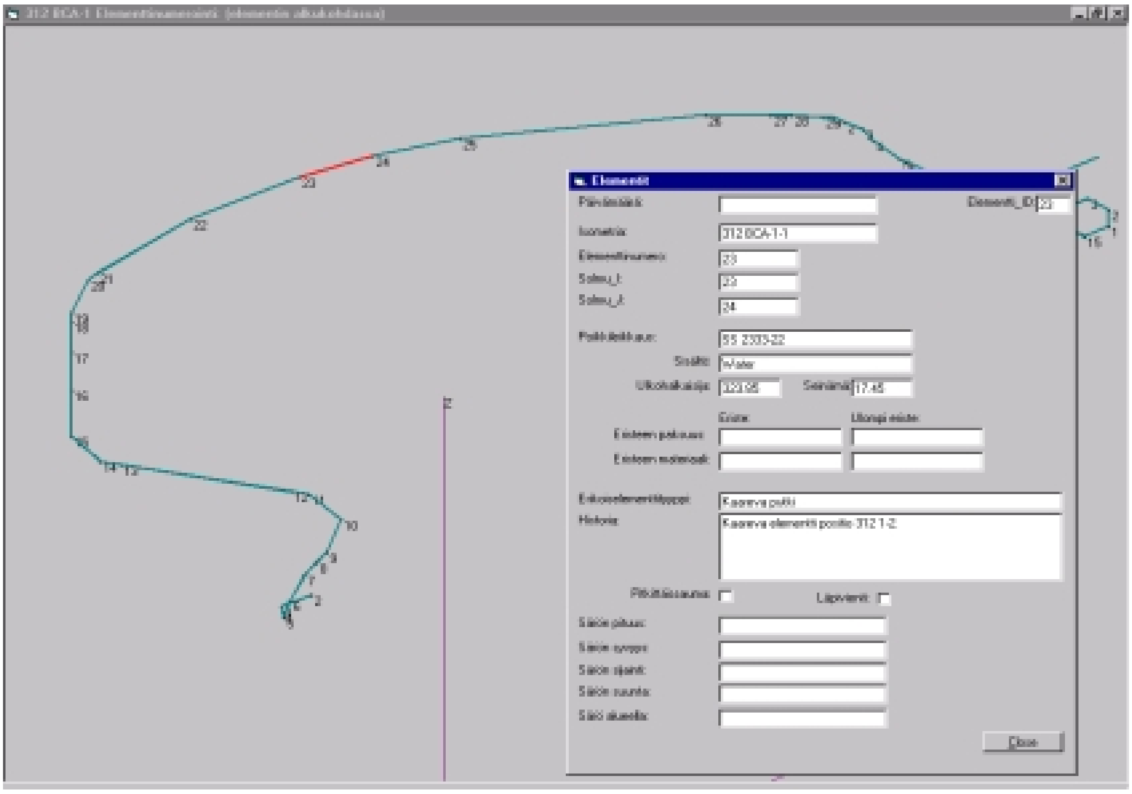


Figure 9. Searching of element data from the data base and visualisation of the piping. The element under consideration is highlighted by red colour.

The three main views of a crack in a weld are shown in Fig. 11. Fig. 11 also depicts how the location of the node in an isometric piping is colour codified according the adjacent elements (blue and red). This visualisation capability can be very useful for preventing mistakes, when a crack has been found in the piping and the corresponding data shall be saved to the data base into a certain node point of the piping. The numerical information concerning the dimensions and location of crack will be added later.

When the system is ready, the user can simply collect all necessary data for crack growth estimation at one command by using the forms shown in Figs. 8 to 11, and ask the system to automatically perform an assessment of the remaining life time.

During the second project year the work will concentrate on developing capabilities for the treatment of loading data in the data base system and on transfer between different modules.

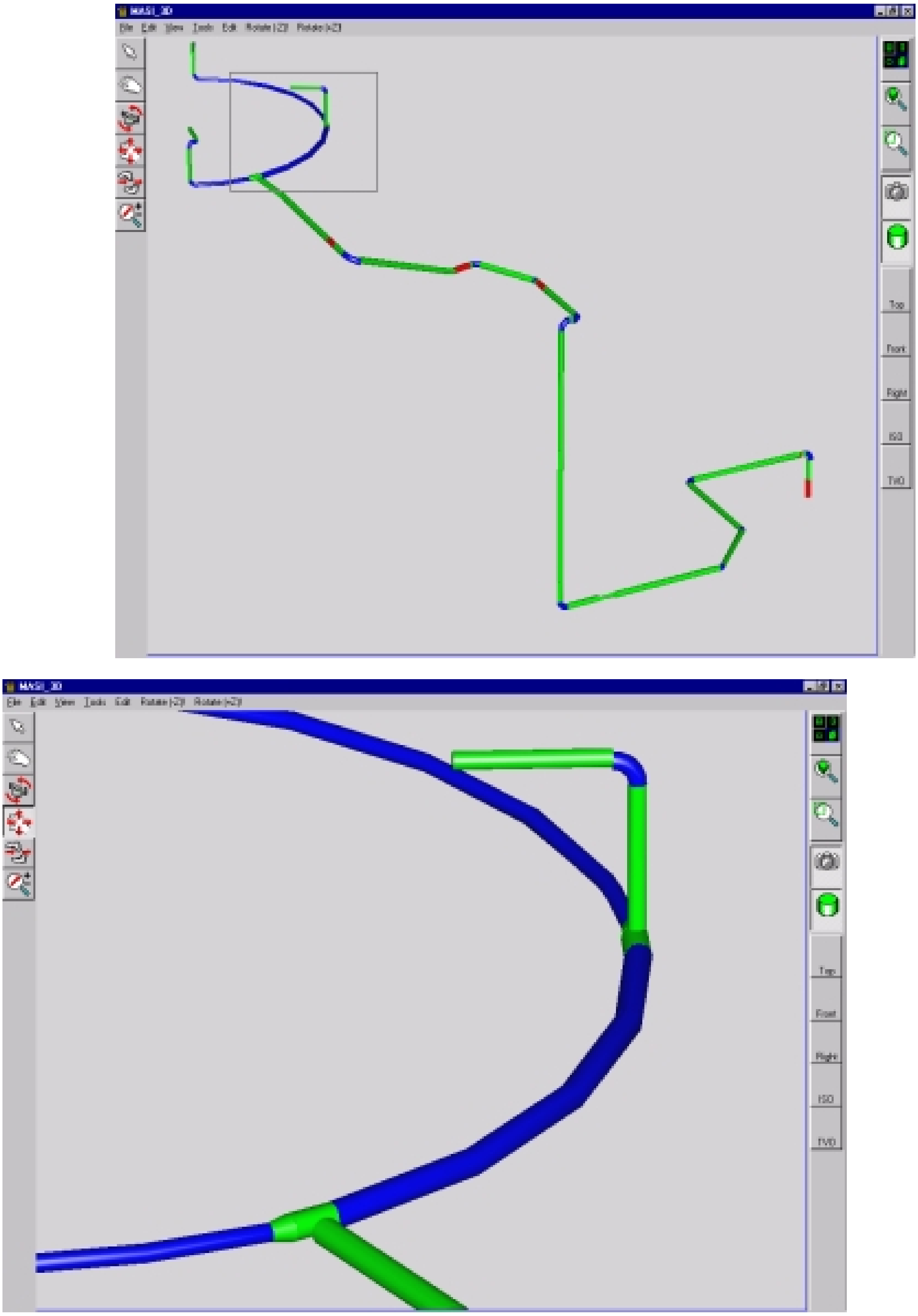


Figure 10. Visualisation and zooming of the piping system. The following colour codification of special elements is applied: straight pipes and T-connections are green, curved pipes and elbows are blue, valves are red.

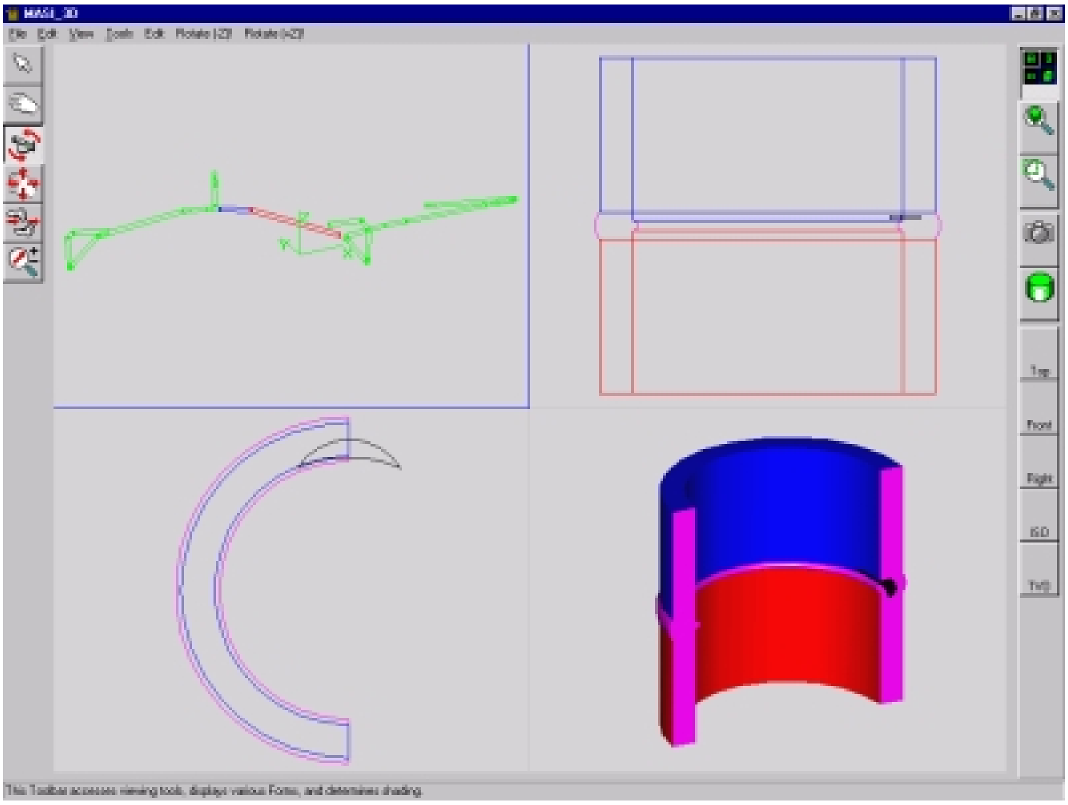


Figure 11. An example of visualisation of a crack.

3.3 Management of materials ageing

The ageing of pressure vessel materials due to neutron irradiation is a major cause for structural integrity concern in ageing nuclear power plants. The surveillance of material ageing is performed by the utility following the regulatory defined standard guidelines.

Cast austenitic stainless steels are materials used for valves and pumps in nuclear power plants. The properties of non-stabilised stainless steels are known to degrade during long term ageing at nuclear power plant (NPP) operational temperatures, but the behaviour of stabilised stainless steels is not so well known.

3.3.1 Subproject activities in 1999

In 1999 this subproject contained the following tasks:

- Experiments to determine mechanisms and rate of re-embrittlement.
- Validation of the irradiation temperature.
- Measurement of through-wall homogeneity of welds and influence of phosphorus content in the unirradiated condition.
- Completion of a research on thermal ageing of titanium stabilised austenitic stainless steel castings.

3.3.2 Irradiation embrittlement, recovery and re-embrittlement

The ageing of pressure vessel materials due to neutron irradiation has been intensively studied for three decades in Finland. One WWER reactor pressure vessel was annealed in 1996 in Loviisa power plant. A current concern is ageing of the vessel after annealing. The aim of this subproject is to identify and quantify uncertainties in the standard surveillance procedure and to improve the reliability of material ageing estimations.

Re-embrittlement

The mechanisms of embrittlement, recovery and subsequent re-embrittlement are not completely clarified. However, re-embrittlement rate can be predicted based on proposed mechanisms, experimental results and phenomenological models. Three models proposed by Kryukov are illustrated in Fig. 12 (Kryukov et al., 1995). The currently available experimental results do not confirm any of the models, but the lateral shift approach gives the best prediction in most cases. In the lateral shift model, the re-embrittlement is supposed to follow the same rate as the initial embrittlement at the same transition temperature level.

Re-embrittlement behaviour of Loviisa-1 type welds was studied using Charpy impact and fracture toughness specimens deposited in the reactor core in a research irradiation chain. The test data is reported in a separate report.

The measured re-embrittlement rate was faster than the estimation based on the lateral shift model. This result deviates from the prediction based on literature, because the lateral shift model has been found conservative in most cases. Hence more data is required on the re-irradation behaviour of the welds.

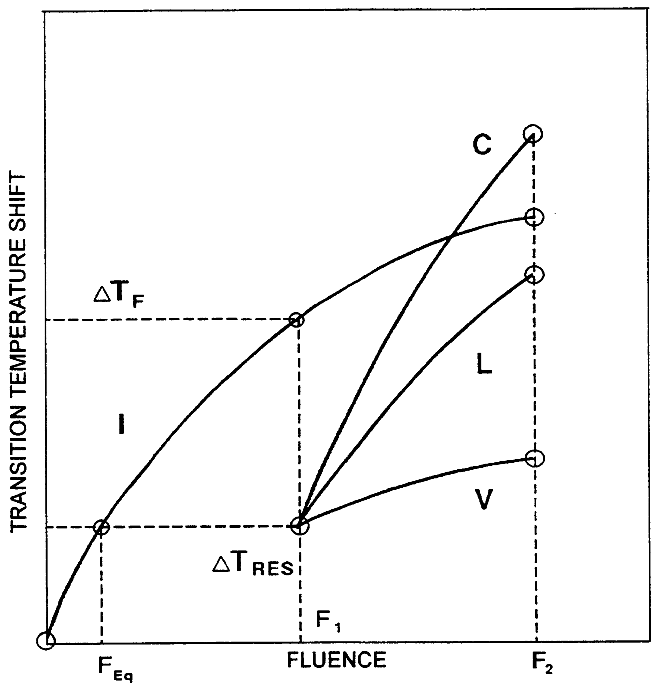


Figure 12. The proposed appraoches for estimating the re-embrittlement behaviour of irradiated and annealed steels. **I** *=* ***I****nitial embrittlement;* **L**, **V** *and* **C** *are re-embrittlement rates according to* ***L****ateral,* ***V****ertical and* ***C****onservative models (Kohopää, 1998).*

Irradiation temperature validation

Temperature of the surveillance and research material samples irradiated in nuclear reactors cannot be measured directly. But gamma heating absorbed on the irradiated material may raise the irradiation temperature above the coolant temperature. As an increase in irradiation temperature reduces the change in material toughness transition temperature, i.e. irradiation shift, improper irradiation temperature may lead to non-conservative embrittlement estimations.

The technical feasibility of the irradiation capsule construction was studied by using intentionally excessive packing tolerances for some specimens and then impact testing these samples. A comparison of the measured transition temperatures is given in Fig. 13. The total irradiation shift for the material is estimated to be more than 100 ^{o}C and the small differences in the transition temperatures are within the data scatter. Thus, the data do not show any indication of excessive irradiation temperature of the specimens and irradiation temperature of the specimens was found to be independent of the applied specimen packing tolerance. Hence the applied capsule construction is considered to work well at least in the neutron and gamma fields in the current Loviisa irradiation locations.

Irradiation temperature is normally monitored by inserting samples of special melting alloys to the irradiation capsules. Ternary Pb-Ag-Sb alloys are commonly used for this purpose and fixed melting temperatures are given for the alloys. This irradiation temperature monitoring technique was studied by calculations and experiments with melting alloy samples.

Calculational melting temperature simulation and preliminary melting temperature measurements indicate that the alloys melt within a relative wide temperature range instead of a fixed temperature. Thus, the preliminary results show that the ternary Pb-Ag-Sb temperature monitoring alloys, even though widely used, are not capable of indicating precisely the irradiation temperatures.

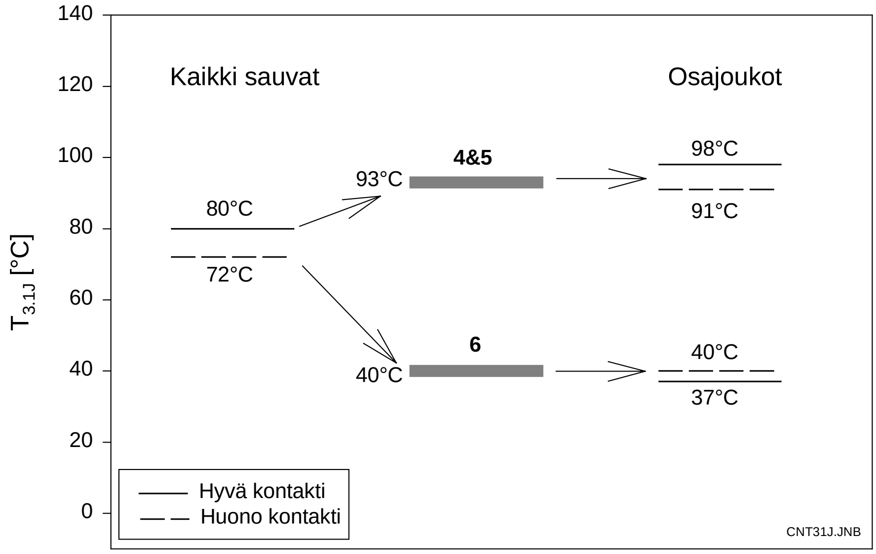


Figure 13. Transition temperatures measured with KLST-specimens with tightly (hyvä kontakti) and loosely (huono kontakti) packed specimens. Material group 4&5 has a fosforus content of 0.040% and group 6 a content of 0.030%.

Phosphorus and through-wall homogeneity of welds

Phosphorus is the main element responsible for irradiation embrittlement of welds in older WWER reactors. The phosphorus content and the irradiation embrittlement sensitivity varies in different parts of the reactor pressure vessel welds. A question was raised, how the fracture toughness varies in unirradiated material. A weld identified by code “501” simulating the WWER RPV welds was chosen as a test material.

As the phosphorus content of weld 501 varies considerable in the depth dimension of the weld, the profile of the fracture toughness based T_0 temperature in the weld was measured in detail for the unirradiated material condition. The measured data is given in a separate report and summarised in Fig. 14. In spite of the variation of phosphorus content the T_0 distribution was noticed to be very homogeneous.

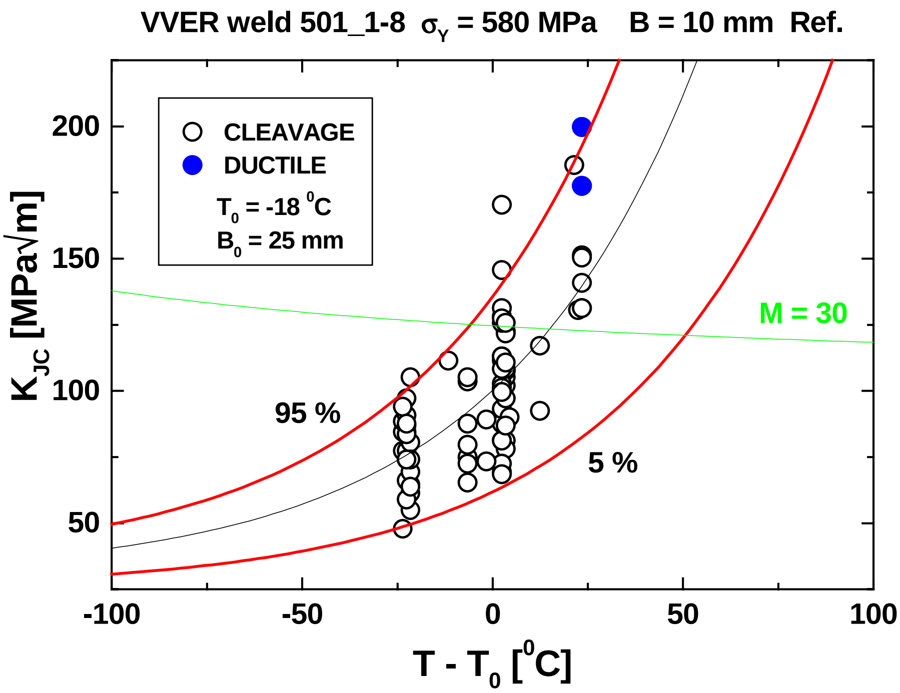


Figure 14. Fracture toughness data of weld 501 measured with specimens taken from the depths 1-8. The content of P varied from 0.030% to 0.040 %. The data indicates good homogeneity.

3.3.3 Thermal ageing of cast stabilised austenitic stainless steel

Cast austenitic stainless steels are materials used for valves and pumps in nuclear power plants. The composition of cast materials is adjusted to achieve a microstructure containing austenite with a small amount of δ-ferrite, which improves the casting, welding and strength properties of the material.

The aim of this investigation was to determine the mechanical properties and microstructure of a Ti-stabilised cast stainless steel material after 12 years of exposure to operational VVER temperature. The results from the VVER aged material were compared to results obtained from a reference material in as-fabricated condition and to the properties of both materials after solution annealing and artificial ageing.

Stabilised and non-stabilised steels

Titanium stabilised cast stainless steel is used in the VVER plants. The amount of δ-ferrite is typically less than 20% in cast non-stabilised stainless steels and less than 10% in cast stabilised stainless steels.

The properties of non-stabilised stainless steels are known to degrade during long term ageing at nuclear power plant (NPP) operational temperatures as low as 250°C. The degradation of mechanical properties due to thermal ageing in non-stabilised steels is known to be due to spinoidal decomposition in the δ-ferrite phase, which results in an increased hardness of the δ-ferrite and reduced toughness of the whole material. Investigations have shown that the degradation of the mechanical properties due to spinoidal decomposition could be recovered by a short annealing of one hour at 550°C. But the properties of cast stainless steels during long term operation can further be influenced by growth of carbides and/or nitrides, especially at the δ-ferrite austenite phase boundaries and in the δ-ferrite and by precipitation of the harmful silicon and nickel rich G-phase (Chung & Chopra, 1987; Chung, 1992; Massoud et al., 1991 & 1993; Jansson, 1990; Chopra, 1990).

Less data is available in the open literature on the behaviour of stabilised stainless steels during thermal ageing. However, it has been assumed that the degradation of mechanical properties in stabilised stainless steel castings due to long term operation at plant operation temperature is minor due to, e.g., the low amount of δ-ferrite.

Experimental

Previous and new experimental results on a cast Ti-stabilised stainless steel, O8X18H10T, are analysed and presented together. The test material had been exposed to operational temperature during 106 000 hours of service in the Kola NPP. For comparison, reference material was taken of a valve that has never been in use, Table 2.

Table 2. Chemical compositions of the materials investigated.

O8X18H10T	**C**	**Si**	**Mn**	**S**	**P**	**Cr**	**Ni**	**Mo**	**Ti**
Kola main gate valve mat.	0.07	0.52	1.60	0.010	0.023	18.0	8.4	0.06	0.62
Reference material	0.08	0.43	1.25	0.011	0.028	18.1	9.9	0.10	0.83

Impact energy transition curves as well as hardness for both materials in different conditions were determined. Additionally, micro-hardness measurements on the δ-ferrite and austenite phases, were performed on both materials. The microstructures were investigated using optical, scanning and transmission electron microscopy. The transmission electron microscopy results are particularly new and important in explaining thermal ageing performance of the Ti stabilised steel.

Results on stabilised austenitic cast steel

The results revealed changes in the mechanical properties and microstructure due to long term exposure to elevated temperature as shown in Table 3. The upper shelf impact toughness values were lower for the aged materials compared to that of a solution annealed and as-fabricated materials. The artificially aged reference material had the lowest upper shelf impact toughness.

The microhardness of the δ-ferrite phase correlates well with the upper shelf impact toughness, with an increase in the hardness corresponding to a decrease in the upper shelf impact toughness.

The results of the investigations performed on the plant aged Ti-stabilised stainless steel casting indicated that 12 years of operation in the NPP temperature may result in minor thermal ageing. It can be observed as changes of precipitation structures, increase of the ferrite microhardness, shift impact toughness transition temperature T_{50} and decrease of upper shelf impact toughness when compared to the reference material in as-fabricated condition. However, the transition temperature is still low and the structural safety of the valve at plant operation temperature has not been markedly affected by the long-term operation.

Microstuctures

The microstructures of the studied materials in all investigated conditions are mainly austenitic with islands of evenly distributed δ-ferrite. Due to the elongated shape of the δ-ferrite islands, the distance between two δ-ferrite islands is, however, much smaller than the average amount of δ-ferrite would indicate. In both plant and artificially aged materials, the δ-ferrite phase boundaries were curved towards the δ-ferrite phase indicating migration of the boundaries of about 2 µm, with precipitates and inclusions left behind at the original phase boundary.

The materials contained inclusions that were common for all conditions, such as cubic shaped or irregular carbonitrides, plate-like titanium sulphides, coarse phosphides and silicon containing inclusions. The phosphides and silicates locate typically at or near the phase boundaries.

Table 3. Summary of the results of impact toughness, microhardness and δ-ferrite measurements on cast Ti-stabilised stainless steel, O8X18H10T in different thermal ageing conditions. **F** *= as fabricated;* **P** *= plant aged;* **A** *= artificially aged;* **S** *= solution annealed.*

Material		impact toughness		δ-ferrite phase	
Origin	**Condition**	**Upper shelf**	**50% trans.**	**Fraction**	**$HV_{0,01}$**
Kola NPP	F	-	-	-	-
	F+P	65 J	-68°C	9,7%	390
	F+P+A	-	-	9,9%	429
	F+P+S	114 J	-129°C	14%	266
Reference	F	76 J	-103°C	7%	350
	F+A	42 J	-113°C	7,8%	491
	F+S	111 J	-124°C	9,4%	276
	F+A+S	39 J	-127°C	-	316
	F+S+A	-	-	10,6%	459

In non-stabilised stainless steels the degradation of material properties and increase of δ-ferrite hardness are caused by spinoidal decomposition in the δ-ferrite (Massoud et al., 1993). But no signs of such spinoidal decomposition were found in the Ti-stabilised stainless steels. However, changes in the precipitation behaviour were observed.

The δ-ferrite phase of the plant aged material contained a high amount of at least partly coherent precipitates with composition near of Ni_3Al_2Ti and size of 10 to 15 nm. Their local distribution in rows, Fig. 15, indicate that they probably have nucleated at dislocations. In the solution annealed and artificially aged material from the Kola main gate valve, only local precipitation of Ti-carbides at the dislocations were observed, but no signs of any Ni-Ti-Al precipitates were observed in the δ-ferrite phase.

The austenite phase of the plant aged material contains thin, about 50 nm thick and more than 2µm long needle-like precipitates with a composition resembling that of the $(Ti,Fe,Ni)_2P$ phosphide inclusions, Fig. 16. The structure of these precipitates is probably tetragonal or ortorombic and the lattice constant in the length direction is about the same as that of austenite, i.e., 3,58Å. These needle-like phosphide precipitates were not observed in the solution annealed reference material.

The precipitation structure influences the hardness and other mechanical properties of the material. Increased hardness and lowered impact toughness of the aged materials depend on types, densities and sizes of the precipitates. The above summarised precipitation structures are presented and discussed in more detail in a conference paper (Ehrnstén et al., 2000).

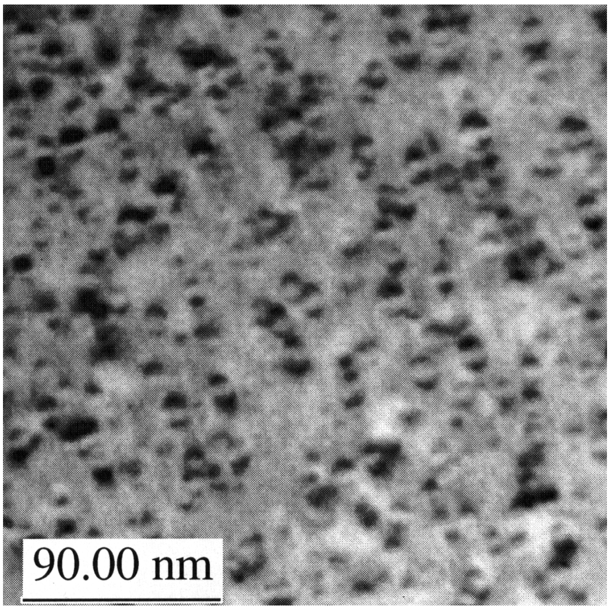


Figure 15. FEGSTEM photographs of Ni_3Al_2Ti type precipitates in the δ-ferrite phase of the plant aged material.

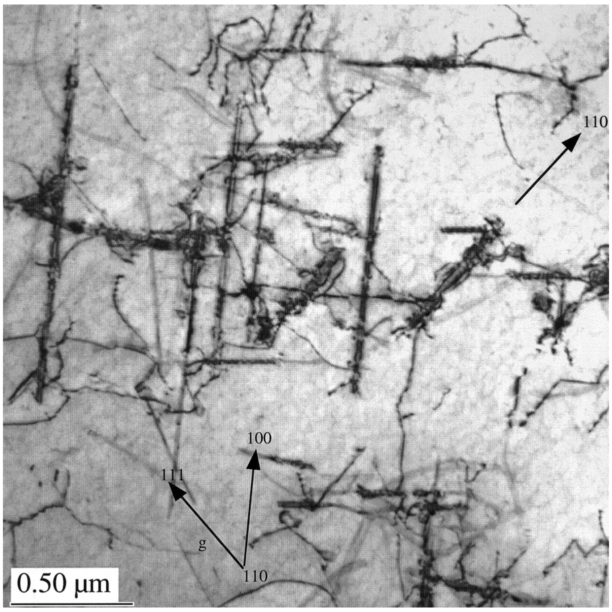


Figure 16. FEGSTEM photographs of needle-like precipitates in the austenite phase of the plant aged material.

Emphases on the studies in year 2000 will be on the re-irradiation behaviour of annealed weld materials. A large series of model alloys (about 34 alloys), which have been originally irradiated in JRC HFR, will be annealed and installed in a research capsule in Loviisa for one year. The key impurity contents, i.e. P, Cu and Ni, which are responsible for irradiation embrittlement as well as re-irradiation embrittlement, are widely and independently varied in the model alloys. The study aims to identify the mechanistic bases of the re-irradiation phenomenon and to develop the chemistry factor for re-embrittlement.

3.4 Non-destructive monitoring of structural integrity

The formation and growth of defects is a major concern in structural integrity and component lifetime management. Non-destructive testing (NDT) methods are used for periodic in service inspections. The reliability of inspection, the probability of finding a defect and its sizing accuracy are of concern. Mechanised ultrasonic inspection technology is developing and gaining new applications in power plants.

3.4.1 Subproject activities in 1999

In 1999 the subproject included the following tasks:

- Development of a new scanner for mechanised ultrasonic inspection of piping welds.
- Testing of the suitability and performance of the new scanner. Pilot inspections were carried out in connection to the normal in service inspections.
- Pilot-qualifications aiming to development of the Finnish practise for inspection qualification.

3.4.2 Development of a mechanised scanner for ultrasonic inspection

The aims of developing mechanised scanners are as follows:

- Reduction in irradiation doses during inservice inspections at NPPs.
- Development of scanners for different components
- Increased reliability of inspection
- Enhanced possibilities for analysing the results
- Qualification of the inspection.

A new type of mechanised scanner was designed and constructed for the ultrasonic inspection of piping welds. This scanner was used in the pilot inspections carried out in connection to the inservice inspections of Olkiluoto NPP. Based on the experience gained, it was decided to continue the development work for the inservice inspections of year 2000. The target of this work is to develop a scanner that can be applied to different inspection areas where the access is limited and the working conditions in manual inspection are difficult. In 1999 a very rapid positioning system of the scanner was developed and the height of the scanner was reduced to allow positioning to inspection items where the height of the scanner is critical dimension limiting the access.

As described above the scanner developed in 1999 was used in the inservice inspections of Olkiluoto plant. Although the number of welds inspected in the pilot inspections at the Olkiluoto plant was small, the basic design of the scanner could be tested and needs for further improvement were identified. One of basic problems of ultrasonic scanners is the time needed for positioning the scanner to the inspection area. By the new construction this time was remarkably reduced and the positioning could be performed by one person only. The overall dimensions and weight of the scanner were also reduced to allow easy handling in industrial environment.

3.4.3 Capabilities and qualification of NDT-techniques

The development of the Finnish practise for inspection qualification was continued in co-operation with the utilities and major inspection companies. First pilot-qualifications were carried out connected to the inservice inspections of Finnish NPPs.

In connection to the participation to the AMES-NDT network a project proposal was prepared to the 5th Framework Programme of EC. The target of this project is to assess the capability of different NDT-techniques to evaluate the ageing of material.

In the AMES-NDT network a pilot exercise with a few samples and techniques was organised. VTT participated this exercise by using ultrasonic back-scattering techniques to evaluate the thermal ageing of steel samples. No strong conclusions can be drawn from the measurements carried out with only two samples but the results indicate that the ultrasonic velocity may correlate with the degree of thermal ageing.

3.4.4 Plans for year 2000

The development of the mechanised scanner for ultrasonic inspection will be continued and again some pilot inspections will be made in connection to the inservice inspections of Olkiluoto plant.

The development of the Finnish practise for inspection qualification will be continued in the national working group and by participating in the ENIQ-network.

A new GRETE-project (Evaluation of NDT techniques for monitoring of material degradation) will be started based on the approval of this proposal to the 5th framework programme of EC. The task of VTT will be to assess the thermal ageing of stainless steel specimens by different ultrasonic measurement techniques. For this some development work will be carried in 2000 (and 2001). The test samples will be measured in late 2001.

4. Effects of environment on component service reliability

4.1 Water chemistry, service reliability and activity levels

Increased power output and introduction of modified water chemistries may influence corrosion of structural materials and the occupational dose rates in nuclear power plants. The activity build-up on the primary circuit components depends on the dissolution, transport, deposition and incorporation of activated corrosion products in the oxide films formed on material surfaces. Oxide films play an important role also in environment assisted cracking (EAC). Understanding the oxide film properties and their correlation with operational parameters, activity build-up and EAC are the topics of this subproject.

The aim of this subproject is to predict and minimise the risks of corrosion, stress corrosion cracking and activity build-up. The experiments are performed partly at the plants and partly in simulated plant conditions in laboratory at VTT.

4.1.1 Subproject activities in 1999

In 1999 the subproject included the following tasks:

- Correlation of water chemistry, oxide films properties, activity build-up and material behaviour in VVER and BWR conditions
- Stability of oxide films during the shut-down process of a VVER plant
- Correlation of oxide films properties and environmentally assisted stress corrosion cracking (EAC) in BWR conditions
- Influence of deposited oxides on the material behaviour of secondary side components in a VVER plant

4.1.2 Correlation of water chemistry, oxide films properties, activity build-up and material behaviour in VVER and BWR conditions

The aim of this task was to plan, design and manufacture an experimental set-up for the monitoring of high-temperature water chemistry parameters and for exposing material samples to the primary coolant at Loviisa 1 and Olkiluoto 1 plants. The obtained data will be later correlated with the operational parameters of the plants.

The following actions were undertaken in 1999:

- A set of flow through cells with data acquisition facilities were designed, manufactured and installed to the Loviisa 1 unit. One flow through cell is used for high temperature water chemistry monitoring and the second one for exposing removable material samples to the primary coolant.
- Similar flow through cells were manufactured for the installation at Olkiluoto 1 unit. Installation will be carried out during the annual outage period in spring 2000.
- Oxide films on samples subjected to the primary circuit coolant during operation at Loviisa 2 unit were analysed to assess the impact of heat-up on the oxide films.

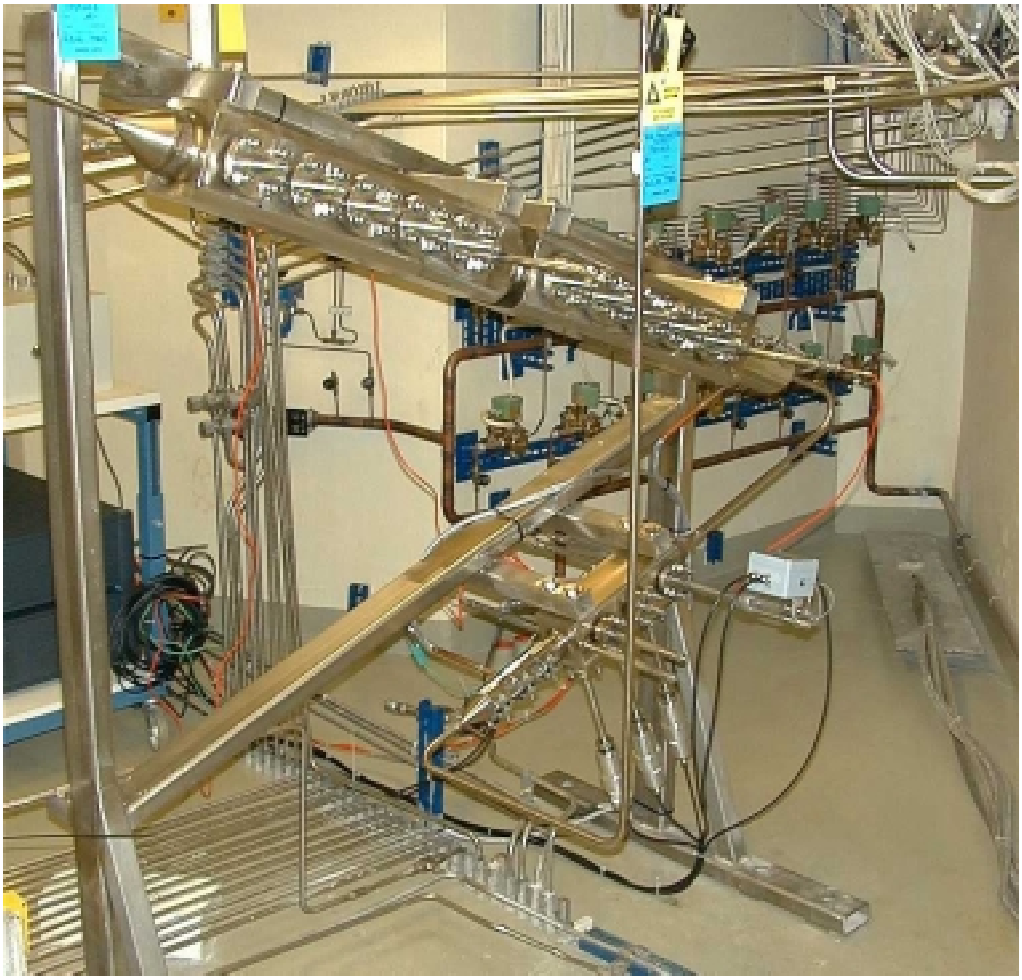


Figure 17. The flow through cells used for monitoring high temperature water chemistry parameters and for exposing material samples to the primary coolant at Loviisa 1 unit.

The flow through cells (Fig. 17) and the related piping at Loviisa 1 unit were insulated in March 2000 and thus the temperature in the cells is now high enough to perform high temperature measurements in representative environments. The preliminary results indicate that all sensors are working and giving reliable results. The first obtained results are similar to the ones obtained earlier at Loviisa 2 unit.

The measured activity levels in the oxide films on samples taken from Loviisa 2 showed that the incorporation of antimony seems to be highest in the beginning of the fuel cycle. A set of samples are being analysed by SIMS, England and the quantified results will be used to correlate the oxide film composition and activity incorporation into the oxide films by the end of April 2000.

4.1.3 Stability of oxide films during the shut-down process of a VVER plant

Hydrogen peroxide (H_2O_2) injections to the primary coolant have been used to facilitate the dissolution of radioactive species from the surfaces of the primary circuit in pressurised reactors during the shut-down periods. However, injection of H_2O_2 has to be performed in such a way that it does not damage the protective properties of oxide films on the surfaces of construction materials. The aim of this task has been to study how the injection of H_2O_2 affects the properties of the oxide films during the simulated shutdown conditions and if the possible changes remain during the subsequent steady-state operation.

The following actions were undertaken in 1999:

- Experiments were performed to estimate the effect of injection temperature of H_2O_2 on the stability of oxide films on stainless steel during a simulated shut-down and the subsequent start-up period.
- A recommendation was given for an injection temperature, which does not result in significant changes in protective properties of oxide films.

The influence of H_2O_2 injection at 50...130°C on the stability of oxide films on stainless steel both during a shut-down period and the subsequent start-up period was experimentally determined in simulated plant conditions. These results demonstrated that the injection of H_2O_2 to the coolant increases the electronic resistance of the oxide film on stainless steel considerably. The lower the injection temperature, the stronger was the influence of the injection of H_2O_2 on the electronic resistance. Combination of these results with the information obtained using other electrochemical techniques indicated that the injection of hydrogen peroxide at the temperature of 130^{o}C results in the lowest transport rate of ions or ionic defects in the film. Thus 130°C may be the best temperature for peroxide injection.

4.1.4 Correlation of oxide films properties and environmentally assisted stress corrosion cracking (EAC) in BWR conditions

Enrichment of SO_4^{2-} and other anions in crevices and cracks has been suggested to accelerate environmentally assisted stress corrosion cracking (EAC) of materials used in in-core components. Such anions may be released for instance from the ion exchange resins used for water purification at plants. The aim of this task has been to assess the stability of oxide films on the walls of stress corrosion cracks in materials exposed to a BWR coolant with different contents of sulphate ions. The stability of the films will in turn be correlated with the susceptibility of the material to stress corrosion cracking.

The following actions were undertaken in 1999:

- The stability of oxide films on AISI 316 NG, Inconel alloy 182 and Inconel alloy 82 were estimated in SO_4^{2-} contents of 0....6000 ppb, which may correspond roughly to bulk coolant contents in the range of 0...20 ppb.
- The results were compared with available data on the susceptibility of the materials to stress corrosion cracking.

An extensive test series focusing on the influence of anions on the stability of oxide films within a stress corrosion crack has been started and is in good progress. Experiments in conditions simulating the occluded water chemistry within a crack (deoxygenated BWR water at 273°C) have been performed for AISI 316 NG, Inconel alloy 182 and Inconel alloy 82 in four different SO_4^{2-} contents. This test series has been agreed to be continued till the summer 2000 in order to draw statistically consistent conclusions.

The experiments simulating the occluded crack chemistry were performed in de-oxygenated environments with sulphate contents in the range 0...6000 ppb. This corresponds to bulk coolant contents of 0...20 ppb, assuming a maximum enrichment factor to be valid. The films were found to be the most stable on Inconel 82 and the least stable on Inconel 182, which is in agreement with earlier results obtained in the range of 0....10 000 ppb, Fig. 18. It was also found that the increase of the sulphate content decreased the stability of the films on all studied materials.

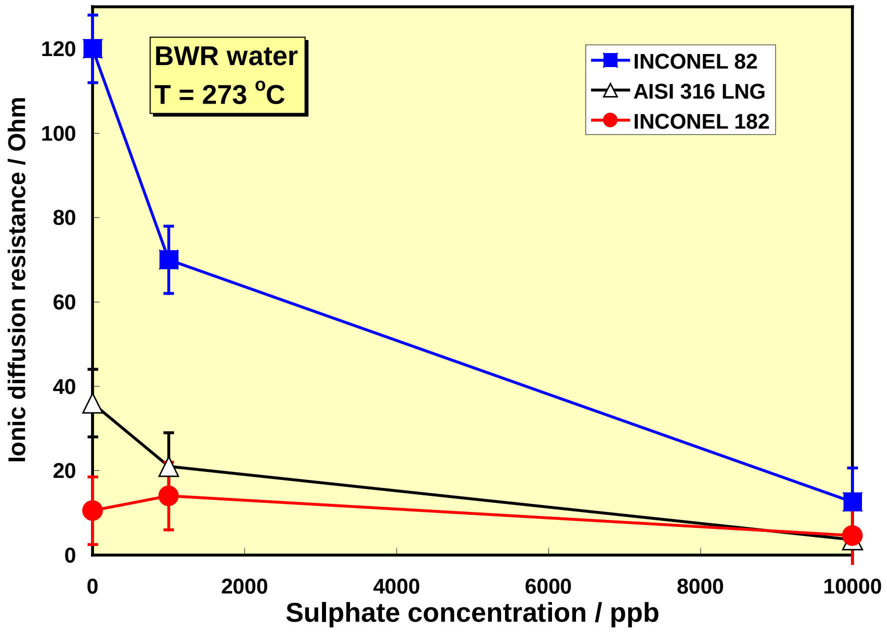


Figure 18. The ionic transport resistance describing the stability of oxide films on AISI 316 NG, Inconel 182 and Inconel 82, shown as a function of the sulphate content in simulated crack chemistry conditions.

The ranking obtained for the stability of oxide films on the studied materials is in qualitative agreement with the ranking of the susceptibility of these materials to stress corrosion cracking. This supports the hypothesis of this investigation, according to which the transport of ionic species through the oxide films on crack walls has a great influence on crack growth rates.

4.1.5 Influence of deposited oxides on the material behaviour of secondary side components in a VVER plant

The aim of the task has been to make a research plan for assessing the risks that oxide deposits cause to the secondary circuit components in a VVER plant.

During 1999 a proposal was prepared in co-operation with Loviisa power plant personnel. The research plan will be realised during the years 2000...2002, and its results will contribute to decisions about the treatment of these oxide deposits.

4.1.6 Plans for year 2000

The experiments during the project year 2000 are going to be performed partly at the plants and partly in simulated plant conditions at VTT. The plans for the year 2000 in the four different sub areas are as follows:

Correlation of water chemistry, oxide films properties, activity build-up and material behaviour in VVER and BWR conditions

- The flow through cells will be installed to Olkiluoto 1 unit in May 2000.
- The first oxide film samples will be removed and analysed from the cell at Loviisa 1 before the shut-down in August 2000 and after the heat-up in September 2000. The high temperature monitoring data and the information obtained from oxide film analyses will be correlated with the data collected by the regular monitoring and analytical routines at the plant.

Stability of oxide films during the shut-down process of a VVER plant

- The results obtained in 1999 in this task will be utilised at the Loviisa plants during the next hydrogen peroxide injection.
- Additional experiments are not scheduled for the year 2000.

Correlation of oxide film properties and environmentally assisted stress corrosion cracking (EAC) in BWR conditions

- The test series for AISI 316 NG, Inconel alloy 182 and Inconel alloy 82 in the SO_4^{2-} content range 0...10000 ppb will be completed.
- More experiments will be performed especially in the SO_4^{2-} content range 3000...10000 ppb to obtain a more accurate estimate of the content at which the stability of oxides on Inconel alloy 82 decreases significantly.
- The influence of nitrate ions on the stability of the same materials will be studied. Nitrates may be released from a different type of ion exchange resins.

Influence of deposited oxides on the material behaviour of secondary side components in a VVER plant

A plan for both theoretical and experimental evaluation of the chemical conditions in crevices beneath a magnetite type deposit has been prepared and accepted in negotiations between VTT and Fortum Heat and Power Oy.

- The chemical conditions forming beneath the deposits will be evaluated by theoretical calculations (MULTEQ programme) and by experimental simulations. Experimental part consist of monitoring the conditions within a pile of magnetite deposit on a steam generator tube placed in a autoclave filled with simulated secondary coolant.
- After obtaining a reliable view of the conditions and possible enrichments close to the tube surface, a test series will be planned to characterise the stability of the steam generator material in a range of possible crevice conditions using electrochemical techniques.

4.2 Stress corrosion cracking in Inconel welds

Inconel alloys 182 and 82 are used for welds in BWR reactor pressure vessels and primary circuits to join stainless steel and structural steel. An important example is the bimetal welds joining the safe ends to pressure vessel nozzles. Comparison of these alternative alloys and determination of safe operation limits in terms of stress corrosion cracking (SCC) are the topics of this subproject.

Stress corrosion cracks have been found in Inconel 182 weldments in several operating nuclear power plants around the world. To mitigate the risk of stress corrosion cracking, replacing of alloy 182 with the alloy 82 has been proposed. So far, no SCC cracks in the alloy 82 have been found in operating power plants. However, alloy 82 has been found susceptible to SCC in laboratory tests with a very high sulphate concentration of 1000 ppb (Marcovits & Giannuzzi, 1994).

The aim of this subproject is to measure the real SCC crack growth rate in Inconel 182 weld metal in BWR conditions and to evaluate the influences of environmental factors and eventual material replacement on the crack growth rate.

4.2.1 Subproject activities in 1999

In 1999 the subproject included the following tasks:

- Laboratory experiments to determine test conditions where intergranular stress corrosion cracking occurs in the studied alloys.
- Crack growth rate tests for the Inconel alloys and reference materials in different sulphate concentrations simulating the enriched conditions in crevices.

The test materials were Inconel alloys 182 and 82 in as welded condition. Typical chemical compositions of these alloys are presented in Table 4. In addition, two types of stainless steel were tested as reference materials. Thermally sensitised AISI 304 as susceptible and AISI 316NG as relatively unsusceptible material to stress corrosion cracking in BWR coolant water.

Table 4. Typical chemical compositions of Inconel alloys 182 and 82, w%.

Alloy	Fe	C	Cr	Mn	Si	S	Ti	Ni
182	8.07	0.03	15.24	7.57	0.52	0.001	0.52	Bal.
82	0.71	0.036	20.23	2.92	0.05	0.001	0.38	Bal.

Pre-fatigued three point bend specimens were fracture tested at 273ºC in simulated BWR coolant in an autoclave connected to a water recirculation loop. Four to six specimens were tested simultaneously by pneumatic servo-controlled loading devices. The crack growth rates were determined in fracture resistance (J-R) curve measurements under slowly rising displacements. Crack length was monitored by the reversing direct current potential drop method.

The inlet and outlet water chemistry parameters pH, conductivity and amount of dissolved oxygen are continuously measured at ambient temperature. Corrosion potential in the high temperature is measured using a Ag/AgCl reference electrode. Concentration of anions, such as sulphates, chlorides, fluorides, nitrates and chromates, are determined periodically.

4.2.2 Relevant crack growth mechanism

The aim of this task was to evaluate the influence of testing conditions on the crack growth mechanisms and, in particular, to find the conditions where intergranular stress corrosion cracking (IGSCC) occurs in laboratory. Test results with this failure mode should be more relevant to practice, because the intergranular mode prevails in service.

The following actions were undertaken during the project year 1999:

- Heat treatments and preliminary metallurgical characterisation of test material.
- Assessment of relevant crack growth mechanisms together with detail planning of experiments.
- Fractographic study of fracture surfaces created in slow rising displacement fracture mechanical tests, similar to J-R -curve measurements.

Sensitivity to thermal ageing

The carbon solubility in these Inconel alloys is lower than in austenitic stainless steels, even at high temperatures. But the chromium diffusion is 3 times faster than in stainless steels. A consequence of the combined low carbon solubility and high Cr diffusion rate is that chromium carbides precipitate in Inconel 182 and 82 at the same temperature range as in austenitic stainless steels. Therefore, stress corrosion susceptibility of these alloys is supposed to increase by thermal ageing as it does for the stainless steels.

The alloys were heat treated at an elevated temperature of 400ºC for 200 hours. Based on the kinetics of the carbide nucleation and growth the treatment is, however, supposed to simulate the effects of a long term exposure to the BWR operating temperatures. This prediction will be later validated through FEGSTEM[3] analyses of grain or dendrite boundary segregation and carbide distribution. These variants will be tested later within this project.

Failure modes

Stress corrosion cracks may grow by different mechanisms. The two basic alternatives are transgranular (TGSCC) and intergranular (IGSCC) growth. A problem rises of the fact that TGSCC tends to dominate in accelerated laboratory testing, but IGSCC is of concern in operating nuclear power plants. In aim to obtain test results relevant also to operation conditions, one must at first develop and verify test conditions capable to reproduce in the laboratory the same failure type which occurs in service.

Crack propagation in the Inconel 182 and 82 weld metals occurs along the dendrite boundaries. The dendrite structure is complicated. The crack path and propagation rate can be affected by the crack orientation, loading geometry and loading type.

---

[3] Field Emission Gun Scanning Transmission Electron Microscope, FEGSTEM (Philips CM 200).

The fracture morphologies revealed in fractographic examination of the fracture surfaces created in different tests are listed in Table 5. An example of crack propagation along the dendrite boundaries in a test specimen of alloy 182 is shown in Fig. 19. This is a remarkable achievement, because with this failure mode obtained test results are more relevant to practice.

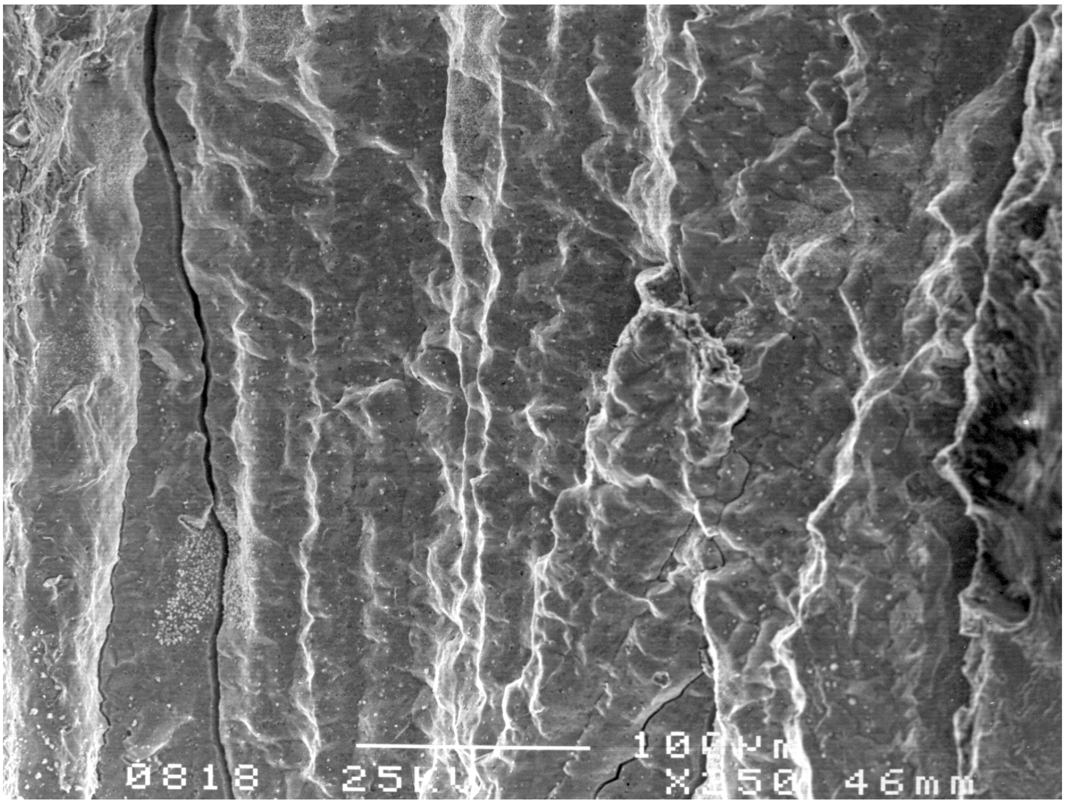


Figure 19. Fracture surface of specimen 182/3/1 showing interdendritic stress corrosion cracking in Inconel alloy 182 weld metal.

4.2.3 Crack growth rate tests

The aim of this task is to measure the influences of thermal ageing, coolant water sulphate concentration, crack orientation and loading type on the intergranular stress corrosion cracking (IGSCC) susceptibility and crack propagation rate in Inconel weld metals 82 and 182. The performance of austenitic stainless steels AISI 316NG and AISI 304 is tested for reference purposes.

The tests are slow rising displacement tests (J-R tests) and combined constant load and corrosion fatigue tests in simulated BWR environment at 273ºC.

The first test series was performed applying a constant load line displacement rate of $2 \cdot 10^{-7}$ mm/s, which resulted in TGSCC. For the next test series 2 and 3 the loading method was changed as follows: Displacement rate of $1 \cdot 10^{-6}$ mm/s until the J-level was above 4 kJ/m^2, after which the rate was reduced to $2 \cdot 10^{-8}$ mm/s.

Results

The results of the first three test series completed during the project year 1999 are presented in Table 5. Two parameters were varied during the tests. The test environment is the same for all specimens in a test series, i.e., being tested simultaneously in the autoclave but the loading is varied individually for each specimen. The second column in Table 5 presents the fracture mechanical loading range in terms of J-integral and the third column presents the sulphate concentration.

A crack growth curve for Inconel 182 is presented in Fig. 20. Fig. 21 shows the measured crack propagation rates as a function of sulphate concentration for the specimens where intergranular stress corrosion cracking was observed on at least part of the fracture surface.

Table 5. Results of stress corrosion crack growth tests in simulated BWR coolant. Temperature was 273ºC and outlet O2 concentration 300 ppb.

Specimen mat./serie/no	J-integral [kJ/m^2]	SO_4 [ppb]	Crack growth rate and mechanism [mm/s]	fracture morphology
82/1/1	0-25 25-40 40-75	≤ 5 10 30	~0 ~0 ~0	No SCC
316NG/1/1	10-18 18-19 NA	≤ 5 10 30	$7.1\text{-}19 \times 10^{-7}$ $1.9\text{-}4.2 \times 10^{-6}$ NA	TGSCC
316NG/1/2	NA 9-18 18-34	≤ 5 10 30	NA 2.5×10^{-7} 2.2×10^{-7}	TGSCC
304/1/1	6-13 13-18 18-24	≤ 5 10 30	7.1×10^{-7} 7.1×10^{-7} $4.7\text{-}6.5 \times 10^{-7}$	IGSCC+TGSCC
82/2/1	NA	<5	~0	No SCC
182/2/1	11-14	<5	NA	Interdendritic (very localized)

(Table continues on next page)

Table 5. continued.

Specimen mat./serie/no	J-integral [kJ/m²]	SO_4 [ppb]	Crack growth rate and mechanism [mm/s]	fracture morphology
182/2/2	4-6	<5	NA	Interdendritic (very localized)
316NG/2/1	10-11	<5	$5x10^{-8}$	TGSCC
316NG/2/2	13-14	<5	$2.5x10^{-8}$	TGSCC+IGSCC
304/2/1	8-9	<5	$3.1x10^{-7}$	IGSCC+TGSCC
82/3/1	42-43	<5	~0	Very localized Interdendritic SCC at the crack tip
	~39	10	~0	
	39-40	30	~0	
	41-42	100	~0	
	43-44	100	~0	
182/3/1	44-47	<5	$3.5x10^{-7}$	3/4 of thickness: Interdendritic, 1/4 of thickness: no SCC
	38-39	10	$3.7x10^{-7}$	
	39-42	30	$4.3x10^{-7}$	
	42-44	100	$4.2x10^{-7}$	
	47-50	100	$3.9x10^{-7}$	
182/3/2	14-16	<5	$7.5x10^{-7}$	Interdendritic (+small ligaments without SCC)
	22-23	10	$7.3x10^{-7}$	
	19-22	30	$1.4x10^{-6}$	
	16-19	100	$1.8x10^{-6}$	
	10-14	100	$4.3x10^{-6}$	
316NG/3/1	20-21	<5	$1x10^{-8}$	TGSCC+IGSCC
	18-19	10	$1x10^{-8}$	
	~19	30	$1x10^{-8}$	
	~20	100	$1x10^{-8}$	
	~21	100	$1x10^{-8}$	
316NG/3/2	~26	<5	NA	TGSCC
	~24	10	NA	
	24-25	30	NA	
	25-26	100	NA	
	26-27	100	NA	
304/3/1	~22	<5	$2.1x10^{-7}$	IGSCC (+locally TGSCC)
	~22	10	$2.3x10^{-7}$	
	~22	30	$2.8x10^{-7}$	
	~22	100	$3.4x10^{-7}$	
	~22	100	$3.7x10^{-7}$	

abbreviations:
- NA = not available, could not be determined from the measured data
- SCC = stress corrosion cracking
- TGSCC = transgranular stress corrosion cracking
- IGSCC = intergranular stress corrosion cracking

Discussion

In sensitised AISI 304, stress corrosion cracks have been observed to grow with rather constant rates regardless of the J-level, whenever the J-integral exceeds a threshold value, J_{SCC}. For AISI 304 the commonly approved threshold is $J_{SCC} \approx 3{,}7$ kJ/m^2, which corresponds to $K_{ISCC} \approx 27$ MPa√m according to the relation $K_I = \sqrt{[J \cdot E/(1-v^2)]}$.

In alloy 82 stress corrosion cracking could be observed only in a very small 20-30 μm deep zone right at the tip of the pre-fatigue crack on the fracture surface of specimen 82/3/1. Because the maximum J-integral values exceeded 40 kJ/m^2 ($K_I > 90$ MPa√m), this observation indicates that the material is not susceptible to stress corrosion cracking in the applied SO_4 concentrations in BWR environment at 273ºC.

In alloy 182 interdendritic cracking was observed even in clean water with a sulphate concentration less than 5 ppb. Crack growth rate in one specimen 182/3/2 showed a clear dependence on the sulphate concentration. The crack propagation rate seems to change within a few hours after the inlet water sulphate concentration is changed, both when it is increased and when decreased.

In AISI 316NG stainless steel some intergranular stress corrosion cracking mixed with transgranular cracking was observed at the low loading rate. However, it is not clear if there are enough SCC susceptible grain boundaries so that the crack could propagate by intergranular SCC mechanism in normal power plant conditions. Eventually, continuously increasing loading is needed to advance the crack through the ligaments between the susceptible boundaries with a transgranular mechanism. No dependency between crack propagation rate and sulphate concentration was observed in this study and the measured crack growth rates were slow in accordance with the literature.

Sensitised AISI 304 stainless steel proved to be IGSCC susceptible at all of the applied sulphate concentrations. Crack propagation rate was dependent on the sulphate concentration, but the scatter between the different test series was large. Overall, the measured crack propagation rates are within the same range as presented in literature for the same temperature. The fracture mode correlated with the loading rate such that TGSCC was related to the dynamic type of loading.

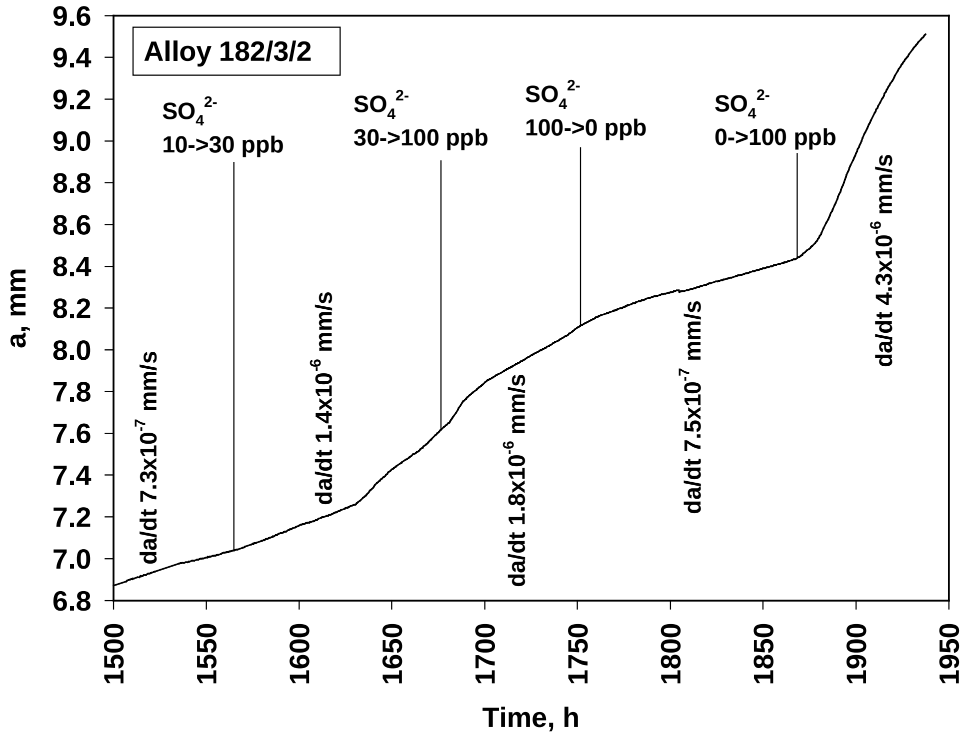


Figure 20. Crack length vs. time curve for Alloy 182 showing the influence of nominal inlet water sulphate concentration on the crack propagation.

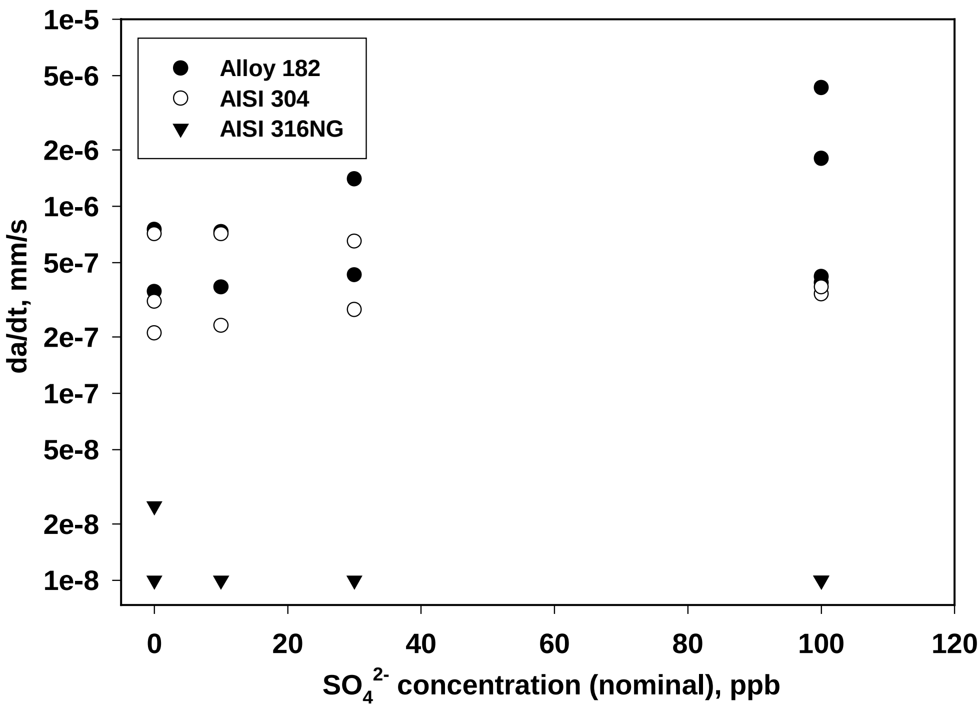


Figure 21. Crack growth rates as a function of sulphate concentration for the specimens where intergranular stress corrosion cracking occurred.

4.2.4 Plans for year 2000

Stress corrosion susceptibility of also these alloys is supposed to increase by thermal ageing. In the next phase of this project, in year 2000, thermally aged Inconel alloys 82 and 182 will be tested. The alloys were heat treated for 200 hours in 400ºC in early 2000 and are currently in testing. This treatment is supposed to simulate the effects of a long term exposure to the BWR operating temperatures. However, the FEGSTEM[4] analyses of grain or dendrite boundary segregation and carbide distribution are still planned after this second project year.

4.3 Mechanisms of environmentally assisted cracking

Within the frameworks of the project ”Rakenteellisen käyttöiän hallinta” in 1999, Laboratory of Engineering Materials in Helsinki University of Technology has been conducting research in the field of degradation of mechanical properties of metals and alloys resulting from the interaction with environment. The work is of scientific nature, but continuous linking to other subprojects and questions faced at the power plants is used to ensure applicability of results in short term to support the applied research and in longer term also the operability of power plants.

4.3.1 Subproject activities in 1999

In 1999 the subproject has been oriented in two directions:

- Modelling and laboratory experiments on hydrogen-induced degradation and the bulk effects of selective dissolution.
- Modelling and laboratory experiments on surface oxidation and selective dissolution.

---

[4] Field Emission Gun Scanning Transmission Electron Microscope, FEGSTEM (Philips CM 200).

Hydrogen effects

The study of the hydrogen effects has been targeted to critical examination of the hydrogen-induced IGSCC mechanism by the HELP mechanism, based on the shielding effect of the dislocation elastic fields. The mechanism was proposed to explain the IGSCC phenomena in, among others, nickel-based Inconel 600 and 690 alloys.

During the study, the activation enthalpies of the diffusion jumps of hydrogen, binding energies to dislocations and the critical temperatures of the Cottrell atmosphere formation were determined. Several conference presentations and a doctoral thesis (Smuk, 1999) "Application of Internal Friction Method for Studying Point Defect Behaviour in Engineering Materials" were prepared on this subject.

Surface interactions

The study of surface interactions with environment, like selective dissolution and oxidation, has been aimed at further development of the vacancy model of mechanical degradation. Experimental work performed on the environmentally assisted cracking of pure copper forms the basis of a doctoral thesis under preparation.

4.4 Irradiation assisted stress corrosion cracking of core components

Despite of the strict water chemistry guidelines, sensitised microstructure of the primary circuit stainless steels coupled with residual stresses can produce susceptibility to stress corrosion cracking (SCC) in the BWR coolant. The necessary condition for the intergranular stress corrosion cracking (IGSCC) to occur, is the presence of a certain amount of oxidising species such as oxygen or hydrogen peroxide together with ionic impurities in the coolant.

The levels of oxidising species can be decreased by adding hydrogen into the feed water. This has been shown to mitigate the susceptibility for the stress corrosion cracking (IGSCC) in BWRs. This applies possibly also for irradiated materials (IASCC). However, due to the high water radiolysis in the reactor core, the potentials of in-core components remain still very high (Cowan, 1996).

Irradiation assisted stress corrosion cracking of reactor core components is a topic for high interest in the international nuclear materials research community. 15 partners from USA, Japan and Europe have joined together in an international group of Co-operative Irradiation Assisted Stress Corrosion Cracking Research Program (CIR) co-ordinated by EPRI. VTT is participating in the CIR programme through in-kind information exchange. The Finnish research contribution to CIR is mainly realised within this project (Toivonen et al., 1998).

4.4.1 Subproject activities in 1999

Experimental research on irradiation assisted stress corrosion cracking is still in its early stages. The generic importance of the topic together with the required efforts and funding provide a good motivation for international co-operation. On the other hand, VTT's experience and facilities provide a strong background for developing suitable experimental techniques. Meanwhile waiting irradiated reactor core component material for laboratory testing, a metallographic investigation was performed and fracture mechanical test methods were developed.

In 1999 the subproject included the following tasks:

- Investigation of the ageing mechanisms in a VVER-440 PWR reactor core component to verify, whether irradiation assisted stress corrosion cracking had occurred in PWR conditions.
- Development of testing methods and research for a suitable loading parameter to investigate SCC crack propagation rate in elastic-plastic conditions.
- Participation to the international Co-operative Irradiation Assisted Stress Corrosion Cracking Research Program (CIR).

4.4.2 IASCC in PWR reactor conditions

The aim of this task was to investigate, whether irradiation assisted stress corrosion cracking, IASCC, can occur in PWR reactor core conditions. Verified evidence was still missing in the time when this project was launched.

IASCC has been reported to occur as intergranular cracking in austenitic stainless steels in oxidizing BWR environments at neutron fluences above 5×10^{20} n/cm^2 (E > 1 MeV) corresponding to about 0.7 dpa (displacements per atom). The threshold fluence for increased risk for intergranular irradiation assisted cracking in non-oxidizing PWR environment is much higher, 2×10^{21} n/cm^2 (E > 1 MeV) (1).

In oxidizing BWR environment, the role of corrosion in IASCC is evidently important, while in a non-oxidizing environment corrosion should not be as decisive. Possible additional factors affecting intergranular cracking are radiation-induced hardening, radiation-induced creep and hydrogen embrittlement. Also swelling, formation of helium bubbles and radiation-induced precipitates may become an issue, especially at higher temperatures or doses.

Failure analysis of a fuel assembly spacer grid sleeve

A fuel assembly spacer grid sleeve had failed after three years of operation in a core of a VVER-440 PWR reactor. Irradiation assisted stress corrosion cracking was suspected and a careful failure analysis was performed (Ehrnstén et al., 1999).

The fuel rod spacer grid is clamped to the central tube with the spacer grid sleeve. The estimated irradiation temperature was 300°C, and the neutron flux at the site of the failed spacer grid was estimated to be as follows: fast flux 2.07×10^{14} n/cm^{2}s (E > 0.624 eV) and thermal flux (E < 0.624 eV) 0.31×10^{14} n/cm^{2}s. The total dose for E > 1 MeV during three years was estimated to be 4.6×10^{21} n/cm^2 or about 7 dpa.

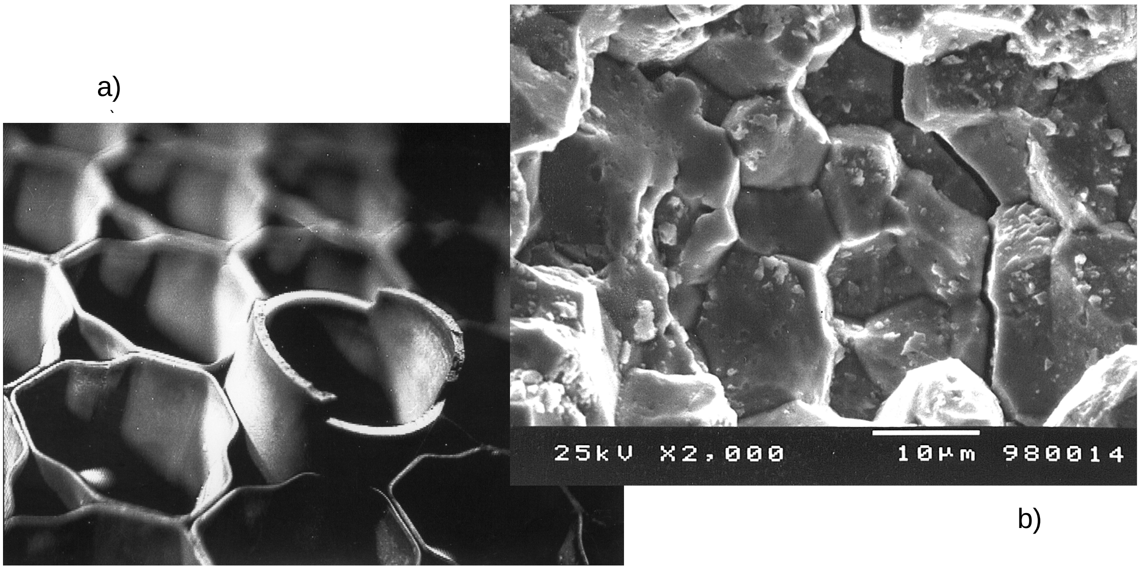
One spacer grid with a failed sleeve (ϕ13 × 0.55 mm) was removed for failure analysis and material investigations. In addition, the material of a similar, unirradiated sleeve was investigated. The material is titanium stabilised austenitic stainless steel of type 06X18H10T. The chemical composition is given in Table 6.

The hardness of the irradiated material was 347 HV1, much higher than the hardness of an unirradiated sleeve, 156 HV1. The grain size of the sleeve material was small, corresponding to ASTM 9. The microstructure contained numerous inclusions and precipitates, i.e., sulphides, phosphides and titanium nitrides and carbides. The failure analysis revealed that the spacer grid sleeve had cracked intergranularly without any detectable plastic deformation, Fig. 22.

Table 6. Chemical composition of the sleeve material.

C	Cr	Ni	Ti	Mn	Si	P	S
0.05	17.50	10.30	0.49	1.50	0.50	0.023	0.010

a)



b)

Figure 22. A macrograph (a) and the intergranular fracture surface (b) of the failed spacer grid sleeve.

Analysis of ageing and failure mechanisms

Both materials were investigated using a Field Emission Gun Scanning Transmission Electron Microscope, FEGSTEM (Philips CM 200). These investigations were focused on the defect structure of the irradiated material as well as on the composition of the grain boundaries. Spot analyses were performed at grain boundaries using a 1 nm beam and at the adjacent grain matrixes using a 20–30 nm beam.

The irradiated sleeve material contained a dense defect structure consisting of mainly interstitial loops and some new precipitates. The main part of the defect structure was found to consist of faulted interstitial loops on {111}-planes. No defect-free zones were observed near the grain boundaries and the average loop size was 10 nm.

Clear grain boundary depletion of chromium and iron and enrichment of nickel and silicon was observed at some grain boundaries in the irradiated material, while no compositional changes were observed at others. Segregation had occurred at grain boundaries where the orientation difference between the adjacent grains was large, while no segregation was observed at grain boundaries where the orientation difference was small. The average amount of chromium depletion was 4.2%, i.e., from 18.9% to 14.7% Cr. The maximum measured depletion of an individual spot analysis was 6% resulting in a chromium concentration below 12%. No consistent segregation of impurity elements like sulphur and phosphorus was observed.

Chromium depletion and nickel enrichment will probably increase the local stacking fault energy and the initiation threshold for glide. This may allow higher stress concentrations to develop at the grain boundaries. On the other hand, irradiation also causes significant hardening of the matrix due to the heavily defected microstructure. The hard matrix together with the increased local stacking fault energy may enable much higher stresses at the grain boundaries than in an annealed material, thus promoting intergranular cracking instead of yielding.

The investigated failure was concluded to be caused by irradiation assisted cracking in the non-oxidizing PWR environment.

4.4.3 Development of crack growth testing methods

The aim of this task was to develop fracture mechanics based testing methods for characterisation of SCC susceptibility. A suitable loading parameter to be correlated to the SCC crack propagation rates in elastic-plastic conditions is lacking.

Sometimes only small pieces of the test material are available. This is a normal case for many in-core components. The samples available may be too small for constant load tests at relevant linear-elastic K_I levels. A question is raised: could also the time dependent EAC tests be conducted by applying elastic-plastic fracture mechanics?

A geometry independent loading parameter, which correlates with the crack growth rate (da/dt), is sought for. To compare the different candidate parameters, three point bending tests on Charpy size pre-fatigued specimens of AISI 304 stainless steel in mill-annealed and in 24 hours in 620ºC sensitised conditions were performed in simulated BWR coolant. Constant displacement and various displacement rates were used in the tests. The obtained crack growth rates are summarised in Fig. 23.

The results indicated that the crack growth rate (da/dt) correlates clearly better with the J-integral rate (dJ/dt) than with the stress intensity factor K_I or K_J. dJ/dt is a parameter which gives a linear contribution to $d\varepsilon_{ct}/dt$, i.e., $(d\varepsilon_{ct}/dt)_{app} \propto dJ/dt$.

Crack tip strain rate is generally assumed to be the da/dt controlling parameter in SCC. But dJ/dt does not explain all observations. A crack may propagate also when $dJ/dt \leq 0$. Therefore, a loading parameter, which takes into account not only the loading rate but also the loading level, is needed. The relation $(d\varepsilon/dt)_{CT} = \alpha^*(d\varepsilon/dt)_{app}$ used in SRRTs is not applicable in this case.

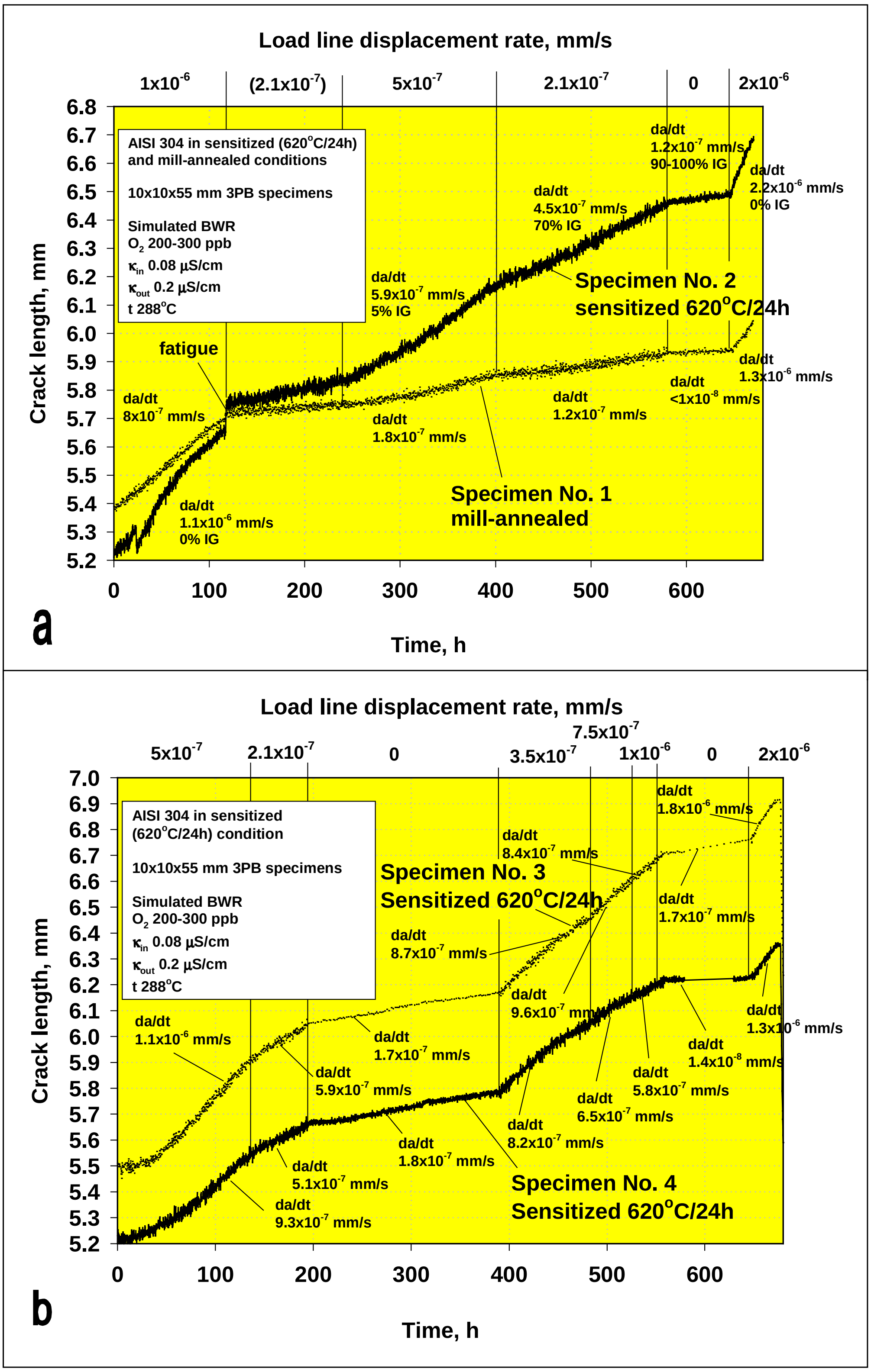


Figure 23. Crack growth curves obtained by different load line displacement rates. A comparison of annealed and sensitized samples (a) and two sensitized samples (b).

The fracture mode changes from intergranular (IGSCC) to mixed IG+TG and finally to pure transgranular (TGSCC) when dJ/dt is increased. But TG is an irrelevant fracture mode when the results are used to predict crack propagation in power plants. Therefore, the laboratory test conditions and methods should be such that IGSCC occurs. The fracture morphologies representing IGSCC and TGSCC stress corrosion cracking mechanisms at different loading rates are shown in Fig. 24.

a)

b)

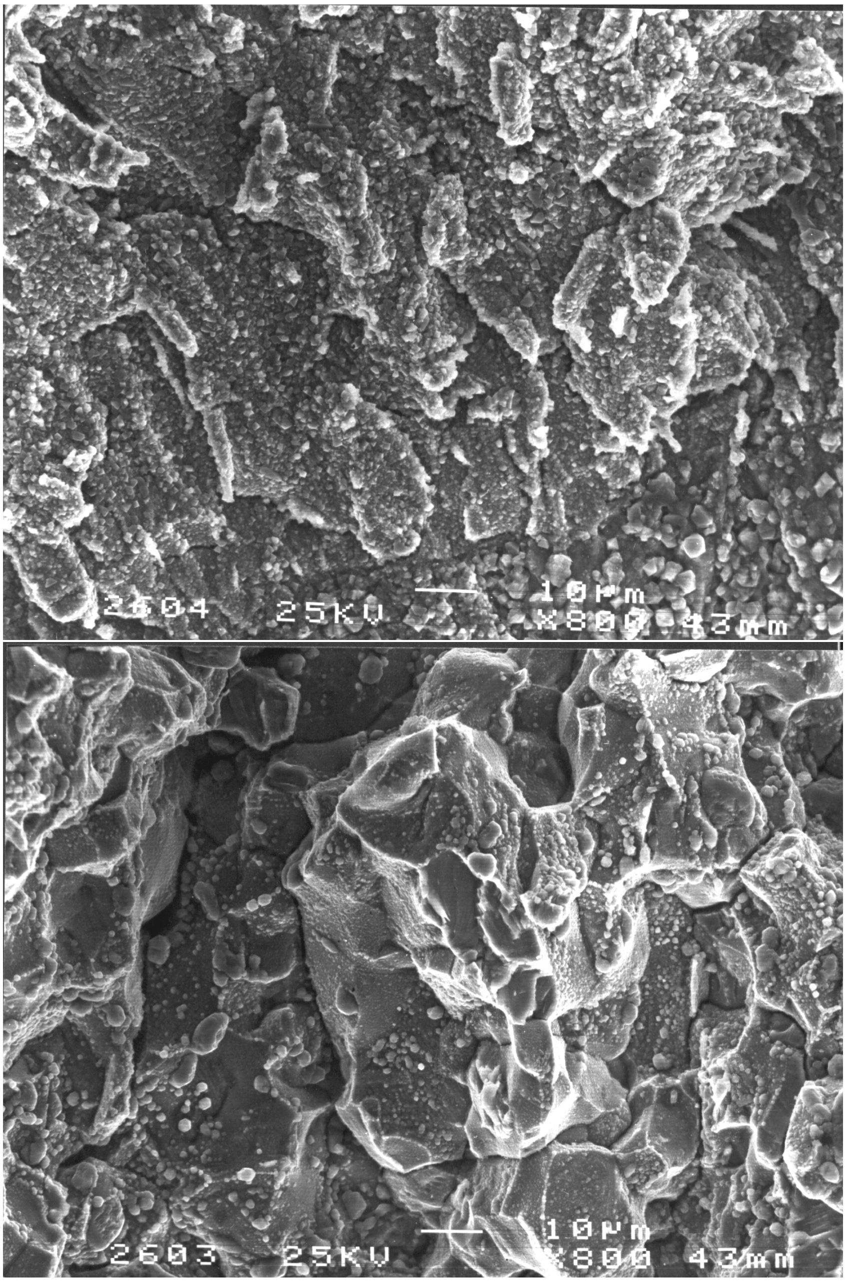


Figure 24. Fracture morphologies in sensitized AISI 304 stainless steel at different load line displacement rates; a) $\dot{\Delta} > 5\cdot 10^{-7}$ mm/s; b) $\dot{\Delta} = 0$ (constant displacement).

5. Summary

The project consisted of several parallel and inter-linked research tasks. These tasks together form an approach for estimating and managing lifetime of critical structural components in power plants. The research investments are expected to pay back through reduced maintenance cost and enhanced operability of the current nuclear reactors. Large additional benefits will be received if the plant lives can be extended as expected.

Similar approaches can be applied for many production plants in energy and process industries, but the applications need to be tailored for the plant specific needs.

Appendix A lists the reports and articles published within this project so far. The main achievements during the project year 1999 are summarised in the following.

Lifetime management and repair welding

1. The expectations and aims of participating industries in developing systems for plant life management were identified and partially harmonised.

2. A relatively large project team consisting of more than 30 specialists was got in full operation with a short notice.

3. A draft report of the literature study to survey the state-of-the-art the newest repair and improvement methods for nuclear power plant components was prepared.

Piping vibrations management

4. A random vibration module for the FPIPE program was developed.

5. Operational and natural mode shapes of the pilot piping were measured.

6. A first iteration round of analyses for the pilot piping case was completed. It included field measurements, modal testing, assessment of excitation and behaviour of supports together with FE analyses using design data.

Program system for piping integrity assessment

7. Development of capabilities for visualisation and input of the crack data.

8. Transformation of geometrical data from data base to FPIPE finite element analysis.

9. Creation of outlines for treatment of loading data.

Management of materials ageing

10. The re-embritlement rate of a Loviisa-type RPV weld was found to be faster than predicted by the commonly assumed lateral shift model.

11. The in Loviisa plant applied surveillance capsule construction is considered to work well at least in the neutron and gamma fields in the current irradiation locations, but the widely used ternary Pb-Ag-Sb temperature monitoring alloys were shown to be incapable of indicating precisely the irradiation temperatures.

12. The results indicated that variation of the phosphorus content does not affect toughness of the RPV weld reference material 501 in the unirradiated material condition.

13. Research on thermal ageing of cast, Ti-stabilised stainless steels was completed. Microstructural differences between the stabilised and non-stabilised as well as between the in service and artificially aged materials were identified.

Non-destructive monitoring of structural integrity

14. A new version of mechanised ultrasonic scanner was developed and successfully tested in pilot inspections at the Olkiluoto plant. It was presented to other industry in the Maintenance 1999 exhibition in Tampere in October 1999.

15. A reduction of the radiation doses during piping inspection was enabled. The time needed for positioning the scanner to the inspection area was remarkably reduced and the positioning can be performed by one person only.

16. The overall dimensions and weight of the scanner were reduced to allow easy handling in industrial environment.

Water chemistry, service reliability and activity levels

17. A set of flow through cells with data acquisition facilities were designed and manufactured for Loviisa 1 unit and Olkiluoto 1 unit. The system was already installed into Loviisa 1 unit and the measurements are going on.

18. Hydrogen peroxide injection studies indicated that 130°C may be the best temperature for peroxide injection without significantly changing the properties of oxide films on construction materials.

19. Stainless steel AISI 316 NG and Nickel base alloys Inconel 182 and Inconel 82 were studied in enriched BWR chemistry conditions, which are expected to occur in a crack tip. The ranking obtained for the stability of oxide films on the studied materials is in qualitative agreement with the ranking of the susceptibility of these materials to stress corrosion cracking.

Stress corrosion cracking in Inconel welds

20. Test conditions where intergranular stress corrosion cracking occurs in the studied alloys were determined through laboratory experiments.

21. Successful crack growth rate tests were performed in different sulphate concentrations. In these tests a clear correlation between sulphate concentration and crack growth rate was observed for the Inconel alloy 182. The alloy 82 was found clearly less susceptible to stress corrosion cracking.

22. The first experimental results give reason to anticipate that a very interesting data set will be obtained within this four year project.

Mechanisms of environmentally assisted cracking

23. One doctoral thesis and altogether eight scientific publications were published. Dr. Smuk successfully defended his doctoral thesis “Application of Internal Friction Method for Studying Point Defect Behaviour in Engineering Materials” in 1999 at the Helsinki University of Technology.

24. The developed material ageing models have been utilised to explain observed ageing of some materials in energy industry applications.

Irradiation assisted stress corrosion cracking of core components

25. The investigation of irradiated and non-irradiated material conditions and a careful failure analysis of a fuel assembly spacer grid sleeve gave evidence supporting that IASCC can occur also in the non-oxidizing PWR reactor core conditions.

26. It was shown that none of the parameters, K_I, J (or K_J) nor dJ/dt can be applied to correlate loading condition and da/dt unambiguously in elastic-plastic loading conditions, and that the influence of dJ/dt on da/dt and fracture morphology seems to be notable.

Acknowledgements

The project “Rakenteellisen käyttöiän hallinta” was started in 1999 for four years. The funding by TVO, Fortum Power and Heat, Fortum Engineering, Neste Engineering, FEMdata Ltd. and VTT Manufacturing Technology is gratefully acknowledged.

Valuable guidance for planning and support for executing the project was received from the project steering group, which was chaired by Mr. Juho Hakala of TVO. The other members were Antero Tamminen, Jyrki Kohopää and Ralf Ahlstrand (Fortum), Erkki Muttilainen (TVO), Matti Ojanen (STUK), Reijo Munther (Tekes), Hannu Hänninen (HUT) and Rauno Rintamaa (VTT).

Many people have contributed by writing ready chapters to this report. The contribution of industrial experts is particularly important in Chapters 3.1 and 3.2. Paulus Smeekes (TVO), Jukka Laaksonen (Neste Engineering), Eero Torkkeli (FEMdata) and Jaakko Rostedt, as well as the subproject leaders and researchers at VTT and HUT have co-authored this report.

References

Allemang, R. J. & Brown, D. L. 1983. A correlation for modal vector analysis. Proceedings of IMAC I. Pp. 110 - 116.

Chung, H. M. 1992. ‘Aging and Life Prediction of Cast Duplex Stainless Steel Components.’ Int. J. Pres. Ves & Piping, 50, pp. 179 - 213.

Chung, H. M. & Chopra, O. K. 1987. ‘Long-term Embrittlement of Cast Austenitic Stainless Steels-Mechanisms and Kinetics,’ Properties of Stainless Steels in Elevated Temperature Service, ed. M. Prager, The Materials Properties Council, Inc., MPC-Vol. 26, 17 - 34, The American Society of Mechanical Engineers, NY 1987.

Chopra, O. K. 1990. ’Thermal Aging of Cast Stainless Steels: Mechanisms and Predictions’, Fatigue, Degradation and Fracture, Ed. By Bamford, W. H. et al., AMES, PVP- Vol. 195, MPC - Vol. 30. Pp. 193 - 214.

Cowan, R. L. 1996. The mitigation of IGSCC of BRW internals with hydrogen water chemistry. Proceedings of water chemistry of nuclear reactor systems 7, Bournemouth, Great Britain. Pp. 196 - 206.

Ehrnstén, U., Karjalainen-Roikonen, P., Nenonen, P., Ahlstrand, R., Hietanen, O., Timofeev, B. T. & Bloomin, A. A. 2000. Properties of cast ti-stabilised stainless steel after long-term ageing. The 6th Int. Conf. Material issues in design, manufacturing and operations of nuclear power plants equipment. CRISM "Prometey". June 19 - 23, 2000. 8 p.

Ehrnstén, U., Nenonen, P., Aaltonen, P., Teräsvirta, R. & Hietanen, O. 1999. Intergranular Cracking of an Irradiated Ti-stabilized Austenitic Stainless Steel Spacer Grid Sleeve from a VVER-440 reactor. Presented at 9th Int. Conf. Environm. Degradation of Materials in Nuclear Power Systems – Water Reactors, Newport Beach, CA, USA, Aug. 1 - 5, 1999. 8 p.

Ewins, D. J. 1986. Modal Testing: Theory and Practice. Letchworth, Herts, U.K.: Research Studies Press Ltd. 269 p.

Jansson, C. 1990. ‘Degradation of Cast Stainless Steel Elbows after 15 Years in Service’, Fontrevaud II International Symposium, Royal Abbey of Fontrevaud-France, 10 - 14 September, 1990.

Kohopää, J. 1998. Effects of post-irradiation thermal annealing on radiation embrittlement behaviour of Cr-Mo-V alloyed weld metals. Acta Polytechnica Scandinavica, Mechanical Engineering Series No. 132, Espoo 1998. 112 p. ISBN 952-5148-64-5

Kryukov, A., Platonov, P., Shtrombach, Y., Nikolaev, V., Langer, R. & Leitz, C. 1995. Irradiation emrittlement and recovery of operating reactor pressure vessel. IAEA specialists meeting on irradiation embrittlement and mitigation, Espoo, Finland, 23 - 26 October 1995. IWG-LMNPP-95/5 IAEA.

Lin, R. M. & Ewins, D. J. 1990. Model updating using FRF data. Proceedings of the 15th International Seminar on Modal Analysis. KU Leuwen, Belgium, September 1990. Pp. 141 - 162.

Marcovits, C. C. & Giannuzzi, A. J. 1994. EPRI Weld-Related Research Activities. TR-104307. Research Project 9002-05. 1994.

Massoud, J-P., Auger, P., Danoix, F., Rezakhanlou, R. & Van Duysen, J-C. 1993. ‘Evaluation of the Thermal Ageing of Duplex Stainless Steels’, Sixth International Symposium on Environmental Degradation of Materials in Nuclear power Systems-Water Reactors, ed. By R. G. Gold and E. P. Simonen, The Minerals, Metals & Materials Society.

Massoud, J. P., Bethmond, M. & Champredonde, J. 1991. ‘Long term aging of cast duplex stainless steels between 300 and 400°C. Relationship between toughness properties and metallurgical parameters’. Duplex Stainless Steels,´91, October 28 - 29, 1991, Beaune Bourgogne, France. Pp. 93 - 100.

Pelli, R. 2000. Uusia korjaus- ja parannusmenetelmiä ydinvoimalaitosmateriaaleille. Espoo: VTT Manufacturing Technology. Report VALB62-001050. 23 p.

Smuk, S. 1999. Application of Internal Friction Method for Studying Point Defect Behaviour in Engineering Materials. Acta Polytechnica Scandinavica. Mechanical Engineering Series No. 140. Helsinki University of Technology. 100 p.

Talja, H., Saarenheimo, A. & Haapaniemi, H. 2000. Updating dynamic FE analysis models with experimental data, a literature study. Espoo: VTT Manufacturing Technology. Report BVAL64-001017.

Toivonen, A., Aaltonen, P. & Mäkelä, K. 1998. VTT Program on Irradiation Assisted Stress Corrosion Cracking, IASCC. EPRI Interim Report.

Appendix A: List of publications

The reports and articles published within this project by September 2000 are listed in following. A few confidential laboratory reports are not listed, but all the main conclusions therein have been summarised in some public reports.

Ehrnstén, U., Karjalainen-Roikonen, P., Nenonen, P., Ahlstrand, R., Hietanen, O., Timofeev, B. T. & Bloomin, A. A. Properties of cast ti-stabilised stainless steel after long-term ageing. The 6th Int. Conf. Material issues in design, manufacturing and operations of nuclear power plants equipment. CRISM "Prometey". June 19 - 23, 2000. 8 p.

Ehrnstén, U., Nenonen, P., Aaltonen, P., Teräsvirta, R. & Hietanen, O. Intergranular Cracking of an Irradiated Ti-stabilized Austenitic Stainless Steel Spacer Grid Sleeve from a VVER-440 reactor. Presented at 9th Int. Conf. Environm. Degradation of Materials in Nuclear Power Systems – Water Reactors, Newport Beach, CA, USA, Aug. 1 - 5, 1999. 8 p.

Hänninen, H., Aaltonen, P., Jagodzinski, Yu., Tarasenko, O. & Smuk, S. On the mechanism of environmentally assisted cracking of pure copper in $NaNO_2$ solution. Presented at Int. Conf. Environ. Degradation of Engineering Materials ´99, Gdansk-Jurata, Poland, Sept. 19 - 23, 1999.

Jagodzinski, Yu., Hänninen, H., Smuk, S. & Tarasenko, O. Hydrogen effects in FCC metals. Presented at ICG-SCC seminar, Turku, Finland, May 18 - 20, 1999.

Jagodzinski, Yu., Hänninen, H., Smuk, S. & Tarasenko, O. Hydrogen-Probe Mechanical Spectroscopy for Studying Local Ordering in Concentrated Substitutional Alloys. Presented at ICIFUAS-12, Buenos Aires, Argentine, July 19 - 23, 1999.

Jagodzinski, Yu., Aaltonen, P., Smuk, S., Tarasenko, O. & Hänninen, H. Internal friction study of environmental effects on metals and alloys. Presented at ICIFUAS-12, Buenos Aires, Argentine, July 19 - 23, 1999.

Jagodzinski, Yu., Hänninen, H., Tarasenko, O. & Smuk, S. Interaction of Hydrogen with Dislocation Pile-Ups and Vacancy Generation at Plastic Deformation. Presented at Int. Conf. Environ. Degradation of Engineering Materials ´99, Gdansk-Jurata, Poland, Sept. 19 - 23, 1999. Article has been submitted to Scripta Materialia.

Laitinen, T., Mäkelä, K., Sirkiä, P. & Mäkelä, M. Olkiluoto 1:n vesikemian monitorointi- ja oksidinäytekennon tarkastusaineisto. Espoo: VTT Manufacturing Technology. Research Report VAL67-001298. Prepared for Teollisuuden Voima Oy. (in Finnish).

Moilanen, P., Arilahti, E., Bojinov, M., Laitinen, T., Mäkelä, K., Mäkelä, M., Mäkinen, R., Saario, T., Sirkiä, P. & Toivonen, A. Pneumatic servo-controlled fracture resistance measuring device (PSFM-Device) and contact electric resistance measuring device (CER Device). Enlarged Halden Programme Group Meeting. Loen, NO, 24 - 29 May 1999. 16 p.

Mäkelä, K., Beverskog, B. & Aaltonen, P. In-core Pd reference electrode to be used in LWRs. Espoo: VTT Manufacturing Technology, 2000. Report VALB443, (draft 13.4.2000). 15 p.

Pelli, R. Uusia korjaus- ja parannusmenetelmiä ydinvoimalaitosmateriaaleille. Espoo: VTT Manufacturing Technology. Research Report VALB62-001050 23 p.

Saario, T., Mäkelä, K., Laitinen, T. & Bojinov, M. Effects of acid-oxidising conditions on oxide films on stainless steel during a simulated shutdown and start-up of a VVER plant. Espoo: VTT Manufacturing Technology. Research Report VAL67-001316. 27 p.

Sirkiä, P., Saario, T., Mäkelä, K., Laitinen, T. & Bojinov, M. Changes in oxide films on Ti-stabilised stainless steel samples during exposure to primary coolants at Loviisa units. Espoo: VTT Manufacturing Technology. Research Report VAL67-001323. 20 p.

Smuk, S., Hänninen, H., Jagodzinski, Yu., Tarasenko, O. & Aaltonen, P. Comparison of Hydrogen Effects on Alloy 600 and 690. Presented at 9th Int. Conf. Environm. Degradation of Materials in Nuclear Power Systems – Water Reactors, Newport Beach, CA, USA, Aug. 1 - 5, 1999.

Smuk, S., Hänninen, H., Jagodzinski, Yu., Tarasenko, O. & Aaltonen, P. Internal friction study of hydrogen effects in Alloy 600 and 690. Presented at European Structural Integrity Society ESIS TC 10 Hydrogen Degradation Committee Seminar, Truskavets, Ukraine, Sept. 16 - 18, 1999.

Smuk, S. Application of Internal Friction Method for Studying Point Defect Behaviour in Engineering Materials. Acta Polytechnica Scandinavica. Mechanical Engineering Series No. 140. Helsinki University of Technology. 100 p.

Solin, J. R & D for corrosion management. ENERTEC Special Helsinki Fair Issue 2000. P. 8 - 9.

Solin, J. R & D for plant life management. Energy in Finland 2000. P. 76 - 77 (Annual special issue of the Finnish journal Energia).

Solin, J. (ed.). Plant life managemet (XVO) report 1999. Espoo: VTT, Technical Research Centre of Finland, 2000. VTT Research Notes 2077. 68 p. + app. 3 p.

Talja, H., Solin, J. & Rintamaa, R. An approach to systematic structural lifetime management. Paper to presented at Int. Conf. Nuclear Energy in Central Europe 2000. Bled, Slovenia. September 11 - 14, 2000.

Talja, H., Saarenheimo, A. & Haapaniemi, H. Updating dynamic FE analysis models with experimental data, a literature study. Espoo: VTT Manufacturing Technology Research Report BVAL64-001017.

Toivonen, A., Moilanen, P., Pyykkönen, M., Tähtinen, S., Rintamaa, R. & Saario, T. The feasibility of small size specimens for testing of environmentally assisted cracking of irradiated materials and of materials under irradiation in reactor core. Nuclear Engineering and Design 193 (1999), pp. 309 - 316.

Toivonen, A. & Aaltonen, P. Relation between loading parameters and SCC propagation rate in elastic plastic loading conditions on small precracked specimens. ICG/EAC Meeting, Williamsburg, 10 - 14.4.2000.

Toivonen, A. Effects of thermal history. BWR coolant sulphate ion concentration, crack orientation and loading type on stress corrosion crack propagation in Inconel Alloys 82 and 182. Interim Report for Teollisuuden Voima Oy. Espoo, 2000. 14 p. (in Finnish)

Valo, M., Koukkari, P. & Pitkänen R. Validation of melting alloy temperature monitors for RPV surveillance. Espoo: VTT Manufacturing Technology, research report, 2000.

Published by

Vuorimiehentie 5, P.O.Box 2000, FIN-02044 VTT, Finland
Phone internat. +358 9 4561
Fax +358 9 456 4374

Series title, number and report code of publication

VTT Research Notes 2077
VTT–TIED–2077

Author(s)
Solin, Jussi (ed.)

Title

Plant life management (XVO). Report 1999

Abstract

Experimental and analytical research is being carried out in an industrially oriented project dealing with on estimating and managing lifetime of critical structural components in energy industry. The research topics included systematic component lifetime management, lifetime of pressure bearing components, piping vibrations and integrity management, management of materials ageing, non-destructive inspection, water chemistry, oxide films and their role in service reliability and build-up of activity levels, stress corrosion cracking in Inconel welds, irradiation assisted stress corrosion cracking of core components, development of crack growth testing methods as well as the mechanisms of environmentally assisted cracking.

The main results of the first project year are summarised in this report.

Keywords
industrial plants, nuclear power plants, life tests, energy production, life (durability), aging (metallurgy), management, cracking, inspection, reliability, service life, pressure bearing components

Activity unit
VTT Manufacturing Technology, Materials and Structural Integrity, Kemistintie 3, P.O.Box 1704, FIN–02044 VTT, Finland

ISBN	Project number
951–38–5786–7 (soft back ed.) 951–38–5787–5 (URL: http://www.inf.vtt.fi/pdf/)	VOSU00318

Date	Language	Pages	Price
February 2001	English	68 p. + app. 3 p.	B

Name of project	Commissioned by
Rakenteellisen käyttöiän hallinta	TVO, Fortum, National Technology Agency (Tekes), Technical Research Centre of Finland (VTT)

Series title and ISSN	Sold by
VTT Tiedotteita – Meddelanden – Research Notes 1235–0605 (soft back edition) 1455–0865 (URL: http://www.inf.vtt.fi/pdf/)	VTT Information Service P.O.Box 2000, FIN-02044 VTT, Finland Phone internat. +358 9 456 4404 Fax +358 9 456 4374

VTT TIEDOTTEITA – MEDDELANDEN – RESEARCH NOTES

VTT VALMISTUSTEKNIIKKA – VTT TILLVERKNINGSTEKNIK – VTT MANUFACTURING TECHNOLOGY

1853 Riipi, Timo. Ruoppaus- ja läjitystekniikoiden valinta maalajien ominaisuuksien ja ympäristövaikutuksien perusteella. 1997. 66 s. + liitt. 40 s.

1854 Lahdenperä, Kari. Varastosäiliöiden pohjien kunnonvalvonta. 1997. 25 s.

1862 Hentinen, Markku, Hildebrand, Martin & Visuri, Maunu. Adhesively bonded joints between FRP sandwich and metal. Different concepts and their strength behaviour. 1997. 44 p.

1880 Heikkilä, Jouko. TOMHID – Tuotantolaitoksen turvallisuuden kartoitusmenetelmä. 1997. 45 s. + liitt. 31 s.

1882 Sarkimo, Matti. Jatkuvan monitoroinnin menetelmät rakenteiden eheyden varmistamiseen ydinvoimaloissa. 1998. 41 s.

1886 Malm, Timo & Järvenpää, Jorma. Pneumatiikalla toteutetun kappaletavara-automaation turvallisuus. 1998. 49 s. + liitt. 23 s.

1920 Taipale, Ville. Osajärjestelmän vaikutus prosessijärjestelmän elinjaksotuottoon. LCP-laskentamalli. 1998. 51 s. + app. 1 s.

1925 Kaski, Petteri, Virolainen, Kimmo, Leino, Tapio & Mörönen, Lasse. Kaatuessaan vaaraa aiheuttavat rakenteet. 1998. 37 s. + liitt. 15 s.

1938 Malm, Timo, Kivipuro, Maarit & Tiusanen, Risto. Laajojen koneautomaatiojärjestelmien turvallisuus. 1998. 72 s.

1978 Salonen, Jorma. Kaasuturbiinien siipimateriaalit. 1999. 75 s.

1983 Siivinen, Jarmo & Mahiout Amar. Pintakäsittelylaitosten jätevesikuormituksen vähentäminen. Osa 1. Kirjallisuusselvitys. 1999. 102 s. + liitt. 12 s.

1987 Hildén, Jouko, Muukkonen, Tatu & Pehkonen, Antero. Hiiliterästen ja ruostumattomien terästen hapettuminen lämpökäsittelyssä ja peittaus. 1999. 59 s.

1997 Jokinen, Petri, Lahtinen, Reima & Lehmus, Eila. Teräsrakenteiden suojaus kaariruiskutetulla sinkkipinnoitteella. 1999. 50 s. + liitt. 14 s.

2008 Kähönen, Asko, Pärssinen, Valtteri, Ilvonen, Reijo & Siljander, Aslak. Putkipalkkien ja korkealujuuksisten terästen käyttö ajoneuvorakenteissa. 1999. 43 s.

2010 Mahiout, Amar & Siivinen, Jarmo. Pintakäsittelylaitosten jätevesikuormituksen vähentäminen. Osa 2. Kokeellinen tutkimus. 1999. 45 s. + liitt. 10 s.

2011 Tonteri, Hannele & Vatanen, Saija. Kierrätettävyys ja elinkaariajattelu ajoneuvojen ja työkoneiden suunnittelussa. 2000. 47 s. + liitt. 8 s.

2012 Korpiola, Kari & Varis, Tommi. Termisesti ruiskutettujen pinnoitteiden mekaaniset ominaisuudet E, ν ja σ. 2000. 39 s.

2020 Korpiola, Kari & Jokinen, Petri. Keraamipinnoitteiden valmistus HVOF-ruiskutuksella. 2000. 76 s. + liitt. 11 s.

2021 Tonteri, Hannele & Vatanen, Saija. Recyclability and life cycle thinking in the design of vehicles and work machines. 2000. 46 p. + app. 8 p.

2036 Parikka, Risto, Mäkelä, Kimmo K., Sarsama, Janne & Virolainen, Kimmo. Hihnakuljettimien käytön turvallisuuden ja luotettavuuden parantaminen. 2000. 77 s. + liitt. 24 s.

2039 Bojinov, Martin, Laitinen, Timo, Moilanen, Pekka, Mäkelä, Kari, Mäkelä, Matti, Saario, Timo & Sirkiä, Pekka. Development of a controlled-distance electrochemistry arrangement to be used in power plant environments. 2000. 48 p.

2063 Tonteri, Hannele, Vatanen, Saija & Kuuva, Markku. Työkoneiden käytön jälkeisen käsittelyn suunnittelu. 2000. 32 s. + liitt. 4 s.

2064 Tonteri, Hannele, Vatanen, Saija & Kuuva, Markku. Design for end-of-life treatment of work machines. 2000. 32 p. + app. 4 p.

2077 Solin, Jussi (ed.). Plant life management (XVO). Report 1999. 2001. 68 p. + app. 3 p.