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A BRIEF LOOK AT DATA ON THE RELIABILITY OF SPRINKLERS USED IN CONVENTIONAL BUILDINGS

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Abstract. Failures of sprinklers to extinguish fires generate a basic need for the assessment and increase of reliability of these crucial safety systems. This in turn creates a demand for input data used for reliability assessment. Broadly speaking, data on sprinkler failures are available in large amounts and some countries have well-established systems of data collection and reporting. Data are accumulated in the sprinklered environments of conventional buildings and some industrial facilities. The compilation of data sets necessary for reliability assessment may face several problems: differences in definition and naming failure modes; differences in the failure of data reporting; the prevalence of a human factor among the causes of sprinkler failures in a conventional building; the influence of ageing, modifications and repairs on sprinkler reliability. The size of data sets can be limited by such factors as limited relevance of data collected in different sprinklered environments, differences in operation conditions and components, ageing of data collected in the past, the concealment of data and/or a high cost of data, poor documentation and explanation of data in available databases. Data on sprinkler component failure rates necessary for fault tree models can be extracted from generic databases. However, databases containing information on the failure rates of sprinkler-specific components do not seem to exist in literature or on the Internet. Scarce data on sprinkler failures can be utilised within the Bayesian format. The potentially critical issue of reliability dependence on sprinkler aging and other changes in time remains unsolved from the standpoint of both theoretical modelling and data collection.

Keywords: sprinklers, fire, data source, database, reliability, failure rate, ageing, human error.

1. Introduction

Sprinkler systems can substantially contribute to the prevention of heavy fires and to the mitigation of fire consequences. When applied in combination with another protective systems (e.g. fire alarm), sprinklers can considerably reduce the risk posed by fires (e.g., Melinek 1993a, b; Rasbash *et al.* 2004; Guanquan and Jinhua 2008; Vaidogas and Juocevičius 2008a, b; Chow and Chow 2009; Gałaj 2009; Hola 2007, 2006, 2009a, b, 2010; Konecki and Półka 2009; Vaidogas 2003, 2006, 2009; Zavadskas and Vaidogas 2009; Lai *et al.* 2010; Vaidogas and Šakėnaitė 2010). Unfortunately, another obvious fact is that sprinkler systems are not fail-safe technical objects. The percentage of fires, in which sprinkler systems do not carry out their extinguishing function, is relatively large. Data on the failures of sprinklers and other active fire protection measures collected over the past 50 years indicate that in some cases the chance of failure is unacceptably high (Rasbash *et al.* 2004; Rönty *et al.* 2004; Nyyssönen *et al.* 2005; Hall 2006, 2010; Koffel 2006; Hoła and Schabowicz 2010; Schabowicz and Hoła 2007).

The problem of sprinkler reliability was addressed by many authors who applied various approaches to dealing with potential sprinkler failure. The approaches range from a simple calculation of country-specific failure rates to the estimation of reliability applying methodological means of quantitative risk assessment (QRA) based on Bayesian reasoning (e.g., Siu and Apostolakis 1986, 1988; Hauptmans *et al.* 2008; Malm and Pettersson 2008). However, the issue of failure data and other information necessary for reliability assessment has not been addressed in a more or less systematic way.

The present paper takes a look at available and accessible data on sprinkler reliability. Several aspects related to the collection of this data are also reviewed. An effort was made to distinguish between failure data collected in conventional buildings and data accumulated in installations of nuclear, offshore and process industries as well as military facilities. Attention was focussed on the wide category of sprinklered conventional buildings that make up the largest part of the sprinklered environment. The main purpose was to assess the data situation in terms of the possibility data sets and other information for the estimation of sprinkler reliability.

2. Sprinkler Failure Modes and Collection of Failure Data

A sprinkler system (briefly, sprinklers) is a relatively complicated technical object that can fail in a variety of

Table 1. Four basic types of sprinkler systems (compiled from SFPE 2002)

Type	Principal components/subsystems	No of components/ subsystems
Wet pipe system	Water supply from the main (water tank); gate valve to control water supply to the system; alarm valve; piping network; sprinkler heads	5
Dry pipe system	Water supply from the main (water tank); gate valve to control water supply to the system; dry pipe valve; piping network; sprinkler heads	5
Deluge system	Water supply from the main (water tank); main control valve; electric sprinkler alarm; deluge valve; release valve; smoke detector; thermal detector; control panel; piping network; battery cabinet	10
Preaction system	Water supply from the main (water tank); main control valve; electric sprinkler alarm; deluge valve; check valve; air supply; smoke detector; thermal detector; control panel; piping network; battery cabinet; closed sprinkler head; system maintaining small fire pressure in the fire network	10

ways (modes). Specific failure modes are also related to a specific type of sprinklers that can have four principal arrangements (Table 1).

These four basic types of sprinklers differ in terms of how water is put into the area of fire and, certainly, of how they fail at a component and system level. The lists of components and subsystems given in Table 1 should be supplemented with critical human "components" (system owner, designer, installer, inspector, maintenance person). A human factor plays a major role in the failures of sprinklers installed in conventional buildings, the safety culture of which is not necessarily very strict (e.g., Hall 2006, 2010).

Contribution of failures at the component level to the sprinkler system failure is represented by means of fault tree diagrams (Rönty *et al.* 2004; Hauptmans *et al.* 2008). Both the identification of system failure modes and the development of fault tree diagrams for them will reveal data necessary for the estimation of system reliability. A unified and, ideally, world-wide classification of the causes and modes of sprinkler failures could improve the collection and exchange of failure data and probably the quality of the received data. Unfortunately, a simple look at literature devoted to sprinkler reliability shows that in the past years, different authors/countries applied different classifications of modes and causes of system failure (Tables 2 and 3). Some authors put modes, causes and circumstances of failures together in one list. Differences between some definitions of failure modes may be only semantic; however, a lack of a unified failure terminology does not facilitate the collection and exchange of data.

Reasons for the variation of failure causes and modes are analysed by Malm and Pettersson (2008). They also detected and addressed an obvious variation of reliability estimates among different sources. An illustration of such a variation is shown in Table 4. In our opinion, variations in reliability estimates as well as a lack of unification in naming the causes and modes of sprinkler failures is among four factors that complicate the estimation of sprinkler reliability (Fig. 1, corners 1 and 2).

One can expect that sprinkler failure terminology is unified in some industries and military environments with high safety culture and a well-developed system of reliability and accident data collection; first of all, we should mention nuclear and offshore industries (e.g., see Cadwallader and Eide 2010 and the references therein, NTNU 2010). However, industrial and military installations are only a small fraction of the sprinklered built environment.

The dominance of a human factor among the causes of sprinkler failures is another issue that complicates reliability estimation (Fig. 1, corner 3). Human errors can be the cause of all types of sprinkler system failures (Fig. 2). Hall (2006, 2010) states that according to US data collected after fires in conventional buildings, almost all sprinkler failures to operate (demand failures) were caused by human errors. Only 2 to 3% of such failures were due to damaged components. It is obvious that at least in buildings with relatively lax safety culture, the problem of sprinkler reliability is largely the problem of human reliability. In this respect, sprinklers are similar to building structures, the failures of which are caused predominantly by human errors (e.g., Melchers 1999). The prediction of improper human behaviour in the design, installation and use of sprinklers requires specific data.

Generic data on human errors are available in the form of human reliability databases, such as THERP, HEART, HRC and INTENT (e.g., Vaidogas 2007;

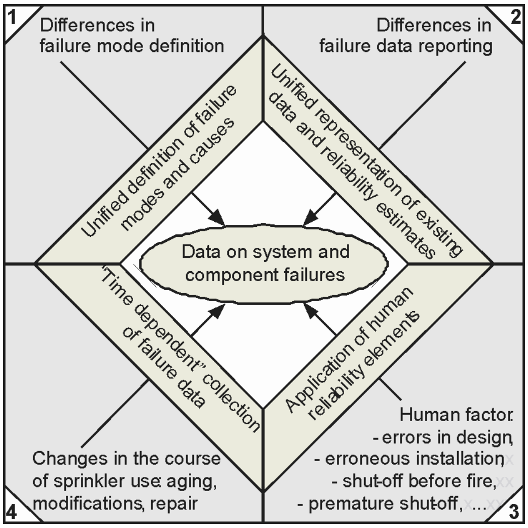

Fig. 1. Four factors complicating the collection and exchange of data on sprinkler reliability (corners 1 to 4) and steps towards possible solutions (inclined segments)

Vlasenko and Kozlov 2009). However, such data were collected mainly in industrial environments. At present, it is not clear to what degree information from such databases is suitable for the estimation of the reliability of sprinklers used in conventional buildings. Any sprinkler-specific database of human reliability is not known to us.

The influence of a human factor now can be approximately assessed from the general studies of sprinkler reliability (e.g., Rönty *et al.* 2004; Malm and Pettersson 2008; Hall 2006, 2010). The incorporation of human errors into fault tree analysis (FTA) aimed at estimating sprinkler reliability can reveal what specific human reliability data may be necessary for estimation (Hauptmans *et al.* 2008). However, FTA as such does not generate data.

Table 2. Lists of modes and causes of sprinkler failures used by different authors

Author(s)	Failure modes and causes
Linder (1993)	Installation errors, design mistakes, manufacturing/equipment defects, lack of maintenance, exceeding design limits, environmental factors
Rönti *et al.* (2004)	Usage failure, maintenance failure, installation failure, device failure, instruction failure
Malm and Pettersson (2008)	No activation of the sprinkler system, fire in an non-sprinklered area with deficient fire compatmentation, an extinguishing agent does not reach fire (insufficient amount of water, inadequate design), sprinkler system shut off
Siu and Apostolakis (1986, 1988)	Failure to actuate given demand (demand unavailability), failure to put out fire given actuation, suppression of fire after a critical set of components has been damaged
Koffel (2006), Hall (2010)	Operational failure/reliability, performance failure/reliability

Table 3. A brief summary of data on sprinkler failure probabilities (Moelling *et al.* 1980, reproduced also by Rönti *et al.* 2004)

Failure mode	Point estimates and 90% confidence estimates of probability per demand		
	Lower bound	Point estimate	Upper bound
Sprinkler heads fail to open	Not reported	$<1\times10^{-6}$ (0.0001%)	Not reported
Fire detectors fail to function	1.89×10^{-3} (0.189%)	2.97×10^{-3} (0.297%)	4.45×10^{-3} (0.445%)
Deluge valves fail to open	8.9×10^{-4} (0.089%)	1.90×10^{-3} (0.19%)	3.58×10^{-3} (0.358%)
Fire pumps fail to start	4.47×10^{-3} (0.447%)	1.40×10^{-2} (1.4%)	2.39×10^{-2} (2.39%)
Check valves fail to open	3×10^{-5} (0.003%)	1×10^{-4} (0.01%)	3×10^{-4} (0.03%)
Alarms fail to function	2.681×10^{-2} (2.681%)	3.62×10^{-2} (3.62%)	4.81×10^{-2} (4.81%)
Personnel fail to trip manual release	Not reported	0.2	Not reported
Frequency of the event "valves closed inadvertently"	5.47×10^{-3} year^{-1} (0.547%)	5.475×10^{-2} year^{-1} (5.475%)	0.5479 year^{-1}

Table 4. A brief summary of data on sprinkler reliability

Country	Reference	Reliability (success rate)	Failure rate
Sweden	Malm and Pettersson (2008)	69% in from 690 fire incidents	31%
Finland		38% in from 351 fire incidents	62%
Norway		74% in from 457 fire incidents	26%
UK	Rutstein and Cooke (1979)	92…97% for various types occupancies	3…8%
		95.6% for all industrial buildings	4.4%
		97.8% (a reliability value taking into account successful sprinkler operation in fires not reported to the brigade)	2.2%
	Malm and Pettersson (2008)	85% from 163 fire incidents in London	15%
Australia and New Zealand	Marryatt (1988)	99% for all building categories	1%
New Zealand	Malm and Pettersson (2008)	96% for 483 fire incidents in 2002–2008	4%
US	Automatic sprinkler performance tables (1970)	90% for all building categories	10%
	Miller (1974)	96% (all building categories for the period 1897–1964, NFPA data)	4%
		85% (for the period 1970–1972, Factory Manual Research Corporation (FMRC) data)	15%
		95% (for the period 1966–1970, US Navy data)	5%
		86% for a wet-pipe sprinkler system	14%
		83% for a dry-pipe sprinkler system	17%
		63% for a deluge system	37%
	Budnick (2001)	81...95% from a review of 13 reliability estimates	5...19%
	Koffel (2006)	91% for all building categories	9%

Changes during a long-lasting life of sprinkler systems are the fourth factor making difficult the collection of failure data suitable to adequate reliability estimation (Fig. 1, corner 4). In conventional buildings, sprinklers are used over several decades and are subjected to gradual ageing. It is natural to expect that ageing along with modifications and repairs "invisibly" influence the reliability of sprinklers. In addition, changes in building ownership or tenancy during the life-time of sprinklers can lead to changes in safety culture and thus the influence of a human factor on possible failures.

Data collection that would allow full-scale time-dependent reliability analysis will require an observation of sprinkler populations lasting many years and, possibly, carrying out accelerated degradation (ageing) tests. Any data collected in such a way is not known to us. We can only notice again that the problem of the time-dependence of sprinkler reliability is similar to the time-dependence of the reliability of building structures (e.g., Melchers 1999; Vaidogas and Juocevičius 2007, 2009; Juocevičius and Vaidogas 2010). Knowledge gained in the latter field can be applied in the former one.

The failure modes of sprinklers also include accidental activation (discharge of water in the absence of fire). Non-fire activation is mainly due to a manufacturing defect, an improper installation or a user error. Data on accidental system activations are presented, among others, by Jensen *et al.* (2006), Butry *et al.* (2007) and Hall (2010). In principle, both the probability of sprinkler failure in fire and in the absence of fire can be estimated by means of FTA. In either case, FTA will require component failure data and human reliability data. At the present time, we are not aware of any open data source that would contain component level data related to non-fire activations.

3. Data related to sprinkler reliability

The potential sources of information that can be used for the assessment of sprinkler system reliability can be classified as follows:

1. Direct post-mortem data on sprinkler system failures during fires;
2. Input data on system component failures for fault tree models developed for specific sprinkler systems;
3. Specific information that may influence the results of sprinkler reliability assessment (e.g., the percentage of fires in which sprinklers operate and which are not reported to the fire brigade, see Rogers 1977; Rasbash *et al.* 2004);
4. Subjective knowledge allowing expert judgment used in QRA models that can be developed for a sprinkler system (e.g., Siu and Apostolakis 1986, 1988).

Hard historic data on sprinkler failures at the system and component level is yielded by the first two information sources. Data from the third data source can, in essence, be attributed to one of the first two sources. The subjective information classified as the fourth data source can be combined with the hard data within the Bayesian approach to QRA (Siu and Kelly 1998; Kelly and Smith 2009).

3.1. Potential Populations for Retrieving Data on System Failures

The number of sprinkler installations in large countries and regions counts millions. The number of fires in sprinklered buildings can be in thousands of events from the population of millions and the number of sprinkler failures in fires can reach hundreds of events (e.g., Rohr 2001; Rohr and Hall 2005; Hall 2010). Thus, at first glance, the possibly large amount of direct data on sprinkler failures might allow assessing sprinkler failure probability by means of the classical (Fisherian) approach. However, the variety of environments, in which sprinklers are installed, and differences within the population of sprinklers may constrain the possibility of estimating reliability directly from failure data.

The size of the population of sprinkler installations and failure data retrieved from this population may be limited by several factors shown in Fig. 2. These factors include:

- the culture of data collection and exchange;
- the relevance of data from different environments;
- possible concealment of failure data.

The collection and exchange of sprinkler reliability data have a different level of organisation in different environments. Data are systematically accumulated and shared in nuclear power plants through a voluntary collaboration of a number of installations worldwide (e.g., Berg and Röwekamp 2000; Atwood *et al.* 2003; Cadawallader 2007). Some other industries, for instance, oil and gas production, have also a well-organised collection of data on the reliability of fire detection and suppression measures (e.g., OGP 2010). However, nuclear power plants as well as some industrial and military installations are a relatively small fraction of the sprinklered build environment. International collaboration in the collection of failure data seems not to be available in the case of sprinkler installations in conventional buildings (e.g., residential, institutional and public ones).

The availability and quality of failure data may be positively influenced by the legislation and/or practice of data collection and reporting in specific countries (Malm and Pettersson 2008). Rasbash *et al.* (2004) praise Australia and New Zealand for establishing a thorough compilation and reporting data on the performance of sprinklers. In these two countries, all sprinkler systems are by law directly connected to fire stations and thus activation is automatically accompanied by the attendance of a brigade. Hall (2006, 2010) describes American fire accident reporting system NFRIS that allows to calculate sprinkler failure rates using US data on fires. Unfortunately, it is difficult to say how much failure data from these three countries is relevant to sprinklered environments in other regions.

Different environments are characterised by different safety culture and, possibly, different dominant causes of failures and the quality of reliability data. One might

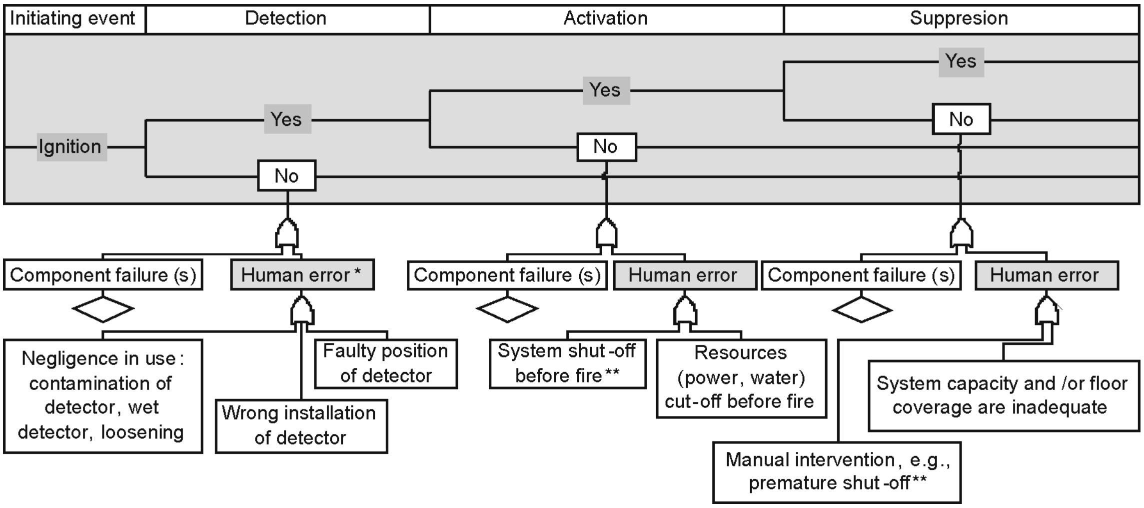

Fig. 2. A schematic event tree shown with the fault trees developed for the illustration of the influence of human error on sprinkler system failure (*according to Nyyssönen *et al.* (2005); **according to Hall (2006))

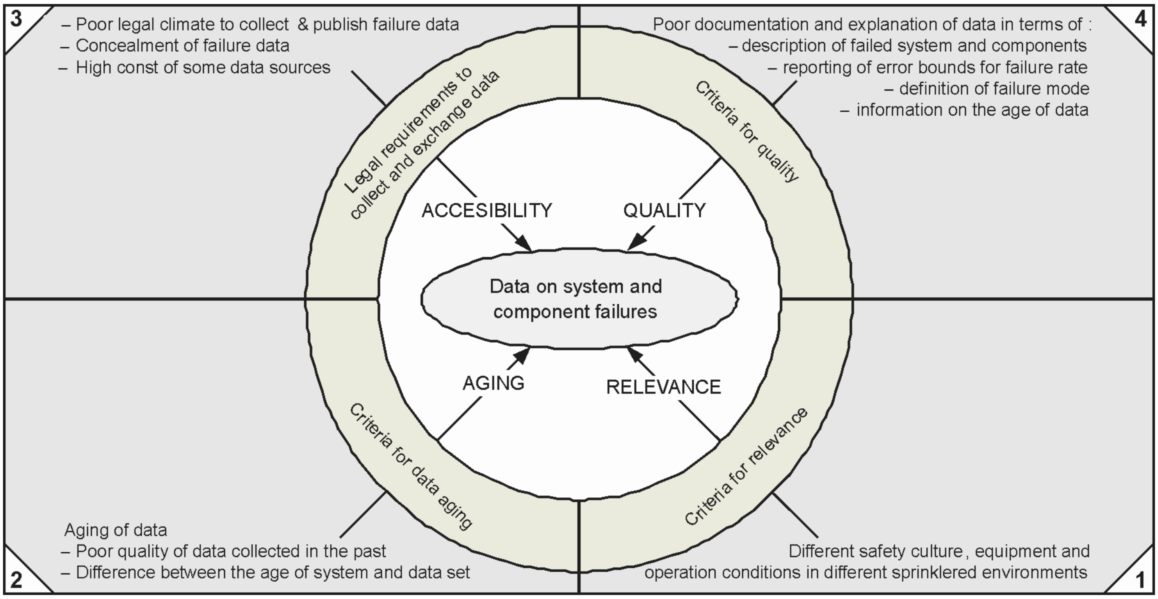

Fig. 3. Four problems related to the collection and use of data on the failures of sprinkler systems and components: problems are shown in corners from 1 to 4; approaches to their solutions are shown in the ring

expect that safety culture in nuclear and military installations is higher than that in conventional buildings. Thus, failure data from nuclear industry can hardly be automatically applied to, for example, domestic sprinklers. Any attempts to measure formally, more or less, the degree of the relevance of system failure data to different environments are not known to us.

The relevance of failure data can be considered on the much more detailed level. It is probable that different manufacturers and installers of a specific sprinkler system achieve a different level of reliability. Therefore, failure data at system and component levels collected by a specific manufacturer may not be applicable to products of other manufacturers.

The relevance of sprinkler failure data can also be influenced by the period in which the data was collected. It is natural to expect that data on failures accumulated in, for example, ‘60s and ‘70s, may not be fully relevant to sprinkler systems manufactured following 30 or 40 years. The general problem and causes of data ageing is mentioned in reliability literature, for instance, by Cadwallader and Eide (2010). However, any study on the “ageing” of data on sprinkler system failures does not seem to be available.

The availability of data on sprinkler failures can also depend on the possible negative influence of these events on the business of system manufacturers and insurance companies. One can expect that, at least in some countries, data on sprinkler failures in some specific built environments are kept secret by insurers and manufacturers for commercial reasons. This may be the cause of the scarceness of such data for those who do not have access to in-house information owned by insurers and manufacturers.

3.2. The Sources of Data on System Failures

Data on sprinkler system failures are published in studies reported between 1950 and 2000. A brief review of such studies is presented in Table 4. Similar reviews with references to individual studies and "raw" estimates of sprinkler reliability are presented by Bukowski *et al.* (1999), Fleming (2004), Rasbash *et al.* (2004), Koffel (2006) and Malm and Pettersson (2008). Studies on sprinkler reliability present information in the form of raw data (e.g., the size of sprinkler population and the number of fires and failures) and data reduced into failure rates and probabilities related to specific failure modes (Rönty *et al.* 2004; Hall 2006, 2010; Koffel 2006). Table 3 is an example of the latter type of data accumulated in four nuclear power plants.

Many of the published studies into sprinkler reliability cover failure data obtained in the specific environment of nuclear power plants (Moelling *et al.* 1980; Berg and Röwekamp 2000; Rönty *et al.* 2004; USNRC 2005; Berg *et al.* 2006). There are also reports covering a wide range of data on sprinkler failures in buildings used outside nuclear industry (Rohr 2001; Rönty *et al.* 2004; Rohr and Hall 2005; Hall 2006; Koffel 2006; Malm and Pettersson 2008). The scope, breadth and reporting periods of the studies cited above vary significantly. A brief look at these studies allows stating that data on system failures are undoubtedly available. However, data accumulated outside nuclear and offshore industries reflect mainly the performance of sprinklers in specific countries within specific periods. Any attempt to develop an international database from such data is not known to us.

It seems that at present one can simply say that a particular set of data (raw data or failure rates) will be suitable for estimating the reliability of a specific sprinkler system only after it is possible to prove that this system belongs to sprinkler population that generated the data set. On the other hand, generic data on sprinkler system failures can be useful for the estimation of system failure probabilities within the Bayesian format, for instance, the development of prior distributions for system failure probabilities (see Sec 4). In addition, hard system failure data can be used for an approximate verification of system reliability estimates obtained by means of FTA.

3.3. Component Failure Data

The estimation of sprinkler system reliability by means of FTA is the opposite of estimation directly from system failure data. FTA requires component failure data and answers to the question where such data can be found are often OREDA data book (OREDA 2002), IEEE Standard 500 (IEEE 1986a,b), or the CCPS Guidelines for process equipment reliability data (CCPS 1989). Cadwallader and Eide (2010) present a review of data sources retrievable in literature available since 1993. A list and short description of component reliability data sources can be found in the website of the Norwegian University of Science and Technology (NTNU 2010).

The above mentioned sources contain only a considerable body of generic data that can be useful as the first approximation of the failure rates of sprinkler system components. For instance, Hauptmans *et al.* (2008) refers to data from three different environments (offshore, nuclear and process plant data) to perform the FTA of a wet sprinkler system. The use of data collected in different environments yields an estimate that undoubtedly may be taken as the first approximation to system reliability. However, the "mixture" of input information may cast a natural doubt upon the relevance of this estimate to each of these environments taken alone, to say nothing of the sprinklered environment in conventional buildings.

The majority of the sources of component failure data are specific to the environments of nuclear, offshore and chemical industries as well as military installations. The range of engineering system components covered by these data sources is very wide. However, specific information on sprinkler system components is not present in them. For instance, OREDA data book includes information on gas and fire detectors and does not say anything about fire extinguishing systems (OREDA 2002). IEEE Standard 500 contains information on the failures of pumps and valves; this information might be applicable to the components of sprinkler systems (IEEE 1986b). However, direct data on sprinkler system components is not available in this data source. We suppose that a special study is necessary to determine whether or to what degree the general sources of data on engineering system component failures can be used to perform FTAs of sprinkler systems installed in conventional buildings.

It is natural to assume that the manufacturers of sprinkler systems installed in conventional buildings, insurers and persons/bodies inspecting and maintaining such systems may possess in-house collections of data on component-level failures. Unfortunately, it does not seem that somebody took an effort to assemble such data into a component-specific database that would be retrievable from literature or Internet. We even did not find any reference to such a database. At present, it is also not clear how fire incident reporting systems, such as NFRIS in the USA and a system developed by Swedish organisation NCO are suitable to extract reliability data related to sprinkler system components.

Some data on sprinkler component failures recorded in nuclear and non-nuclear environments are presented in the report prepared by Rönty *et al.* (2004). However, this report can hardly be considered a systematic database.

4. Bayesian Inference and Data on Sprinkler Failure

4.1. Data Required by Usual Bayesian Schemes

A large set of failure data allows calculating an accurate frequent estimate of sprinkler reliability. A usual estimate is a confidence interval of binomial parameter p or Poisson parameter λ. Rönty *et al.* (2004) and Nyyssönen *et al.* (2005) present an interval estimation of λ for sprinklers and fire detection and alarm systems. As sprinklers operate on demand and not over time, the following consideration will focus on binomial parameter p.

Data on sprinkler failures can be scarce due to various reasons. Some of them were considered in Sections 2 and 3.1. Data scarceness can also be faced during the prediction of human errors and acts of negligence in installation and the use of sprinklers and other fire safety systems. Data on sprinkler ageing and the influence of modifications and repairs on the process of ageing may also be scarce from the standpoint of frequentist estimation.

Bayesian inference is used for dealing with small data sets as well as for combining several sources of information for the estimation of distribution parameters. To our knowledge, the first application of Bayesian inference to scarce sprinkler failure data collected in nuclear installations was done by Siu and Apostolakis (1986, 1988) in 1980. As applied to the estimation of p, Bayesian inference uses subjective believes and/or data from different sources to specify prior density $\pi(p)$ as well as the so-called plant-specific data E to update $\pi(p)$ to posterior density $\pi(p \mid \mathrm{E})$ (e.g., Siu and Kelly 1998).

The widely known schemes of parameter estimation are hierarchical Bayes and empirical Bayes methods (e.g., Atwood *et al.* 2003). QRA literature describing these methods is, as a rule, semantically oriented to nuclear power plants. However, both methods can be directly applied to the case of sprinklers, as long as failure data is available and can be arranged according to the schemes of applying these methods. The position of raw data on sprinkler failures in a special case of the hierarchical Bayes method is illustrated in Fig. 4.

One can see several points of estimating Bayesian parameter considered to be problematic:

1. The expression of failure data in forms E and E_k shown in Fig. 4 requires the collection and exchange of raw data as well as a careful characterisation of the environment that generated each pair (r_i, n_i). Unfortunately, we do not know any reports about an attempt to form data E for at least most typical sprinklered environments.
2. It might be problematic to state what are similar, but not identical, sprinklered environments (or plants in conventional terms of QRA) and what degree of difference between such environments is still acceptable?
3. Data E and E_k do not contain direct information on human errors and ageing as the potential causes of sprinkler failures. Thus, estimates $\pi(p)$ and $\pi(p \mid \mathrm{E})$ will not allow saying anything about the contribution of these factors to failures.

It is difficult to clearly state how much probability p is influenced by ageing, repairs and modifications of sprinklers. However, the existence of upwards or downwards trend in p and other changes of p over time will require to apply time-dependent modelling that must be backed by specific failure data.

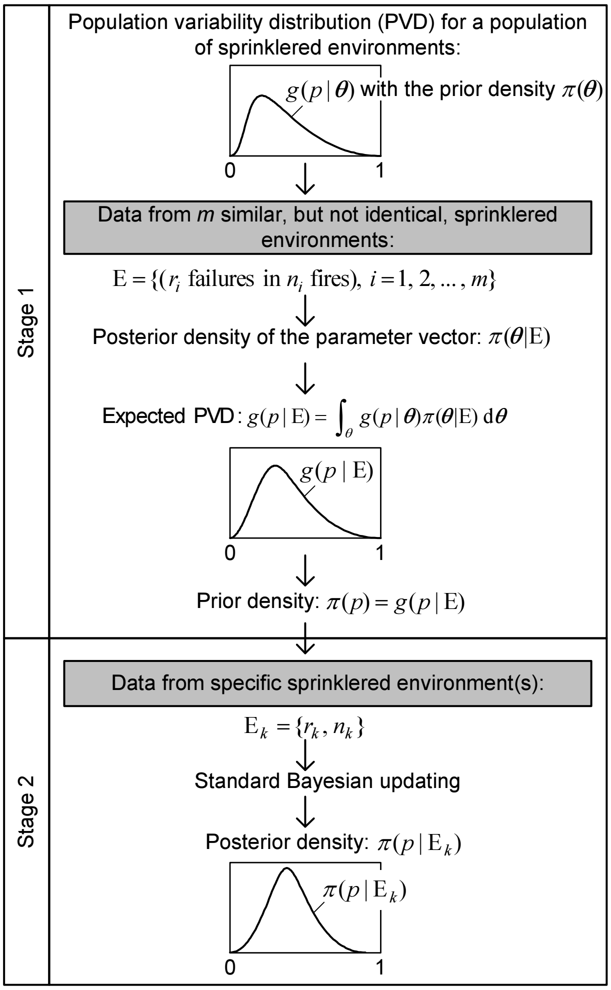

Fig. 4. The position of data on sprinkler failure in the two-stage Bayes method applied to binomial parameter p (this method is a special case of the hierarchical Bayes method, e.g., Siu and Kelly 1998)

4.2. Data on Ageing Analysis

The basic model of ageing is a time trend (gradual change) in p expressed as $p(t)$ (Fig. 5). The standard choice of $p(t)$ is the logit model:

$$\ln(p(t)/(1 - p(t))) = \alpha + \beta t, \tag{1}$$

with intercept parameter α and trend parameter β. They can be estimated from data by means of either frequentist or Bayesian inference (Atwood *et al.* 2003). The presence of the trend can also be checked from available data by applying either frequentist or Bayesian methods (Kelly and Smith 2009). If $p(t)$ is small, the logit model can be approximated by the log linear model:

$$\ln(p(t)) = \alpha + \beta t. \tag{2}$$

Raw data used to test for the presence of trend and to obtain confidence intervals of $p(t)$ (in the frequentist case) and posterior distributions of $p(t)$ (in the Bayesian case) must be collected by counting the number of demands and the number of failures on demand during some period of time. This data must be generated by a population of objects (say, sprinklers of specific type) to which the object under analysis can be attributed.

To carry out frequentist or Bayesian analysis, raw data is combined into bins, usually, calendar years. In this way, the so-called binned binomial data are obtained. As we did not find an example of binned data related to sprinkler failures, such data is illustrated in Table 5 for a demand event in nuclear industry (high pressure coolant

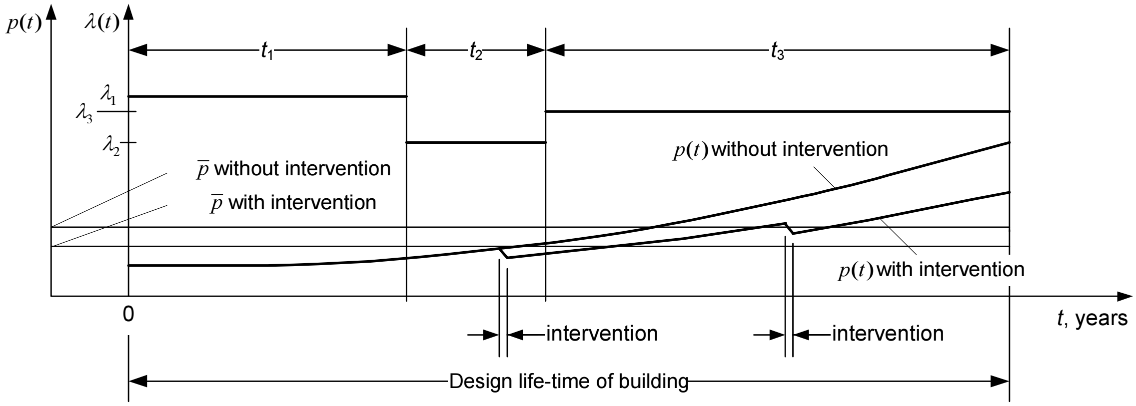

Fig. 5. Two evolutions of sprinkler failure probability $p(t)$ during the life-time of the building divided in three periods with different fire hazards expressed by annual fire rates (Poisson parameters) λ_1, λ_2, and λ_3

injection). Binned binomial data can also be obtained by testing some number of components during an annual plant outage (Pulkkinen and Simola 2000).

We suppose that, in principle, binned binomial data can be extracted from general data on sprinkler failures. Binning must be preceded by the determination of relevant population that will generate data. A natural choice is population consisting of nominally identical or very similar components or systems installed in comparable environments. At the present time, any attempts to analyse time trend in the failures of sprinklers by means of binned binomial data are not known to us.

Table 5. Binned data on failures in demand for a critical system in 23 nuclear reactors (Atwood *et al.* 2003)

Calendar year (bin)	Number of failures	Number of demands	Exposure time (years)*
1987	4	16	14.63
1988	2	10	14.15
1989	1	7	15.75
1990	3	13	17.77
1991	2	9	17.11
1992	0	6	17.19
1993	0	2	17.34

* The number of years in the bin when the reactors were producing steam

One can expect that the trend in sprinkler failure probability p will be positively influenced by the interventions of relatively short duration (maintenance, modifications and repairs of sprinklers) (Fig. 5). Changes in $p(t)$ may take place several times within the life-time of sprinklers and parent building. In principle, it is possible to accumulate data that indicates time, duration, technical content and the rate of interventions. However, theoretical models that would allow relating such data to potential changes in $p(t)$ are not available to date. Thus, it is not clear how to collect data that could "feed" such models.

If failures of some sprinkler component are detected during routine inspections and this leads to repairs, the formalism of reparable systems can be applied to predict the failure rate of this component, $\lambda(t \mid a, b)$ (parameter of a non-homogenous Poisson process). Data used for estimating a and b are successive failure times (e.g. Deshpande and Purohit 2005). The estimation of a and b is possible in the Bayesian format (Kelly and Smith 2009). Unfortunately, it is not clear how to determine the exact failure times of sprinkler components if inspections are relatively rare, for example, annual ones. Even if data are available, the relation between models $\lambda(t \mid a, b)$ and $p(t)$ must be developed.

5. Conclusions

This paper presented a review of problems related to the collection of data on the reliability of fire sprinklers. Attention was focussed on sprinkler installations in conventional buildings. These sprinklered environments were opposed to industrial and military installations differing from conventional environments in terms of safety culture and practice in data collection and exchange. The main findings formed in the course of review preparation are as follows:

1. Failure data recorded after fires in sprinklered buildings and possibly routine inspections of sprinklers are undoubtedly available. In some countries, data collection and reporting is well-organised outside industrial and military environments. However, the compilation of the entire body of data was made without a general, international agreement, and therefore the body of collected data is not sufficiently systematic.

2. The main obstacles to a systematic collection of data sets that would allow a smooth assessment of sprinkler reliability can be detected with relative ease: (i) differences in the definition and naming of failure modes; (ii) differences in reporting failure data; (iii) the prevalence of a human factor among the causes of sprinkler failures in a conventional building; (iv) the influence of ageing, modifications and repairs on reliability.

3. The accumulation, availability and quality of data on sprinkler system failures is negatively influenced by several factors: (i) the limited relevance of data collected in sprinklered environments with different safety culture, operation conditions and different sprinkler components; (ii) ageing of data collected in the past; (iii) the concealment of data and a high cost of data; (iv) poor documentation and explanation of data in available data bases.

4. Several authors have demonstrated that the assessment of sprinkler system reliability is possible by fault tree analysis. Input data necessary for analysis consists of component failure rates and human failure (error) probabilities. Despite the fact that there are numerous failure rate data sources, any sprinkler-specific databases, that would yield ready-to-use input information for fault tree analysis, do not seem to be available.

5. The amount of data available for assessing sprinkler reliability at a system and component level can vary from case to case. If the set of failure data is small, an application of Bayesian inference is a natural choice for reliability assessment. The standard scheme of Bayesian inference based on homogenous binomial distribution is directly applicable to this end. On the other hand, the standard (homogeneous) binomial scheme is not fully correct because it ignores the ageing of sprinklers and other changes in time.

6. An in-depth study, which allows speaking with certainty about the influence of time effects on sprinkler reliability, seems not to exist. In the theory, the formal schemes developed and applied mainly in a nuclear field could allow testing for the presence of a trend to sprinkler failure probability and to modelling this trend. However, sprinkler-specific data expressed as binned binomial data necessary for trend analysis was not extracted and reported in any publication to date.

7. Theoretical models that allow relating maintenance, repairs and modifications of sprinklers to reliability were not developed to this day. Thus, a collection of data that could “feed” these models remains a task to be solved in the future.

The general conclusion that can be drawn considering this paper is that the present situation of data on sprinkler reliability is not mature enough to make reliability assessment a routine procedure applicable to the sprinklered environments of the most conventional buildings. In some countries, the situation in view of data is better than that in others; however, a lack of a well-established exchange of data on sprinkler failure recorded in conventional buildings will not facilitate reliability assessment.

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TRUMPA DUOMENŲ APIE ĮPRASTINIUOSE PASTATUOSE ĮRENGTŲ SPRINKLERIŲ PATIKIMUMĄ APŽVALGA

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Santrauka

Nereti sprinklerių atsakai, gesinant gaisrus, verčia vertinti šių kritinių saugos sistemų patikimumą. Dėl to reikia kaupti ir apdoroti duomenis, kurių reikia vertinant patikimumą. Duomenų apie sprinklerių atsakus yra daug. Kai kurios šalys turi gerai sudarytas sprinklerių patikimumo duomenų rinkimo ir skelbimo sistemas. Duomenys renkami apie sprinklerius, įrengtus tiek įprastiniuose pastatuose, tiek pramoniniuose objektuose. Tačiau duomenų patikimumui vertinti rinkimas susiduria ir su kai kuriais sunkumais. Nėra sutartinės sprinklerių atsakų apibrėžimo ir įvardijimo praktikos, ataskaitos apie atsakus dažnai labai skiriasi, patikimumo vertinimą sunkina ir tai, kad vyraujanti įprastinių pastatų sprinklerių atsakų priežastis yra žmonių klaidos. Patikimumo vertinimą apsunkina ir sprinklerių senėjimo reiškinys, sistemų modifikavimai ir remontai. Patikimumo duomenų kiekį riboja ir tai, kad duomenys, gauti skirtingose eksploatavimo aplinkose, tinka tik toms aplinkoms. Sprinklerių eksploatacija ir aplinkos sąlygos gali būti skirtingos. Duomenų kiekį riboja ir jų kaina, senėjimas bei slėpimas. Duomenys, kaupiami kai kuriose bazėse, būna nepakankamai paaiškinti ir netinkamai dokumentuoti. Kai sprinklerių sistemos patikimumas vertinamas taikant atsakų medžio analizę, įvesties duomenys gali būti gauti ir iš bendrųjų patikimumo duomenų bazių. Tačiau literatūroje ir internete negalima rasti duomenų bazės, kurioje būtų sukaupti duomenys būtent apie sprinklerių sistemų komponentų patikimumą. Kai patikimumo duomenų trūksta, jį galima vertinti taikant Bajeso metodus. Tiek teorinis modeliavimas, tiek duomenų rinkimas šiandien dar neleidžia atsižvelgti į fizinį sprinklerių senėjimą bei modifikacijas, kurios gali labai paveikti šių sistemų patikimumą.

Reikšminiai žodžiai: sprinkleriai, gaisras, duomenų šaltinis, duomenų bazė, patikimumas, atsako dažnis, senėjimas, žmogaus klaida.

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