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Reliability of sprinkler systems
Exploration and analysis of data from nuclear and non-nuclear installations

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Abstract

Sprinkler systems are an important part of fire safety of nuclear installations. As a part of effort to make fire-PSA of our utilities more quantitative a literature survey from open sources worldwide of available reliability data on sprinkler systems was carried out. Since the result of the survey was rather poor quantitatively, it was decided to mine available original Finnish nuclear and non-nuclear data, since nuclear power plants present a rather small device population. Sprinklers are becoming a key element for the fire safety in modern, open non-nuclear buildings. Therefore, the study included both nuclear power plants and non-nuclear buildings protected by sprinkler installations.

Data needed for estimating of reliability of sprinkler systems were collected from available sources in Finnish nuclear and non-nuclear installations. Population sizes on sprinkler system installations and components therein as well as covered floor areas were counted individually from Finnish nuclear power plants. From non-nuclear installations corresponding data were estimated by counting relevant things from drawings of 102 buildings, and plotting from that sample needed probability distributions. The total populations of sprinkler systems and components were compiled based on available direct data and these distributions.

From nuclear power plants electronic maintenance reports were obtained, observed failures and other reliability relevant data were selected, classified according to failure severity, and stored on spreadsheets for further analysis. A short summary of failures was made, which was hampered by a small sample size. From non-nuclear buildings inspection statistics from years 1985–1997 were surveyed, and observed failures were classified and stored on spreadsheets. Finally, a reliability model is proposed based on earlier formal work, and failure frequencies obtained by preliminary data analysis of this work. For a model utilising available information in the non-nuclear data body, it has to be analysed more comprehensively, than was possible in these studies.

Keywords
fire extinguishers, nuclear power plants, fire safety

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Preface

This study was carried out as a part of the Fire Safety Research project (FISRE) which is one of the projects in the Finnish Research Programme on Nuclear Power Plant Safety (FINNUS).

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Contents

List of symbols and acronyms

a	Parameter in a distribution
A	Floor area of a building or part of it [m^2]
A_0	Constant in equations containing floor area of a building or part of it [m^2]
b	Parameter in a distribution
BWR	Boiling water reactor
c	Normalization coefficient in a distribution
f	Frequency of fires [1/a]
F	Coefficient of influence of fire resistance of structures
FM	Factory Mutual
FMEA	Failure mode and effect analysis
f(n)	Frequency function of statistical distribution
IRI	Industrial Risk Insurers
LOSP	Loss of offsite power
M	Number of counts of an object within limited bounds
n	Number of sprinkler heads, value of a discrete stochastic variable, parameter in a distribution
N	Number of demands, coefficient of influence of standard fire protection measures, number of observations in a sample
NFPA	National Fire Protection Association (USA)
NPP	Nuclear power plant
NRC	US Nuclear Regulatory Comission
p	Probability value, parameter in a distribution
P	Probability function, potential loss
PSA	Probabilistic safety assessment/analysis
PWR	Pressurized water reactor
R	Risk

S	Coefficient of effects of special fire protection measures
SVK	Federation of Finnish Insurance Companies
	Sprinkler classes
	HH High hazard
	LH Light hazard
	OH Ordinary hazard
T	Stochastic time variable
WWI	The first world war
WWII	The second world war
X	General stochastic variable
x	Value of a general stochastic variable
x_0	Parameter in Weibull distribution
z	Quantile of a cumulative distribution
α	Parameter in Weibull distribution
β	Parameter in Weibull distribution
λ	Failure rate in a distribution, [1/a]
ν	Number of degrees of freedom

1. Introduction

Internationally nuclear industry has been pioneers in implementation of risk analysis on several of its subsectors. Professor Norman Rasmussen lead a large research commission which produced WASH-1400 (1975) generally known as Rasmussen report. This was an impressing monument on the early efforts of quantitative risk analysis on a complicated system. However, accidents have driven the development of nuclear risk analysis since then. For example, the first version of Rasmussen report sent for comments did not mention word 'fire'. Large fire in Browns Ferry NPP 1975 induced production of a fire analysis in the final version of the report, which is still very useful. It was estimated that the total contribution of fires increased core melt probability by 20% (Levine & Rasmussen 1984). Three Mile Island accident 1979 sparked in the US a second wave of PSA-studies of five commercial nuclear power plants, which resulted in another massive publication series (NUREG-1150, 1989).

Some review of relevant historical developments is made below to facilitate location of literature, which especially for fire related matters is difficult to trace from earlies years. Majority of these studies were carried out earlier outside this project. Fires have remained on the background as one of the external events in the designs of first generations of NPPs, but what is more important, they have been assessed mostly on qualitative basis only. For NUREG-1150 fire analyses of five plants were performed in three steps: initial plant visit, screening of potential fire locations, and accident sequence quantification. Direct quotation from uncertainty analysis of the procedure: 'Distributions for needed data were developed by the analysis staff using operating experience and experimental results'. US NPP fire regulations were prescriptive, but the effectivity of them was badly damaged by scandal-like circumstances. Recovering from the turmoil caused by Chernobyl accident 1986 there were during 90's in US repeated actions to develop also the fire safety part of PSA guidelines to the same technical level as the parts dealing with other physical phenomena. Comission paper SECY-98-058 coined these actions to 'pursue to develop a rulemaking for transitioning to a more risk-informed, performance-based structure for fire protection regulation of nuclear power plants' to three options: (1) develop a performance-based, risk-informed fire protection regulation, (2) develop a performance-based, risk-informed consensus standard, (3) maintain the existing fire protection regulations and guidance. The NRC policy followed now is option 2 as a results of discussion followed by development of NFPA 805 (2001) standard. A new guideline for application of NFPA 805 as a consensus standard is currently underway in the US.

Since most countries are following US developments also in the Finnish nuclear research program FINNUS the general goal of fire project FISRE was to develop fire risk analysis further for living PSA. A special emphasis was placed to improve calculation tools used to support PSA-analyses. This goal was approached on three fronts: (a) experiments and modelling on hardware, (b) software development and assessment, as well as (c) processing of statistical information (Keski-Rahkonen 2000, 2002b). Project FISRE was organised into three subprojects the titles of which cover roughly the fronts mentioned above. The last of them was 'active fire protection equipment' which was further divided into two parts: reliability of (1) fire detection and (2) sprinkler extinguishing systems. The task concentrated on front (c), although due to lack of international literature some modelling of hardware had to be carried out belonging to front (a).

From the floor area protected by sprinkler systems in Finland less than 1% are in NPPs (Rönty & Keski-Rahkonen 2001). Still sprinkler technology in NPPs is almost identical with the technique used in other industrial installations. Only maintenance actions and periodic testing are better controlled in NPP than elsewhere. Therefore, it was decided to study sprinklers from all systems, especially important was to utilise all available statistical sources.

There is an other motivation to go outside NPPs. Today's architectural vogue prefers large open spaces, where modifications are easily made if the use of space changes. This increases the fire compartment sizes compared to earlier Finnish buildings, and prescriptive dimensioning according to our traditional fire regulations cannot be followed. Experience and statistical studies indicate, fire risk increases with the size of fire compartment (Tillander et al. 2002). This has to be compensated by other means as a consequence of equivalency concept required by fire regulation. The most important compensation is sprinklers. A fire risk analysis is carried out to prove fulfilling of equivalency. Simple calculations show, the reliability of sprinkler system is the key element in maintaining acceptable fire safety in large spaces. A recent review outlines development of fire risk analysis on this non-nuclear sector (Keski-Rahkonen 2002a).

Reliability of sprinkler installation is defined as a probability of successful extinguishing operation in case of fire. The probability is determined using general methods of reliability and statistical analyses. For assessing reliability of sprinkler installations in Finland in a quantitative way the goal was to mine available statistical data and evaluate them to see, whether a usable model can be made. To this end a general reliability model was made (Hassinen 2000a, 2000b, 2001), sprinkler population in selected buildings (Rönty & Keski-Rahkonen 2001), and nuclear power plants (Rönty 2001) was calculated, data bases of faulty operations in NPPs (Rönty 2001) and other buildings (Hassinen & Keski-Rahkonen 2003) were made, and finally some preliminary summary analyses were attempted (Hassinen & Keski-Rahkonen 2003).

1.1 On history of risk analysis

Putting reliability of operative fire fighting systems in historical context, it is useful to look on the development of theory of risk analysis (Knight 1991, Høyland & Rausand 1994, Ericson 1999). Military and nuclear industries have been on the leading edge also in introducing modern techniques to safety related issues. Reliability of complicated technical systems was a major issue in military aviation during and since WWI. Statistical methods were introduced to measure reliability in a quantitative manner as a number of accidents per hour of flight time. Statistical basis of quality control of industrial products was introduced in US early 1930's by Walter Shewhart, Harold W. Dodge and Harry G. Romig, but were not implemented in any greater extend before the war. During WWII in Germany as a result of failures in V-1 missile program a mathematician Robert Lusser was called in. He derived the *probability product law of series components*: the system reliability is the product of the reliabilities of individual components that make up the system. In large systems the reliability may be rather low although the individual components have high reliabilities.

In 1950's and 1960's ballistic missile and space programs accelerated needs for very reliable complicated systems. Failure mode and effect analysis (FMEA) was developed in late 1950's. A journal *IEEE – Transactions of Reliability* was started 1963, and the first series on textbooks on reliability appeared during 1960's.

As a part of US Air Force Minuteman II missile program H.A. Watson (1961) at Bell Telephone Laboratories created fault tree technique. Scientists at the Boeing Company led by David F. Haasl (1965) improved the technique to a modern theory, and Robert Schroeder introduced 1966 computer programs like BACSIM and AFDT for both qualitative and quantitative fault tree analysis (Ericson 1999). Fire risk analysis on commercial nuclear installations has been practised since 1950s (Bernero 1984, Silberberg et al. 1986) with landmarks like WASH-740 (1957) and the Rasmussen report (WASH-1400, 1975). A textbook used in 1970's as course material for NRC personnel had an ominous name 'Fault Tree Handbook' (Vesely et al. 1981). By now various versions of quantitative risk analyses have become routine practises on many fields of industries, and several standards on the procedures has been published. Statistical data has been collected and published for the public use on some fields like T-Book (1992, 2000) and OREDA (1992).

Detailed decision trees for fire safety analysis of non-nuclear buildings were constructed (Thompson 1975a, 1975b, 1975c, 1977) but were forgotten slowly despite wide publicity. Although risk analysis had by mid 1970's developed to the stage that quantitative fire risk analyses in general, and unavailabilities of active fire protections systems particularly could have determined, neither one took place. The reason for the first was probably lack of fire models practicable in large spaces. There was nothing which would have prevented developing reliability models for active fire protection systems starting from component reliabilities. Some large private companies and some public institutions made that. Unfortunately, that information is not available on public domain.

1.2 History and utility of sprinkler systems

The first patent for a sprinkler system was granted in England to Ambrose Godfrey early eighteenth century (Anon. 1996a). Without going to the long and crooky early history the real sprinkler age started a century ago in the US. Development of new sprinkler ideas was catalyzed by disastrous fires in Chicago 1871 and Boston 1872 leading to increase of fire insurance costs. Frederick Grinell introduced 1882 a new design of sprinkler head (Nash & Young 1991, Anon. 1996b). The second boosting factor was based on performance studies 1883 leading to creation of the first sprinkler rules in 1885 (UK) and 1886 (US), (Nash & Young 1991, Anon. 1996a). There was also a strong owner interest by some New England forward-thinking cotton mill owners, who banded together to form mutual insurance companies. Factory Mutual System, still a strongest company promoting sprinkler technology, is a direct result of these efforts. Meeting of representatives of US insurance inspection bureaux in 1895 and 1896 lead to founding of National Fire Protection Association in 1896. The major products of this non-profit organization have been NFPA standards (the first sprinkler standard already 1896, now known as NFPA 13), fire codes, and handbooks, which have guided development of the field throughout the world, (Nash & Young 1991).

The sprinkler rules were one of the first early modelling approaches to utilise collected experience and information on fire protection systems now know as *narratives* (Watts, Jr. 1995). A step forward towards more systematic way of modelling is *checklists*, which are used especially applying coded rules to single buildings. A further step by *ranking* is widely used by insurance industry for pricing purposes as well as generally for risk assessment. Ranking is carried out often using point schemes, where an object to be rated is compared against a proven standard case by numerical ranking factors. American insurance rating is widely based on these ranking methods since the publishing of the famous Dean schedule in 1902 and on its later improvements utilising statistical information. In Europe a similar but more systematic approach was made in Switzerland by M. Gretener in 1960. The *Gretener Method* is updated periodically using accumulating fire statistics from Switzerland, where they are public by law (Anon. 1984). The basic idea derives directly from the textbook definition of risk $\boldsymbol{R}$ (Watts, Jr. 1995)

$$\boldsymbol{R} = \boldsymbol{f} \ \boldsymbol{L} = \frac{\boldsymbol{f} \ \boldsymbol{P}}{\boldsymbol{N} \ \boldsymbol{S} \ \boldsymbol{F}} \tag{1}$$

where ***f*** is the frequency of fires, and ***L*** is the loss in a fire. The Gretener Method starts by expressing the loss ***L*** by potential loss ***P*** reduced by fire protection measures: ***N*** standard fire safety measures, ***S*** special measures, and ***F*** fire resistance of structures. The numerical values of these parameters are derived from fire statistics. The effect of sprinklers is included in ***S***. Calculating backwards it is possible to estimate the overall efficiency of sprinklers from recommended values of ***S***. The improvement of fire safety by automatic sprinkler installation is estimated to be a factor of 2 and for deluge systems a factor of 1.7, (Anon. 1984). These numbers are not detailed enough for the purposes of reliability studies attempted here. The Gretener Method has been adapted in modified form in several other environments like the method E.R.I.C. (Cluzel & Sarrat 1979), and applications for Russian museums (Ševčuk & Prisadkov 1997). In E.R.I.C. the improvement by sprinklers was estimated for life safety to 15% and material losses to 60% and 90% for single and double water supplies, respectively.

A major improvement in evaluating effect of sprinkler systems was by Ramachandran (1973, 1979/80, 1982a, 1982b, 1991a, 1991b, 1992) now a classical theory. He studied effectiveness of sprinklers in industrial premises by using extreme value theory on statistical data of fire losses. His recent monograph (Ramachandran 1998) is still one major document quantifying statistical theories and utility of sprinklers in terms of monetary units. Ramachandran uses the old idea of the dependence of fire ignition and losses on the floor area of the building (Johansen 1979), and develops it into quantitative methods to evaluate various influences from the basic statistical distributions of the ignition and loss data. Applying them on available British fire statistics he could evaluate the average monetary value of sprinkler systems, at the reliability level applied during the period covered by statistics, to various branches of industry. Ramachandran did not yet make use of the reliability theory to be able to tailor the suppression systems to meet challenges of individual buildings, which is our goal in this study.

Sprinklers are considered for reason the most effective means of automatic mitigation of fire risk in industrial buildings. Surprisingly, their effectiveness in terms of reliability theory is partially anecdotal in scientific sense *in open literature*, since reliable data on the performance of sprinkler systems are very limited. The existing references are rather old (Anon. 1970, Watanabe 1979, Thomas 1981), of limited utility or component selection for a real sprinkler system design (T-Book 1992, 2000, OREDA 1992) or both (WASH-1400, 1975; McCormick 1981, Green 1982). Obviously there is also quantitative information on their performance, but not much in detail *on public domain*. Only very recently (Hall 1993 a, b) has made a wider analysis on American data collected by NFPA, and Linder (1993) from another database, the results of which will be explained below.

1.3 Reliability of sprinkler systems

The purpose of the present study is to carry out a failure mode and effect analysis (FMEA) of sprinkler systems starting from the component level (*the bottom-up approach*) (Høyland & Rausand 1994). The limited scope is to assess reliability of sprinkler systems in Finnish nuclear power plants by studying relevant collected maintenance reports from their whole lifetime. Since the probability to observe rare events from such material is still rather small, an attempt was made to enlarge the population of components in two other directions: (i) Finnish non-nuclear sprinkler installations, which might be different from nuclear applications, but as a much larger population offer still a relevant surrogate data for nuclear applications, and (ii) two Swedish nuclear power plant units, which for building layout have some similarity with our TVO units. Unfortunately, the additional information analyzed so far form these plants limits to failures of main control valves only.

As raw data relevant technical documents were obtained from NPPs. Number of sprinkler system components was counted from drawings included in documentation. Failure reports were extracted from the maintenance report data banks from all NPPs in electronic form: Lo 1 & 2: February 1, 1981 – August 1, 2000, TVO 1 & 2: September 1, 1981 – May 17, 2000. They were either transformed or read directly on spreadsheets, sorted out in appropriate way, printed out, and inspected individually to classify observed failures. Classification was coded report by report into additional columns of the spreadsheets, and obtained numerical data was reduced using different statistical methods.

Non-nuclear data was obtained from various inspection documents/records of Federation of Finnish Insurance Companies (SVK). The observed inspection statistics covered years 1985–1997. More difficult was to find the population of sprinkler system components. For that purpose a sample of 102 sprinklered buildings was studied as explained in detail in Section 3. Furthermore, installation statistics covering years 1968–2000 were used, and a model was created to estimate the best available values of sprinkler component population.

2. Literature survey on reliability of sprinkler systems

Best references on sprinkler data are already aged as the state-of-the-art report confirms conclusively, (CSNI 2000). For nuclear power plants statistical information is in principle, best available, because these installations are operated under very tight public control. Observations are available on phenomena and variables, which are not available from conventional buildings. However, there is a major drawback by retaining on nuclear facilities: their population is very small as compared to population of other sprinklered installations. Therefore, we have tried to survey both nuclear and non-nuclear data if available to get at least surrogate data for nuclear applications. When comparing a few utilities, like those in Finland, plant specific differences might be considerable as demonstrated by Apostolakis (1986), but for a larger population of buildings great number of differences contribute randomly broader distributions. This data can give order of magnitude hints on the possible size of plant specific features.

A literature study on reliability of sprinkler installations was started by a search in relevant databases. The results are explained below in arbitrary order.

2.1 Number of sprinkler heads operating

One of the simplest quantitative ways of estimating the response of a sprinkler system to a fire is to count the number of sprinkler heads operating in the case of fire. Because there is a fair variation of ambient conditions of sprinklered buildings, the number of operating heads in fire is no fundamental quantity. Despite that it reflects, on an average manner, the temporal development of the dynamic system driven by the developing fire and counteracted by the fire sprinkler system. NFPA (Anon. 1970) collected a large body of statistics on sprinkler operation. A fair fit by inspection (Figure 1) of the observed conditional probability $f(n)$ of exactly n heads operating due to fire was obtained using a relationship

$$f(n) = n^{-a} / \zeta(a); \quad a > 1; \quad n = 1,2,3 \ldots \tag{2}$$

where a is an exponent determined from statistical data, and the normalising factor $\zeta(a)$ is the Riemann zeta-function (Abramowitz & Stegun 1970, Gradshteyn & Ryzhik 1980). The fits were very good for wet pipe systems (Figure 1, uppermost part).

The error bars indicate statistical fluctuations only. They are counted in Figures 1 and 2 and several other figures of this paper from the error formula of Poisson distribution. If in a group within a collection period M observations are made, the standard deviation of random statistical fluctuations becomes $\sqrt{M}$, which is asymptotically valid if $M > 10$, (Beers 1953).

For dry pipe systems probability of releasing more heads remains bigger. Therefore, simple application of Equation (2) did not yield a plausible fit. Somewhat later it was found Baldwin and North (1971, 1973) had treated the problem more thoroughly based on American and British data. Instead of Equation (2) they used a two-parameter function

$$f(n) = n^{-a-b\ln n} / c(a,b); \quad a,b > 0; n = 1,2,3 \ldots \qquad (3)$$

where now there is a second parameter ***b*** to be determined by curve fitting to data. The normalisation factor ***c(a,b)*** is now a function of fitting parameters ***a*** and ***b***, and must be calculated numerically. Values of the fitted exponents are given in Table 1.

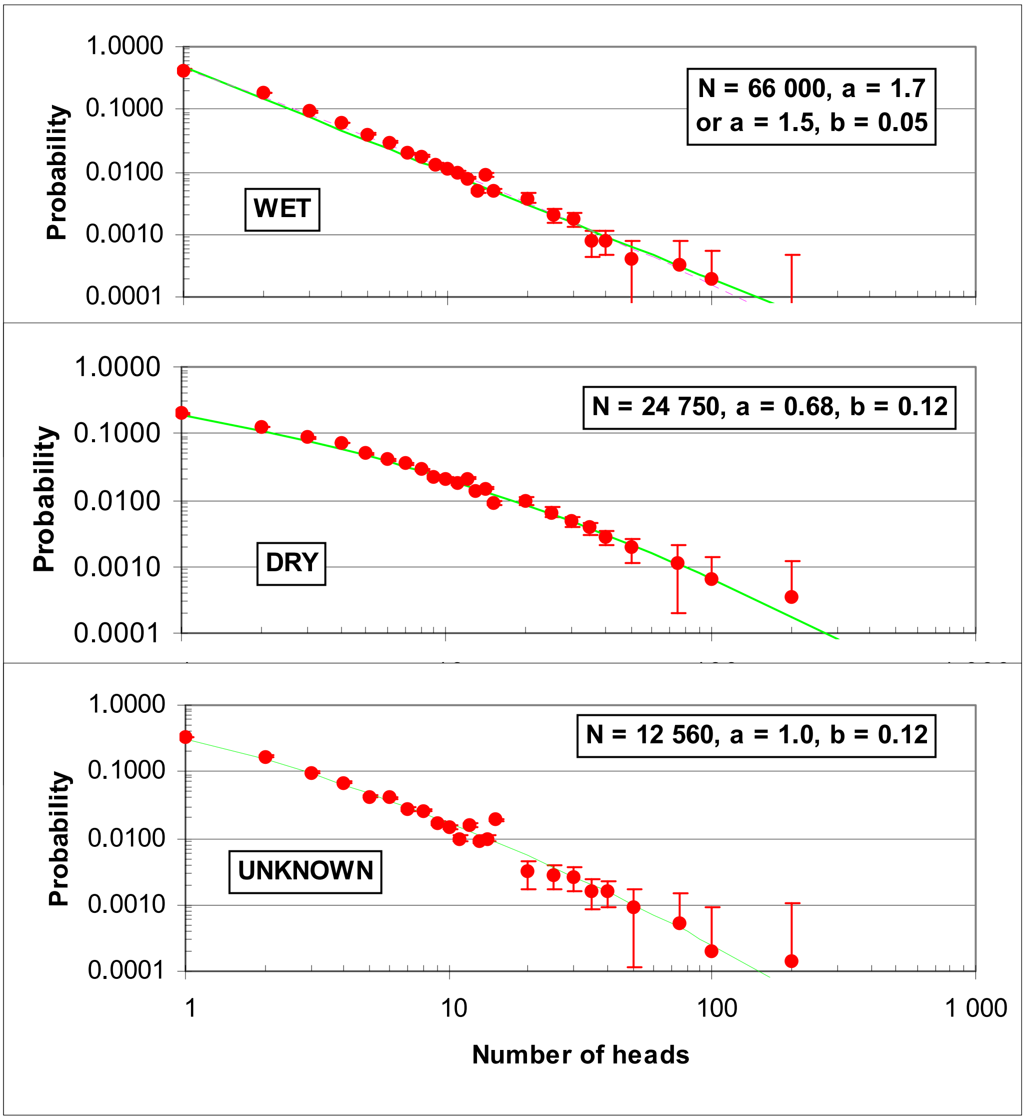

Figure 1. Probability of responding heads of wet, dry, and unknown pipe fire sprinkler systems according to an NFPA study (Anon. 1970).

Baldwin and North (1973) noticed a formal similarity between Equation (3) and formula describing fire losses, which Ramachandran had derived in 1969. They propose a speculative derivation on the model for the number of opening sprinkler heads. They show that presuming an exponential initial fire growth, and a negative exponential distribution time from ignition to control by sprinklers, a distribution of Equation (3) is obtained. They called the model speculative, because they did not have sufficient data to prove the case.

Three other smaller studies on sprinkler head operations are shown in Figure 2. Industrial Risk Insurers' (IRI) data included N = 1470 observations of sprinkler operations under fire condition (Linder 1993). Equation (2) fitted reasonably well within error bars. Collection of FM data (N = 2860) from years 1978–1987 (Solomon 1997) does not fit very well on Equation (2) but excellently on Equation (3). In an inventory of New York City high rise office fires early seventies (Anon. 1976) fair fit for Equation (2) is obtained. The statistical error bars are here big because of small sample size, N = 84. For the same reason, fit on Equation (3) is not feasible. In a recent Japanese study (Yamashita & Shioya 1994) a bigger sample (N = 204) observations were also in accordance of Equation (2). The same was observed in Japan earlier from a smaller sample (Watanabe 1979). Table 1 summarises the parameters from these curve fittings.

Table 1. Fitting parameters to Equations (2) and (3) for the number of sprinkler heads opening.

Population	***N***	***a***	***b***	$\zeta(a)$	***c(a,b)***
NFPA wet	66 000	1.7	NA	2.05	NA
		1.5	0.05	NA	2.19
NFPA dry	24 750	0.68	0.12	NA	5.26
NFPA unknown	12 560	1.0	0.12	NA	3.14
IRI	1 470	1.5	NA	2.57	NA
		1.2	0.12	NA	2.49
FM	2860	1.4	NA	2.99	NA
		0.6	0.25	NA	3.52
New York high rise	84	2.5	NA	1.34	NA
Japan	204	2.6	NA	1.31	NA
	96	1.0	0.01	NA	7.00

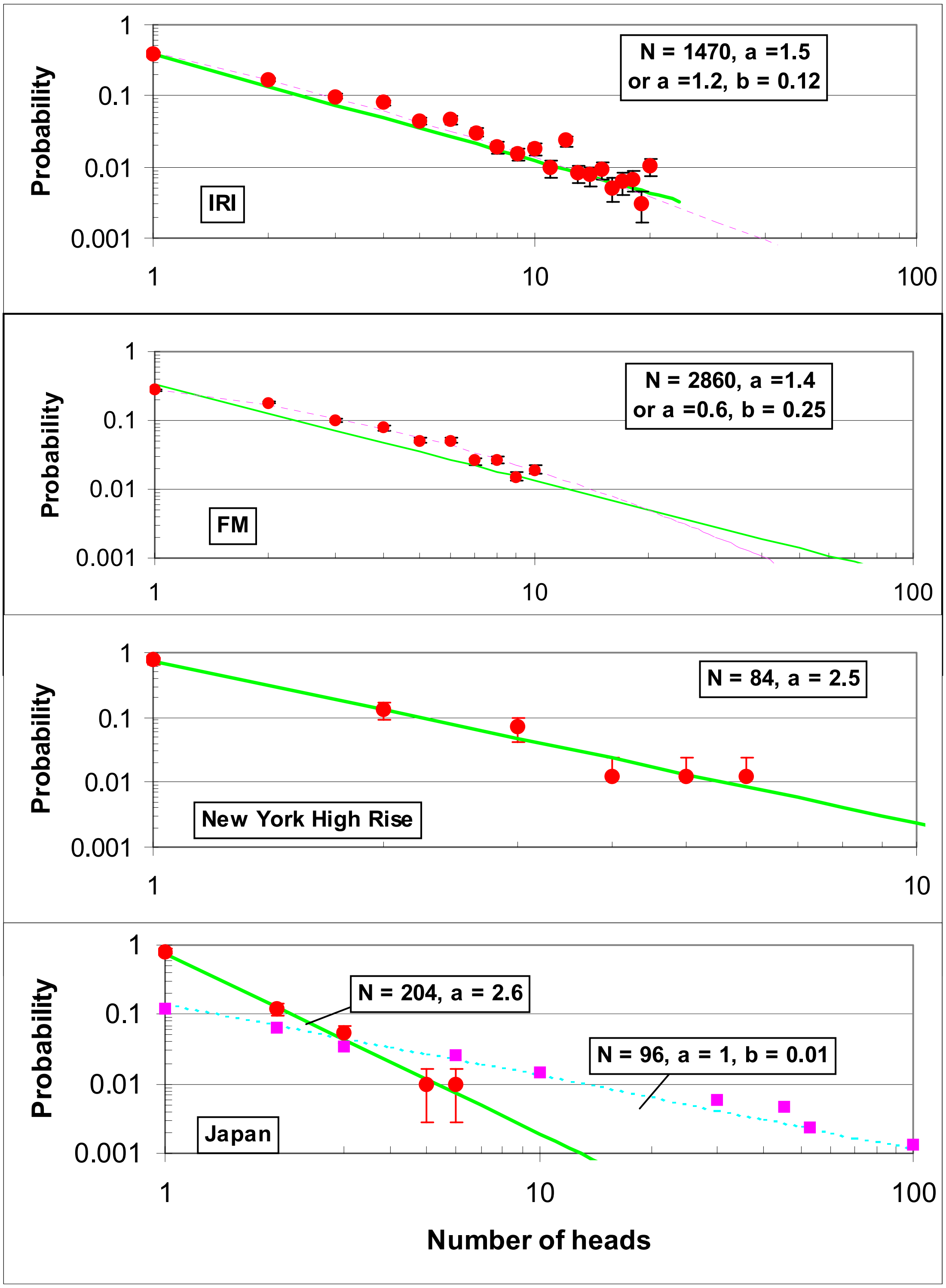

Figure 2. Probability of the number of responding heads of fire sprinkler systems according to IRI (Linder 1993), FM (Solomon 1997), New York high rise offices (Anon. 1976), and Japanese studies (N = 96: Watanabe 1979, N = 204: Yamashita & Shioya 1994).

2.2 Overall reliability

The largest available study on sprinkler performance (Anon. 1970) yields a rough 90% reliability of sprinkler systems. This is in line with a more recent American survey shown in Figure 3, (Linder 1993). Although partially sprinklered buildings form a considerable hazard consistent with data presented in Figure 3, the result is not yet statistically very significant due to a small number of collected fire incidents. Furthermore, from short reports it is rather difficult to understand, how and on what criteria data was collected. The best information of Figure 3 is semiquantitative, that in a few percent of cases only sprinklers failed to control the fire.

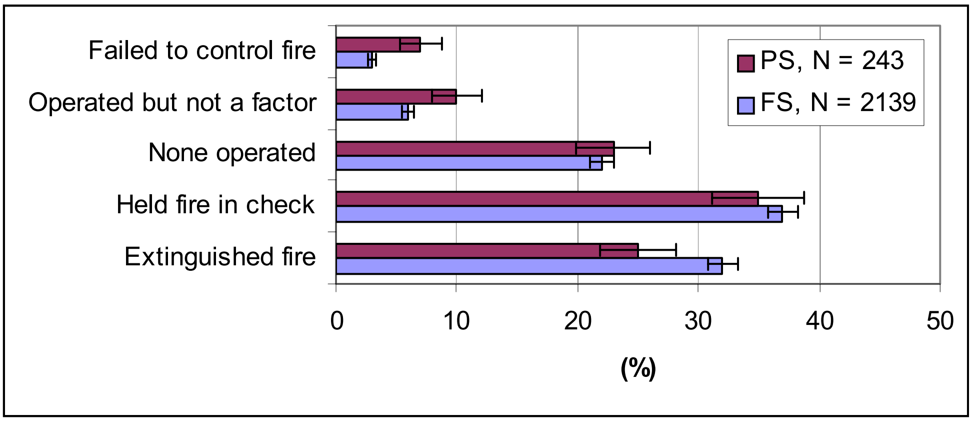

Figure 3. Overall reliability of sprinkler systems in fully (FS) and partially (PS) sprinklered buildings, (Linder 1993).

Table 2. US sprinklered property (S) damage in fires 1982–1991 as compared to damage in non-sprinklered (NS) properties, (Hall 1993a).

Building category	**Number of fires**		**Estimated total loss (million USD)**		**Property loss per fire (1000 USD)**		**Ratio S/NS**
	S	NS	S	NS	S	NS	%
Manufacturing	61 700	70 700	798.7	1 964.4	12.9	27.8	46
Stores & offices	36 800	192 600	385.6	3 474.7	10.5	18.0	58
Public assembly	25 800	130 900	160.7	2 112.0	6.2	16.1	39
Hotels and motels	11 400	37 800	50.6	385.9	4.5	10.2	44

Krasner et al. (1985) present an extended report on data analysis on NPPs, and it is still a very good theoretical guideline for reliability data analysis of active fire protection devices. It contains a good review on mainly non-nuclear data on fire suppression systems. Rate of success of sprinkler operations is generally in 90 ... 95% range, but no detailed data are given.

In Table 2 average sprinkler impact on US property protection is estimated from fire losses of years 1982–1991. Depending of the category of the building the average loss on sprinklered (S) buildings is 39 ... 58% of the non-sprinklered (NS) loss. There are a number of publications on some limited aspects of sprinkler reliability, which are here only listed (Milne 1959, Rutstein & Gilbert 1978, Finucane & Pinkney 1989, Boyd & Lucarto 1986). In Australia a thorough study of sprinkler effectiveness in shopping premises was made (Bennets et al. 1996, 1998, Thomas 1998). A new interest for obtaining reliabilities of active fire protection systems has arisen in the US recently. As a result some available, albeit old data have been collected (Scarf 1993, Fantauzzi 1997, Bukowski et al. 1999). On the reliability of some parts of water supplies one recent study is available (Isaksson et al. 1998).

2.3 Reliability of sprinkler systems and system components

2.3.1 Theoretical models

The systems are presumed to have a constant failure rate λ. Then the number of failures X within a given time interval T is Poisson-distributed random variable. Time between failures is exponentially distributed, and the system does not have memory. Here it means, that the earlier phases of the history of the system do not influence on the occurence of failures after an arbitrary time of start of observations. An estimate for the failure rate is then given by (Green & Bourne 1972, OREDA 1992)

$$\hat{\lambda} = \frac{x}{T} \tag{4}$$

and the 90% confidence interval for $\hat{\lambda}$

$$P\left(\frac{1}{2T} z_{0.05,2N} < \hat{\lambda} < \frac{1}{2T} z_{0.95,2(N+1)}\right) = 0.90 \tag{5}$$

where $\chi^2_{\alpha,\nu}$ denotes the lower 100α percentile in a χ^2 -distribution with ν degrees of freedom (Abramowitz & Stegun 1970). The circumflex on the symbol means an estimated value. If no failures occur in the given time interval the upper 90% confidence estimate for the frequency is given by

$$P(\hat{\lambda} < \frac{1}{2T} z_{0.9,2} \approx \frac{2.302588}{T}) = 0.90 \quad (6)$$

For estimation of constant demand probability p for a particular failure mode, within a period of event data surveillance a total number of N demands are made. If failures are independent, the number of failures X is a stochastic variable with a binomial distribution. Maximum likelihood estimator for p yields (Green & Bourne 1972, OREDA 1992)

$$\hat{p} = \frac{x}{N} \quad (7)$$

where lower p_{min} and upper p_{max} bounds at 90% confidence intervals are given by

$$p_{min} = x / \{x + (N - x + 1) f_{0.95,2(N-x+1),2x}\} \quad 8)$$

$$p_{max} = (x+1) f_{0.95,2(x+1),2(N-x)} / \{N - x + (x+1) f_{0.95,2(x+1),2(N-x)}\} \quad (9)$$

$f_{\alpha,v1,v2}$ is the 100α percentile in a Fisher distribution with $v1$ and $v2$ degrees of freedom (Abramowitz & Stegun 1970). If no failures occur in the given time interval the upper 90% confidence estimate for the probability is given by

$$p_{max} = f_{0.9,2,2N} / \{N + f_{0.9,2,2N}\} \approx \chi_2^2 / \{N + \chi_2^2\} \approx 2.302588 / \{N + 2.302588\} \quad (10)$$

where the approximate numerical estimate is valid, when N is large (>30).

Since the application of Equations (4)–(10) is not always straightforward for those not working professionally with statistics, some examples are given here using guidance given in detailed text on the theme (Green & Bourne 1972).

Example 1. In Table 20 below 3 identical fire pumps were monitored for 18.71 a, and 6 failures of severity 2 were observed. Calculate the point estimate, and its lower and upper bound at 90% confidence level.

Point estimate of failure rate of Poisson distribution follows from substitution on Equation (4)

$$\hat{\lambda} = \frac{X}{T} = \frac{6}{3 * 18.71\, a} = 0.107 / a$$

Lower bound for the failure rate is given by Equation (5)

$$\frac{1}{2T} z_{0.05,2N} = \frac{1}{2 * 3 * 18.71\,a} CHIINV(1-0.05;2*6) = \frac{1 * 5.23}{2 * 3 * 18.71\,a} = 0.0466 / a$$

Correspondingly for the upper bound Equation (5) yields

$$\frac{1}{2T} z_{0.95,2(N+1)} = \frac{1}{2 * 3 * 18.71\,a} CHIINV(1-0.95;2*(6+1)) = \frac{1 * 23.68}{2 * 3 * 18.71\,a} = 0.211 / a$$

where 100α percentile in a χ^2 -distribution with v degrees of freedom is given in the function notation of Microsoft® Excel spreadsheet for easy application of numerical calculations. The finalt result at 90% confidence level is (rounded to two significant figures)

$$0.047 / a \le \hat{\lambda} \le 0.21 / a$$

Example 2. What would be an estimate of failure rate in Example 1, if no failures were observed during the period?

Substituting in Equation (6) gives

$$\hat{\lambda} \le \frac{1}{2T} z_{0.9,2} = \frac{1}{2 * 3 * 18.71\,a} CHIINV(1-0.9;2) = \frac{4.6052}{2 * 3 * 18.71\,a} = 0.041 / a$$

Example 3. In Table 6 testing 1624 times of 58 dry sprinkler systems in German PWR1 nuclear power plant automatic actuation did not function properly 47 times. What is the unavailability per demand of these sprinkler systems?

Maximum likelihood estimate from binomial distribution of these systems is according to Equation (7)

$$\hat{p} = \frac{x}{N} = \frac{47}{1624} = 0.029$$

The lower bould results from substitution into Equation (8)

$$p_{min} = \frac{x}{x + (N - x + 1) f_{0.95,2(N-x+1),2x}} =$$

$$\frac{47}{47 + (1624 - 47 + 1)\, FINV(1 - 0.95;2*47+1);2*(1624-47))}$$

$$\frac{47}{47 + (1624 - 47 + 1) * 1.298} = 0.022$$

where 100α percentile in a F-distribution with ***v***1 and ***v***2 degrees of freedom is given in the function notation of Microsoft® Excel spreadsheet for easy application of numerical calculations. Correspondingly the upper bound results from substituition into Equation (9)

$$p_{max} = \frac{(x+1) f_{0.95,2(x+1),2(N-x)}}{N - x + (x+1) f_{0.95,2(x+1),2(N-x)}}$$

$$\frac{(47+1)\, FINV(1-0.95;2*(47+1);2*(1624-47))}{1624-47+(47+1)\, FINV(1-0.95;2(47+1);2(1624-47))} =$$

$$\frac{(47+1)*1.254}{1624-47+(47+1)*1.254} = 0.037$$

The outcome of this testing is finally for the unavailability per demand

$$0.022 \le \hat{p} \le 0.037$$

Example 4. In Table 5 testing 616 times 6 fire pumps in German PWR1 nuclear power plant resulted always in satisfactory operation. What is the upper limit for unavailability per demand of these pumps?

Direct application of Equation (10) estimates the unavailability per demand

$$p_{max} \le \frac{f_{0.9,2,2N}}{N + f_{0.9,2,2N}} = \frac{FINV(1-0.95;2;2*616)}{616 + FINV(1-0.95;2;2*616)} = 0.0049$$

2.3.2 Statistical literature data

Moelling et al. (1980) collected sprinkler failure data from four NPPs, and made models and sensitivity analyses. Their estimates are reproduced in Table 3. They noticed that inadvertently closed valves (ICV) is the most important reason for system failure. This dependence is largely due to the importance of the valves forming a single train from the yard loop fire water piping to the spray distribution piping. They recommend that inspecting the important single train valves more often than once a month, current American practise by then, would reduce system failure probability substantially.

Table 3. Reliability of sprinkler systems (Moelling et al. 1980).

Failure mode	**Probability per demand**		
	Lower bound[a]	Point estimate	Upper bound[a]
Sprinkler heads fail to open		<1E-6	
Fire detectors fail to function	1.89E-3	2.97E-3	4.45E-3
Deluge valves fail to open	8.9E-4	1.90E-3	3.58E-3
Fire pumps fail to start	4.47E-3	1.40E-2	2.39E-2
Check valves fail to open	3E-5	1E-4	3E-4
Alarms fail to function	2.681E-2	3.62E-2	4.81E-2
Personnel fail to trip manual release		0.2	
Valves closed inadvertently[b]	5.47E-3	5.475E-2	0.5475

[a] Confidence estimates, 90% limits
[b] Frequency [1/a]; not data but desired range for operation.

Observed values from two German nuclear power plants are available from years 1988–1994 (Berg et al. 1997, Röwekamp et al. 1997, FKS 1997, Röwekamp & Berg 2000). The first power plant has two units of BWR available the whole 7 year periods, and the second plant has two units of PWR available for 7 and 4 (1991–1994) reactor years, respectively. Thus totally 21 reactor years of operating experience were available for the study. Data on the failures are given in Table 4, plant specific failure rates in Table 5, plant specific unavailabilities in Table 6, and finally comparison of unavailabilities with data from other sources in Table 7.

Table 4. Observed failures in sprinkler system study of German NPPs.

System	Population	Device time	Function tests	Failures	
		[a]		crit.	non-crit.
German BWR					
Dry sprinkler	111	778	1554	28	29
- total failure				1	
- automatic actuation only				27	
Wet sprinkler	119	834	1666		35
Gas extinguisher (CO_2)	4	28	56		4
Fire pumps	4	28	364		5
Wall hydrants	195	1366	2730		83
German PWR					
Dry sprinkler	58	406	1624	47	14
- total failure					
- automatic actuation only				47	
Fire pumps	6	42	616		3
Wall hydrants	146	1023	1022	7	

Table 5. Some plant specific failure rates of critical failures [1/a] of extinguishing systems of German NPPs.

System	**BWR**	**PWR1**	**PWR2**
Dry sprinkler			
-total failure	2.0E-3	1.3E-3	1.4E-3
-automatic actuation only	3.6E-2	1.1E-1	5.1E-3
Wet sprinkler	6.3E-4		
Gas extinguisher (CO_2)	1.8E-2		
Fire pumps	1.8E-2	1.2E-2	3.3E-6
Wall hydrants	3.9E-4	7.5E-3	9.6E-4

Table 6. Some plant specific unavailabilities per demand of extinguishing systems of German NPPs.

System	**BWR**	**PWR1**	**PWR2**
Dry sprinkler			
-total failure	9.9E-4	3.2E-4	6.5E-4
-automatic actuation only	1.8E-2	2.9E-2	2.5E-3
Wet sprinkler	3.2E-4		
Gas extinguisher (CO_2)	9.2E-3		
Fire pumps	1.4E-3	8.5E-4	1.6E-5
Wall hydrants	1.9E-4	7.4E-3	9.5E-4

The content of Table 7 is also presented graphically in Figure 4 with some error bars using hardware classes by Mancini (as referenced in Kumamoto & Henley 1996). Error bars are determined from a logarithmically normal distribution at 5 ... 95% reliability interval (Berg et al. 1997, Röwekamp & Berg 2000). It is noted that sprinkler systems belong to Class 1 (major mechanical systems) or Class 2 (electro-mechanical systems). Class 3 is formed from mechanical components (pumps, valves, etc.) and Class 4 from electrical components (relays, breakers, switches, etc.). Also German fire pumps and wall hydrants in Figure 4 seem to fall roughly within their proper classification in Class 3.

Table 7. Comparison of unavailabilities per demand of extinguishing systems (Röwekamp et al. 1997).

Study	**Dry sprinkler (total failure)**	**Dry sprinkler (automatic actuation only)**	**Wet sprinkler**
German BWR	9.9E-4	1.8E-2	3.2E-4
German PWR1	3.2E-4	2.9E-2	
GAL 80[a]	6.3E-3		
NOR 83[b]	4.9E-2		
GRS 85[c]	7.0E-2		
BOH 90[d]	4.0E-2		
German non-n.[e]	6.5E-2		

[a] Galucci (1980) as referenced by Röwekamp et al. 1997.
[b] Millstone 3 PRA (1983) as referenced by Röwekamp et al. 1997.
[c] GRS (1985) as referenced by Röwekamp et al. 1997.
[d] Bohn & Lambright for NUREG-1150 (1990) as referenced by Röwekamp et al. 1997.
[e] Non-nuclear German data by GRS (1985) as referenced by Röwekamp et al. 1997.

In Figure 5 a fault tree of sprinkler system is presented based on a study of maintenance records of 97 Japanese installations including 121 991 sprinkler heads and 707 piping systems (Watanabe 1979). Watanabe uses for the system three different probability concepts

- reliability: probability of performing the specified function under specified conditions for a specified time without failure,

- capability: probability of achieving the operational demand under specified conditions satisfactorily, and

- availability: probability of operating satisfactorily at any given time under specified conditions.

The effectiveness of the system is the product of these three factors. The total sprinkler system reliability was 0.989, capability (design adequacy) 0.999, and availability 0.993 leading to total effectiveness of 0.98. In Figure 5 the source of these different factors is given in detail.

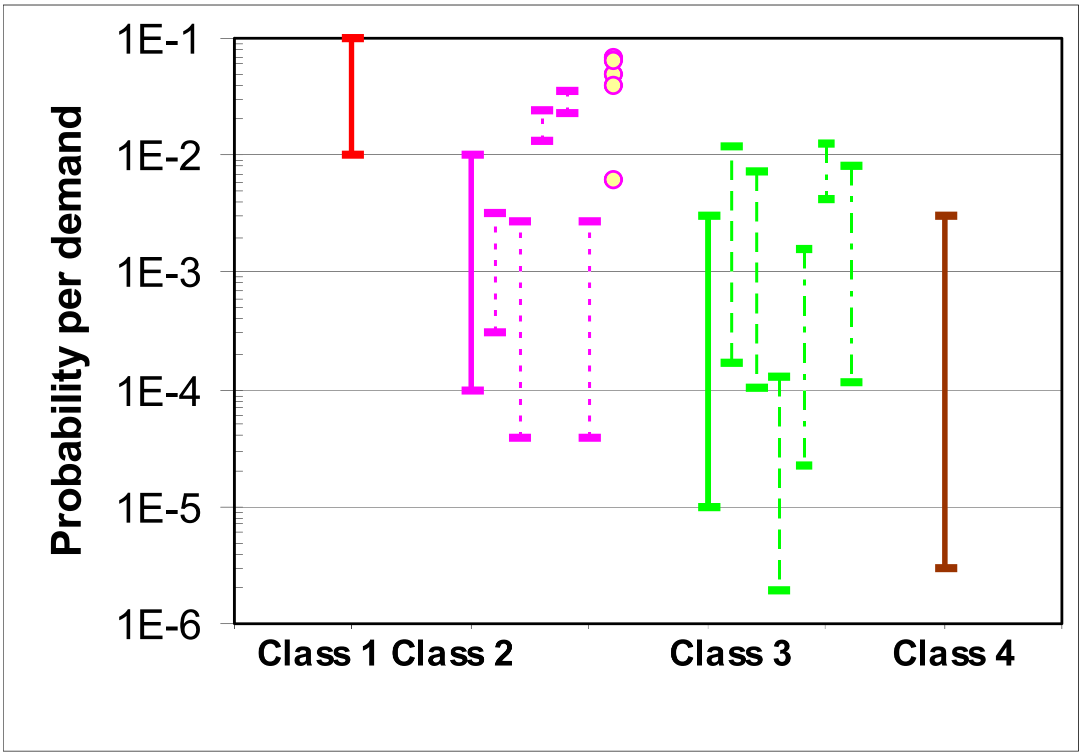

Figure 4. Unavailability classes 1 to 4 of hardware (thick full lines), sprinkler systems data from German NPPs (dotted lines), other sprinklers systems (dots) presented in Table 7, as well as fire pumps (dashed lines) and wall hydrants (dash-dotted lines) in Table 6.

Contribution to total inefficiency is given in Figure 5 in %. The first number in parentheses is the failure rate per million hours, and the second number is coined to criticality (Høyland & Rausand 1994), but he does not explain detail, how it is calculated. There is no description on the type of buildings used in this study, but a vague hint on high rise, where again pump motor is the most important single component. Therefore, the utility of these figures is limited, but the model used is general in principle.

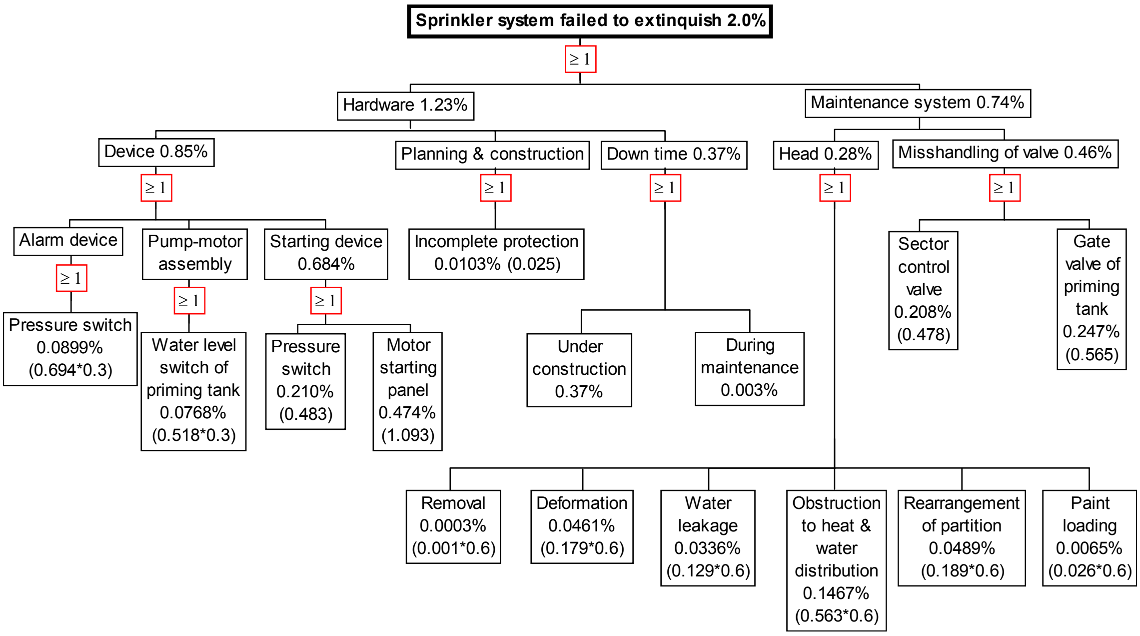

Figure 5. Contribution of different parts of the system to the total reliability of Japanese sprinkler installations (Watanabe 1979). Figures outside parentheses denote probability of unsuccess in %. Multiplicand and multiplier in parentheses: the failure rate [1/1E6 h] of well-maintained systems, and criticality, respectively.

2.4 Other data

Hotta (1995) presents an example of a new commercial Japanese sprinkler system, used in a large complex of Yebisu Garden Place in Tokyo consisting almost 50 hectars of floor area in eleven different buildings up to 40 floors high. Therefore the system is engineered to higher performance than conventional systems (Figure 6), and can be used as a subsystem of fire protection in demanding applications. In the block diagram NS valve unit controls the pressure to achieve an optimum drop size. In addition it contains remote sensing possibilities of the valves, pumps and control electronics to ensure higher reliability, facilitate maintenance, condition monitoring and testing, as well to tailor operation conditions during duty.

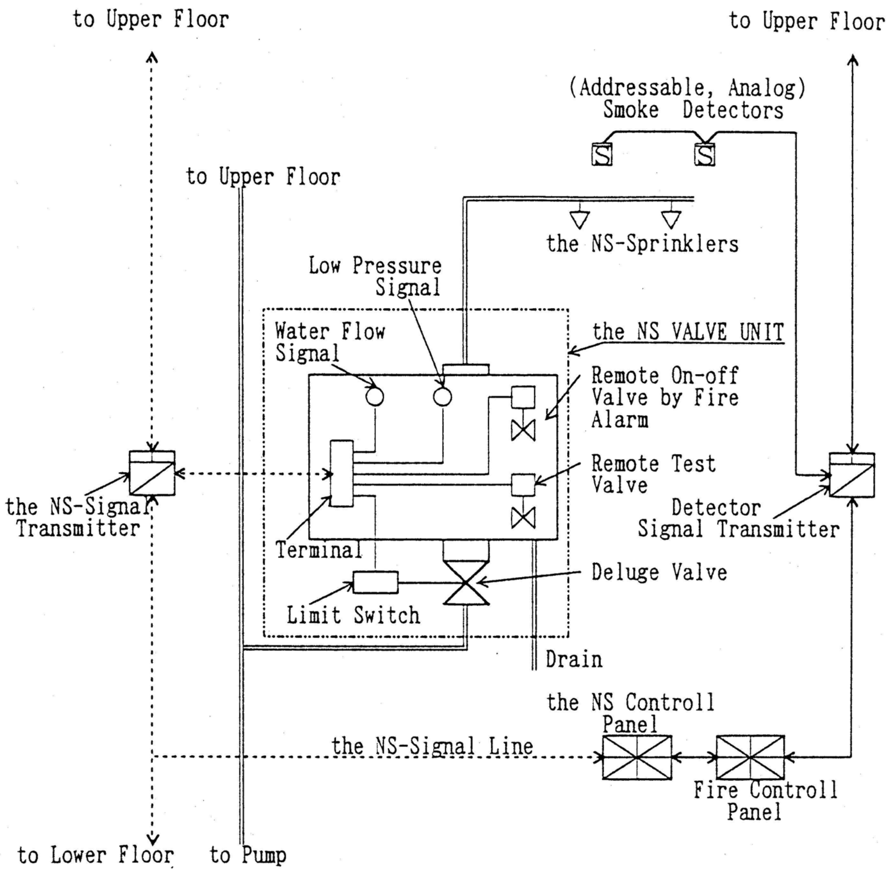

Figure 6. Piping and instrument diagram of an engineered Japanese NS sprinkler system (Hotta 1995).

According to a short series of tests the new system performed better due to more efficient use of water than the conventional sprinklers although the number of heads, pressure and water flow was smaller. No data was available on reliability, but Figure 6 shows, which components were estimated worthwhile to monitor continuously.

The leading reasons of unsatisfactory sprinkler operations are listed in Tables 8 and 9. In Table 8 quantitative information is given (Hall 1993a) on problem groups based on published NFPA data of 3134 fires during 1925–1969 (Anon. 1970).

McKinnon and Tower (1976) report lists reasons for unsatisfactory sprinkler system performance based on American data that Hodnett (1985) repeats in his book. The older series is the NFPA data referred to above, but no details were given for the period 1970–1974. Results are shown in Table 9 for two periods of time, and combining information from Hall (1993a). About a third of failures results from shut off, a quarter from partial protection, and 4% from inadequate maintenance. Partial protection and faulty building construction have increased by a factor of 3 and 2, respectively during 1970 - 74 as compared to the earlier period. All other factors have decreased.

Table 8. Reasons for unsatisfactory sprinkler performance by problem groups (in %) (Hall 1993a).

Problem group		**Percentage of cases**
A	Failure to maintain operational status of system	53.4
B	Failure to ensure adequacy of system for complete coverage of current hazard	21.6
C	Defects affecting but not involving sprinkler system	15.9
D	Inadequate performance by sprinkler system itself	5.6
E	Other	3.6

Table 9. Reasons for unsatisfactory sprinkler system performance (in %), (McKinnon & Tower 1976, Hall 1993a).

	Problem	**1925–1969**	**1970–1974**
A1	Water shut off	35.4	29.8
A2	Inadequate maintenance	8.4	4.0
A3	Obstruction to water distribution	8.2	5.6
A4	System frozen	1.4	?
B1	System not adequate for level of hazard in occupancy	13.5	7.1
B2	System designed for partial protection only	8.1	26.1
C1	Inadequate water supply	9.9	7.1
C2	Faulty building construction	6.0	13.0
D1	Antiquated system	2.1	7.3
D2	Slow operation of sprinklers	1.8	
D3	Defective drypipe valve	1.7	
E1	Exposure fire	1.7	
E2	Other or unknown	1.9	

Effects of spurious suppression events in NPPs were studied by Lambright et al. (1989) applying an event database for 1980–1987. Totally 71 spurious suppression events were observed, on the average 0.14/a for BWRs and 0.13/a for PWRs, respectively. Three leading causes for spurious events were maintenance/testing, unknown cause and personnel. In most cases these events affected safety-related systems, but others led to unavailability of parts of suppression systems. The contribution of spurious suppressions was considerable to estimated loss of offsite power (LOSP) and station transient incidents.

Nash and Young (1991) present some data of sprinkler system and component reliabilities, the majority of which is already presented above. There is data of 535 UK sprinkler failures or operation under non-fire conditions from years 1965–1975. However, data is so shortly described, that compilation of any real probabilities or frequencies is impossible. They also quote data on sprinkler head testings in time interval 1960–1970, where new as well as old and doubtful heads were tested for water release and pressure. Probability of 0.010 was observed for complete blockage, 0.024 for partial blockage, and 0.030 for leak in pressure test. Comparing these two sets of data reveals, that during installation and maintenance procedures there must happen a strong selection of faulty components. Otherwise, there would be orders of magnitude differences upwards in the number of non-fire operations.

3. Physical size of sprinkler installations

A key question for calculating failure rates is to know the size of the component population as a function of time during the years inspected. Since it was not known prior to our study laborious efforts were needed to estimate it. From nuclear installations real drawings and component lists were obtained. These were used to count the number of different components, and length of pipelines used. Additionally, floor areas of rooms were recorded to estimate component densities. This is needed to bind sprinkler installation reliability to fire frequencies, which are known per floor area (Rahikainen & Keski-Rahkonen 1998, Tillander & Keski-Rahkonen 2001, 2002). Sprinklering of Finnish NPPs has not changed markedly since construction, thus the population has remained constant.

For non-nuclear buildings a two step approach was used. First, sprinkler component data were counted from drawings of 102 buildings. From that sample a set of needed probability distributions were plotted. Second, the total populations of sprinkler systems and components were compiled based on available direct data and these distributions as described in more detail below.

3.1 Categories of sprinklered buildings

The sample of 102 buildings was chosen in non-random way from the buildings for which drawings were available. It represents some 5% of the number of sprinklered buildings in Finland. From earlier similar experience we knew, access to such material is very difficult if the objects were chosen randomly as would be the procedure in a well designed statistical experiment. Taking the risk our sample is biased, Figure 7 shows, how representative it was for the stock of buildings in Finland using data of census in 1990 (Statistics Finland 1990). On left percentage of the number of buildings, and on right percentage of the floor area in the sample, in Finnish building stock (BS) and building stock, from which residential buildings has been subtracted (BS-Res). No ready statistical data were available for the stock of sprinklered buildings. The central column in Figures 7 is the whole building stock, and the left columns of sample deviates significantly from them. Practically no residential buildings are sprinklered in Finland, which account for the great majority of the whole building stock. Subtracting residential buildings as is done in right columns, we see that both number and floor area are of the same magnitude in all building categories when comparing these two sets of data. Therefore, it can be concluded, that our sample a representative albeit not necessarily an unbiased selection of the stock of sprinklered buildings.

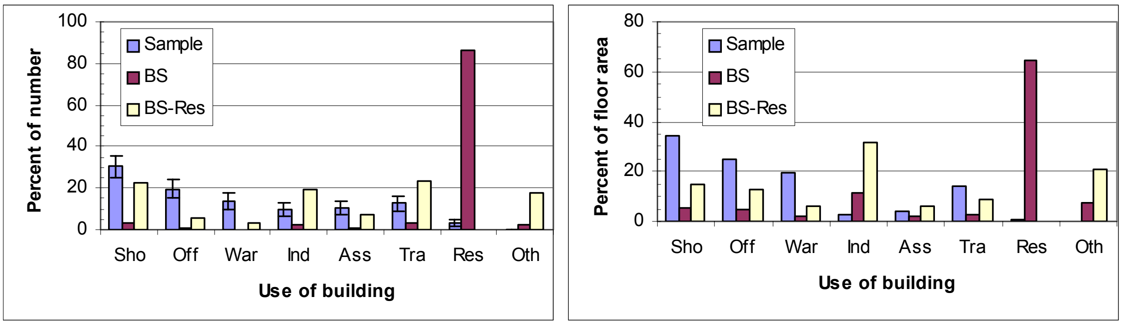

Figure 7. Comparison of use of building in the counted sample with building stock of Finland. On left percentage of the number of buildings, and on right percentage of the floor area in the sample, in Finnish building stock (BS) and building stock, from which residential buildings has been subtracted (BS-Res). Building categories: Sho: shop, accommodation, restaurant buildings, Off: offices, War: warehouses, Ind: industrial, Ass: assembly buildings, Tra: Transport service buildings, Res: residential, Oth: other building.

3.2 Results from a sample of non-nuclear buildings

Drawings on totally 102 sprinklered buildings were obtained from a consulting and engineering company, three sprinkler installation firms, and from the archives of SVK. This selection was non-random as explained above, but it was one of the easiest ways to get hold on such material.

3.2.1 Protected floor area in sprinklered buildings

Cumulative distribution of protected floor area in 102 non-nuclear buildings is plotted in Figure 8. Curve fitting by inspection using a cumulative Weibull distribution (McCormick 1981)

$$F(x - x_0) = 1 - exp\left\{-\left[(x - x_0)/\beta\right]^{\alpha}\right\} \quad \alpha > 0, \beta > 0, \quad 0 \le x_0 \le x \le \infty \qquad (11)$$

where x is the floor area [m^2], yields a good fit with parameters: x_0 = 194 m^2, α = 0.8, and β = 8 000 m^2. This distribution is used for compilation of various reliability-related variables later. For cumulative estimates median ranks were used throughout (McCormick 1981).The floor areas are protected floor areas in the building and are often only a part of the total building.

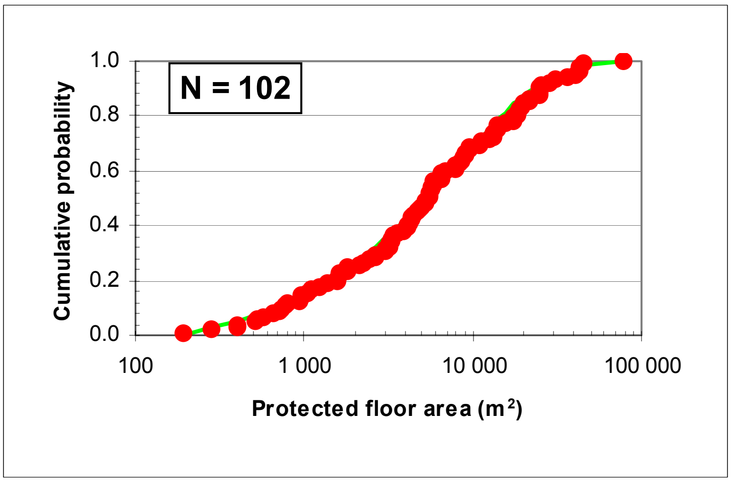

Figure 8. Cumulative distribution of the floor area in sprinklered buildings (dots), and a three-parameter Weibull distribution fit (line) on the data.

Figure 9 sheds light to temporal behaviour on the sizes of sprinklered installations. There has been some changes, but on various directions. Buildings started during the economical recession (1996–1998) were somewhat smaller than on the other times. The latest buildings (1999–2000) are markedly larger than before.

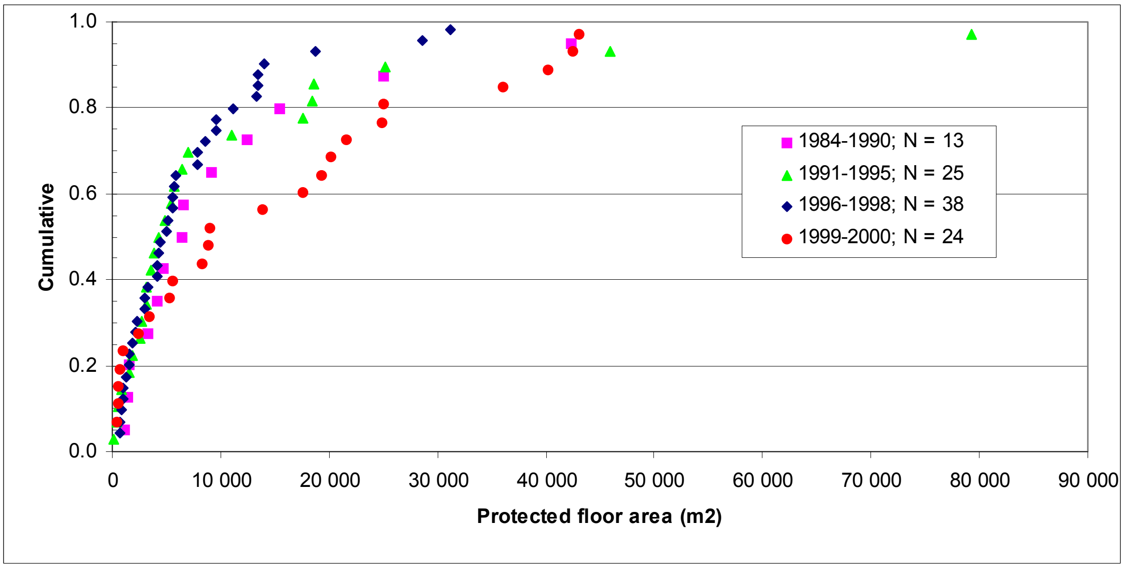

Figure 9. Dependence of cumulative protected floor area on the building year.

The other way of looking things is to divide between new installations and changes or extensions as plotted in Figure 10. The latter group is clearly smaller than the former. Rough curve fittings using three parameter Weibull distributions yield parameters: (New) x_0 = 194 m^2, α = 0.9, and β = 13 000 m^2, and (Changes + Extensions) x_0 = 285 m^2, α = 0.9, and β = 36 000 m^2.

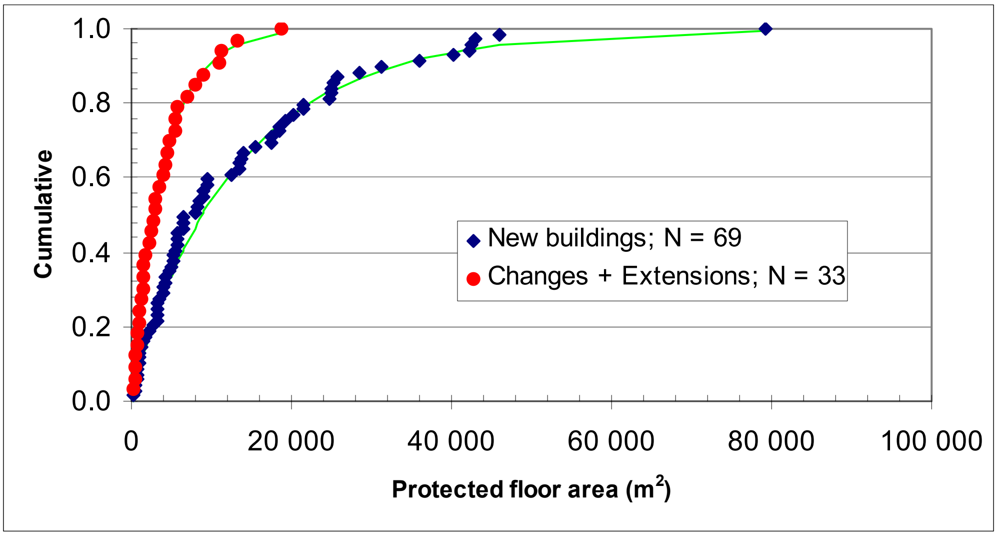

Figure 10. Cumulative probability function of protected floor area: new buildings (diamonds), changes and extensions (dots).

3.2.2 Sprinkler head density

Figure 11 presents numbers of sprinkler heads per counted buildings divided to sprinkler classes (CEA 1998) high hazard HH (squares) and ordinary hazard OH (dots). In light class the number of observations was so small, it is not shown in Figure 11. A rough Weibull distribution fit according to Equation (11), where $\boldsymbol{X}$ is now the number of sprinkler heads, was made resulting to parameters: HH: $\boldsymbol{x_0}$ = 80, $\boldsymbol{\alpha}$ = 0.7, and $\boldsymbol{\beta}$ = 6500; OH: $\boldsymbol{x_0}$ = 6, $\boldsymbol{\alpha}$ = 0.7, and $\boldsymbol{\beta}$ = 400.

Cumulative distribution of sprinkler head density in 102 non-nuclear buildings is plotted in Figure 12 by dots. Curve fitting using a cumulative Weibull distribution of Equation (11), where now $\boldsymbol{X}$ is the nozzle density [1/m^2], yields a good fit with parameters: $\boldsymbol{x_0}$ = 0.0775/m^2, $\boldsymbol{\alpha}$ = 1.7, and $\boldsymbol{\beta}$ = 0.05/m^2. Plotting the density by the separate floors (N = 545, squares) gives a wider distribution of sprinkler head density as shown more clearly on Figure 12b. Since the sampling was not random, the difference between these two results cannot be quantified fully. It only indicates, that local variations in the same building of sprinkler head densities might be considerable. If the densities were counted by rooms, even a wider distribution would have resulted. This would be the most rational way of looking for the head density, because room walls are the first fire barrier. The variation probably reflects also local needs/limitations caused by functions and barriers of the compartment, and in-field responses on them during planning and installation of the system.

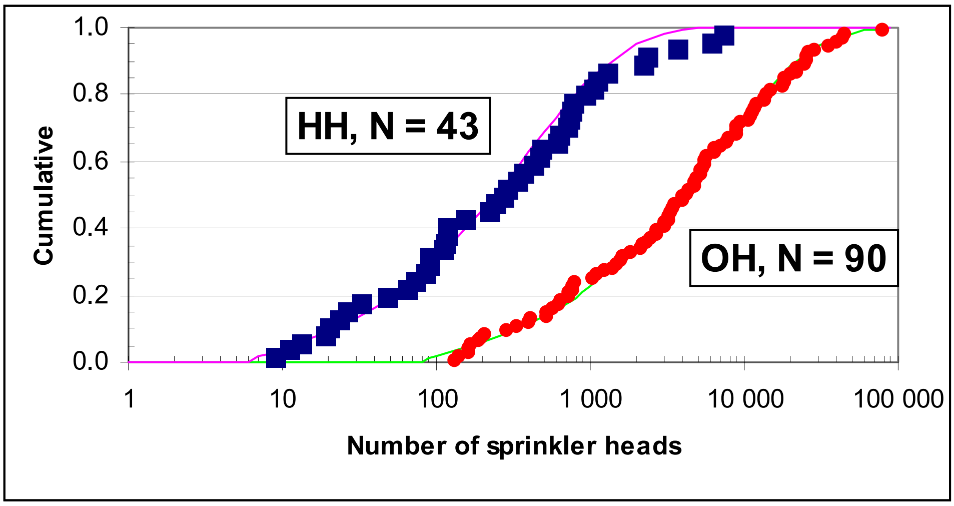

Figure 11. Distribution of sprinkler heads by counted buildings and sprinkler classes (high hazard HH, squares, and ordinary hazard OH, dots) with fitted Weibull distributions (solid lines).

Figure 13 shows dependence of the number of sprinkler heads on the protected floor area ((a) on linear, and (b) on logarithmic scale) for different sprinkler classes (CEA 1998): light hazard LH (N = 4), diamonds, ordinary hazard OH (N = 91), dots, and high hazard HH (N = 43), squares. The hazard class has no effect on the number of sprinkler heads, within statistical accuracy. Number of sprinkler heads depends linearly on the floor area as shown on Figure 13a except in the smallest protected areas below some hundreds of square meters (Figure 13b). Number of sprinklers $\boldsymbol{n}$ depends on the protected floor area $\boldsymbol{A}$ on both lines shown on Figure 13a

$$\boldsymbol{n} = \boldsymbol{A} / \boldsymbol{A_0} \tag{12}$$

where rough estimation by inspection yields: $\boldsymbol{A_0}$ = 9 m^2 for the lower, and 6.25 m^2 for the upper curve, which here can be taken as upper and lower estimation of the average dependence on floor area. These curves show, that the density of sprinkler heads is on the average greater than required by sprinkler rules, where maximum areas $\boldsymbol{A_0}$ are for: LH 21 m^2, OH 12 m^2, and HH 9.0 m^2, (CEA 1998). Therefore, the lower curve corresponds to high hazard class (HH). Only a few points of ordinary hazard (OH) are below it.

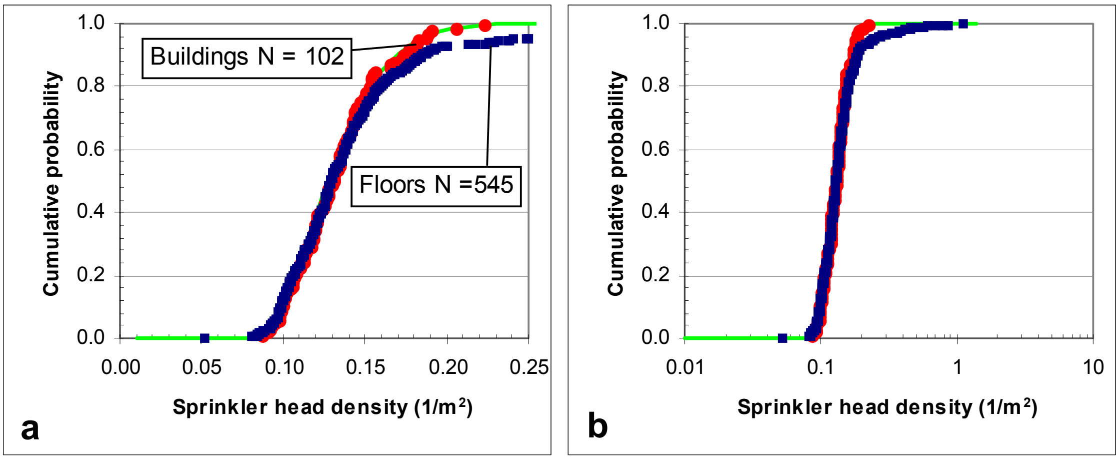

Figure 12. (a) Cumulative probability function of sprinkler head density (dots) in non-nuclear buildings, and by different floors (squares) with a Weibull fit (thick solid line). (b)The same plot using a logarithmic density scale.

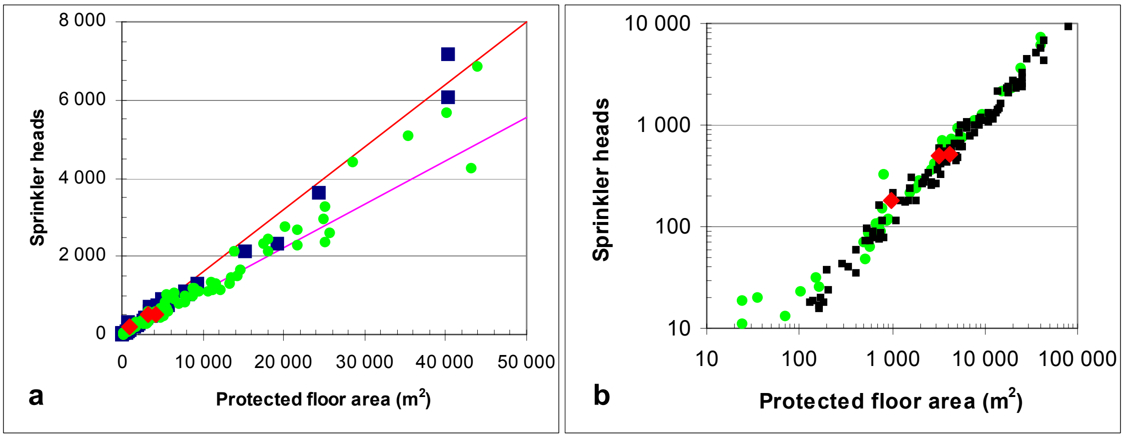

Figure 13. Dependence of the number of sprinkler heads on the protected floor area ((a) on linear, and (b) on logarithmic scale) for different sprinkler classes: LH, diamonds, OH, dots, HH, squares.

3.2.3 Main distribution and range pipe length

Cumulative distribution of main distribution pipe length (dots), and range pipe length (diamonds) in sampled buildings with Weibull distribution fits (solid lines) are shown in Figure 14. Curve fitting using a cumulative Weibull distribution of Equation (11), where now $\boldsymbol{X}$ is the pipe length [m], yields a good fit with parameters: main distribution pipe: $\boldsymbol{x_0}$ = 10 m, $\boldsymbol{\alpha}$ = 0.8, and $\boldsymbol{\beta}$ = 1200 m; range pipe: $\boldsymbol{x_0}$ = 80 m, $\boldsymbol{\alpha}$ = 0.8, and $\boldsymbol{\beta}$ = 4000 m. In Figure 15 is shown dependence of length of pipe per floor area [m/m^2] on the length per sprinkler head [m] of main distribution pipes (dots) and range pipes (squares) with a linear fit (solid line). The same solid line fits to both sets of observations, as it should, because it also implies area per sprinkler heads. A good value for the fit here is 8 m^2 per head. This is in accordance with the results obtained from Figure 13a and Equation (12).

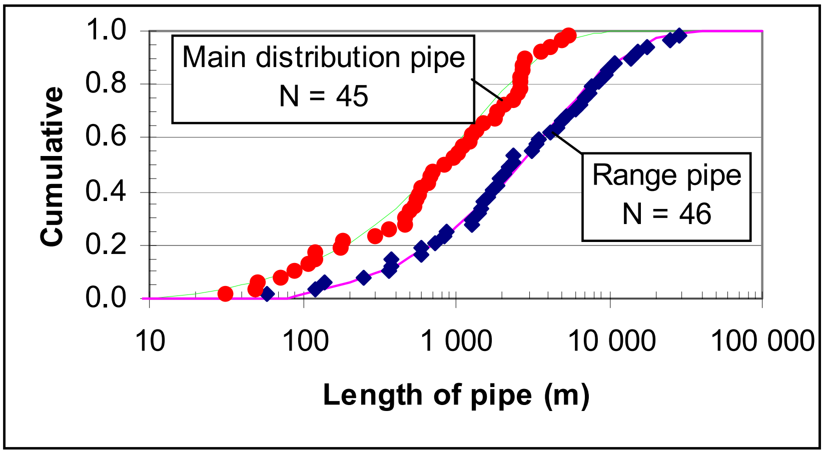

Figure 14. Cumulative distribution of main distribution pipe length (dots), and range pipe length (diamonds) in sampled buildings with Weibull distribution fits (solid lines).

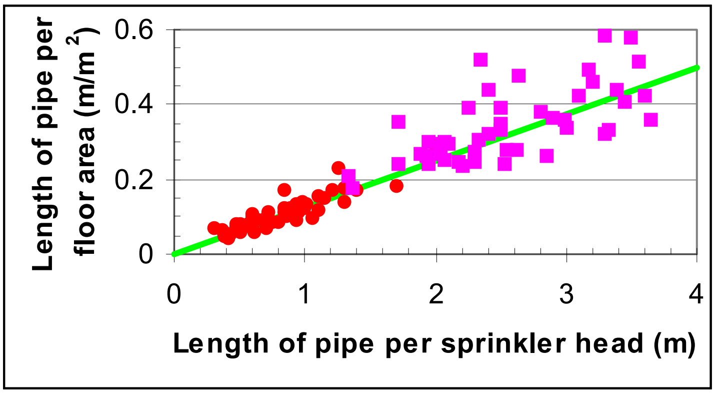

Figure 15. Dependence of length of pipe per floor area [m/m²] on the length per sprinkler head [m] of main distribution pipes (dots) and range pipes (squares) with a linear fit (solid line).

In Figure 16 are plotted cumulative distribution of pipe length per floor area [m/m²]: observations of main distribution pipe (squares) and range pipes (dots). Rough Weibull fit (full lines), where now $\boldsymbol{X}$ is the pipe length per floor area [m/m²], yields a good fit with parameters: main distribution pipe: x_0 = 0.02 m/m², α = 2, and β = 0.1 m/m²; range pipe: x_0 = 0.16 m/m², α = 2, and β = 0.2 m/m². In figure 17 dependence of range pipe length per floor area on the main distribution pipe length per floor area is plotted. The values scatter around an average, but there is no systematic dependence indicated. Similarly in Figure 18 dependence on range pipe length per floor area (a) and main distribution pipe length per floor area (b) on protected floor area. Again no systematic dependence on floor area is observed.

Figure 19 contains the same material as Figure 15, but viewed from a different perspective. Here it is shown, how the observed points scatter around the average point.

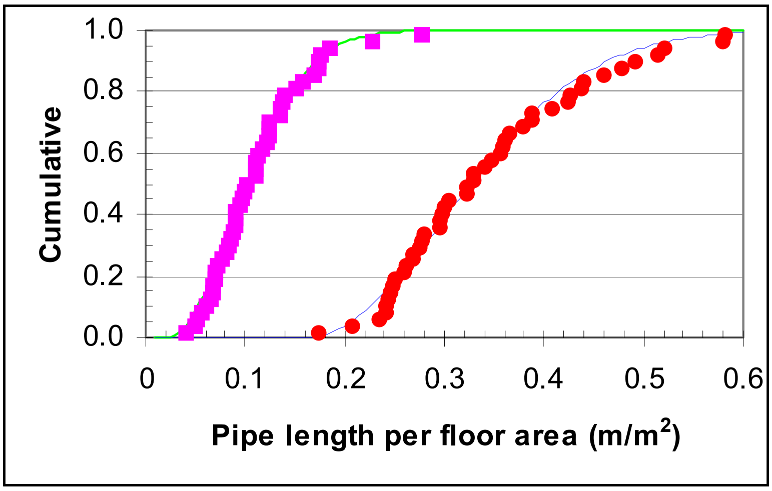

Figure 16. Cumulative distribution of pipe length per floor area [m/m²]: observations of main distribution pipe (squares), range pipes (dots), and Weibull fit (full lines).

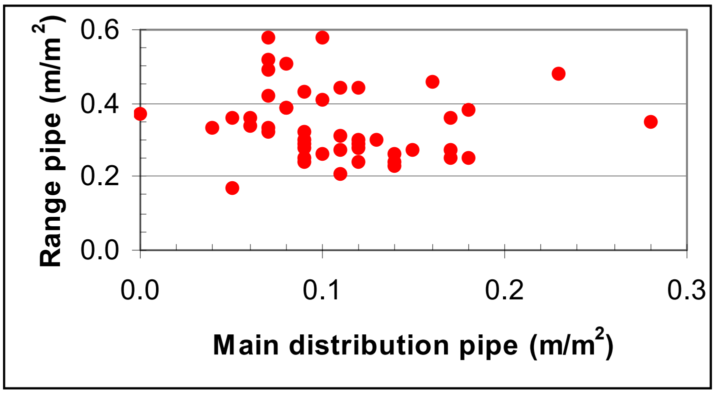

Figure 17. Dependence of range pipe length per floor area on the main distribution pipe length per floor area.

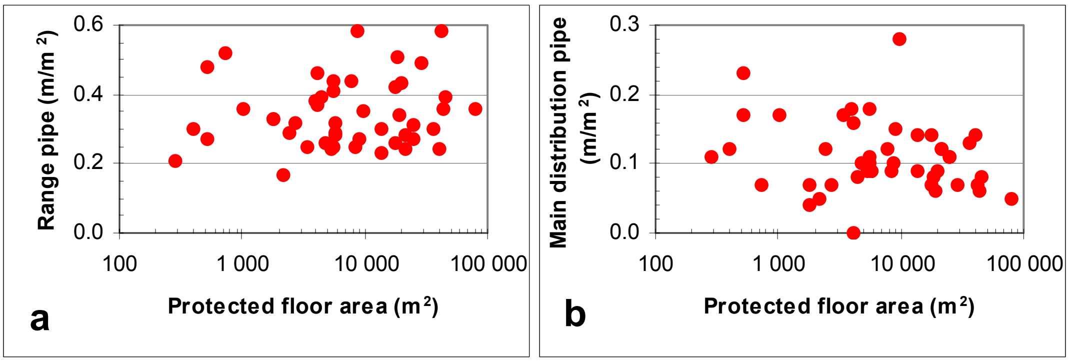

Figure 18. Dependence on range pipe length per floor area (a) and main distribution pipe length per floor area (b) on protected floor area.

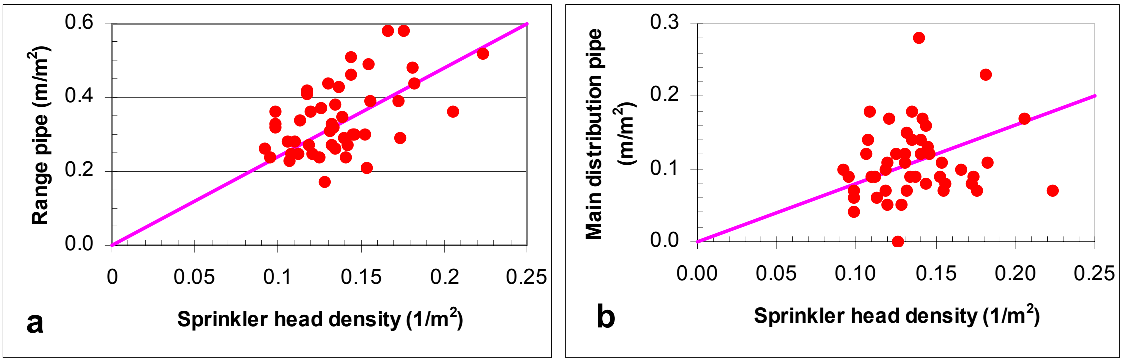

Figure 19. Dependence on range pipe length per floor area (a) and main distribution pipe length per floor area (b) on sprinkler head density: observations (dots), linear fit (full line).

3.2.4 Control valve sets

Figure 20 present number of control valves as a function of floor area using two scales of the latter: (a) linear scale, and (b) logarithmic scale to emphasise smaller range of the area. The linear fit for the number of valves $\boldsymbol{n}$ indicated by full line in Figure 20a is given by a modified form of Equation (12)

$$n \geq A / A_0 \tag{12'}$$

where now the lower limit is given by A_0 = 5260 m^2. The observations (dots) fall on direct lines indicating that floor areas and number of valves were counted independently of each other, and not by counting individually areas covered by a single valve, which would be the accurate way of measuring the dependence. In Figure 21 is plotted the area per control valve [m^2] as a function of protected floor area [m^2]. The numbers on top of the full lines indicate how many valves were involved on each of the single lines. The result reveals that the areas although determined mostly separately for each valve, were in later data reductions summed together, and the protected area in a building was obtained by division.

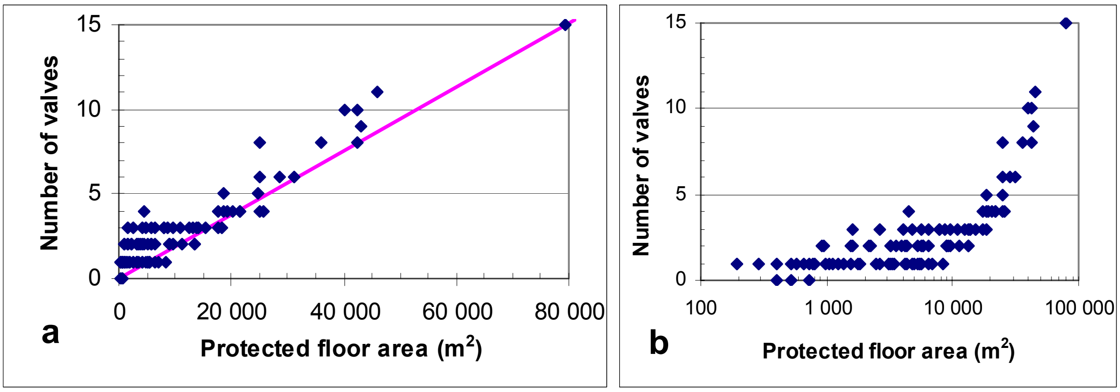

Figure 20. Number of control valves as a function of floor area [m^2] using (a) linear and (b) logarithmic scale of the floor area.

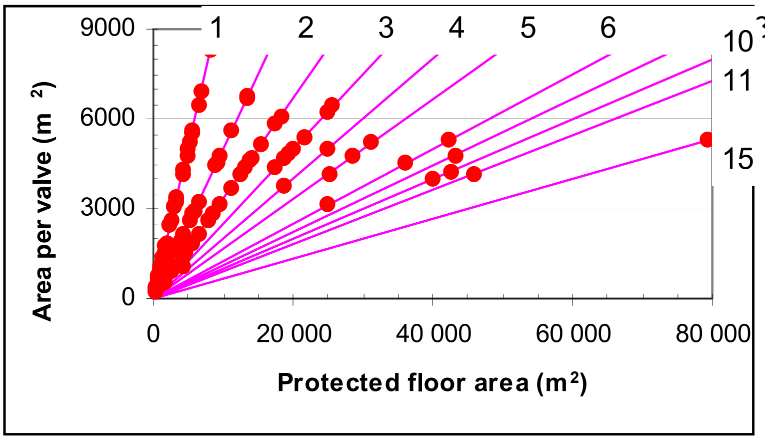

Figure 21. Area per control valve [m^2] as a function of protected floor area [m^2].

In Figure 22 are plotted cumulative distribution of the number of control valves in an installation: observations (dots), and a rough Weibull fit (full lines). Now X is the number of control valves. A fair fit results with parameters: $x_0 = 0.5$, $\alpha = 1$, and $\beta = 2.1$. Trying discrete distributions the best fit was obtained using a negative binomial distribution (Abramowitz & Stegun 1970), where the probability $P(s,n)$ to find a system with exactly s valves of maximally n valves is given by

$$P(s,n) = \binom{n+s-1}{s} p^n (1-p)^s \qquad (13)$$

Cumulative of *P(s,n)* are denoted by diamonds in Figure 22 with parameters $\boldsymbol{n}$ = 15, and $\boldsymbol{p}$ = 0.85. Both these distributions are obtained using curve fits by inspection. These distributions are needed in error analyses when estimating populations. There are no fundamental models behind these fits. Either one of them is sufficient for error estimation. Also there is no point to use any more refined methods to non-linear curve fitting because of small amount of data.

3.2.5 Water supply

In Table 10 the water supplies in the sample of 102 buildings are shown. In Figure 23 this sample is compared with two other statistical sample populations of Finnish sprinkler water supplies. Results show, that even this small sample was representative of the water supplies, within error bars indicated, of the total sprinkler installation population.

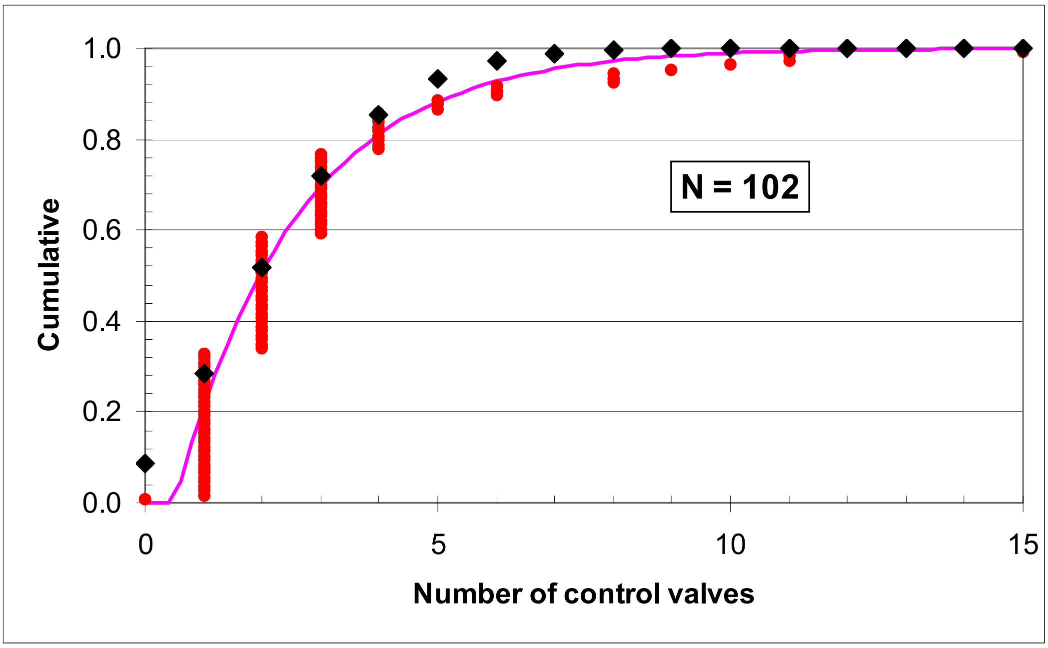

Figure 22. Cumulative distribution of the number of control valves (dots) with a Weibull fit (full line) and a negative binomial fit (diamonds).

Table 10. Water supplies in the sample of 102 buildings studied.

Water supply		**Number of observations**
TMB	Town main fed from both ends	43
OTM	Town main fed from one end	6
	Town main fed from both ends + 1–3 pumps	18
StT	Storage tank + 1–3 pumps	16
PrT	Pressure tank	1
	Fire department connections	3
OWS	Unknown	15

3.3 Determination of populations in non-nuclear buildings

For determination of failure frequencies of sprinkler installations or its components, the size of the population must be known from which the failures arouse. The populations of Finnish sprinkler installations and components was estimated by using installation statistics collected by SVK from years 1968–2000 shown in Figure 24. Amounts of annually installed systems (diamonds; left-hand scale) are summed up to a cumulative (right-hand scale) as a direct maximal sum (squares) or to an estimated total cumulative (triangles) taking into account wasted installations disassembled, but for which there are no direct statistics available. Real populations fall within these two curves.

Using information in Figure 24 as well as earlier studies (Rönty 2001, Rönty & Keski-Rahkonen 2001), which are explained thoroughly above, cumulative sprinkler system or component plots as a function of time were obtained up to year 2000: distribution of water supplies (contained in Figure 23), number of installed sprinkler systems (Figure 24), number of installed control valve sets without separation (Figure 25), total main distribution pipe length in sprinklered buildings (Figure 26), total range pipe length in sprinklered buildings (Figure 27), number of installed sprinkler heads (Figure 28), number of diesel driven pumps (Figure 29), number of electrical pumps (Figure 30), protected total floor area in sprinkledred buildings (Figure 31), and average protected floor area per sprinkler system (Figure 32). In Table 11 total amounts of Finnish sprinkler installations and components are given by the end of year 2000 for quick reference of the studied population.

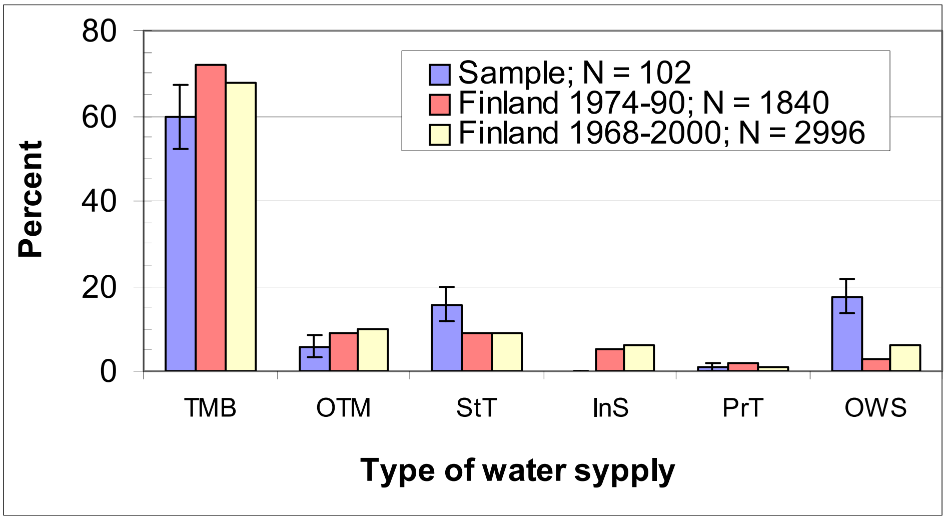

Figure 23. Distribution of water supplies in the sample, and two national estimates.

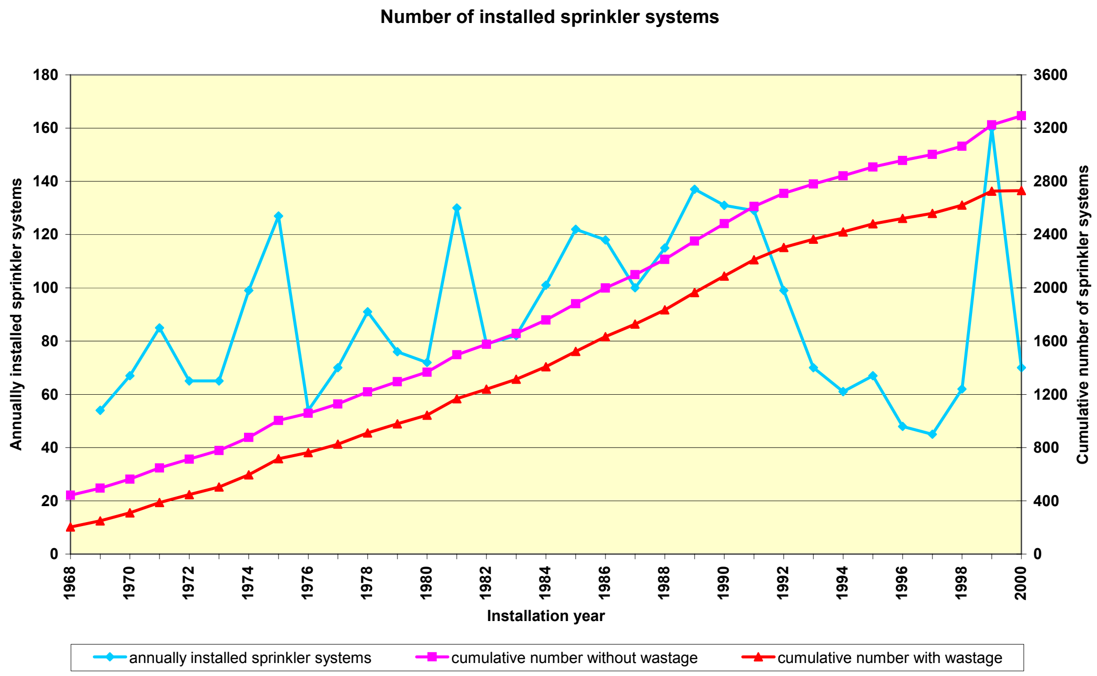

Figure 24. Number of installed sprinkler systems 1968–2000 totalling to operating experience between 48 800 and 60 500 system years.

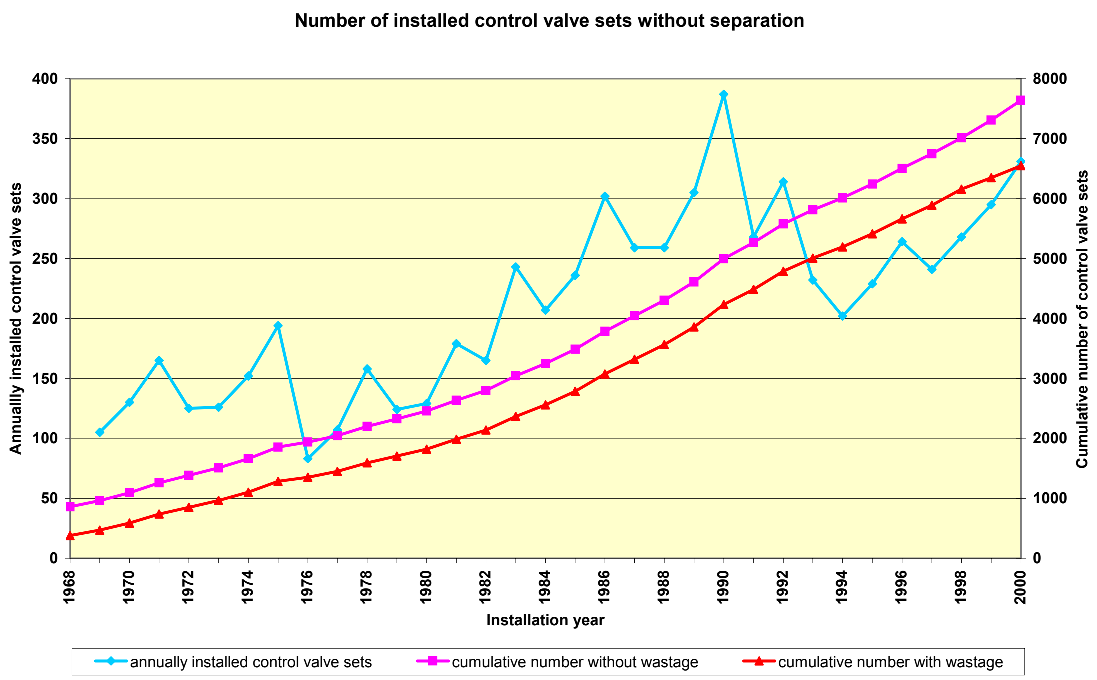

Figure 25. Number of installed control valve sets without separation 1968–2000 totalling to operating experience between 9 970 and 12 300 valve years.

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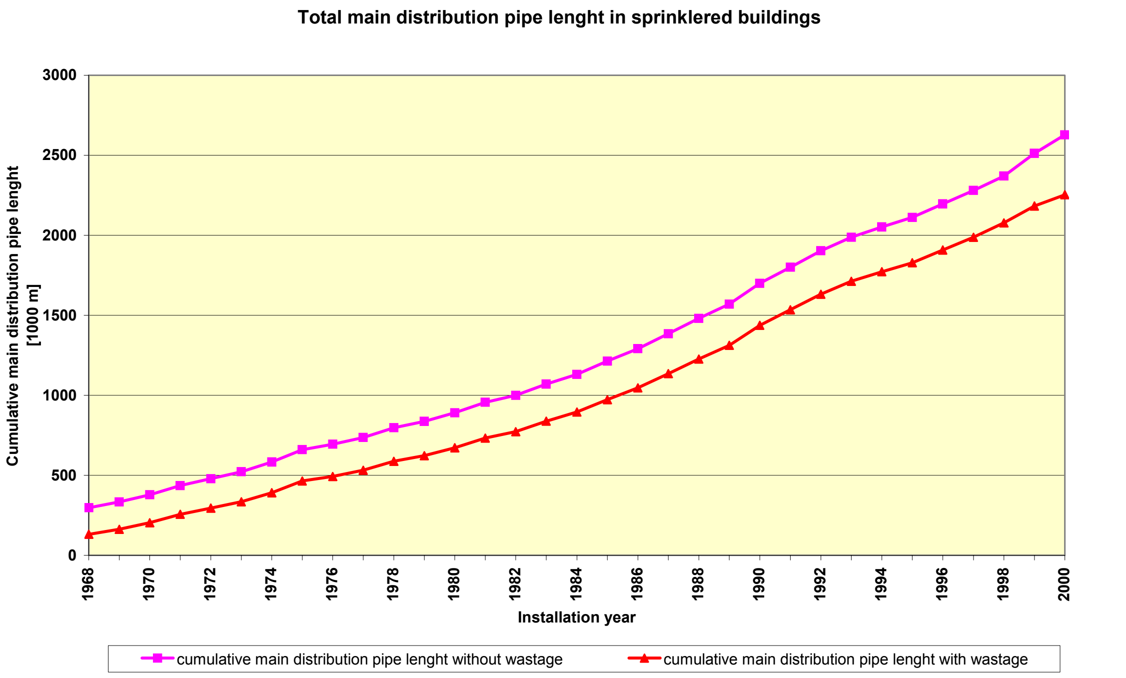

Figure 26. Total main distribution pipe length (km) in sprinklered buildings 1968–2000 totalling to operating experience between 34.4 and 42.3 pipe length years [in million am].

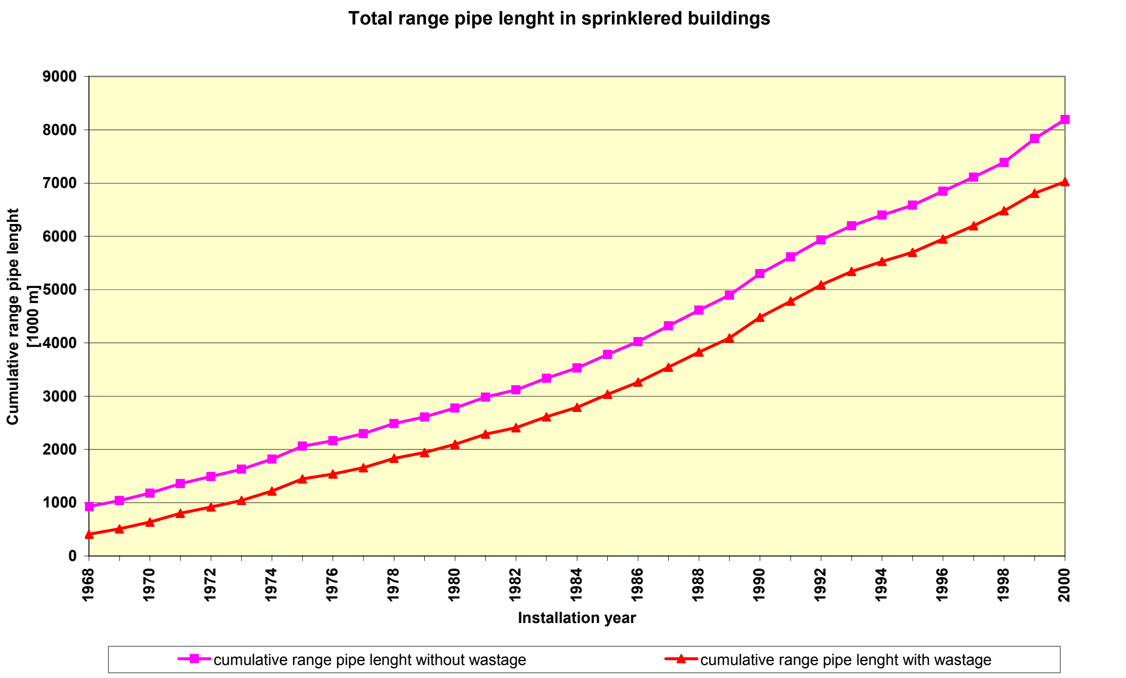

Figure 27. Total range pipe length in sprinklered buildings 1968–2000 totalling to operating experience between 107 and 132 pipe length years [in million am].

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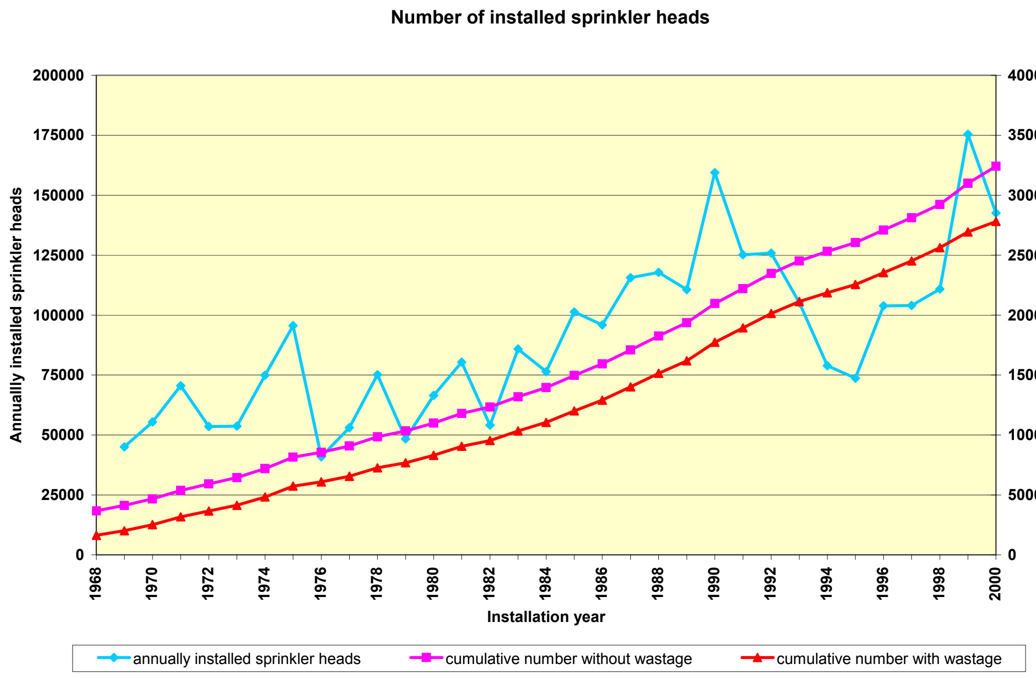

Figure 28. Number of installed sprinkler heads 1968–2000 totalling to operating experience between 42.4 and 52.2 million head years.

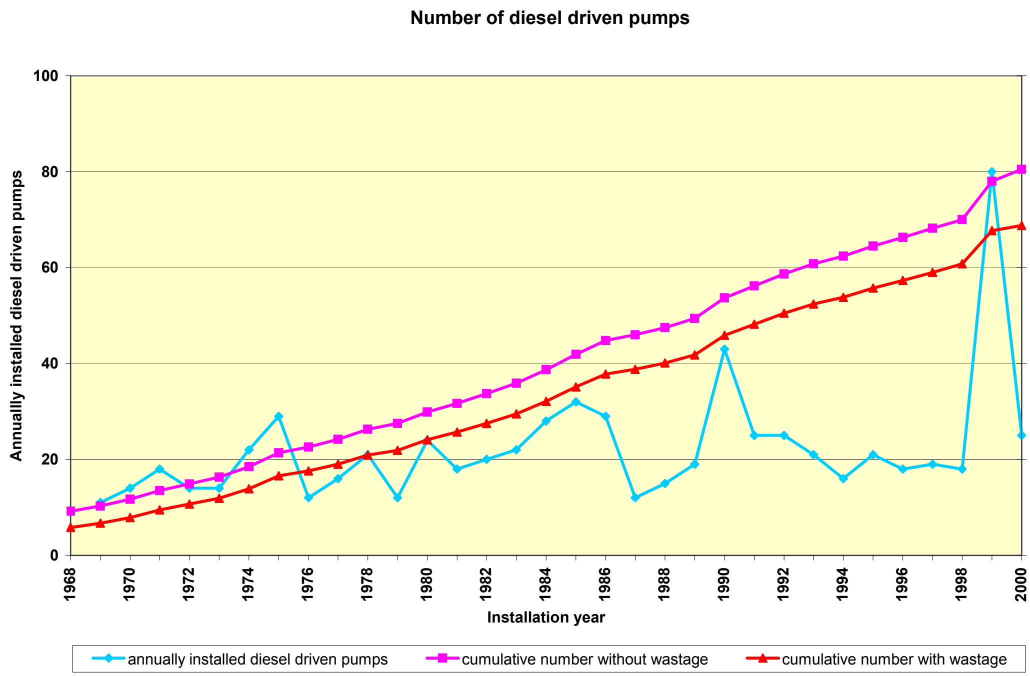

Figure 29. Number of diesel driven pumps 1968–2000 totalling to operating experience between 11 200 and 13 400 pump years.

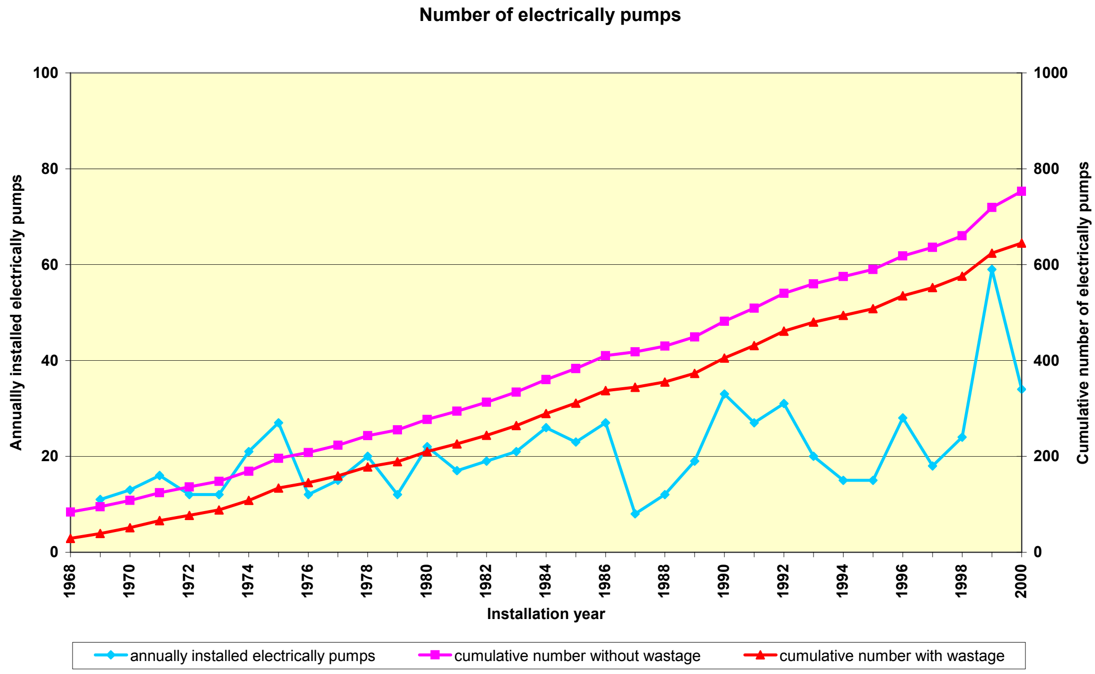

Figure 30. Number of electrical pumps 1968–2000 totalling to operating experience between 9 900 and 12 300 pump years.

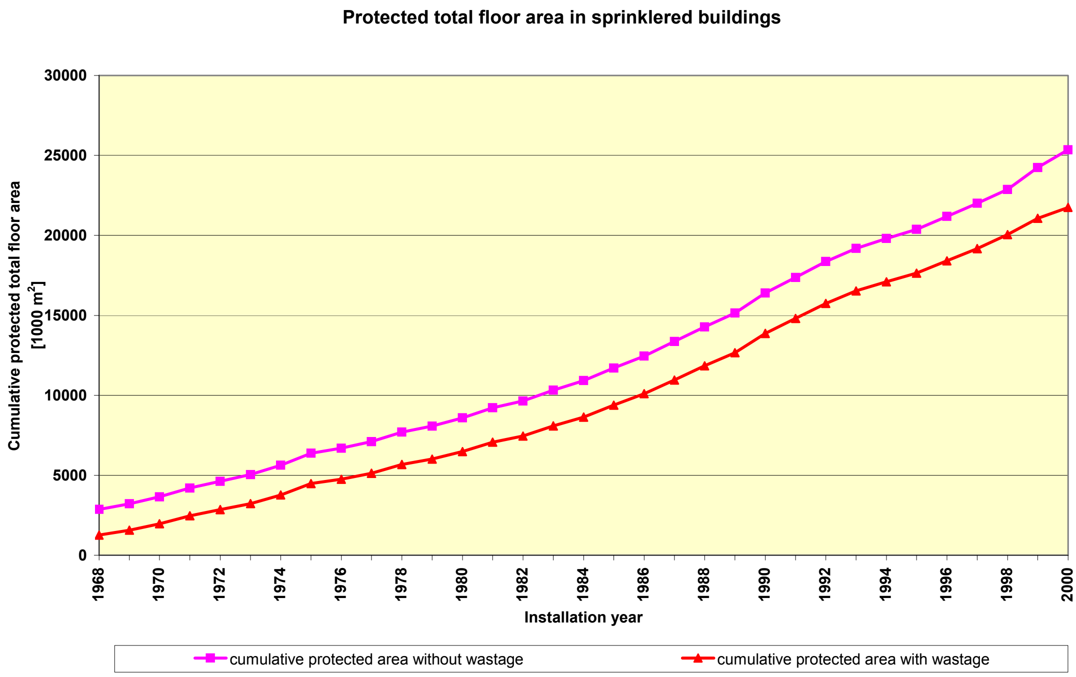

Figure 31. Protected total floor area in sprinklered buildings 1968–2000 totalling to operating experience between 332 and 408 area years [in million m^2a].

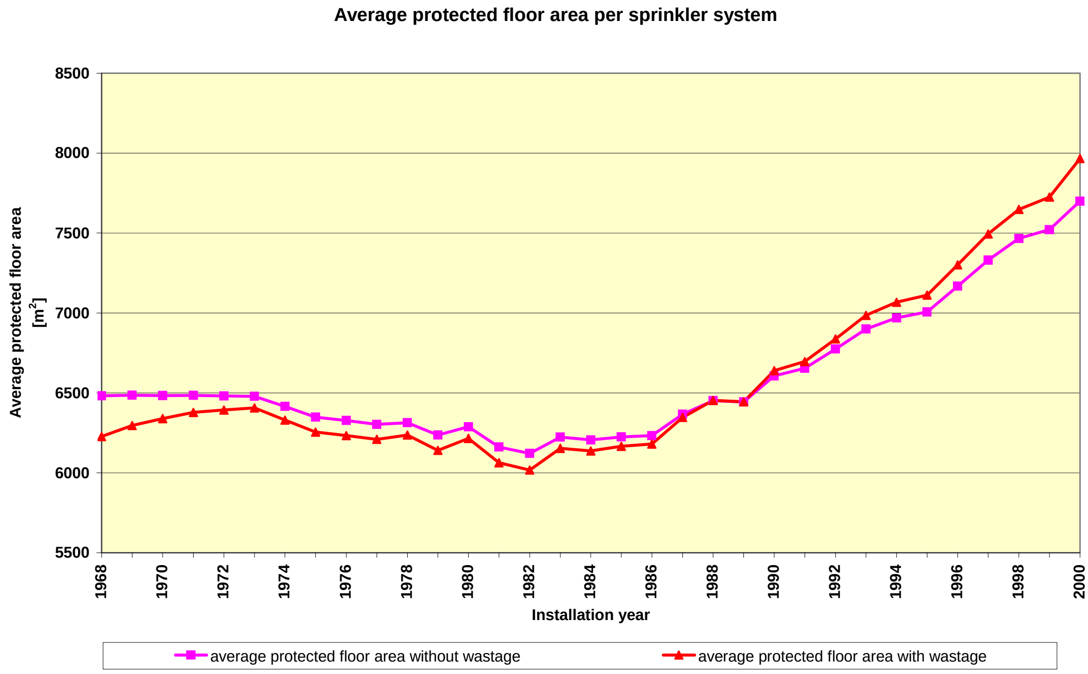

Figure 32. Average protected floor area per sprinkler system 1968–2000 totalling to operating experience between 217 and 218 area years [in tausend m^2a].

Table 11. Summary of sprinkler installations and components in Finland by the end of year 2000.

Equipment or component	**Quantity**	**Dimension**
Number of installed sprinkler systems	3 000	
Number of installed control valve sets	7 000	
Total main distribution pipe length	2 400	km
Total range pipe length	7 500	km
Installed sprinkler heads	3 000 000	
Diesel driven pumps	750	
Electrical pumps	700	
Town main, the most common ws	80	%
Protected total floor area	23	km^2
Average protected floor area	7 800	m^2

3.4 Nuclear installations in Finland

The characteristics of sprinkler system installations in Finnish NPPs are presented in Tables 12–14. In Table 12 protected floor areas as well as number of sprinkler heads are given. Table 13 lists other sprinkler related components, but is unfortunately not exhaustive. Control valve sets are listed in Table 14. The water supply in Olkiluoto is a gravity tank of 2000 m^3 capacity. From three centrifugal fire pumps one is electrically driven, two driven by diesel engines. One pump is on reserve. The capacity of water tanks in reserve is 2x250 m^3. In Loviisa there are two gravity tanks each containing 1500 m^3. Four electrically driven fire pumps can be replaced if needed by three diesel engine driven pumps. The volume of a water tank in reserve is 1500 m^3. Both of these water supplies fulfil class A requirements of sprinkler rules (CEA 1998).

Table 12. Protected floor areas [m^2] and number of sprinkler heads per NPP unit in Finland

NPP	**System**	**Type**	**Protected floor area** [m^2]	**Sprinkler heads**
Olkiluoto	Turbine water sprays	Dry-pipe, pre-action, open heads	727	149
Olkiluoto	Turbine hall, general	Wet pipe	4 667	579
Olkiluoto	Cable tunnels	Wet pipe, multiple control	4 914	698
Olkiluoto	Sprinkler protection of cable spaces below control room	Dry-pipe, detector sprinklers, closed heads	1 503	239
Loviisa	Turbine water sprays	Dry-pipe, detector sprinklers, open heads	1849	605
Loviisa	Turbine hall, general	Wet pipe	11 399	2 139
Loviisa	Cable spaces water spray	Dry-pipe, pre-action by smoke detectors, open heads	6 184	2 385

Table 13. Components of different parts of sprinkler installations in Finnish NPPs.

NPP	**Room**	**Type**	**Heads**		**Floor area**	**Pipe [m]**		
			Spr	Det	[m²]	Range	Main	Dry
Lo	Turbine hall, g	wet, autom.	2139	256	11 399	5 594		
Lo	Turbine, WS	dry, autom.	605		1 849	1 697		1 421
Lo	Cable tunnels	dry, deluge	2385		6 184	6 581		
Ol	Turbine hall	wet	579		4 667	1 349	702	
Ol	Turbine, WS	dry, autom.	149	95	727	773		
Ol	Cable tunnels	wet	698		4 914	1 666	930	
Ol	Cable sp, cab.	dry	239	239	1 503	577	160	723

g, general protection by sprinklers below ceiling, WS, water spray

Table 14. Control valve sets in NPPs.

System	**Control valve**		
	Type	Release	Amount
Ol, turbine, general	wet	automatic	4
Ol, turbine, water spray	deluge	automatic	12
Ol, cable tunnels	wet	automatic	4
Ol, control room cables	pre-action alarm	automatic	4
Lo, turbine, general	wet	automatic	6
Lo, turbine, water spray	deluge	automatic	4
Lo, turbine, water spray	deluge	manual	20
Lo, cable tunnels	solenoid valve	automatic	47
Lo, cable tunnels	solenoid valve	from CR	24
Lo, cable tunnels	manual valve	manual	8
Lo, diesel building	wet	automatic	2
Lo, auxiliary pump house	wet	automatic	1

4. Non-fire failure statistics

Reliability analysis of a system is based on statistical determination of frequencies of initiating events and branching ratios in event and fault trees as well as reliabilities of its components. The following statistics collected by SVK were used as raw material: installation statistics 1968–2000, inspection statistics 1985–1997, and operational statistics 1983–2000 (fires + leaks).

Until now only installation and inspection statistics have been studied preliminarily to extract Finnish sprinkler installation population until year 2000 as presented in Figure 24. The relative amounts of various failure types were also determined from periodic inspection reports during 1985–1997. Total amount of inspections was 4013 and number of observed failures 7485. The number of different types of failures was 458. The failures were classified according to failure severity to four and failure cause to five different categories.

From nuclear power plants electronic maintenance reports were obtained, observed failures and other reliability relevant data were selected, classified according to failure severity, and stored on spreadsheets for further analysis. A short summary of failures was made, which was hampered by a small sample size.

4.1 Failure classification according to severity

Failures can be classified in a number of ways (H∅yland & Rausand 1994). Although there are even standards on the classification like BS 4778, EuReDatA 1983, and US MIL-STD-882, no unique single system is evident. The major idea of these standards is the same, but practical implementation depends on the viewpoint of the study, nature of the system, and on the quality of the data. For NPPs, where failures of components were surveyed, three categories of failure criticalities were used (OREDA 1992). Failure numbers in parentheses are numerical values of severity used later in respective tables. For classification the operation of the system was used as a criterion, not a function of a component.

Critical failure (1): The component does not fulfil its mission. The failure is sudden and causes cessation of one or more fundamental functions, e.g. a pump does not start, or stops, a valve does not open or close. A critical failure requires immediate corrective action in order to return the item to a satisfactory condition.

Degraded failure (2): A failure that is gradual, partial or both. It does not cease the fundamental functions but compromises one or several functions. In time such a failure may develop into a critical failure, and therefore corrective actions should be taken as soon as possible. Small leakage, wear and natural ageing are examples of such failures.

Incipient failure (3): An imperfection in the state or condition of an item so that a degraded or critical failure can be expected to result if corrective action is not taken. Corrective action can be postponed to a suitable time. Incipient failures do not essentially increase unavailability. Corrosion failures are an example of incipient failures in sprinkler installations.

For non-nuclear installations the viewpoint was from the system level using as criterion consequensies to the system because no detailed component lists were available, and because also statistical data on causes of failures were not very detailed. Therefore the classification chosen follows the basic idea used in US MIL-STD-882 as follows:

Failure group 1 (critical failure): Failure of installation or part of it, e.g. main control valve closed or fire pump does not start.

Failure group 2 (consequentially critical failure): Failure of installation or part of it, which allows system operation, but may result in slower extinguishing or increased losses, e.g. too high bays, or missing fire alarm.

Failure group 3 (degraded failure): Failure of installation or part of it, which allows system operation, but if corrective action is not taken, may result in a critical failure due to changes in environment or failures in other parts of the installation, e.g. tripped dry alarm valve, or missing pressure switch.

Failure group 4 (incipient failure): Failure of installation or part of it, which does not prevent operation essentially, or a failure, the effect of which on the system is not yet proven, e.g. block plan missing, or alarm tests not performed.

4.2 Failure classification according to failure cause

Classification of failure causes is a useful concept especially from the viewpoint of corrective actions, because it indicates directly on which part of the system or administration of it one has to direct them. Failure causes are often classified into three categories (Kumamoto & Henley 1996): primary failure, secondary failure, and command fault.

Usage failure: Failure or change of environment caused by user operations, which prevents system function or compromises its operation. Failure cause: command fault by plant personnel. Examples: sprinkler installation has been totally closed off, or fire load has been increased substantially.

Maintenance failure: Neglect of maintenance of the installation or part of it. Failure cause: secondary failure due to plant personnel. Examples: testing of pumps neglected, or the responsible service person not named.

Installation failure: Installation of the system or part of it wrong or incomplete. Failure cause: secondary failure due to plant personnel. Examples: dry upright pattern heads installed downwards, or lower pressure alarm missing.

Device failure: Nonfulfillment or degradation of the function of the system or part of it. Failure cause: primary failure due to natural ageing. Examples: diesel pump does not start or a valve leaks.

Instruction failure: Neglect of maintenance of instructive material of the installation. Failure cause: secondary failure due to plant personnel. Example: missing service manual.

4.3 Failures in non-nuclear installations

The amounts of failures were determined from periodic inspection reports from years 1985–1997 and classified according to failure severity and failure cause. Graphical presentations of these are given in Figure 33 for all kinds of failures in all systems. In Figure 34 failures in whole installation are given independent of its composition. Figures 35 to 42 present failures in various components or parts of the installation.

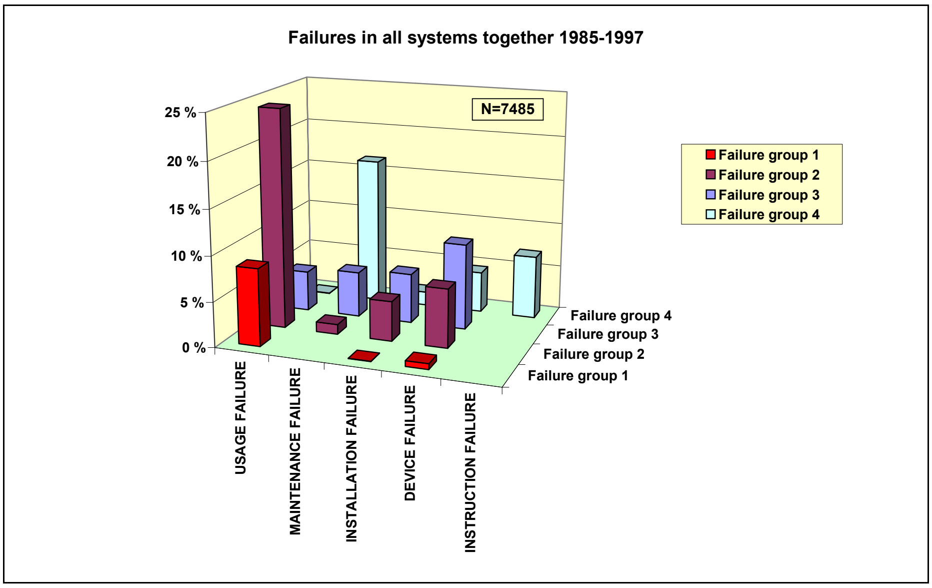

Figure 33. Total number of all kinds of failures in all systems classified according to failure cause and failure severity (failure group 1–4) 1985–1997.

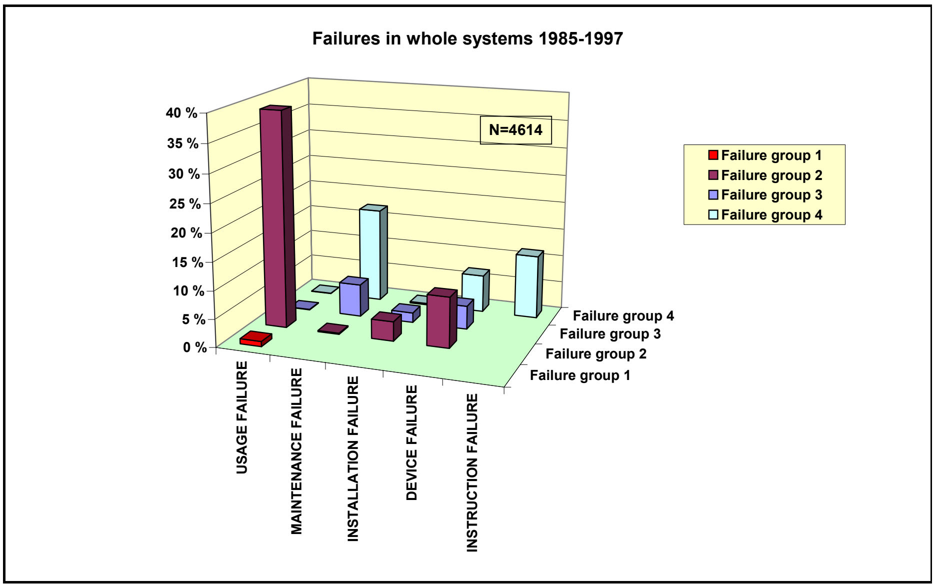

Figure 34. Failures in whole systems classified according to failure cause and failure severity (failure group 1–4) 1985–1997 from a total operating experience of 4013 system years.

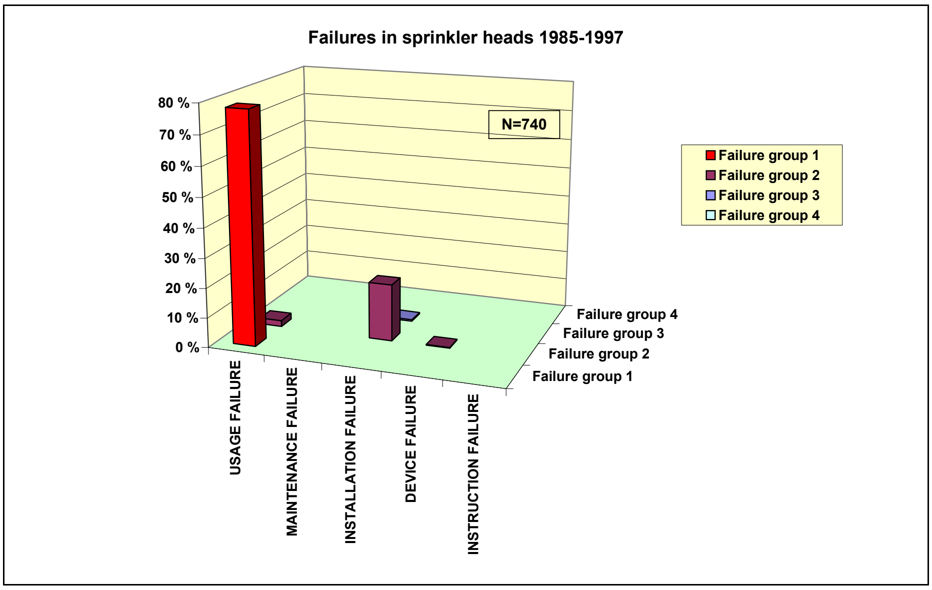

Figure 35. Failures in sprinkler heads classified according to failure cause and failure severity (failure group 1–4) 1985–1997 from a total operating experience of 3.49 million head years.

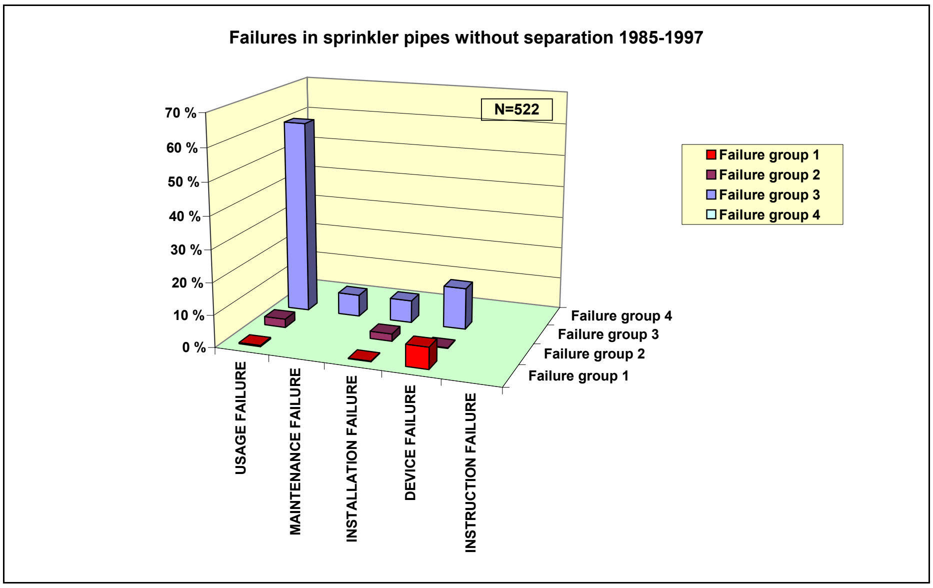

Figure 36. Failures in sprinkler pipes without separation classified according to failure cause and failure severity (failure group 1–4) 1985–1997 from a total operating experience of 11.6 million am of pipe exposure.

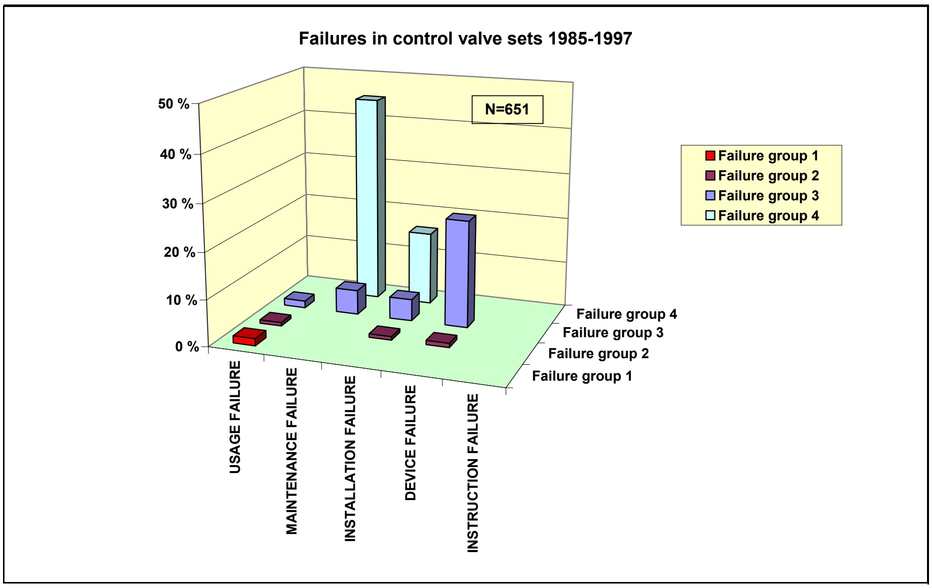

Figure 37. Failures in control valve sets classified according to failure cause and failure severity (failure group 1–4) 1985–1997 from a total operating experience of 8300 valve years.

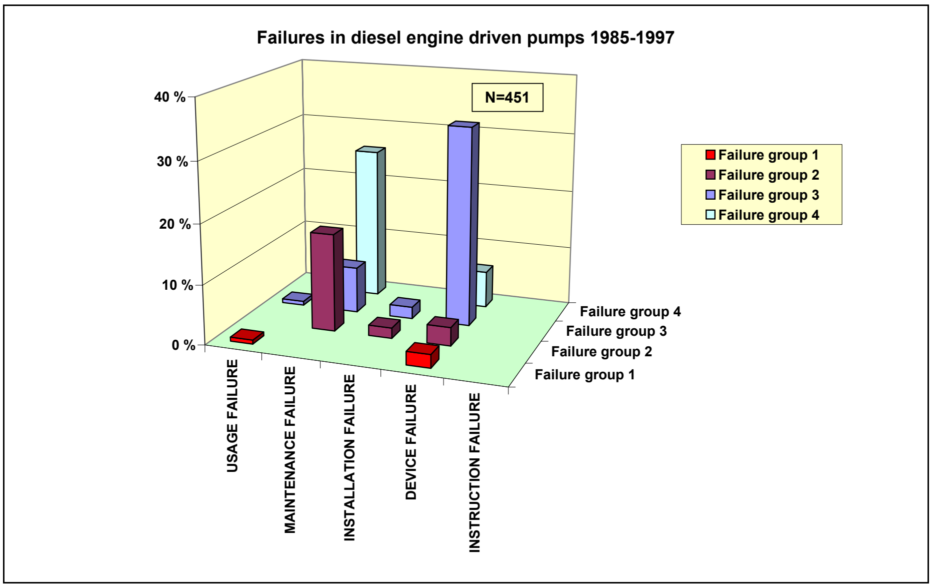

Figure 38. Failures in diesel engine driven pumps classified according to failure cause and failure severity (failure group 1–4) 1985–1997 from a total operating experience of 889 pump years.

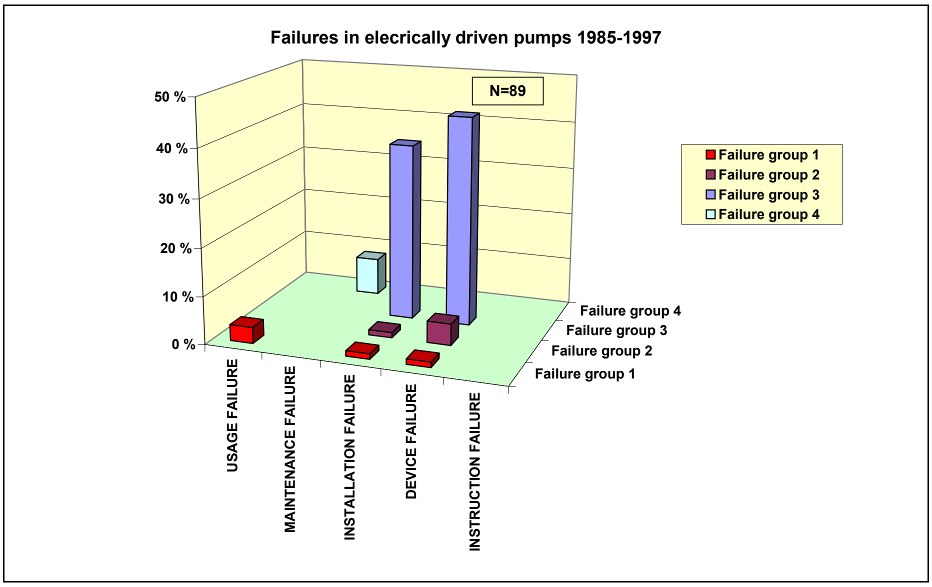

Figure 39. Failures in electrically driven pumps classified according to failure cause and failure severity (failure group 1–4) 1985–1997 from a total operating experience of 805 pump years.

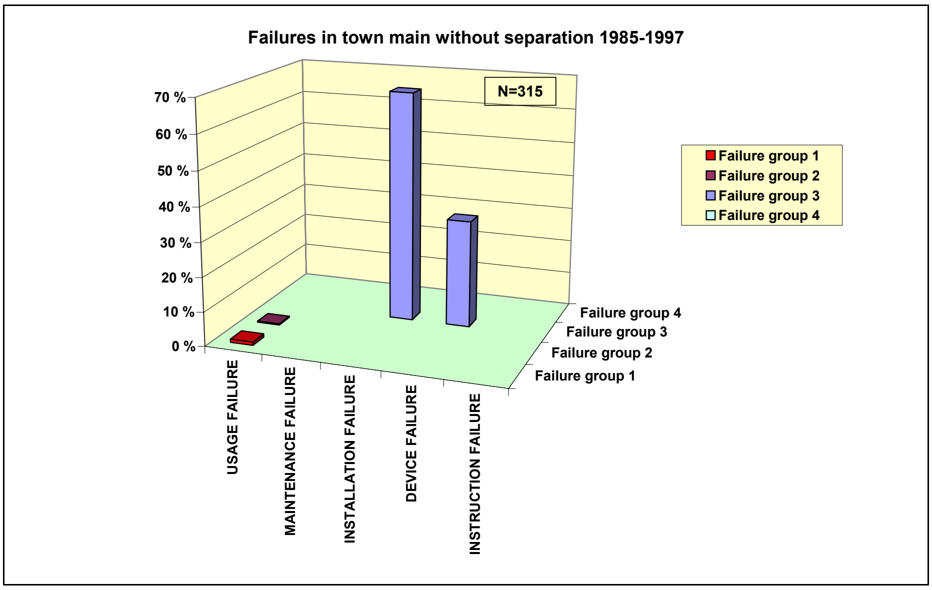

Figure 40. Failures in town main without separation classified according to failure cause and failure severity (failure group 1–4) 1985–1997 from a total operating experience of 3140 water source years.

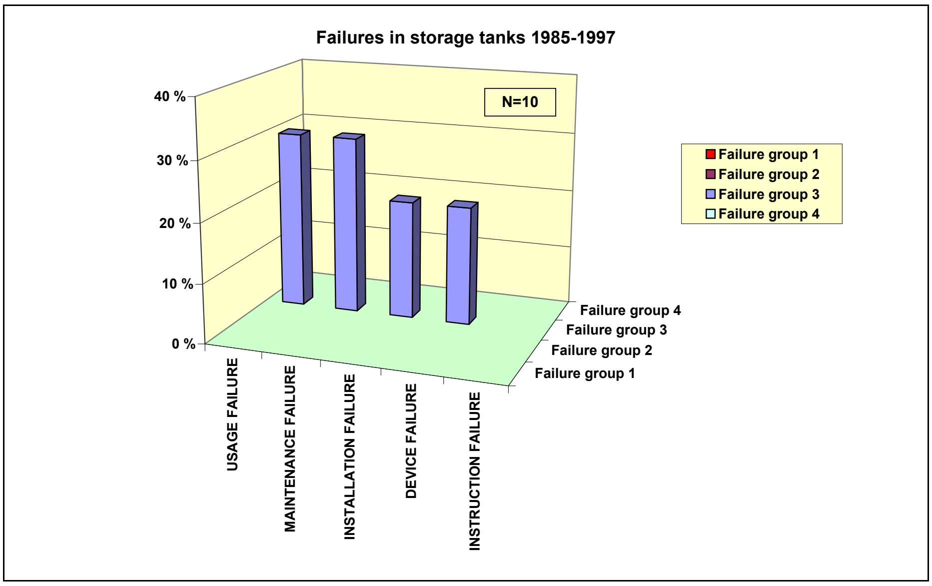

Figure 41. Failures in storage tanks classified according to failure cause and failure severity (failure group 1–4) 1985–1997 from a total operating experience of 353 tank years.

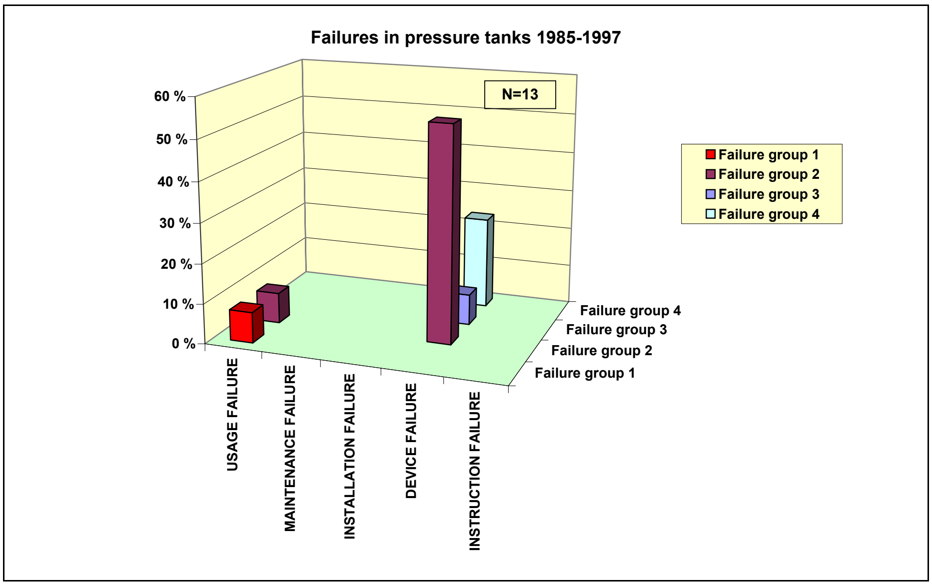

Figure 42. Failures in pressure tanks classified according to failure cause and failure severity (failure group 1–4) 1985–1997 from a total operating experience of 51 tank years.

4.3.1 Five most common failure causes

Five most common failure causes according to classification presented in Chapter 4.2 were in non-nuclear installations as shown in Tables 15 to 19.

Table 15. Five most common usage failures.

	Description	**Number**
1.	Unsprinklered rooms added	475
2.	Exceeding of storage height	377
3.	Painted-over sprinklers	304
4.	Painting cover of sprinklers not removed	210
5.	Sprinkler tubes used to hang on inappropriate things or material	195

Table 16. Five most common maintenance failures.

	Description	**Number**
1.	Alarm tests not carried out	273
2.	Reserve sprinklers missing	203
3.	Dry alarm valve tests not carried out	160
4.	No corrections taken on items given in the previous inspection protocol	159
5.	Stainer not cleaned	110

Table 17. Five most common installation failures.

	Description	**Number**
1.	Pressure low -alarm missing	174
2.	Locking of alarm valves in the open position	104
3.	Sprinklers installed in wrong position	62
4.	Sprinkler heads not installed below HVAC ducts	47
5.	Sprinkler heads in cooker hood missing	45

Table 18. Five most common device failures.

	Description	**Number**
1.	Hydraulic alarm clock defect	145
2.	Pressure low -alarm defect	87
3.	Surveillance alarms defect	85
4.	Sink of testing device flooded	84
5.	Testing device clogged	65

Table 19. Five most common instruction failures.

	Description	**Number**
1.	Block plan missing	215
2.	Circuit diagram missing	134
3.	Alterations not added to block plans	65
4.	Alterations not added to circuit diagram	30
5.	User manual faulty or missing	25

4.3.2 Time dependence of observed failures during inspections

In Figure 43 the average number of failures per inspection report is plotted as a function of inspection year for non-nuclear installations. It indicates that the number changes roughly by a factor of 2 during these years. One way of interpreting this might be, that the condition of the sprinkler installation changes respectively with time: improving 1990–1992 (happy system), and deteriorating since then (sad system). Looking on the instruction given for inspectors, and the inspection reports themselves, this interpretation seems far-fetched. Rather, it is our view based on the study of inspections that the major component of this change is caused from the variation of inspection practises. Without this variability the points in Figure 43 might lie closer on a line. The message of Figure 43 thus indicates mainly the predictive accuracy of the periodic inspection process: average 2.0 failures per inspection +60%, -40%. These 'data' are ment to those responsible for system maintenance policy as indicators, which need deeper study before profound conclusions.

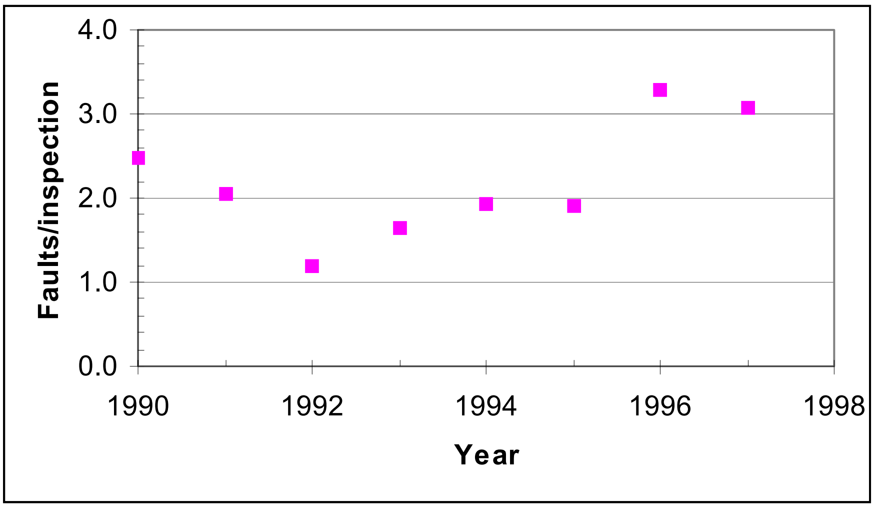

Figure 43. Dependence of number of failures per inspection on the inspection year.

4.4 Sprinkler installation failures in NPPs

Failures of sprinkler installations in Finnish NPPs were collected as describe above. The results are presented in Tables 20 to 25, where direct raw observations are noted together with a calculated point estimate of failure rate using as dimension [1/a] or [1/am] depending on which is the appropriate one. The number of failures of most of the components is so small, that a *frequentist* approach to determine the failure frequency as used in Tables 20 to 25 is not sufficient. Therefore, in Chapter 5.1.1 comparison between some of the failure rates are made after calculating also their error margins.

4.4.1 Olkiluoto sprinkler installations

Failures in Olkiluoto sprinkler installations are presented in Tables 20 and 21. The number of failures in Olkiluoto fire pumping system is rather small. Table 20 concentrates on the components the failures of which are considered *a priori* most important for the function of the system. The failures of electrically driven and diesel driven fire pumps has been summed. In Table 21 wet alarm valves is the component group, which has the highest failure frequency.

Table 20 Failures in Olkiluoto fire pumping system, August 1, 1981 – May 17, 2000, (Pop = population, Num = number of failures, Sev = severity of failure).

Component		**Failure rate**				
Name	Pop	Num	Sev	Failure rate [1/a]		
				min	point est	max
Fire pump	3	3	1	1.46E-2	5.34E-2	1.38-1
		6	2	4.66E-2	1.07E-1	2.11E-1
		1	3	9.14E-4	1.78E-2	8.45E-2
Jockey pump	2	5	1	5.26E-2	1.34E-1	2.81E-1
		1	2	1.37E-3	2.67E-2	1.27E-1
Reserve fire pump	2	1	1	1.37E-3	2.67E-2	1.27E-1
Compressor	1	2	2	1.90E-2	1.07E-1	3.36E-1

4.4.2 Loviisa sprinkler installations

Failures in Loviisa sprinkler installations are given in Tables 22 to 25. Fire pump is the component in Loviisa fire pumping system, which has the highest failure frequency (degraded failure, severity 2) of 0.28/a, whereas the frequency of critical failures (severity 1) is 0.86E-2. For turbine water sprays systems, Table 23, most common failures occur in pressure gauges and switches. Ceiling protection system of Loviisa turbine hall is a regular wet pipe installation, Table 24. Wet alarm valve has the highest failure frequency, but the failures are not critical. Most common failures in Loviisa cable tunnels, Table 25, occur for solenoid valves, some of which are critical. Also water hydrant failures are rather frequent, although mainly leakages, and thus not critical.

Table 21. Failures in Olkiluoto sprinkler installations, August 1, 1981 – May 17, 2000, (number of failures: TVO1 + TVO2 = total). Note different dimension for pipes.

Component		**Failures**		**Failure rate** [1/a]		
Name	Pop	Number	Sev	min	point	max
Sprinkler head	2516	0+2 = 3	1	7.55E-6	4.25E-5	1.34E-4
		6+27 = 33	2	5.13E-4	7.01E-4	9.37E-4
Sprinkler pipe [1/am]	9170 m	3+8 = 11	2	3.60E-5	6.41E-5	1.06E-4
		4+3 = 7	3	1.91E-5	4.08E-5	7.66E-5
Air pipe [1/am]	2000 m	1+0 = 1	1	1.37E-6	2.67E-5	1.27E-4
		7+11 = 18	2	3.11E-4	4.81E-4	7.13E-4
		0+1 = 1	3	1.37E-6	2.67E-5	1.27E-4
Wet alarm valve	8	6+5 = 11	2	4.12E-2	7.35E-2	1.22E-1
Solenoid valve	16	1+1 = 2	1	1.19E-3	6.68E-3	2.10E-2
		3+0 = 3	2	2.73E-3	1.00E-2	2.59E-2
Main control valve set	24	1+1 = 2	1	7.91E-4	4.45E-3	1.40E-2
		4+6 = 10	2	1.21E-2	2.23E-2	3.78E-2
Pre-action valve	1	1+0 = 1	2	2.74E-3	5.34E-2	2.54E-1
Pressure switch	36	2+5 = 7	1	4.88E-3	1.04E-2	1.95E-2
		1+5 = 6	2	3.88E-3	8.91E-3	1.76E-2
Water pressure gauge	56	3+4 = 7	1	3.14E-3	6.68E-3	1.25E-2
		4+1 = 5	2	1.88E-3	4.77E-3	1.00E-2
Alarm test valve	24	2+2 = 4	1	3.04E-3	8.91E-3	2.04E-2
		0+8 = 8	2	8.87E-3	1.78E-2	3.21E-2
Main control valve closed-indication	24	2+1 = 3	1	1.82E-3	6.68E-3	1.73E-2
Flow gauge	30	1+4 = 5	1	3.04E-3	8.91E-3	2.04E-2
		3+6 = 9	2	8.36E-3	1.60E-2	2.80E-2

Table 22. Failures in Loviisa fire pumping system, February 1, 1989 – August 1, 2000.

Component		**Failure rate** [1/a]				
Name	Pop	Number	Sev	Min	Point est	Max
Fire pump	4	4	1	2.95E-2	8.64E-2	1.98E-1
		13	2	1.66E-1	2.81E-1	4.46E-1
Jockey pump	2	2	1	1.53E-2	8.64E-2	2.72E-1
		5	2	8.51E-2	2.16E-1	4.54E-1
Check valve	6	2	1	5.11E-3	2.88E-2	9.06E-2
		7	2	4.73E-2	1.01E-1	1.89E-1
Safety valve	1	1	2	4.43E-3	8.64E-2	4.10E-1
Pressure gauge	19	2	1	1.62E-3	9.09E-3	2.86E-2
		2	2	1.62E-3	9.09E-3	2.86E-2
Pressure gauge	6	5	2	2.84E-2	7.20E-2	1.51E-1

Table 23. Failures in Loviisa turbine hall water spray systems, February 1, 1989 – August 1, 2000, (number of failures: Lo1 + Lo2 = total). Note different dimension for pipes.

Component		**Failures**		**Failure rate** [1/a]		
Name	Pop	Number	Sev	Min	Point est	Max
Sprinkler pipe [1/am]	3400 m	1+2 = 3	2	2.08E-5	7.62E-5	1.97E-4
		1+1 = 2	3	9.03E-6	5.08E-5	1.60E-4
Air pipe [1/am]	2840 m	1+0 = 1	1	1.56E-6	3.04E-5	1.44E-4
		4+2 = 6	2	7.95E-5	1.82E-4	3.60E-4
Alarm valve	24	0+1 = 1	1	1.85E-4	3.60E-3	1.71E-2
		0+1 = 1	2	1.85E-4	3.60E-3	1.71E-2
Pressure gauge	4	2+0 = 1	1	7.67E-3	4.32E-2	1.36E-1
		1+0 = 1	2	1.11E-3	2.16E-2	1.02E-1
Pressure switch	24	9+5 = 14	1	3.05E-2	5.04E-2	7.88E-2
		1+0 = 1	2	1.85E-4	3.60E-3	1.71E-2
Alarm test valve	24	1+0 = 1	2	1.85E-4	3.60E-3	1.71E-2
Check valve	24	1+0 = 1	2	1.85E-4	3.60E-3	1.71E-2
Fire alarms	24	1+0 = 1	1	1.85E-4	3.60E-3	1.71E-2

Table 24. Failures in Loviisa turbine hall ceiling protection systems, February 1, 1989 – August 1, 2000, (number of failures: Lo1 + Lo2 = total). Note different dimension for pipes.

Component		**Failures**		**Failure rate** [1/a]		
Name	Population	Number	Sev	Min	Point est	Max
Sprinkler head	4278	10+5 = 15	2	1.87E-4	3.03E-4	4.66E-4
		0+3 = 3	3	1.65E-5	6.06E-5	1.57E-4
Sprinkler pipe	11 190 m	1+2 = 3	1	2.74E-6	1.54E-5	4.86E-5
[1/am]		1+1 = 2	2	2.54E-5	5.40E-5	1.01E-5
		2+1 = 3	3	6.31E-6	2.32E-5	5.98E-5
Deluge valve	4	1+2 = 3	2	1.77E-2	6.48E-2	1.67E-1
Wet alarm valve	6	1+1 = 2	1	5.11E-3	2.88E-2	9.06E-2
		12+14 = 26	2	2.62E-1	3.74E-1	5.19E-1
Test valve piping	6	3+0 = 3	2	1.18E-2	4.32E-2	1.12E-1
Retarding chamber	6	0+2 = 2	2	5.11E-3	2.88E-2	9.06E-2

Table 25. Failures in Loviisa cable tunnels, February 1, 1989 – August 1, 2000, (number of failures: Lo1 + Lo2 = total). Note different dimension for pipes.

Component		**Failures**		**Failure rate** [1/a]		
Name	Pop	Number	Sev	Min	Point est	Max
Sprinkler head	4770	0+1 = 1	1	9.27E-7	1.81E-5	8.59E-5
Sprinkler pipe [1/am]	13 150 m	2+0 = 2	3	2.33E-6	1.31E-5	4.13E-5
Solenoid valve	79	8+3 = 11	1	6.74E-3	1.20E-2	1.99E-2
		27+30 = 57	2	4.94E-2	6.23E-2	7.77E-2
		0+2 = 2	3	3.88E-4	2.19E-3	6.88E-3
Operation time-limit	8	0+5 = 5	1	2.13E-2	5.40E-2	1.13E-1
By-pass of magnet valve/motor valve	79	2+0 = 2	1	3.88E-3	2.19E-3	6.88E-3
		0+2 = 2	2	3.88E-3	2.19E-3	6.88E-3
Water hydrant valve	212	0+5 = 5	1	8.03E-4	2.04E-3	4.24E-3
		28+17 = 45	2	1.41E-2	1.83E-2	2.35E-2
Pressure switch	79	1+4 = 5	1	2.15E-3	5.47E-3	1.15E-2
Test valve	79	1+1 = 2	1	3.88E-3	2.19E-3	6.88E-3
		1+3 = 4	2	1.49E-3	4.37E-3	1.00E-2
Manual alarm valve	79	0+1 = 1	1	5.61E-5	1.09E-3	5.19E-3
		0+2 = 2	2	3.88E-3	2.19E-3	6.88E-3
Safety valve	2	2+5 = 7	2	1.42E-1	3.02E-1	5.68E-1
Fire alarms	79	0+1 = 1	1	5.61E-5	1.09E-3	5.19E-3

5. Failure rates

5.1 Comparison of NPP sprinkler installations

Comparison of failure rates between Loviisa and Olkiluoto for some common components is made in Table 26 by presenting direct point estimates of failure rates with their error estimates at 90% confidence level, and looking statistically significant differences between them. In Figure 44 these frequencies are plotted graphically with error bars like in Figure 4 using Manchini hardware classes.

Table 26. Comparison of point estimates of failure rates [1/a] of some components between Loviisa and Olkiluoto NPPs (S = severity of failure).

Component	**S**	**Loviisa**			**Olkiluoto**		
		min	point est	max	min	point est	max
Fire pump	1	3.0E-2	8.6E-2	2.0E-1	1.5E-2	5.3E-2	1.4E-1
	2	1.7E-1	2.8E-1	4.5E-1	4.7E-2	1.1E-1	2.1E-1
Jockey pump	1	1.5E-2	8.6E-2	2.7E-1	5.3E-2	1.3E-1	2.8E-1
	2	8.5E-2	2.2E-1	4.5E-1	1.4E-3	2.7E-2	1.3E-1
Sprinkler head	2	1.9E-4	3.0E-4	4.7E-4	5.1E-4	7.0E-4	9.4E-4
Solenoid valve	1	6.7E-3	1.2E-2	2.0E-2	1.2E-3	6.7E-3	2.1E-2
	2	4.9E-2	6.2E-2	7.8E-2	2.7E-3	1.0E-2	2.6E-2
Wet alarm valve	2	2.6E-1	3.7E-1	5.2E-1	4.1E-2	7.4E-2	1.2E-1

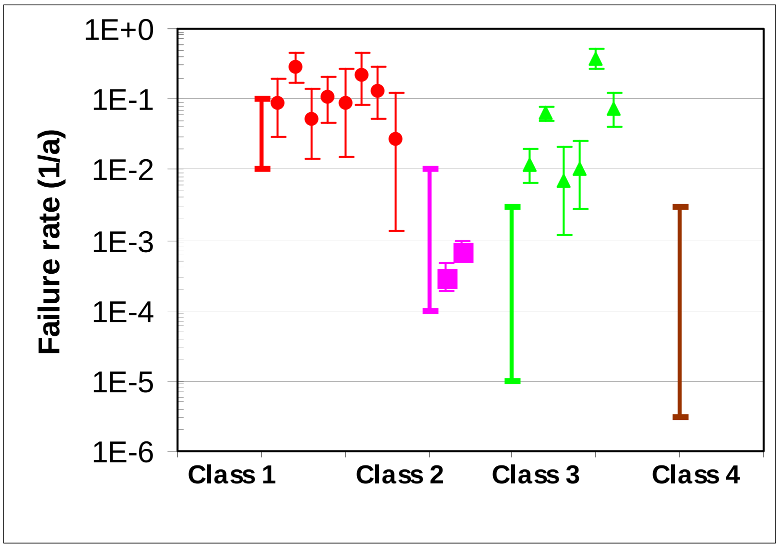

Figure 44. Failure rates [1/a] with error bars of some sprinkler installation components of Finnish NPPs from Table 26 presented on a plot showing Mancini hardware classes: pumps (dots), sprinkler heads (squares) and valve systems (triangles).

5.2 Estimation of non-nuclear component and subsystem failure rates

Using the studied non-nuclear material, preliminary rates of critical failures were calculated as presented in Table 27. These values are initial estimates and are not yet intended to be used for professional purposes, because of insufficient critical evaluation of data. Table 27 only presents order of magnitude values of these frequencies unavailable until now from a real statistical material from Finland. In later analyses internal evaluation of data and comparison with material from elsewhere will be made.

Table 27. Group 1 failure rates of sprinkler installation components according to Finnish statistics for years 1985–1997.

Component	**Failures**	**Exposure**	**Failure rate** [1/a]		
		device years	min	point	max
Town main	3	2137	2.6 E-4	1.0 E-3	2.5 E-3
Storage tank	0	353	NA	NA	6.5 E-3
Pressure tank	1	51	1.0 E-3	2.0 E-2	9.3 E-2
Alarm valves	10	8300	6.5 E-4	1.2 E-3	2.0 E-3
Pipe array	38	11 600 000[a]	2.4 E-6[b]	3.3 E-6[b]	4.3 E-6[b]
Sprinkler heads	577	3 490 000	1.5 E-4	1.7 E-4	1.8 E-4
Diesel driven pump	13	889	8.7 E-3	1.5 E-2	2.3 E-2
Electr. driven pump	5	809	2.5 E-3	6.2 E-3	1.3 E-3
Sprinkler installation	42	4013	8.0 E-3	1.1 E-2	1.4 E-2

[a] Length years [am], b Unit [1/am].

6. Reliability model of sprinkler systems

Non-nuclear buildings inspection statistics from years 1985–1997 were surveyed, and observed failures were classified and stored on spreadsheets. Finally, a reliability model is proposed based on earlier formal work (Hassinen 2000). Examples of some of the detailed systems are shown in Appendix A, Figures A3–A5 with explanation of used symbols in Figures A1–A2. Fault tree symbols are presented in Figure A6, and derived fault trees in Figures A7–A9.

System models depicted in Appendix A are comprehensive, but unfortunately too detailed for analysis using data from available statistics. Since even in future there is not much hope to get more comprehensive data, the models has to be simplified. A general fault tree of an object threatened by fire is given in Figure 45, (CIB 1983). It contains most the elements of fire protection met in practical situations. Only fire detection and alarming is missing explicitly, although it can be thought to be part of the fire extinguishing boxes. This whole study tries to extend the box 'Sprinkler fails' in Figure 45 deeper to root causes. To construct a proper fault tree trial and error method has to be used. As an example for practical reasons a system like that presented in Figure A4 with a full fault tree up to component level, Figure A8, must be simplified considerable, because detailed enough statistical data are not available.

Starting to model sprinkler installation itself Figure 46 a fault tree of failure of automatic extinguishing is divided into characteristic groups of functioning. In Figure 47 a respective system is presented, where the major indication of fire alarms becomes from sprinkler heads, and is divided to root components.

For a reliability model of a large sprinkler system in extended industrial objects Figure 48 present a fault tree down to some subsystems containing of blocks of components like water supplies, pump systems, and several pipe arrays of different sprinkler installations. The sprinkler system fails to operate, when its subsystems coupled in series or parallel in a way derivable from Figure 48. Details of subsystem connections vary from system to system. Fault tree presented in Figure 49 penetrated one level deeper in root causes of one box in Figure 48, installation failures dividing it in two groups: control valve set failures, and pipe array failures. For real installations details and presumably also reliabilities of control valve sets vary a lot. Therefore, it is so far better to consider it only as a subgroup of components. Pipe arrays have two major components rather universal: pipes, and sprinkler heads. Although even here much finer subdivision is possible but hardly accessible from statistics, division into two parts is well motivated. Such division has been already made above as becomes apparent from Tables 23 to 27.

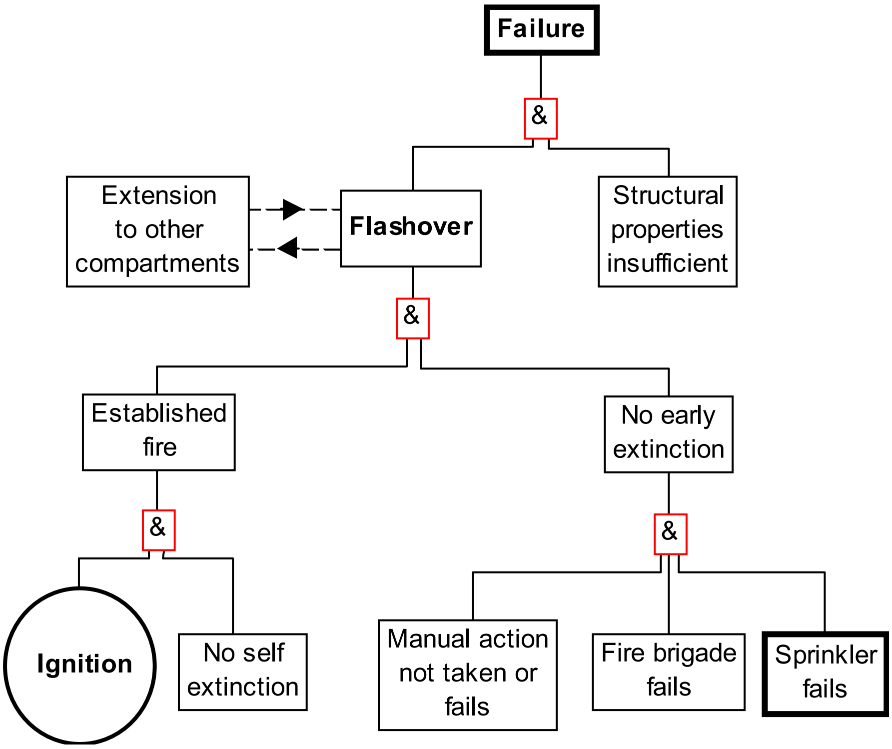

Figure 45. Fault tree of structural failure in a building due to fire (CIB 1983).

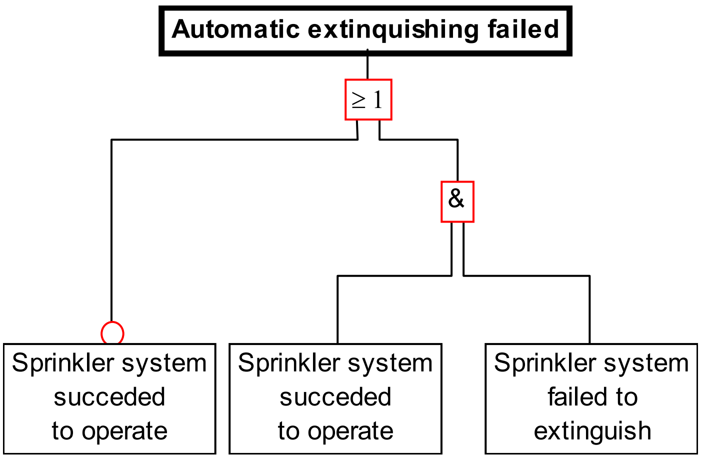

Figure 46. Fault tree of failure of automatic extinguishing.

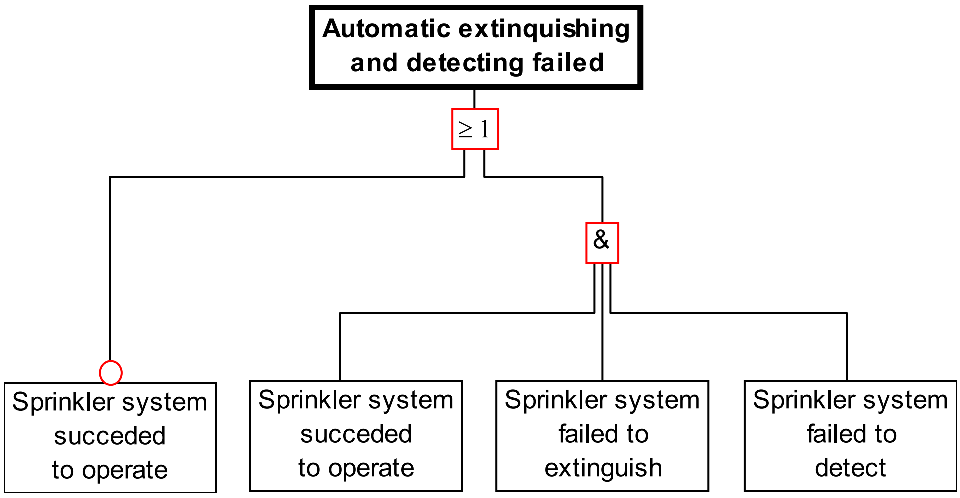

Figure 47. Failure tree of automatic extinguishing and detecting.

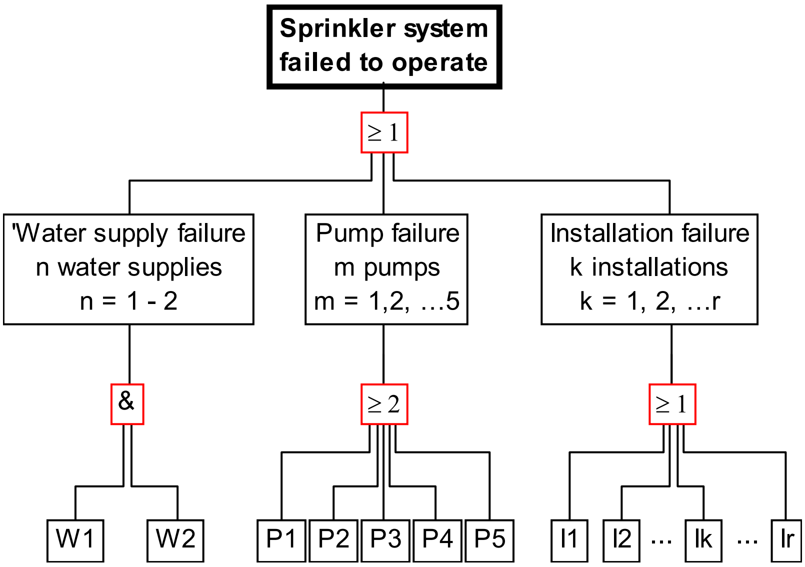

Figure 48. Generalised fault tree of a sprinkler system.

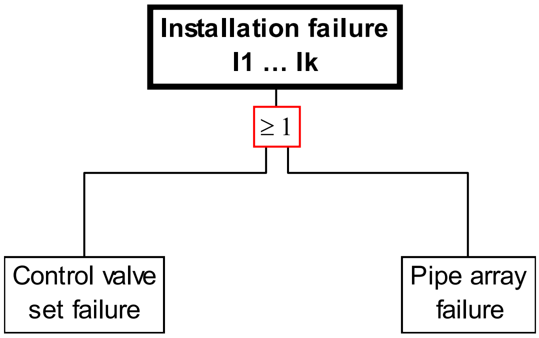

Figure 49. Fault tree of sprinkler installation.

Failure frequencies obtained by preliminary data analysis of this work are presented in Table 27. For a model utilising all the available information in the non-nuclear data body, it has to be analysed more comprehensively, than was possible in these studies.

7. Discussion and conclusions

This paper presents the first more extended scientific study of sprinkler system reliability in Finland. Also international models and comparisons were only few, and no detailed models of carrying out reliability determination of sprinklers from any study was available. Much of pioneering work had to be carried out, and even some efforts, which afterwards seem to lie on side tracks of trunk lines. Therefore, no complete analysis or final results are tried to present here. Instead, a compilation of the major results obtained so far is the goal of this work. In terms of reliability analysis of sprinkler installations the data collected here give the first scientifically based possibility to make an overview of the properties of sprinkler systems in Finland as a whole, and may additionally give some hints on the importance of some components/subsystems from the viewpoint of the reliability of the total system. It is hoped the results of this paper offer some of the prerequisities and necessities of sprinkler system data and models needed for deeper analysis of the properties of the systems to be carried out later.

For non-nuclear installations component populations were estimated on available statistical material. Non-fire failures were analyzed and counted, and some preliminary failure frequencies were determined. Analysis of operational statistics have been started but no results of them are included here. Despite these defiences some general conclusions can be already made on the factors influencing the reliability of non-nuclear sprinkler systems: (a) usage failures are mainly critical failures, (b) maintenance faults are mainly incipient failures, (c) frequency on installation and device failures is already at tolerable level, (d) correlation between maintenance and device failures needs to be studied more thoroughly, (e) increasing of reliability of sprinkler installations is possible by (e1) decreasing of usage failures, and (e2) improving maintenance.

From Finnish NPPs through count on composite populations, and component failures was made as well as determination of component failure frequencies using *frequentist* approach. Since number of failures was small due to tiny component populations, further analysis of frequencies and unavailabilities has to be made by applying also *Bayesian* techniques when possible.

Comparing quality of statistical data from NPPs and non-nuclear buildings it became clear, that there is a big difference between them from the point bearing on reliability of the system. It became clear, that data collection system has to be redesigned for non-nuclear buildings to gap these shortages. Even more important based on the observations above it can be concluded, that the owners and users of buildings have a key role for maintaining the reliability of once installed sprinkler systems. This observation should be brought to clear attention for large public construction works, where life safety is mainly based on the protection provided with automatic sprinkler systems. In these buildings the right and timely actions of users as well as proper maintenance of the systems are really crucial.

In Finland collection of reliability data has become more difficult as a result of the reform of regulations on sprinkler inspection institutions, where SVK lost its practical monopoly in controlling sprinkler installation systems. New regulations (SM 967) do no obligate collection of statistical data. The current authorities (especially TUKES) should promptly take proper actions to make sure, that sprinkler statistics would be collected, for which SM 967 gives a sufficient authorization. For practical use these data should be stored in an electronic data base like PRONTO maintained by Ministry of the Interior for fire statistics. Furthermore, national guidelines are needed for sprinkler inspectors for collection of relevant data, which in addition of the maintenance would also include the most important data needed to assess the reliability of the sprinkler systems.

8. Summary

Spinkler systems are an important part of fire safety of nuclear installations. As a part of effort to make fire-PSA more quantitative a literature survey of available reliability data on sprinkler systems was carried out. Since the result of the survey was rather poor quantitatively, it was decided to mine available Finnish data. Nuclear power plants present a rather small device population. Sprinklers are becoming a key element for the fire safety of modern, open non-nuclear building. Therefore, the study included both nuclear power plants and non-nuclear buildings protected by sprinkler installations.

Data needed for estimating of reliability of sprinkler systems were collected from available sources in nuclear and non-nuclear installations. Population sizes on sprinkler system installations and components therein as well as covered floor areas were counted individually from Finnish nuclear power plants. From non-nuclear installations corresponding data were estimated by counting relevant things from drawings of 102 buildings, and plotting from that sample needed probability distributions. The total populations of sprinkler systems and components were compiled based of available direct data and these distributions.

From nuclear power plants electronic maintenance reports were obtained, observed failures and other reliability relevant data were selected, classified according to failure severity, and stored on spread sheets for further analysis. A short summary of failures was made, which was hampered by a small sample size. From non-nuclear buildings inspection statistics from years 1985–1997 were surveyed, and observed failures were classified and stored on spread sheets. Finally, a reliability model is proposed based on earlier formal work, and failure frequencises obtained by preliminary data analysis of this work. For a model utilizing available information in the non-nuclear data body, it has to be analysed more comprehensively, than was possible in these studies.

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Appendix A: Sprinkler diagrams and fault trees

Symbols used in schematic circuit diagrams represented in Figures A1 and A2, and three examples of sprinkler system schematic diagrams in Figures A3–A5. Fault tree symbols are presented in Figure A6, and fault trees of the three example diagrams are presented in Figures A7–A9, (Hassinen 2000a).

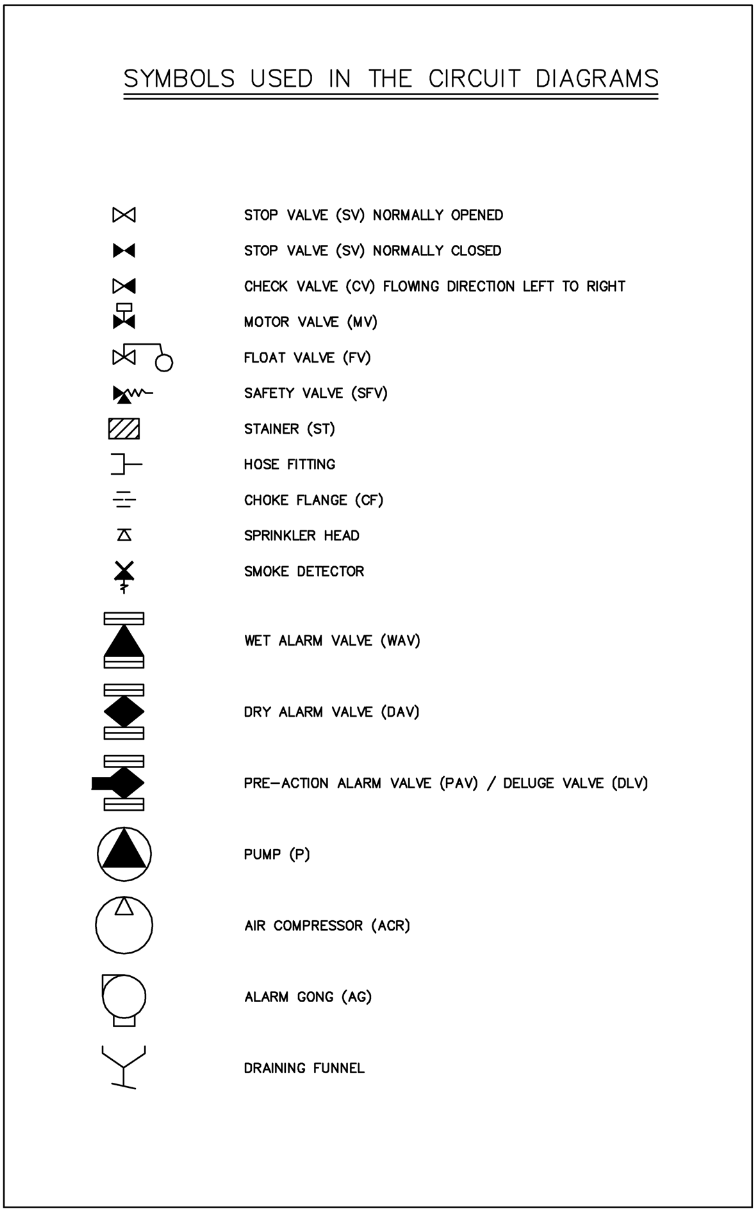

Figure A1. Symbols used in sprinkler circuit diagrams.

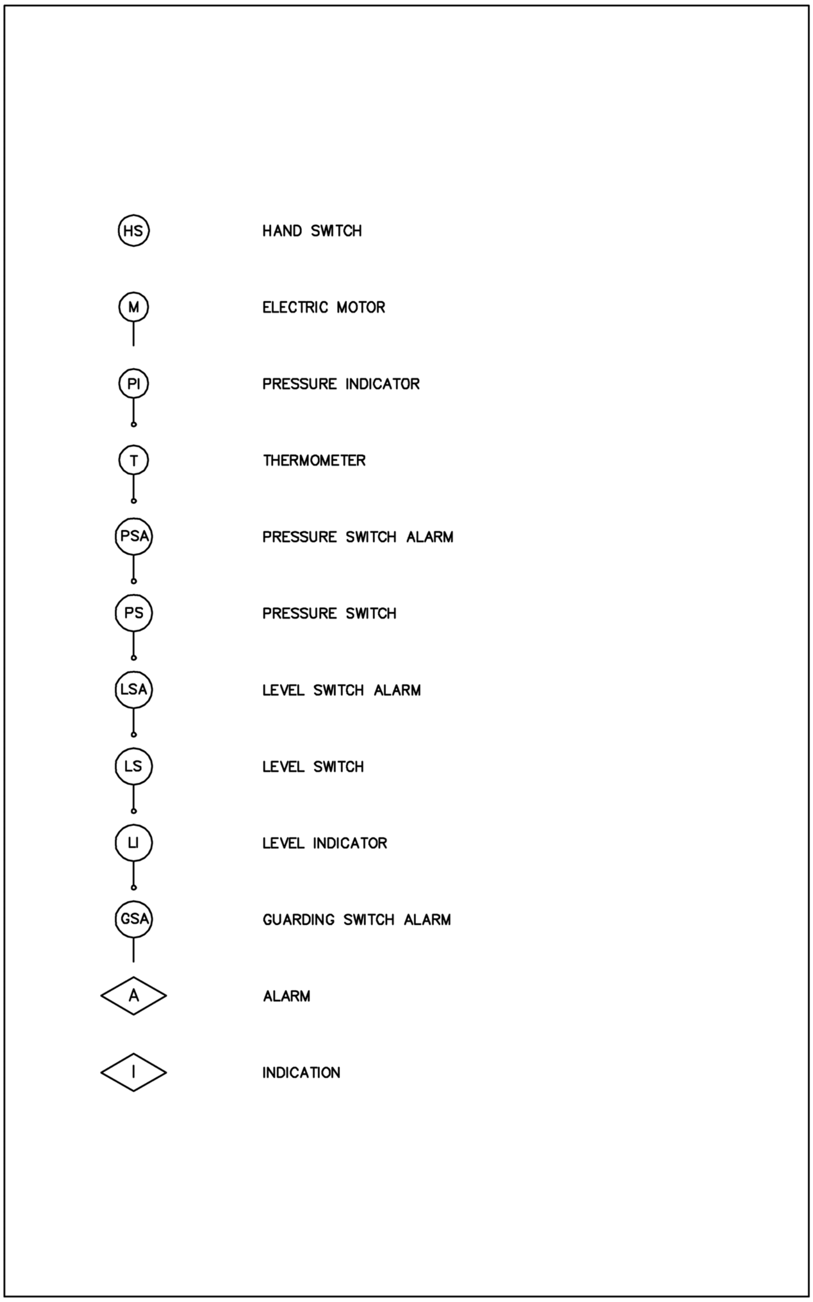

Figure A2. Symbols used in sprinkler circuit diagrams, continued.

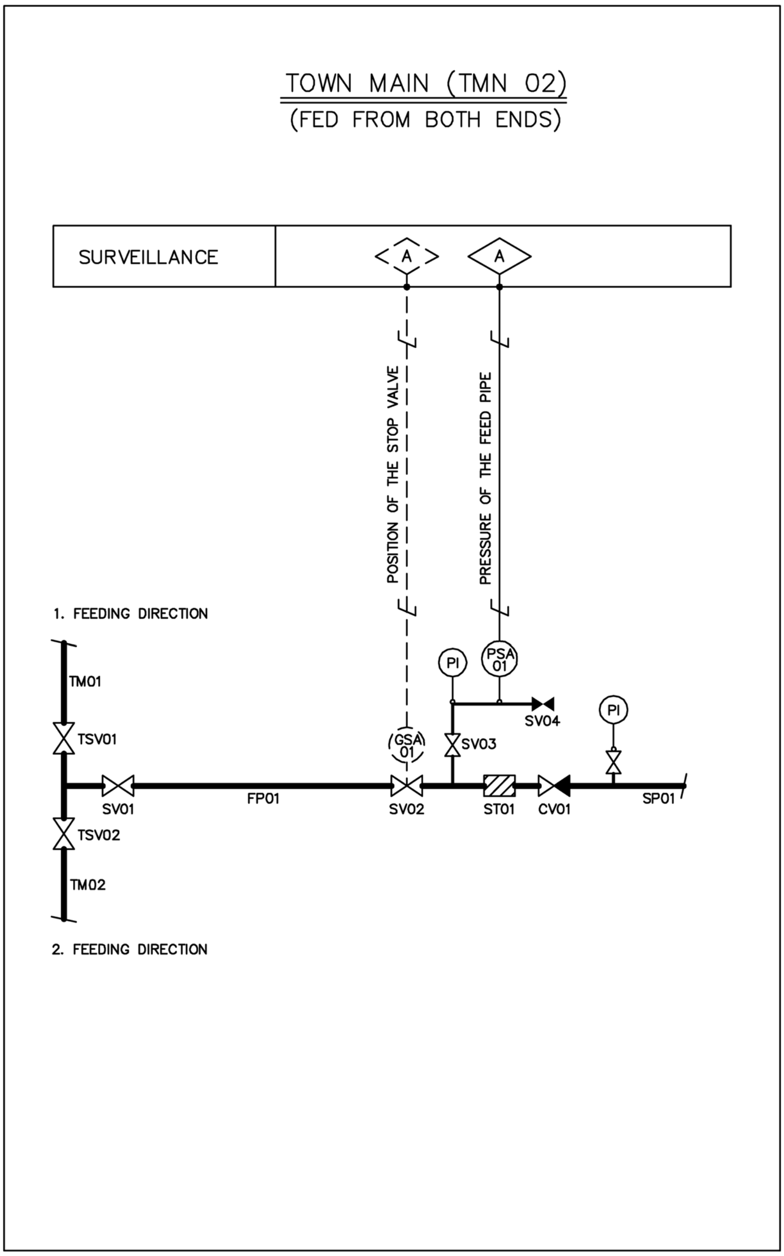

Figure A3. Schematic circuit diagram of town main water supply.

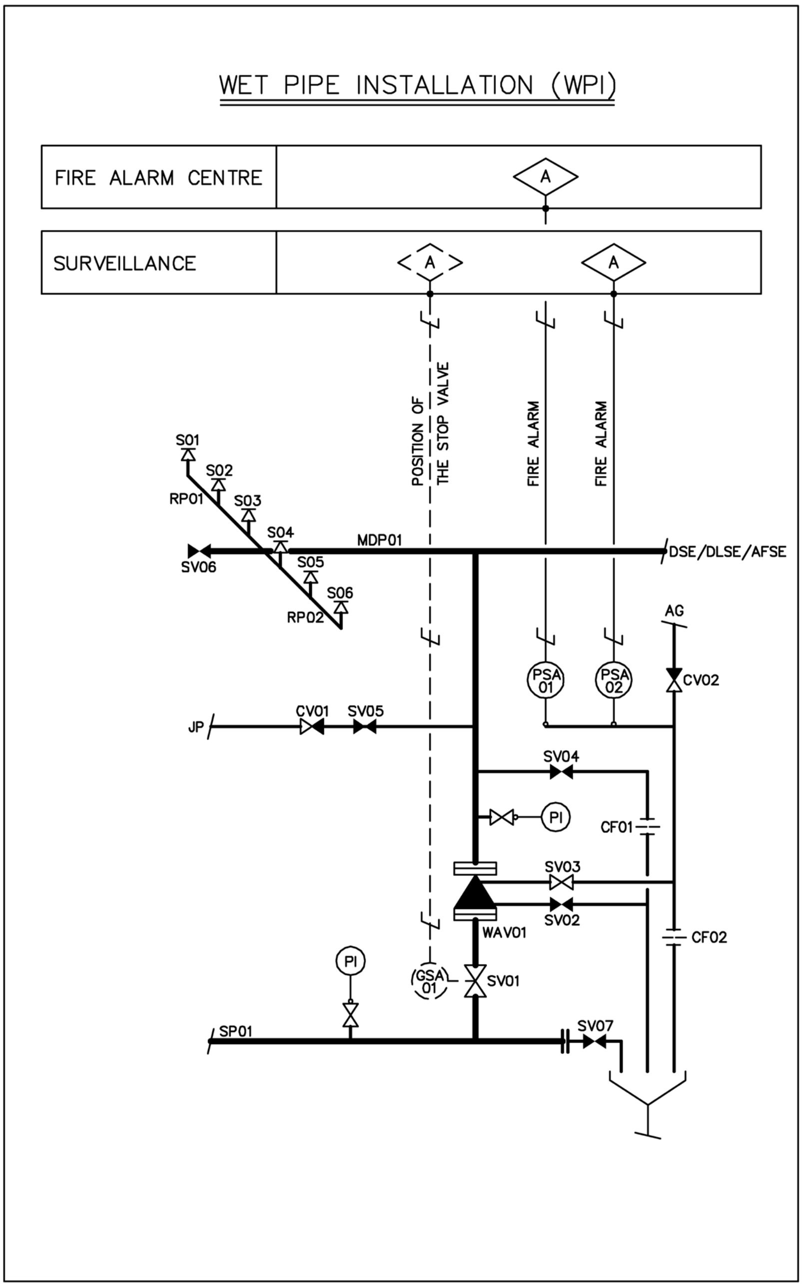

Figure A4. Schematic circuit diagram of a wet pipe installation.

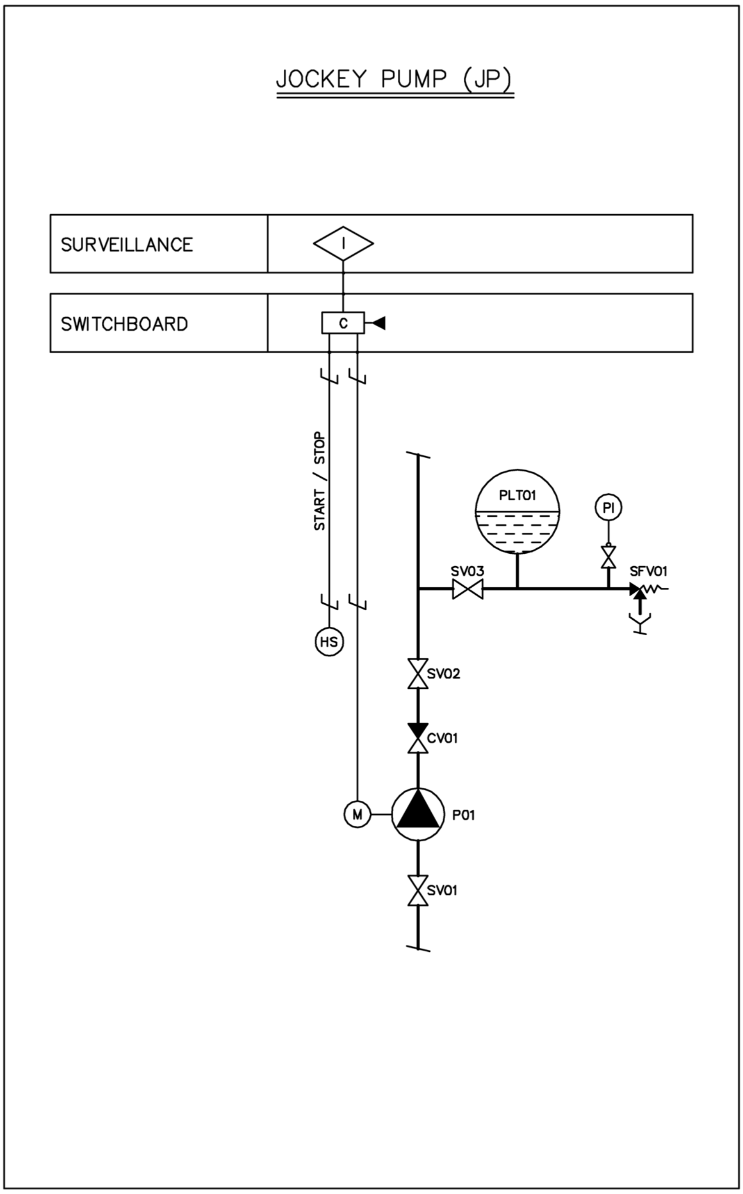

Figure A5. Schematic circuit diagram of a jockey pump.

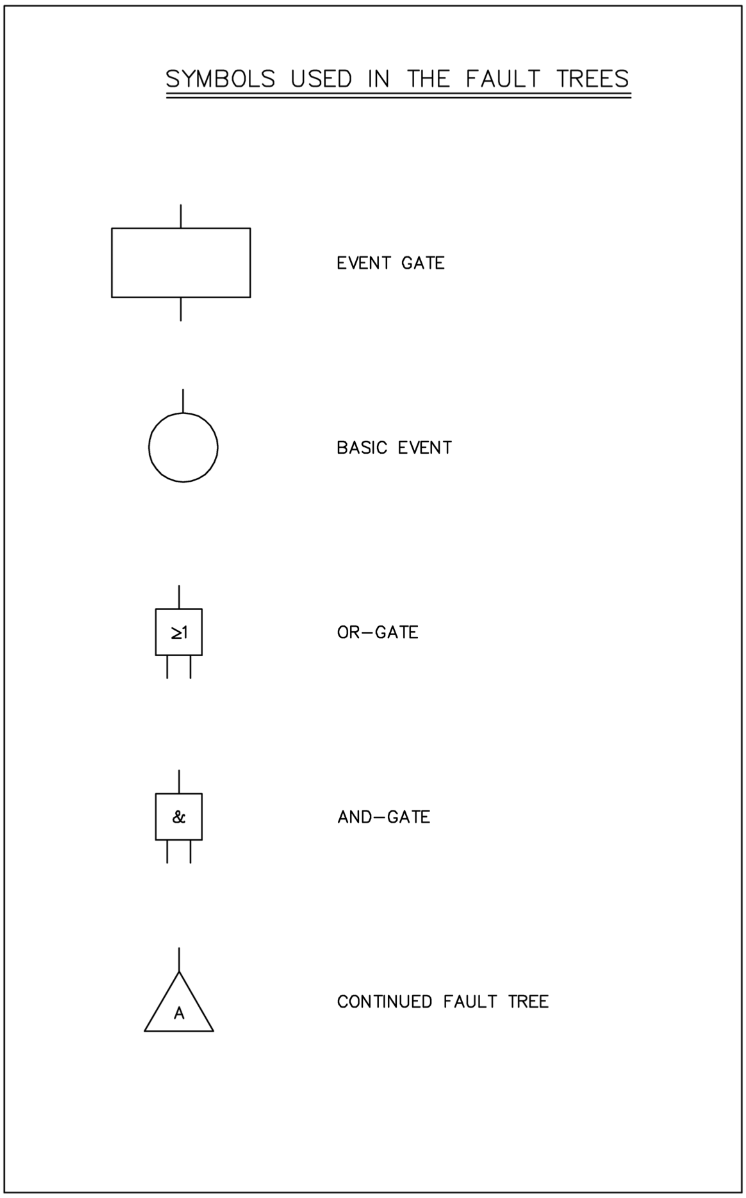

Figure A6. Symbols used in the fault trees.

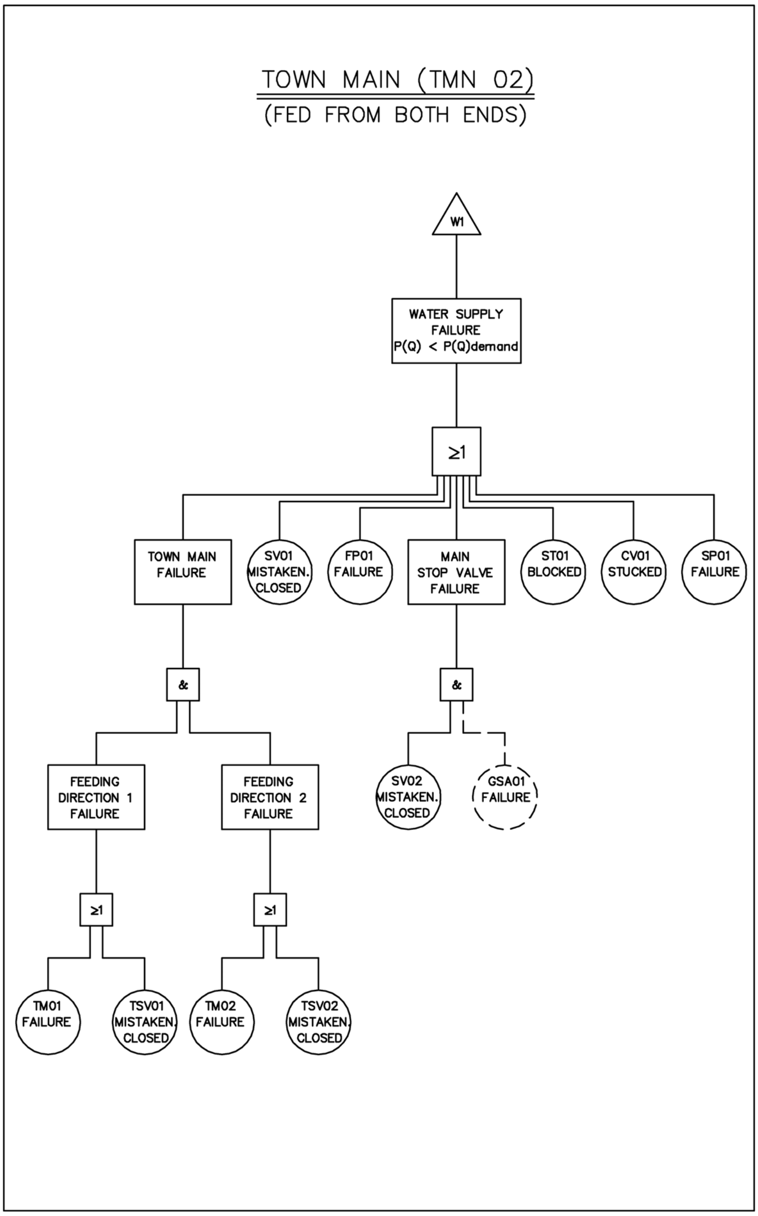

Figure A7. Fault tree of town main water supply presented in Figure A3.

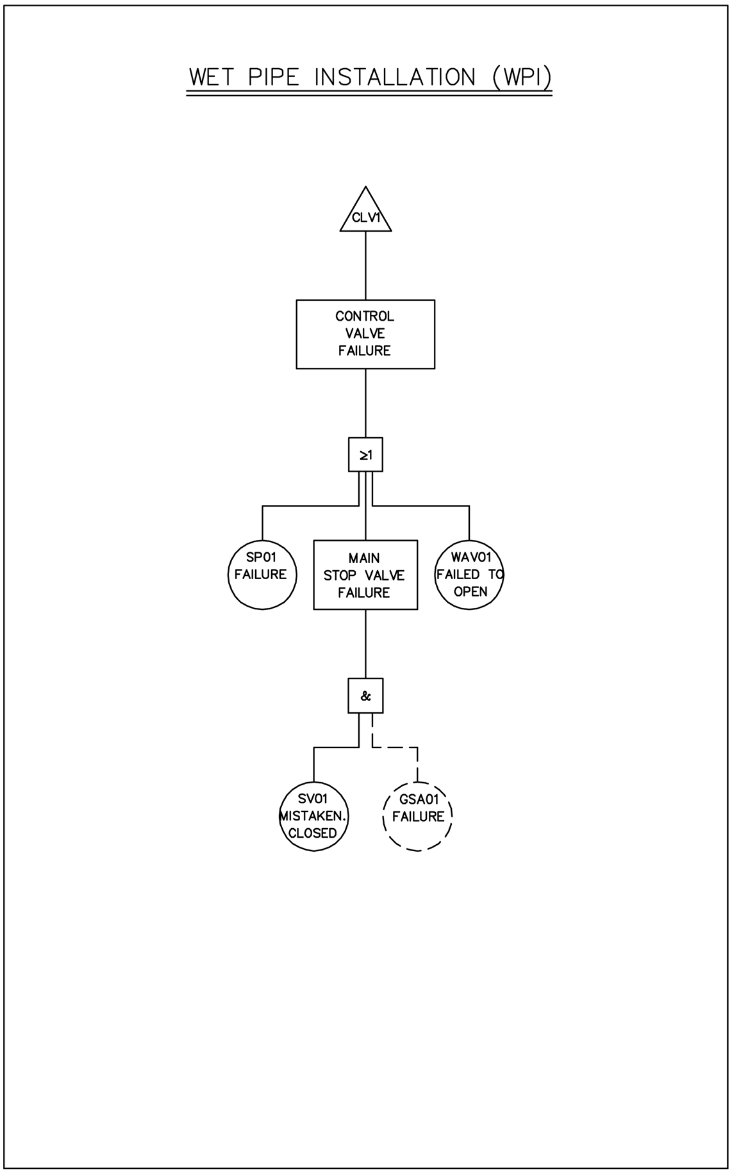

Figure A8. Fault tree of a wet pipe installation presented in Figure A4.

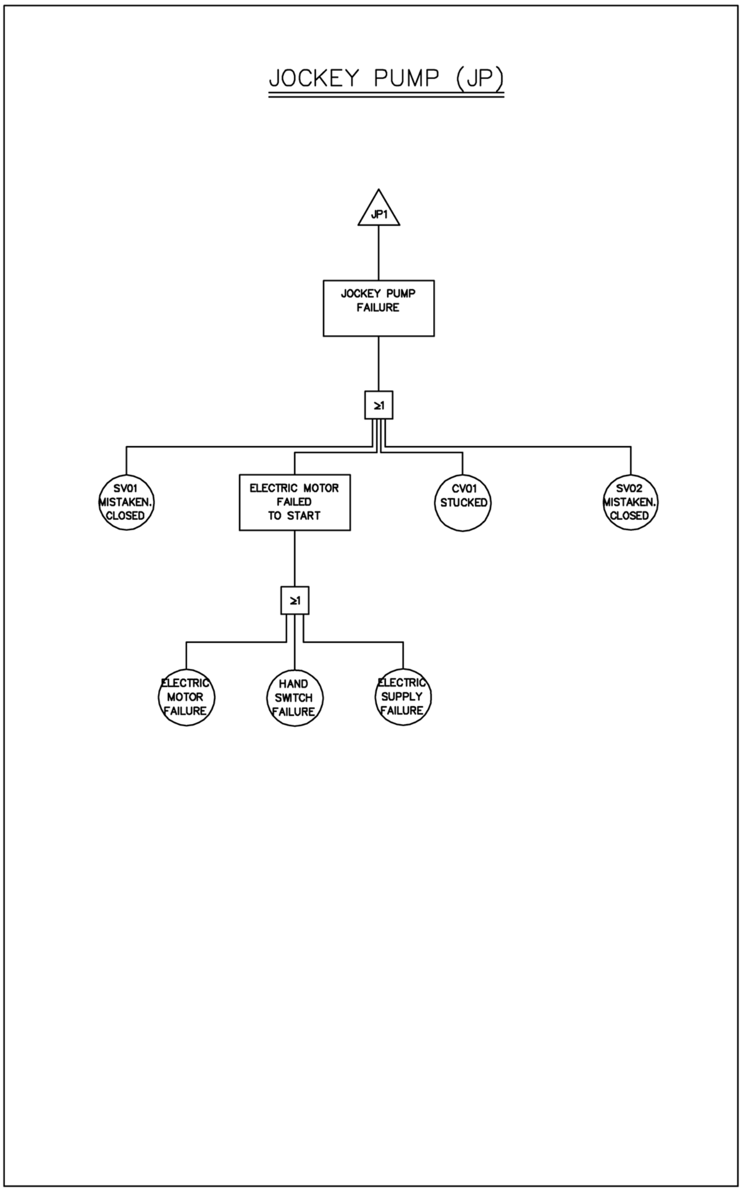

Figure A9. Fault tree of a jockey pump presented in Figure A5.

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