Høgskulen på Vestlandet

Collecting, Analysing, and Presenting Reliability Data for Automatic Sprinkler Systems

Master's Thesis in Fire Safety

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This work has been completed as part of the Master's program in Fire Safety at Høgskulen på Vestlandet (Western Norway University of Applied Sciences). The student is responsible for the methods used, the results obtained and the conclusions and assessments in the work.

ABSTRACT ENGLISH

Much work has gone into studying the reliability of sprinkler systems, but there are large level differences between the studies. For example, a recent study in the United States (National Fire Protection Association Research, 2017) sets reliability level at 88%, while a study in Australia and New Zealand finds 99.5% (Maybee, 1988) and one in the UK says 93% (Optimal Economics, 2017).

For this Master's thesis, I conducted a critical review of the following studies: National Fire Protection Association (NFPA) reports from 1970, 2019, 2017, "*Fire - A Century of Automatic Sprinkler Protection in Australia and New Zealand - 1886 to 1986*" (Marryat, Rev. 1988) and "*Efficiency and Effectiveness of Sprinkler Systems in the United Kingdom: An Analysis from Fire Service Data*" (Optimal Economics, 2017). The review of these gave many questions and answers.

I validated the studies using document analysis, basing the analysis on how a scientific investigation should be carried out. All had problems in four out of seven possible areas: 1. unclear issues, including missing definitions and intentions of the investigations; 2. uncertain data collection process; 3. varying quality of analysis and lack of quality assurance; 4. lack of systematic presentation and discussion.

Based on this finding, I concluded that none of the reports on sprinkler reliability can be taken into account for a general documentation on reliability or on future probability for sprinkler systems to function as designed.

Document analysis has primarily been a tool for social science, but as this thesis shows, it is very useful in the field of fire science. Based on the findings from the document analysis, I propose a modified methodology adapted to the scientific principles of fire science. This is exemplified by two proposals for studies, the first descriptive and the second explanatory.

Efforts to provide reliable data for sprinkler systems have major implications for the reliability of all passive and active fire protection as well as performance-based design.

ABSTRAKT NORSK

Mye arbeid er lagt ned på å kartlegge pålitelighet for sprinklersystemer, men det er store nivåforskjeller i undersøkelsene. Eksempler på dette er blant annet den siste undersøkelsen til (National Fire Protection Association Research, 2017) i USA som setter pålitelighetsnivået til 88%. En studie fra Australia og New Zealand fant en pålitelighet på 99,5% (Maybee, 1988) og en studie fra Storbritannia er på 93% (Optimal Economics, 2017).

I denne masteroppgaven gjennomførte jeg en kritisk litteraturgjennomgang på følgende undersøkelser: National Fire Protection Association (NFPA) sine rapporter fra 1970, 2019 0g 2017, «*Fire - A Century of Automatic Sprinkler Protection in Australia and New Zealand - 1886-1986*» (Marryat, Rev. 1988), og "*Efficiency and Effectiveness of Sprinkler Systems in the United Kingdom: An Analysis from Fire Service Data*" (Optimal Economics, 2017). Gjennomgangen av disse gav mange spørsmål og få svar.

De nevnte undersøkelsene ble derfor ved hjelp av dokumentanalyse validert opp mot hvordan en vitenskapelig undersøkelse skal utføres. Valideringen viste at samtlige undersøkelser sviker på fire av syv områder: 1. Uklare problemstillinger, inkludert manglende definisjoner og hensikt med undersøkelsene. 2. Usikker innsamlingsprosess av data. 3. Varierende kvalitet på analysen og manglende kvalitetssikring. 4. Manglende systematikk i presentasjon og diskusjon.

Basert på denne valideringen, konkluderte jeg med at ingen av de undersøke rapportene på sprinklersystem kan tas til inntekt for en generell dokumentering av pålitelighet eller en fremtidig sannsynlighet at de vil virke som designet.

Dokumentanalyse har primært vært et redskap for sosial- og samfunnsvitenskap, men har i denne masteroppgaven vist seg å være meget nyttig også innen brannfag. Med utgangspunkt i funnene fra dokumentanalysen presenterer jeg forslag til endret metodikk tilpasset de naturfaglige premisser som ligger innenfor vårt fagområde; brann. Dette er eksemplifisert med to forslag til undersøkelser, den første er beskrivende og den andre forklarende.

Arbeidet med å fremskaffe pålitelighetstall for sprinklersystemer, har store implikasjoner for pålitelighetsarbeid på alle passive og aktive brannsikringstiltak, samt ytelsesbasert design.

PREFACE

This Master's thesis marks the completion of the two-year program in Fire Safety at Western Norway University of Applied Sciences. During the whole period, I have also been Managing Director of Slokkesystemer AS (Extinguishing Systems Ltd.).

My interest in automatic extinguishing systems was awakened when I saw Jim Ford, Fire Chief of Scottsdale, AZ, on the Discovery Channel program "In Blaze". The concept of having a "firefighter" on duty 24/7 was very appealing because the results were smaller fires, fewer deaths and injuries, to a very affordable cost. After fulfilling my Bachelor's degree in Fire and Safety Engineering with a thesis on "Comparison of sprinkler and water mist system" in 2005, I had the opportunity to take a study tour to Scottsdale and meet Jim Ford and his colleagues.

I worked for a sprinkler company after school for some years and then for a water mist company. A commonality was that they had the only solution to every fire challenge and this could be solved with a sprinkler or water mist. I stared to work for myself in 2010 as an entrepreneur, with the business idea that I should provide the customer the best solution and where there was more than one solution, let the customer chose.

Because of my interest and expertise in extinguishing systems, I have been working with standards and guidelines and have acted as a board member on Norway's only branch association for contractors, manufacturers, and private and public enterprises for all fire engineering disciplines, Brannfagelig Fellesorganisjon (Joint Organization for Fire Protection Norway).

When it was time to select the topic for my Master's thesis, reliability was a natural choice. My starting idea was to write about why there is a different "reliability" from one study to another in the same country (for example FM vs. NFPA), from one country to another (for example US vs. UK). Could this be explained by different standards and regulations in engineering, assembly, and inspection/ maintenance over time? It soon became clear that these contribute to reliability, but I did not yet understand why there are so many different terms (reliability / success/ performance/ operating/ effectivity, to mention a few). After reading many reports on the subject, I understood that some more basic scientific questions were at stake.

This triggered my quest to understand how reliability are understood by the data collector, collected and how data are analysed and presented. It also became clear that this work was not

only of interest to me and my supervisors. The information should be shared for the interest for all the fire community. Hence my decision to write it in English.

This work has taught me that the interconnections of fire science, extinguishing systems, and statistical processing are complex. I am grateful that I have been allowed to take so much time to get to the heart of the subject. Many books, reports, and articles (many not mentioned here) have expanded my knowledge. That so many have given their time and effort to do qualitative and quantitative investigations of reliability is impressive. I stand on the shoulders of giants.

My work would not be possible without the support of my family, Aleksander, Katarina and Anders, and my best friend and wife, Karin.

I also want to thank my supervisor at the school, Ajit Kumar Verma, for his guidance.

My friend, PhD Scholar Rune Zahl-Olsen, provided invaluable help in my attempt to understand the world of research.

Thanks to National Fire Sprinkler Network (NFSN) with Steven Mills and Terry Mc Dermott, for their cooperation and their invitation to visit them and speak at their annual general meeting.

Thanks to the professors at Worcester Polytechnic Institute, Fire Protection Engineering Department, for their input and their invitation to be a guest speaker on the topic of reliability.

Thanks to the research team at Factor Mutual (FM) Global and Thomas Roche for his help in arranging the meeting.

Thanks to National Fire Protection Association (NFPA) with Marty Ahrens for their invaluable help finding reports and articles, answering my questions, and meeting me to discuss some of my findings.

Last, but not least, I want to thank Brannfagelig Fellesorganisjon (Association for Fire Safety Norway/AFSN) for their economic support of my trips abroad. My work would not be the same without their help.

DEFINITIONS

The definitions are based on “Kollegiet for brannfaglig terminologi” (Kollegiet for brannfaglig terminologi, u.d.), if not specified otherwise.

AES: Short form for Automatic Extinguishing Systems. Used in (National Fire Protection Association Research, 2017).

Active fire protection measures: Technical fire protection with a function activated after fire is detected, auto fire alarm is triggered, or officials are notified.

Data analysis: The process of developing answers to questions through the examination and interpretation of data. The basic steps in the analytic process consist of identifying issues, determining the availability of suitable data, deciding which methods are appropriate for answering the questions of interest, applying the methods, and evaluating, summarizing, and communicating the results (Statistics Canada, 2018).

Engineer: Person with technical education (Store norske leksikon, 2018).

Engineering: Engineering consists of making calculations, overviews, drawings (principle and detail) and descriptions of a project (Store norske leksikon, 2018).

Fire extinguishing equipment: Manual or automatic system designed to extinguish or control a fire.

Fire alarm system: A system for fire detection and alarm with fire detector, alarm device, central control unit and, if necessary, an orientation board.

Flashover: Transition to a state where all surfaces of combustible materials in a room participate in a fire.

Ignition: The start of combustion.

Inspection and maintenance: Inspection is the examination of status in relation to requirements, and maintenance refers to repairs, replacements, remedies (defects, errors and omissions), and servicing of active and passive fire protection measures so they function as required.

Residential sprinklers system: Simplified sprinkler system adapted to residential housing.

Sprinkler system: Automatic stationary system that aids in the detection and control of fire to prevent flashovers in the room of fire origin, to improve the chances for occupants to escape or be evacuated, and to control or extinguish a fire. A sprinkler system consists of system valves, piping, and sprinkler heads with water as the primary extinguishing agent.

Sprinkler head: Nozzle for spreading water as part of a sprinkler system. The nozzle may be open or equipped with a thermally sensitive opening mechanism.

Sprinkler or fire pump: Pump systems, including automatic starting devices, which are used to obtain sufficient water or pressure to the sprinkler system.

RTI: RTI is a short form for Response Time Index measured in metres / second$^{1/2}$. A fast response sprinkler has a thermal element with an RTI of 50 (Ms)$^{1/2}$ or less; a standard response sprinkler has a thermal element with an RTI of 80 (Ms)$^{1/2}$ or more (National Fire Protection Association, 2016).

Water density: Number of litres of water supplied to the fire zone per square metre and minute.

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1. INTRODUCTION

1.1. BACKGROUND

Since the introduction of extinguishing systems, from perforated pipes linked to water tanks or outlets, to the first sprinkler in 1864, when Henry Parmelee produced an automatic sprinkler, and the first "practical automatic sprinkler" in 1874 (TYCO, 2005), the use of automatic sprinkler systems as a tool against fire loss has been popular. In the beginning, this was driven by success stories about systems that saved buildings, allowing business to continue after a relatively short time. But over the years, with the establishment of building codes and as insurance companies began to ask for loss and risk numbers, there was a need for regulations. Sprinklers were installed differently from plumber to plumber, and this was quickly becoming a nightmare. In 1895, a group of men met in Boston to discuss this and to establish national sprinkler rules for the USA. This was the start of the National Fire Protection Association (NFPA), formally founded in 1896 (National Fire Protection Association , 1995).
NFPA began to work with fire from an engineering point of view and to develop codes and standards. It became one of the most important organization in the world and has now published more than 300 standards (NFPA, 2018).

With a set of rules and under the watchful eyes of the insurance business, failures and successes could now be tracked. In the years to come, there was increasing interest in measuring sprinklers' performance and improving the standards. This required new test methods, improved technology, and available statistics.

Although there are several types of stationary automatic extinguishing systems, the focus of this dissertation is on fire sprinkler systems because of the amount of available data. There are data over time, from different countries and for different regulations and standards.

Reports and articles look at many different levels and assess many different scores of reliabilities, using terms such as success, performance, performance effectiveness, operating reliability, operational efficiency, and effectiveness. NFPA ("Automatic Sprinkler Performance Tables, 1970 Edition, pp. 35-39) finds sprinklers in the USA are operating at 79.2 - 98.2% reliability, and it terms this range as "*satisfactory sprinkler performance*" depending on the individual hazard class; overall, the reliability is 96.2% for all types of hazard classes. Other US studies suggest lower performance is achieved. For example, Factory Mutual (FM) says reliability is only 86.1% (Kelly, 2003).

A study in Australia and New Zealand on data from 1886 to 1986 gives 99.5% (Marryat, Rev. 1988). In the UK, newer studies suggest 93% (Optimal Economics, 2017). Norway has several different percentages. SINTEF, now RISE Fire Research, reports: *"For all categories of buildings, the average likelihood of the sprinkler operating (i.e. operational reliability) is about 95% and varies between 92-97% (95% confidence interval)"* (Bodil Aamnes Mostue og Kristen Opstad ved SINTEF, 2002). This contrasts with a report from *Opplysningskontoret for sprinkleranlegg* (Information office for sprinkler system), now *Opplysningskontoret for automatiske slokkeanlegg* (Information office for automatic extinguishing systems), that says, "*Only 8% of the systems meet the minimum requirements of today's regulations*" (Opplysningskontoret for automatiske slokkeanlegg, 2003). This needs to be explained.

1.2. DESCRIPTION OF THE MASTER'S THESIS

The use of different words for reliability, like success/ performance/ operating/ effectiveness/ operational effectiveness, for sprinkler systems indicates that there is no consensus in the fire engineering community, among various authorities, or across different insurance companies about the content and meaning of reliability. Does lack of consensus also indicate that data collecting, analysis, and presentation are done differently? If we are to use historical data on sprinklers as a basis for determining reliability, we must do so in a scientific way. Has this been done? The use of critical review is based on the desire to seek out the reasons for both the diversity in reliability level and lack of consensus on important concepts.

The Master's thesis will:

1. Conduct a critical review of the relevant literature.
2. Investigate how data are collected, analysed, and presented in selected studies; determine if this done using scientifically accepted methods.
3. Develop methodologies and proposals for studies with general scientific value.

The reason for this research is to increase knowledge of the reliability of fire sprinkler systems. Fires kill many people every year and cost a lot of money. Any improvement in knowledge and application of this knowledge will create better fire countermeasures and improved sprinkler systems would save lives and money.

1.3. METHODOLOGY

This work is an article-based thesis. The first article is the literature review and the document analysis; the second suggests a methodology and forms for future studies. The articles have been sent to SFPE Journal for peer review for publication. Since the articles is still in the handling prosses before the thesis have been handed in to examination, I have not included the instructions for authors (but they can be found her: https://www.springer.com/engineering/civil+engineering/journal/10694?detailsPage=pltci_3034059)

There are three ways to read this thesis. One is to read the articles in chapter 5 and 6; Article "How Reliable are Reliability Data for Sprinklers?" and Article "New Methods for Collecting, Analysing, and Presenting Reliability Data". Two is to read as an article-based thesis from the start, the articles, and the last chapter; Appendix 7: Conclusion. The third is to read as regularly monographic thesis; from the start and skip the articles.

I used the guidelines given by (Vitenskapelig Høyskole, 2018) with formatting instructions from (Høyskolen Stord/Haugesund, 2018). The introduction of the thesis is an introduction to a monograph. Quotations are marked with quotation marks and are in italic text, regardless of length.

Both the first article and the appendix begin with a review of the literature on success/reliability of sprinklers. The selection of work for review is explained in Chapter 4: Today's data: a study of the literature. The critical review is extended to a qualitative document analysis (Jacobsen, 2015) to examine the particular surveys of interest. Document analysis is primarily a tool of the social sciences. While an overview is useful to find out what has been written in a particular area, document analysis is a systematic tool to learn more about the subject of interest. It can be used when:

a) It is impossible to get primary data
b) A researcher wishes to learn how others have interpreted a situation, event, or data
c) A researcher wishes to learn what has been done or said

Critical findings are examined and presented in the appendix.

Part three and article two examine the elements influencing the reliability of sprinkler systems and suggest how data should be collected, analysed, and presented in descriptive and explanatory studies.

1.4. LIMITATIONS

The literature shows different levels of success/reliability over both time and in different types of buildings. This is not of interest here, as this thesis is concerned with the collection of data, the general use of data and the presentation of data.

Many things influence success/reliability, but they are not the primary object of this dissertation. The issue is to establish a general definition of reliability and explain how to conduct scientific studies.

There is little focus on all physical fires, except for a general introduction to fire theory with a focus on fire growth and the use of different type of sprinkler system.

2. FIRE AND SPRINKLERE EXTINGUSHING THEORY

What is a fire, how does it behave and what happens to a fire when there are water-based sprinklers in the compartment? This brief introduction answers these questions.

2.1. FIRE

A fire is an uncontrolled, non-explosion combustion that releases heat, often but not always as visible flames and/or embers, smoke in the form of odour, gases and incompletely burned particles. Gases could be CO and CO^2, and incompletely burned particles are often visible, as for example, soot. The three prerequisites for fire are flammable material, oxygen, and heat. (Store norske leksikon, 2018)

2.2. COMBUSTION

Combustion of solid materials is the chemical process where heat decomposes flammable material to the point where it releases enough flammable gas and particles to substance the fire. Combustion can start with a build-up of heat caused by organic material stacked in such a way that heat released in an exothermic reaction cannot be conducted away; the reaction grows beyond this point to start combustion (smouldering fire). At some point, the smouldering will come to the surface and be in direct contact with air (oxygen); at this point, the heat will be sufficient to ignite the decomposed products. Combustion can also be started by heat from any source, such as exposure to open flames. In such instances, both fire and ignition sources are available, and ignition can start at lower temperatures than the transition from smouldering to open fire (Drysdal, 1998).

2.3. ROOM FIRE

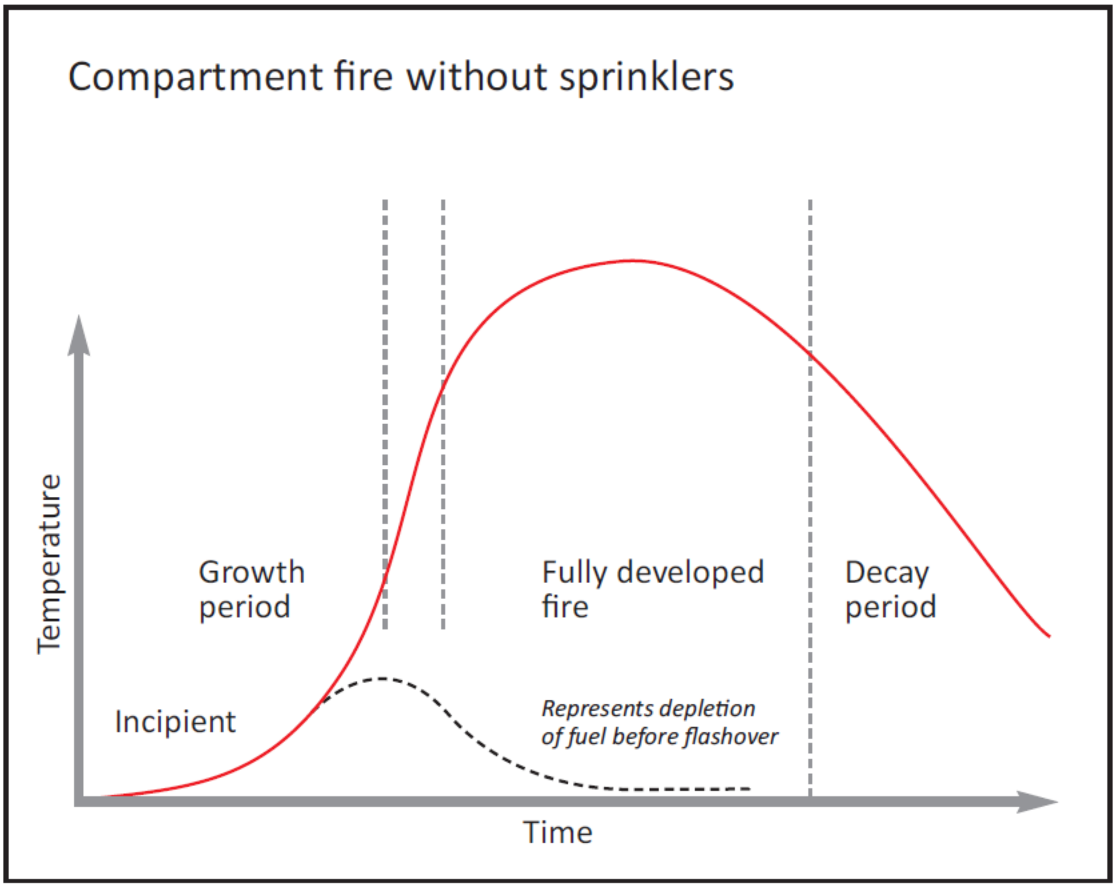
A room or compartment fire, under well-ventilated conditions, has three characteristics periods.

The first is the growth or pre-flashover period; the temperature is relatively low, and the fire is located close to the origin. As pointed out earlier, a fire can start several ways. Most start slowly, this does not have to be the case. It can take just a minute (e.g. dry Christmas tree in a living room) or a few minutes ("…. *the mode of burning/combustion may depend more on the physical state and distribution of the fuel, and its environment, than on its chemical nature* " (Drysdal, 1998) page 1.

The fully developed fire period could start with a flashover or with a post-flashover fire. All combustible materials are involved, and flames seem to fill the space.

In the third period, the amount of material in flames is reduced and the temperature/heat release rate drops to 80% of its peak value.

Figure 1 Classic time/temperature curve for compartment fire



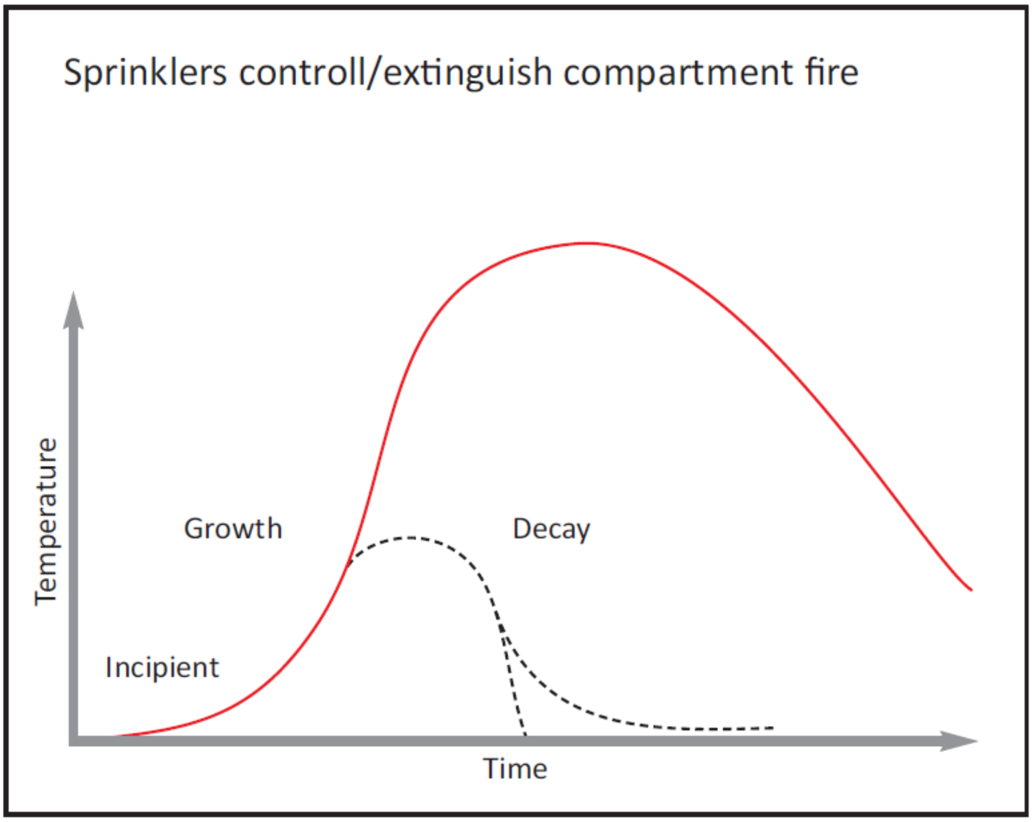
Dotted line represents decrease of fuel before flashover.

2.4. SPRINKLER: CONTROL AND EXTINGUISHING

Sprinklers have been used since the 1860s because water is cheap, available, environmentally safe, and easy to use as a measure to control or extinguish a fire. In addition, the construction of sprinklers is relatively simple, with valves, an alarm and sprinkler heads. Water has the capability to absorb heat, to make flammable materials like cellulose products "inflammable" by filling the surface with water, and to vaporize droplets and displace oxygen (inertization). This ability corresponds to what has been called the fire triangle (Society of Fire Protection Engineers, 2016).

Little research considers the effect of different types of sprinklers compered to discussion of hydraulic calculation (one example is the SFPE Handbook of Fire Protection Engineering Fifth Edition where there are no chapter on sprinkler, but to on calculation). Some work looks at residential sprinklers, storage sprinklers and other specialised types of sprinklers, including test protocols and reports. The most common views of the effect of sprinklers are shown in Figure 2. Simply stated, the fire ignites and grows until the sprinkler activates.

Figure 2 Time/temperature curves of sprinklers controlling/extinguishing compartment fire



Even if there is little research on the effect of sprinklers as fire control or extinguishing systems within a building, some studies suggest that sprinklers extinguish fires in under 1% of the cases where they are used (National Fire Protection Association Research, 2010); see Table 13 in this reference. This problematizes the word extinguishing system, and the percentage applies to all fires regardless of whether a sprinkler is present or not. A 1998 estimate says 7.2 % of all structures have sprinklers (Table 1). This indicates that around 12% of all fires in buildings with sprinklers are extinguished.

Most studies conclude sprinklers are effective with 4 or fewer heads operating (Table 6 B). For example, the previously mentioned report says in 92% of the cases, the sprinkler operated. This means that a functioning sprinkler system have three outcomes: extinguish the fire, control it so that manual intervention (e.g. fire brigades) can put the fire completely out and postpone flashover to the point sprinkler have no more control (if no manual intervention is done).

2.5. SPRINKLER: POSTPONE FLASHOVER

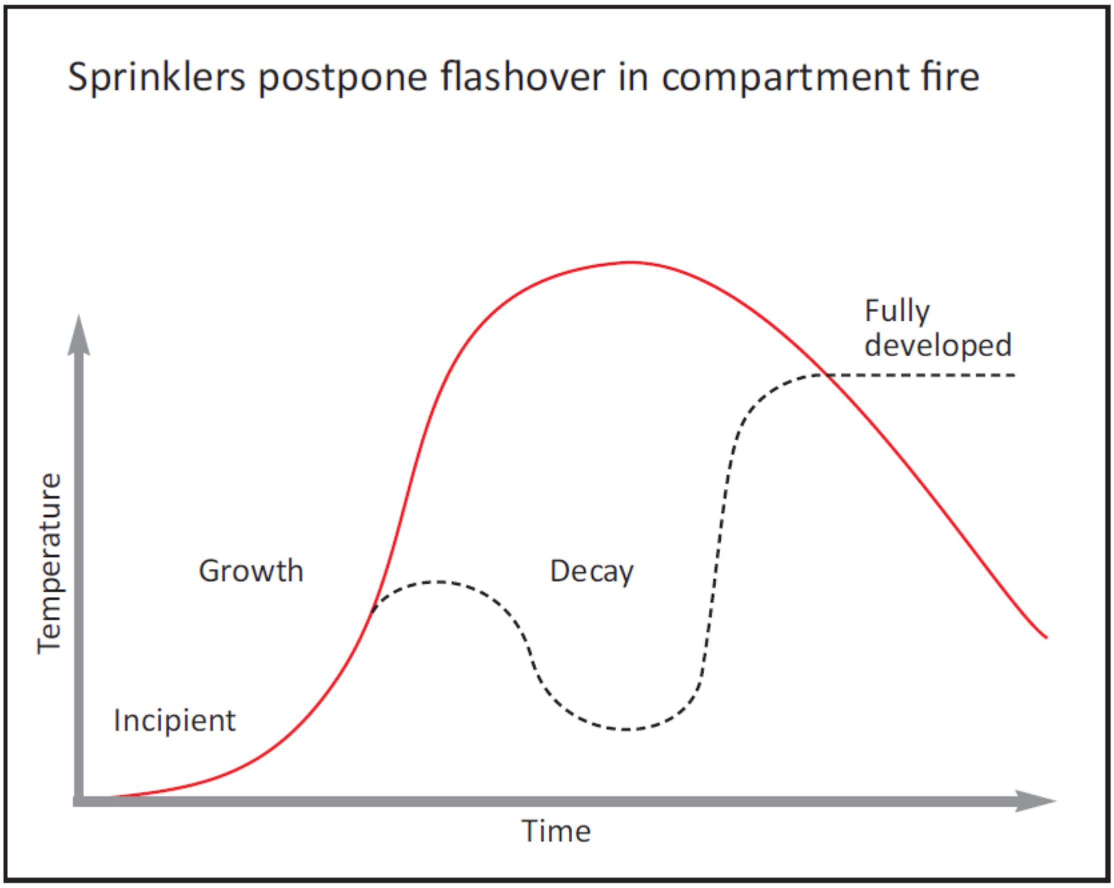
What about the third outcome? Large fires in recent years, in residential buildings like the Avalon apartment complex in Edgewater, New Jersey (NFPA, 2018) and other buildings like warehouses (NFPA, 2017), have resulted in large property losses. They have all been sprinkled. Some of the losses are explained by causes like the water being shut off, larger and/or more flammable material then the design of the sprinkler system was meant to cover, or lack of maintenance. Except in cases when the system is shut off, there is a similarity between these types of fires and how both standard sprinkler systems behaves when it is overrun, and residential sprinkler systems behaves.

Let’s consider two scenarios. In scenario one, a fire ignites in a commercial building, and grows to the point where the sprinkler activates. But for unknown reasons or faults in design, obstacles in water distribution, or other reasons, the fire is not extinguished or controlled. It continues to grow. More sprinklers are activated, but this does not extinguish or control the fire.

In scenario two, a fire occurs on a balcony in a residential building/house, protected by a residential sprinkler system like NFPA 13D or 13R. The fire grows; the heat destroys the window and moves to the living room. The sprinkler activates, and the system operates. At the same time, the fire moves into the attic where there are no sprinklers. The fire goes through the ceiling and activates more sprinklers, but the system has no effect.

Both scenarios are represented in Figure 3.

Figure 3 Time/temperature curves of sprinklers postpone flashover in compartment fire



As the figure shows, there is a time when the fire is under temporary control (at least inside where people live/is). This period may be characterized by lower temperatures (and probably heat release) that postpone flashover, give better visibility, reduce the production of hazardous gases and particles (the droplets probably also wash the smoke and reduce the hazardous environment), and because the sprinkler system is activated, this alarms the building, neighbourhood, and emergency response. All these actions help to manage escape and prolong escape time.

UL 1626 “Standard for Residential Sprinklers for Fire-Protection Service” is conducting a 10-minute fire test where a maximum allowed temperature (behind the finished surface of the ceiling material directly above the test fire) must not exceed 260°C. This indicates that fire extinguishing is not the aim; rather, the goal is to prolong flashover and escape time. When looking at standards for residential sprinkler e.g. NFPA 13D, the purpose is in line with the fire test:

“*1.2.1 The purpose of this standard shall be to provide a sprinkler system that aids in the detection and control of residential fires and thus provides improved protection against injury and life loss.*

1.2.2 A sprinkler system designed and installed in accordance with this standard shall be expected to prevent flashover (total involvement) in the room of fire origin, where sprinklered, and to improve the chance for occupants to escape or be evacuated.”

When it comes to duration time, this too reflect the standard: “*6.1.2 Where stored water is used as the sole source of supply, the minimum quantity shall equal the water demand rate times 10 minutes unless permitted otherwise by 6.1.3*”. According to NFPA, no data support the view that the level of protection goes up when the water lasts longer than 10 min (National Fire Protection Association, 2018).

3. RELIABILITY THEORY

What is reliability? The word reliability is often used inaccurately, but here reliability means the ability to function as intended. More precisely, it is the characteristic of or the expression of the ability of a component or system to perform an intended function. This includes the probability distribution of the component or system's lifetime, statistical life expectancy, expected number of failures per unit of time, and the likelihood that something will work at a specific time (Aven, 2006)

3.1. PROBABILITY DISTRIBUTION OVER THE LIFETIME

Is a system more reliable when new or after some time? Suppliers and contractor are obviously interested in this question. If a system is very complicated, the chances that they will have to adjust it within the warranty period are higher than for a simpler system. If a system is simple, like many sprinkler systems (except systems with pumps) (Frank, Gravestock, Spearpoint, & Fleischmann, 2013), it is more likely to have an exponential growth in unreliability over time. This is more interesting for the owner, since the cost of maintaining the system reliability follows the same curve. Probability distributions are used to describe reliability over time.

3.2. STATISTICAL LIFE EXPECTANCY

How long will a sprinkler system or its components last? Perhaps this is not the right question. Perhaps we should ask: How long will it take before the cost of maintenance justifies replacing it with new components or an entirely new system? Statistical life expectancy is the number of years a component or system is designed to withstand normal load and external stresses.

3.3. EXPECTED NUMBER OF FAILURES PER UNIT OF TIME

Since every component has a possibility of failure, every sprinkler system must have a plan for inspection and testing, both by the owner/user and by independent competent persons. Without regular control, the number of failures will increase. This is often measured as mean time to failure (MTF).

3.4. THE LIKELIHOOD THAT SOMETHING WILL WORK AT A SPECIFIC TIME

When there is a possibility that something will work at any given time, there is also a possibility that it will not work at any specific time. Owners need to know the likelihood that a device will not fail in a certain time interval or the likelihood that it will be functional. The likelihood that it will work is the possibility that it will work at any specific time minus the possibility that it will not work.

3.5. SPRINKLER RELIABILITY

It is important to separate the strictly operational from efficiency in a sprinkler system. There is a clear separation of the demands placed on a component before it can be used as a part of sprinkler system (testing and approval) and the challenge posed by different water supplies and building designs to operate efficiently. All sprinkler standards are written to make sure that approved component is engineered, installed, inspected, and maintained in a way that ensures it will work as intended.

- **Operational reliability** or just **operationality** (not to be confused with reliability) is a measure of the probability that a protection system or part of it will operate when needed.
- **Performance reliability** or **efficiency** (performance is not the best word; efficiency is of more interest) a measure of the adequacy of the system to successfully perform its intended function under specific fire scenario conditions. In other words, does the system perform effectively in accordance with its design and purpose?

Intended function refers to the correct/proper design following a sprinkler standard. Sprinkler reliability is the ability to function as designed.

Sprinkler **reliability** is the ability to function as intended (designed) **= operationality x efficiency** (Barry, 2002)**.**

4. TODAY'S DATA: A STUDY OF THE LITERATURE

Where should a master's thesis like this one start? There are at least three different approaches.

1) Perform a literature search to get a historical overview.
2) Search for the historical development of systems and standards and create an overview.
3) Look for reference material.

Literature search: I conducted a search in Google Scholar to get data for sprinkler systems relevant to the following: automatic fire sprinkler systems, reliability, success, suppression. This gave 19 100 results sorted after relevancy.

The search was expanded to include: historical data, NFPA material and comparisons of this work. Since the story of the sprinkler is closely linked to NFPA and other American organisations like Underwriters Laboratories (UL) and Factory Mutual (FM) and because NFPA started The NFPA Fire Records files in 1897, NFPA was included in the search. This gave 1 360 results sorted after relevancy.

A search in Academic Search Elite gave 1 424 results the first time and 1 003 the second time.

Some studies stand out because of the number of times they have been cited in other studies, reports, and articles on reliability. Especially helpful in tracking these were literature overviews like *Estimates of the Operational Reliability of Fire Protection Systems* (Bukowski. R. W., 1999), *Automatic Sprinkler System Reliability* (Budnick, 2001) and *Reliability of Automatic Sprinkler Systems* (Koffel, 2006). Koffel's overview is presented on the next page. The three overviews are used in my review of the literature.

Only English written studies are included in this review, but for Norwegian readers, I have included data from one Nordic study.

Table 1 Koffel' s overview of previous studies

Reference	Reliability of Success	Comments
Marryat[1]	99.5	Inspection, testing, and maintenance exceeded normal expectations and higher pressures
Maybee[2]	99.4	Inspection, testing, and maintenance exceeded normal expectations.
Powers[3]	98.8	Office buildings only in New York City
Powers[4]	98.4	Other than office buildings in New York City
Finucane et al.[5]	96.9 – 97.9	
Milne[6]	96.6/97.6/89.2	
NFPA[7]	88.2 – 98.2	Data provided for individual occupancies – total for all occupancies was 96.2%.
Linder[8]	96	
Richardson[9]	96	
Miller[10]	95.8	
Powers[11]	95.8	Low rise buildings in New York City
US Navy[12]	95.7	1964 – 1977
Smith[13]	95	UK data
Miller[14]	94.8	
Budnick[15]	92.2/94.6/97.1	Values are lower in commercial uses (excludes institutional and residential)
Kook[16]	87.6	Limited data base
Ramachandran[17]	87	Increases to 94% if estimated number of fires not reported is included and based upon 33% of fires not reported to fire brigade.
Factory Mutual[18]	86.1	1970 – 1977
Miller[19]	86	Commercial uses (excludes institutional and residential)
Oregon State Fire Marshal[20]	85.8	1970 – 1978
Taylor[21]	81.3	Limited data base

[1] Marryat, H. W., *Fire: A Century of Automatic Sprinkler Protection in Australia and New Zealand 1886 – 1986*, Australia Fire Protection Association, Melbourne, Australia.
[2] Maybee, W. W. "Summary of Fire Protection Programs in the U.S. Department of Energy—Calendar Year 1987," U.S. Department of Energy, Frederick, MD, August 1988.
[3] Powers, R. W. "Sprinkler Experience in High-Rise Buildings (1969-1979)," *SFPE Technology Report 79-1*, Society of Fire Protection Engineers, Boston, MA, 1979.
[4] Powers, R. W., ibid
[5] Finucane, M, and Pickney, D. "Reliability of Fire Protection and Detection Systems," United Kingdom Atomic Energy Authority, University of Edinburgh, Scotland.
[6] Milne, W. D., "Automatic Sprinkler Protection Record," *Factors in Special Fire Risk Analysis*, Chapter 9, pp. 73-89.
[7] NFPA. "Automatic Sprinkler Performance Tables, 1970 Edition," *Fire Journal*, July 1970, pp. 35-39.
[8] Linder, K. W. "Field Probability of Fire Detection Systems," Balanced Design Concepts Workshop, NISTIR 5264, R.W. Bukowski (ed.), Building and Fire Research Laboratory, National Institute of Standards and Technology, September 1993.

[9] Richardson, J. K. "The Reliability of Automatic Sprinkler Systems," *Canadian Building Digest*, Vol. 238, July 1985.
[10] Miller, M. J. "Reliability of Fire Protection Systems," *Loss Prevention ACEP Technical Manual 8*, 1974.
[11] Power, R. W., ibid.
[12] Kelly, Kevin J. "Trade Ups", *Sprinkler Quarterly*, Summer 2003
[13] Smith, Frank. "How Successful are Sprinklers," *SFPE Bulletin*, Vol. 83-2, April 1983, pp 23-25.
[14] Miller, M. J., ibid.
[15] Budnick, Edward J., ibid.
[16] Kook, K. W. "Exterior Fire Propagation in a High-Rise Building," Master's Thesis, Worcester Polytechnic Institute, Worcester, MA, November 1990.
[17] Ramachandran, Ganapathy. "The Economics of Fire Protection," New York: E & FN Spon, 1998.
[18] Kelly, Kevin J., ibid.
[19] Miller, M. J., ibid.
[20] Kelly, Kevin J., ibid.
[21] Taylor, K. T. "Office Building Fires…A Case for Automatic Fire Protection," *Fire Journal*, 84(1), January/February 1990, pp. 52-54.

4.1. REVIEW OF THE STUDIES

Note that this review does not attempt to judge the value of existing studies. Nor is it intended to obtain data. No non-English studies are included.

Table 2 Overview of literature

Reference	(Bukowski. R. W., 1999)[1]	(Budnick, 2001)	(Koffel, 2006)[2]
Marryat (Marryat, Rev. 1988)	Yes	Yes	Yes
NFPA (National Fire Protection Association, 1970)[3]	Yes	Yes	Yes
Milne (Milne, 1959)	Yes	Yes	Yes
Powers (Powers, 1979)	Yes	Yes	Yes
Factory Mutual (Miller, 1973)[4]	Yes	Yes	Yes? C
Smith (Smith, How Successful are Sprinklers, 1983)	No, B	No, B	Yes
Richardson (Richardson, 1985)	Yes	Yes	Yes
Finucane, M, and Pickney, D. (Finucane, Reliability of Fire Protection and Detection Systems, 1987)[5]	Yes	Yes	Yes
Maybee (Maybee, 1988)	Yes	Yes	Yes
Linder (Linder, 1993)	Yes	Yes	Yes
Taylor (Taylor, 1990)	Yes	Yes	No, B
Kook (Kim, "Exterior Fire Propagation in a High-Rise Building," a Master's Thesis,, 1990)[6]	Yes	Yes	Yes
Ramachandran (Ramachandran, 1998)	No, B	No, B	Yes
Budnick (Budnick, 2001)	A		Yes

[A] New report after comparison was made

[B] Not included. Reason not known.

[C] There are three references to Miller, Myron J. on Koffel's list.

[1] There are three other listings in "Table 2. Reported Automatic Sprinkler Reliability Data (percent)," that have no reference and are therefore not included here.

[2] There is one listing of US Navy in "***Table 1***". This reference to the maritime sector is not relevant to this overview and is therefore not included here.

[3] The performance is given as **79.2 – 98.2**%, not **88.2 – 98.2** %

[4] In the reference list, this is listed as: Miller, M. J. (1974), "Reliability of Fire Protection Systems;" Loss Prevention ACEP Technical Manual, 8, 1974. I have only been able to find: Miller, Myron J. (1973), "The Reliability of Fire Protection Systems;" at Factory Mutual Research Corporation for The AIChE Loss Prevention Symposium, Philadelphia, PA, November 11-15, 1973, where performance is given as **85%**, not **96%**.

[5] In the reference list, this is given as: Finucane M, Pinkney D (1988) Reliability of fire protection and detection systems. Report Number SRD R431 United Kingdom Atomic Energy Authority Safety and Reliability Directorate, University of Edinburgh, Scotland, p 15. I have only been able to find: Finucane M, Pinkney D (1987). Reliability of Fire Protection and Detection Systems. Recent Developments in Fire Detection and Suppression systems (p. 20). Edinburgh, Scotland: University of Edinburgh, Unit of Fire Safety Engineering, where performance is given as **95**%, not **96.9 – 97.9**%

[6] The citation of Won Kook Kim is uncertain, because Kook is the surname.

After I reviewed the list, several concerns become apparent:

1. Even if there is a reference to sources, this does not mean that they exist or is available for others.
2. It is not certain that the authors have the correct result.
3. It is not certain that the authors have read the reference.
4. Some authors of comparative studies do not give any new quantitative data. If references do not exist, the number may not be correct; there is an appearance of much data, but this may not be the case. This is a circle of thrust that could be misleading.

Since this study looks at reliability within a geographic area and in data over some time, the review choses studies based on four criteria. The first criterion is that they must be studies of raw data on reliability. Comparative studies or studies using reliability data from other studies or studies without reference are excluded. These include:
(Budnick, 2001): Data from others applied.
(Ramachandran, 1998): Cost-benefits analysis. Data from others applied.
(Linder, 1993): Conference presentation. No references.
(Finucane, Reliability of Fire Protection and Detection Systems, 1987): Conference paper. Data from others applied.
(Richardson, 1985): Data from others applied.
(Smith, How Successful are Sprinklers, 1983): Data from others applied.

The second criterion is applicability; studies done in a small area, like specific building types and during a very limited time, are excluded, as they have limited application for this study. The third criterion is the exclusion of older studies. The rapid changes in sprinkler technology since the end of the 1970s, with the development of quick response sprinklers of different types (like residential and ESFR), must be reflected. The following are excluded:
(Kim, "Exterior Fire Propagation in a High-Rise Building," a Master's Thesis,, 1990): Exterior fire propagation in high-rise building.

(Taylor, 1990): What part did detection and suppression play in office building fires. Data from 1982 – 86.

(Maybee, 1988): Only for U.S. Department of Energy - calendar year 1987

(Powers, 1979): Buildings in New York. Data from 1969 – 1979

(Miller, 1973): Only for the year 1970, -71 and -72. Limited data.

(Milne, 1959): Old study, pre-1959.

The fourth criterion is relevant newer studies. National Fire Protection Association has published two major studies since 2006, making NFPA of particular interest. It is possible to use the newer work to compare earlier figures from the same organisation. A 2017 study for the United Kingdom (UK) is also included; it fulfils the requirements and is a European study.

Table 3 Overveiw of relevant studies

Reference	Success, individually and average (%)	Applied area/ Focus/Comments	Comments
Marryat (Marryat, Rev. 1988)	95.3 – 100 99.5	Inspection, testing, and maintenance exceeded normal expectations, and higher pressures.	Data from 1886 – 1986.
NFPA (National Fire Protection Association, 1970)	79.2 – 98.2 96.2	Data from 1897 – 1969 was 95.8% in average.	Data from 1897 – 1924 and 1925 - 1969
NFPA (National Fire Protection Association Research, 2010)	80 – 94 91	This study was done on sprinkler and other automatic fire extinguishing equipment	Data from NFIRS 2004 – 2008
NFPA (National Fire Protection Association Research, 2017)	81 – 91 88	This study was done only for sprinkler	Data from NFIRS 2010 – 2014
NFSM (Optimal Economics, 2017)[1]	92 – 97.7 93.6[2]	United Kingdom	2017

[1] This report uses the terms performance effectiveness and operating reliability. They have been multiplied to determine reliability as in other studies.

[2] In Appendix 3: Studies in United Kingdom, these findings are gone through; the percentage given her is **87%.**

Without adding newer studies, there are only two studies on the list of studies of raw data. The New Zealand (Department of Building and Housing, 2005) states:

"recognise that there is as yet inadequate data for fire engineering to achieve the accuracy that is expected from, for example, structural engineering. In particular, the probabilities used for a fire analysis must be based on fire statistics derived from a comparatively small

data pool of mainly overseas buildings of unknown design. That applies not only to fire scenarios but also to the proper functioning of critical systems including the sprinklers, … There appears to be no certainty as to the extent to which those statistics and probabilities are appropriate for use in the New Zealand context."

I decided to use critical review, to find underlying reasons or causes for the diversity in terms and reliability level.

5. ARTICLE "HOW RELIABLE ARE RELIABILITY DATA FOR SPRINKLERS?"

The first of two articles sent SFPE Journal.

5.1. ABSTRACT

There are given many definitions and level of score on reliability for a sprinkler system, like; success; performance effectiveness; operating reliability; operational effectively; etc. It is therefore important to find out what the sprinkler reliability means, even if the literature today give few answers on this. My critical review of the selected literature lead to many questions and few answers. There seem to be some more fundamental issues on stake here. Thus, the question was: are the studies done in a satisfactory, scientific way? To investigate this, combined two types of methodology, how to conduct surveys and document analyse. Even if several factors indicate the studies of interest in general was done in a scientific way, all the surveys were found to fail on four areas of methodology. Firstly, lack of clear purpose/problem. Secondly, data collection. Thirdly, quality assurance of the analysis. Fourthly, presentation with discussions. The conclusion is that surveys in question cannot be used to stat a general view of sprinkler reliability or future probability.

Keywords: Sprinkler; Survey; Reliability; Critical review; Document analysis.

5.2. INTRODUCTION

Since the introduction of extinguishing systems, from perforated pipes linked to water tanks or outlets, to the first sprinkler in 1864, when Henry Parmelee produced an automatic sprinkler, and the first "practical automatic sprinkler" in 1874 (TYCO, 2005), the use of automatic sprinkler systems as a tool against fire loss has been popular. In the beginning, this was driven by success stories about systems that saved buildings, allowing manufacturing to continue after a relatively short time. But over the years, with the establishment of building codes and as insurance companies began to ask for loss and risk numbers, there was a need for regulations. Sprinklers were installed differently from plumber to plumber, and this was quickly becoming a nightmare. In 1895, a group of men met in Boston to discuss this and to establish national sprinkler rules for the USA. This was the start of the National Fire Protection Association (NFPA), formally founded in 1896 (National Fire Protection Association , 1995).

With a set of rules and under the watchful eyes of the insurance business, failures and successes could now be tracked. In the years to come, there was increasing interest in measuring sprinklers' performance and improving the standards. This required new test methods, improved technology, and available statistics.

Reports and articles look at many different levels and assess many different scores of reliabilities, using terms such as success, performance, performance effectiveness, operating reliability, operational efficiency, effectivity. NFPA (National Fire Protection Association, 1970) finds sprinklers in the USA are operating at 79.2 - 98.2%, and it terms this range as "*satisfactory sprinkler performance*" depending on the individual hazard class; overall, the reliability is 96.2% for all types of hazard classes. Other US surveys suggest lower performance is achieved. For example, Factory Mutual (FM) says reliability is only 86.1% (Kelly, 2003).

A study in Australia and New Zealand on data from 1886 to 1986 gives 99.5% (Marryat, Rev. 1988). In the UK, newer studies suggest 93% (Optimal Economics, 2017). Norway has several different percentages. SINTEF, now RISE Fire Research, reports: *"For all categories of buildings, the average likelihood of the sprinkler operating (i.e. operational reliability) is about 95% and varies between 92-97% (95% confidence interval)"* (Bodil Aamnes Mostue og Kristen Opstad ved SINTEF, 2002). This contrasts with a report from *Opplysningskontoret for sprinkleranlegg* (Information office for sprinkler system), now *Opplysningskontoret for automatiske slokkeanlegg* (Information office for automatic extinguishing systems), that says, "*Only 8% of the systems meet the minimum requirements of today's regulations*" (Opplysningskontoret for automatiske slokkeanlegg, 2003). This enormous difference needs to be explained.

There are two common approaches to quantify reliability:

1. Component-based (fault tree)
2. System-based (incident data)

Component-based studies use data from individual components to estimate a system's effectiveness. System-based studies incorporate failure and ineffectiveness on a component level. This study is system-based, as this a tested method to get data on how a system has historically behaved and to compare these to other similar data.

There are many definitions of what a sprinkler system should do (reliability, success, performance, performance effectiveness, operating, operating reliability, operational effectively). Reasons for the diversity include different standards, different practices of engineering and installation, different national regulations and planning and building acts, and different regulations on inspection and maintenance, and perhaps many more. As part of my master thesis, *Collecting, Analysing, and Presentation of Reliability Data for Automatic Sprinkler Systems*, I performed a critical review of the literature. The idea was to use knowledge gained from the review to determine reliability, based on an index of practices within the above-mentioned areas. As it went, the task become to find out if there was reliable data on sprinkler reliability. To find out this, the use of document analysis based on how a scientific survey should be conducted and contain, was done.

5.3. LITERATURE REVEIW

Some studies stand out because of the number of times they have been quoted, used in other studies and reports, and cited in articles on reliability. Especially helpful in tracking these are literature overviews like *Estimates of the Operational Reliability of Fire Protection Systems* (Bukowski. R. W., 1999), *Automatic Sprinkler System Reliability* (Budnick, 2001) and *Reliability of Automatic Sprinkler Systems* (Koffel, 2006). **Table 4** indicates which studies are most widely cited.

Table 4 Overview of literature search

Reference	(Bukowski. R. W., 1999)**1**	(Budnick, 2001)**2**	(Koffel, 2006)
Marryat (Marryat, Rev. 1988)	Yes	Yes	Yes
NFPA (National Fire Protection Association, 1970)3	Yes	Yes	Yes
Milne (Milne, 1959)	Yes	Yes	Yes
Powers (Powers, 1979)	Yes	Yes	Yes
Factory Mutual (Miller, 1973)4	Yes	Yes	Yes? C
Smith (Smith, How Successful are Sprinklers, 1982)	No, B	No, B	Yes
Richardson (Richardson, 1985)	Yes	Yes	Yes
Finucane, M, and Pickney, D. (Finucane, Reliability of Fire Protection and Detection Systems, 1987)5	Yes	Yes	Yes
Maybee (Maybee, 1988)	Yes	Yes	Yes
Linder (Linder, 1993)	Yes	Yes	Yes
Taylor (Taylor, 1990)	Yes	Yes	No, B
Kook (Kim, "Exterior Fire Propagation in a High-Rise Building," a Master's Thesis, 1990)6	Yes	Yes	Yes
Ramachandran (Ramachandran, 1998)	No, B	No, B	Yes
Budnick (Budnick, 2001)	A		Yes

[A] New report after comparison was made

[B] Not included. Reason not known.

[C] There are three refences to Miller, Myron J. in Koffel's list.

[1] There are three other listings in "Table 2. Reported Automatic Sprinkler Reliability Data (percent)," that have no reference and are therefore not included here.

[2] There is one listing of US Navy in "Table 1". This reference to the maritime sector is not relevant to this overview and is therefore not included here.

[3] The performance is given as **79.2 – 98.2%**, not **88.2 – 98.2%.**

[4] In the reference list, this is listed as: Miller, M. J. (1974), "Reliability of Fire Protection Systems;" Loss Prevention ACEP Technical Manual, 8, 1974. I have only been able to find: Miller, Myron J. (1973), "The Reliability of Fire Protection Systems;" at Factory Mutual Research Corporation for The AIChE Loss Prevention Symposium, Philadelphia, PA, November 11-15, 1973, where performance is given as **85%**, not **96%**

[5] In the reference list, this is given as: Finucane M, Pinkney D (1988) Reliability of fire protection and detection systems. Report Number SRD R431 United Kingdom Atomic Energy Authority Safety and Reliability Directorate, University of Edinburgh, Scotland, p 15. I have only been able to find: Finucane M, Pinkney D (1987). Reliability of Fire Protection and Detection Systems. Recent Developments in Fire Detection and Suppression systems (p. 20). Edinburgh, Scotland: University of Edinburgh, Unit of Fire Safety Engineering, where performance is given as **95%**, not **96.9 – 97.9%.**

[6] The citation of Won Kook Kim is uncertain, because Kook is the surname.

Note that this review does not attempt to judge the value of existing studies. Nor is it the approach to obtain the data or the data application that is under review.

After reviewing available literature on the list over, there are several concerns:

5. If there is reference to sources, that do not mean that they exist.
6. It is not sure that former authors have the result right.
7. It is not sure that former authors have read the reference.
8. If there is a circle of thrust, this also lead to a circle of refence. Since some authors have done a comparative study, used former data in their study, etc. they are afterwards included in reference list. If this is based on reference that do not exist, the results are not correct, they only add an appearance that there is much data on this area and that it is good, when perhaps this is not the case.

Since this study are looking at reliability within a geographic area and with data over some time, the review choses studies based on four criteria. The first criterion is that they must be studies of raw data on reliability. Comparative studies or studies using reliability data from other studies or studies without reference will be excluded are excluded. The second criterion is applicability; studies done in a small area, like specific buildings types and during a very limited time, are excluded, as they have limited application for this study. The third criterion is the exclusion of older studies. The rapid changes in sprinkler technology since the end of the 1970s, with the development of quick response sprinklers of different types (like residential and ESFR), must be reflected in some studies. The fourth criterion is relevant newer studies. National Fire Protection Association has publicized two major studies since 2006, making NFPA of particular interest. It has one study on the list already, making it possible to use the newer work to compare figures from the same organisation. A 2017 study for the United Kingdom (UK) is also included; it fulfils the requirements and is a European study.

Only studies written in English are included in this review.

Table 5 Overview of relevant studies

Reference	Success, individual and average (%)	Applied area/ Focus/Comments	Comments
Marryat (Marryat, Rev. 1988)	95.3 – 100 99.5	Inspection, testing, and maintenance exceeded normal expectations, and higher pressures.	Data from 1886 – 1986.
NFPA (National Fire Protection Association, 1970)	79.2 – 98.2 96.2	Data from 1897 – 1969; 95.8% on average.	Data from 1897 – 1924 and 1925 - 1969
NFPA (National Fire Protection Association Research, 2010)	80 – 94 91	This study was on sprinklers and other automatic fire extinguishing equipment	Data from NFIRS 2004 – 2008
NFPA (National Fire Protection Association Research, 2017)	81 – 91 88	This study was only for sprinklers	Data from NFIRS 2010 – 2014
NFSM (Optimal Economics, 2017)1	92 – 97.7 93.62	United Kingdom	Data from IRS 2011-2015
[1] This report uses the terms performance effectiveness and operating reliability. They have been multiplied to determine reliability as in other studies. [2] In the complete Master thesis "Appendix 3: Studies in United Kingdom", these findings are gone through and it her adds up with **87%**.			

Without adding newer studies, there are only two studies on the list of studies of raw data. With the words of New Zealand (Department of Building and Housing, 2005):

"recognise that there is as yet inadequate data for fire engineering to achieve the accuracy that is expected from, for example, structural engineering. In particular, the probabilities used for a fire analysis must be based on fire statistics derived from a comparatively small data pool of mainly overseas buildings of unknown design. That applies not only to fire scenarios but also to the proper functioning of critical systems including the sprinklers, … There appears to be no certainty as to the extent to which those statistics and probabilities are appropriate for use in the New Zealand context."

What conclusions can we reach?

5.4. EXAMPLES OF UNCERTAINTY IN REVIEW OF SPRINKLER RELIABILITY STUDIES

The studies in **Table 5** trigger several questions, but before continuing, I will note that these examples in no way represent a complete list. I refer readers to the approximately 45 pages in the appendices in my master thesis where I explain each study in more detail. The appendices give a more extensive overview, including mathematical errors, illogical conclusions, and other central areas. I cannot cover all of them in this article.

Example 1:

In September 2010, NFPA's Fire Analysis and Research Division released "US Experience with Sprinkler and Other Automatic Fire Extinguishing Equipment" (National Fire Protection Association Research, 2010). As the report makes clear, there have been many changes since the "Automatic Sprinkler Performance Tables" were published in the NFPA *Fire Journal* in 1970 (National Fire Protection Association, 1970). Some of the changes are obvious; for example, the earlier report has five pages and the more recent one has 87 pages. More importantly, NFPA has made major changes in methodology and presentation.

The data used in this report not only come from NFPA's databank, but also from the detailed information available in Version 5.0 of the U.S. Fire Administration's National Fire Incident Reporting System (NFIRS 5.0). These fires are reported by the US municipal fire departments, so the report excludes fires reported only to federal or state agencies or industrial fire brigades.
On the basis on the findings, in Fact Sheet, page vii, the report states: "*In reported structure fires large enough to activate them, sprinklers operated in 91% of fires in sprinklered properties*." Furthermore, *"In reported structure fires large enough to activate them, sprinklers operated and were effective in 87% of fires in sprinklered properties"*. These findings are shown in **Table *21***.

Table 6 Automatic extinguishing equipment reliability and effectiveness, by property use 2004-2008 structure fires (excluding fires reported as confined fires)

A. All Sprinklers

			When equipment was present, fire was large enough to activate equipment, and sprinklers were present in fire area			
Property Use	**Number of fires per year where extinguishing equipment was present**	**Per Cent of fires too small to activate equipment**	**Number of fires per year**	**Per Cent where equipment operated (A)**	**Per Cent effective of those that operated (B)**	**Per Cent where equipment operated effectively (A x B)**
All public assembly	1 350	50%	680	89%	92%	82%
Eating or drinking establishment	770	46%	410	90%	90%	81%
Educational property	810	71%	240	85%	96%	82%
Health care property*	1 320	69%	400	87%	97%	84%
Residential	6 760	44%	3 790	94%	97%	91%
Home (including apartment)	4 860	38%	3 000	94%	97%	92%
Hotel or motel	810	60%	330	91%	98%	89%
Dormitory or barracks	260	62%	100	91%	99%	90%
Rooming or boarding house	210	47%	110	93%	96%	90%
Board and care home	170	60%	70	91%	97%	89%
Store or office	2 590	54%	1 200	89%	97%	86%
Grocery or convenience store	510	60%	210	88%	95%	83%
Laundry or dry cleaning	240	47%	130	91%	95%	87%
Service station or motor vehicle sales or service	110	32%	80	93%	94%	87%
Department store	370	61%	150	88%	98%	86%
Office	520	62%	200	89%	97%	86%
Manufacturing facility	2 470	42%	1 420	90%	93%	84%
All storage	600	35%	390	80%	96%	76%
Warehouse excluding cold storage	340	34%	230	85%	97%	82%
All structures**	16 600	49%	8 430	91%	96%	87%

* Nursing home, hospital, clinic, doctor's office, or development disability facility.

** Includes some properties not listed separately above.

Table 21 states that 49% of all fires to which the fire department responded were too small to activate the extinguishing system. When an extinguishing system was present, the fire was large enough to activate the equipment in 51% of the cases, and sprinklers were present in the fire area in 91% of the cases and in 87% of these, the equipment operated effectively.

The reports do not have definitions or explanation to how central key questions is answered or found, like: "*Percent of fires too small to activate equipment.*" How small is too small? Presumably a smouldering fire would, in many cases, not give off enough heat to activate a thermal bulb on a sprinkler head, but this is not defined, and there is no explanation of how the key findings were derived. This could also be applied to the Omega sprinkler failure, when studies discovered that roughly one-third of Omega sprinklers failed to operate under fire with the required pressure (Fire engineering, 1997).

Failure should be of interest for the fire community in general, including fire departments and regulatory agencies alike.

Example 2:

One of the report that have been given most credit when it comes to success for sprinkler system is, the comprehensive work by Henry William (Harry) Marryatt, *Fire – A Century of Automatic Sprinkler Protection in Australia and New Zealand – 1886-1986*" (Marryat, Rev. 1988). This 478 pages long book takes a close look at the history of sprinklers in Australia and New Zealand, including technical aspects of discharging water and water damage, performance analysis (both general and detailed), safeguarding life, causes of fire, incendiarism[1], the operation of sprinkler on flammable liquids, electrical equipment, explosions, fires involving high piled storage, smoke and heat venting in relation to sprinklers, fires with large numbers of sprinklers operated, exposure fires, partial protection, fires not controlled by sprinklers, fires involving multiple-jet controls[2] and economic considerations and cost-benefit analysis.

This book is now in its second edition. It comes with definitions, abbreviations, conversion rates and explanatory notes.

[1] The act or practice of an arsonist; malicious burning or inflammatory behaviour; agitation
[2] Multiple jet or spray controls is at thermic controlled valve, often bulb equipped, that release water from more than one open jet, spray, or sprinkler heads over a design area.

Table 7 Number of sprinklers operating in US and Australia/New Zealand by per cent

	United States[1]				**Australia and New Zealand**		
Number of Sprinkler Operating	Wet System Per Cent	Dry System Per Cent	Total Numbers of Fires	Total System Per Cent	Number of Fires	Total Numbers of Fires	Total System Per Cent
1	42.6%	20.1%	29 733	37.4%	5 816	5 816	64.55%
2 or fewer	61.0%	32.7%	43 396	54.6%	1 431	7 247	80.41%
3 or fewer	70.2%	41.5%	50 769	63.8%	553	7 800	86.54%
4 or fewer	76.2%	48.7%	55 795	70.1%	290	8 090	89.79%
5 or fewer	80.2%	53.7%	59 156	73.4%	189	8 279	91.84%
6 or fewer	83.2%	57.8%	61 814	77.7%	144	8 423	**93.44%**
7 or fewer	85.2%	61.3%	63 724	80.1%	87	8 510	94.40%
8 or fewer	87.0%	64.2%	65 348	82.2%	76	8 586	95.24%
9 or fewer	88.3%	66.4%	66 571	83.7%	50	8 636	95.79%
10 or fewer	89.4%	68.5%	67 629	85.0%	47	8 683	**96.31%**
11 or fewer	90.4%	70.3%	68 533	86.2%	22	8 705	96.55%
12 or fewer	91.2%	72.4%	69 464	87.3%	24	8 729	96.82%
13 or fewer	91.7%	73.8%	69 990	88.0%	31	8 760	97.16%*
14 or fewer	92.6%	75.3%	70 788	89.0%	32	8 792	97.51%
15 or fewer	93.1%	76.2%	71 313	89.7%	22	8 814	97.75%
20 or fewer	95.0%	81.0%	73 347	92.2%	59	8 873	98.39%
25 or fewer	96.0%	84.3%	74 464	93.6%	36	8 909	98.79%
30 or fewer	96.9%	86.7%	75 411	94.8%	23	8 932	99.05%
35 or fewer	97.3%	88.6%	75 976	95.5%	12	8 944	99.17%
40 or fewer	97.7%	90.0%	76 472	96.2%	8	8 952	99.25%
50 or fewer	98.1%	91.9%	77 079	96.9%	6	8 958	99.31%
75 or fewer	98.9%	94.7%	77 995	98.1%	10	8 968	99.41%
100 or fewer	99.4%	96.3%	78 533	98.7%	4	8 972	99.45%
200 or fewer	**99.8%**	**99.7%**	**79 384**	**99.8%**	**1**	**8 973**	**99.46%**
All fires	100.0%	100.0%	79 544	100.0%	49	9 022	100.00%

[1] This numbers have been updated to 1925-1969 numbers from the Automatic Sprinkler Performance Tables (National Fire Protection Association, 1970) and not the original version of 1925-1964 in Table 4.
*This is specified as 96.16 in the original table. This cannot be true and have been changed.

The book states before the table on page 91: "*It will be seen from Table 4 which follows that one sprinkler head in operation was required in 64.55% of fires, while 6 sprinkler heads or fewer were required in* ***93.36%*** ** of fires, and 10 sprinkler heads or fewer were required in* ***96.16%*** ** of fires*". The problem is that the table gives **93.44%** and **96.31%** respectively (and this number has been checked against a previous table in the book that gives the precise per cent against number of sprinkler heads operating) (* author's highlight). Both text and table cannot be correct.

Chapter 15, “Fires in which large numbers of sprinkler heads operated”, takes a closer look at fires with a large number of sprinkler heads, more specifically, fires with more than 10 sprinkler heads operating: *“It has already been shown in Chapter 4 that the percentage of fires in Australia and New Zealand controlled with six (6) or less sprinkler heads in operation, and ten (10) or less respectively, were as follows*:

Table 8 Fires in which 6 or less and 10 or less sprinklers were in operation

6 or less sprinklers in operation		
1886-1968	**1968-1986**	**100 Years**
94%	**91.69%**	**93.39%***
10 or less sprinklers in operation		
1886-1968	**1968-1986**	**100 Years**
96.7%	**95.13%**	**96.60%***

*****This is third place where we see a difference in the number of sprinkler heads in operation. If this includes “*not controlled*”, both numbers should be higher than 93.44% and 96.31%.

While the NFPA table separates wet and dry systems, this book does not. Under “Dry pipe and marine automatic sprinkler system” in the same chapter, the author says that “*one of the important differences in results when comparing the number of sprinkler heads in operation on fires in Australia and New Zealand with those in the United States is that there are very few dry pipe systems in these two countries, so few that* ***no fires**** *have been recorded for this type of installation* (* author’s highlight). *However, four fires in marine automatic sprinkler systems have been recorded.*”

Table 5 gives the following explanation of high reliability: “*Inspection, testing, and maintenance exceeded normal expectations, and higher pressures*”. However, the systems in this survey are wet systems (dry systems have larger fire growth because of the time water must travel from the sprinkler alarm valve to the area of fire; the fact that dry systems have more inherent possibility of failure is another factor), all fires where sprinklers were shut off (except where arson was involved) are excluded, the fact that most of the cases come from

Wormald International Group of Companies[3] (which may have a self-interest in collecting good reports) may explain the high reliability, and the fact that 99.5% is referring to 200 sprinkler operating.

5.5. DOCUMENT ANALYSIS

A critical review of the selected literature leads to many questions and few answers. Could there be some more fundamental issues on stake here, and how should they be reviewed? Within the social sciences, including history, social anthropology, political science, socioeconomics, psychology, and so on, there is a social science methodology. The two of interest here is: how to conduct surveys and document analyse (Jacobsen, 2015). Document analyse, or source examination is the analysis of documents (secondary data) to answer the research question (problem) by collecting and analysing other words, phrase, stories on a topic, and reports. While a literature review tries to find theory or practice hole (or abundance), document examination is a systematic tool to examine all types of documents to find the answer to the question(s). This is helpful when:

a) it is impossible to collect primary data
b) it is desirable to find out how others have interpreted situations, events, or data
c) it is desirable to find out what has been done or said

Many different words are used to describe reliability (success, performance, performance effectiveness, operating, operating reliability, effectivity, operational effectively), and there are large gaps between the different levels or scores of reliabilities from one study to another. In addition, key findings are not always explained in a satisfactory way. Thus, the question is: are the studies done in a satisfactory, scientific way? Are the results trustworthy? Can they be applied as documented expected reliability within the geographic area of the study?

5.5.1. DOCUMENT ANALYSIS VALIDATION

The following steps must be taken to fulfil the requirements of a scientific study.

[3] The American conglomerate Tyco International, acquired the company in 1990.

1. Development of problem and purpose
    1.1. Is the issue clear?
    1.2. Is it descriptive or explanatory (causal)?
    1.3. Can it be generalized?
2. Choice of design
    2.1. Intensive (deep) or extensive (width) study design
    2.2. Descriptive or explanatory
3. Type of data (qualitative or quantitative)
4. Method of data collection
    4.1. Operationalization: make a concept measurable
    4.2. Design of the study
    4.3. Sourced and use of sources
5. Selection and limitation
6. Analysis
7. Quality assurance of the analysis
    7.1. Conceptual validity
    7.2. Validation of contexts
    7.3. External validity
    7.4. Are the results trustworthy?
8. Discussion and presentation
    8.1. Methodological discussion
    8.2. Substantial discussion – connection of findings and theory
    8.3. Presentation (also uncertainty)

This list provides a systematic tool of document analysis that can be used on the reports or studies of interest. In this article, although five studies of interest are shown in **Table 5**, we will only look at "US Experience with Sprinkler and Other Automatic Fire Extinguishing Equipment 2004-08" (National Fire Protection Association Research, 2010). The rest of the analysis appears in the thesis. Validation with respect to the eight steps given above, is answered in

Table 9 by Yes, No or Not sure.

Table 9 Document analysis of US experience with sprinkler and other automatic fire extinguishing equipment 2010

Preparation and collecting		Analysing		Presentation	
1. Development of problem and purpose	No[4]	6. Analysis	Yes[14]	8. Discussion and presentation	No[21]
a) Is the issue clear?	No[1]			a) Methodological discussion	Yes[18]
b) Is it explanatory (causal) or descriptive?	No[2]			b) Substantial discussion (connection of findings and theory)	No[19]
c) Can it be generalized?	Yes[3]			c) Presentation (also uncertainty)	No[20]
2. Choice of design	Yes[7]	7. Quality assurance of the analysis	No[17]		
a) Intensive (deep) or extensive (width) study design.	No[5]	a) Conceptual validity	No[15]		
b) Descriptive or explanatory	Yes[6]	b) Validation of contexts	Yes[16]		
		c) External validity	Not sure		
		d) Are the results trustworthy?	Not sure		
3. Type of data (qualitative or quantitative)	Yes[8]				
4. Method of data collection	No[12]				
a) Operationalization: make a concept measurable	No[9]				
b) Design of the survey	No[10]				
c) Source and use of sources	Yes[11]				
5. Selection and limitation	Yes[13]				

[1] It is not clear what sprinkler reliability and effectiveness are. Even if there is no definition, there is a statement that effectiveness should be measured relative to design objectives and the design purpose is to confine a fire to the room of origin. This has not been proved to be right.
[2] They study both.
[3] The first line is “Sprinklers are a highly effective and reliable part...”. This is generalizing.
[4] The sum of a, b, and c.
[5] Both. Extensive when using the US Fire Administration’s National Fire Incident Reporting System (NFIRS 5,0) corrected with NFPA Fire Record Department and over 57 000 fires and intensive design when there are many variables.
[6] Explanatory. Not only low ineffectiveness, but also causes/reasons (Figure 11 to 13).
[7] The sum of a and b.
[8] Quantitative.
[9] Even if performance/effectiveness/reliability could be objectively measured, it is how the filler of the form perceives performance/effectiveness/reliability that is noted and used in the analysis.
[10] Design of study does not consider type of system.
[11] NFPA study uses NFIRS to scale the numbers; NFIRS is a voluntary system.

[12] The sum of a, b, and c.
[13] Only buildings and excluding partially protected buildings.
[14] The report.
[15] Even if 49% of the fires were too small to activate equipment, there is no discussion or validation of how this affected performance/reliability.
[16] Tables 4 and 5 show correlation; cause comes before effect in time and control on other conditions. The fact that "Fires too small to activate" is not supported with either qualitative or quantitative data, have not been considered.
[17] The sum of a, b, and c.
[18] Section 1 and Appendix A.
[19] Either fire theory (including extinguishing) or reliability theory is discussed or defined.
[20] Appendix A has a discussion on uncertainty, but this is not specified in numbers. Lack of uncertainty analysis.
[21] The sum of a, b, and c.

1.1.1. SUMMARY OF THE DOCUMENT ANALYSIS

The basis for choosing these surveys for analysis is whether they can be used in a scientific way as a general basis for predicting the reliability of the sprinkler system. It must be stressed that this analysis does not attempt to judge the value of those studies. **Table 10** shows the studies after validated trough document analysis.

Table 10 Overview of document analysis validation for the examined studies

Reference	1.	2.	3.	4.	5.	6.	7.	8.	SUM
Marryat (Marryat, Rev. 1988)	No	Yes	Yes	No	No	No	No	No	**No**
NFPA (National Fire Protection Association, 1970)	No	Yes	Yes	No	Yes	Yes	Not sure	No	**No**
NFPA (National Fire Protection Association Research, 2010)	No	Yes	Yes	No	Yes	Yes	No	No	**No**
NFPA (National Fire Protection Association Research, 2017)	No	Yes	Yes	No	Yes	Yes	No	No	**No**
NFSM (Optimal Economics, 2017)	No	Yes	Yes	No	No	Not sure	No	No	**No**

1, Development of problem and purpose
2. Choice of overall survey design
3. Type of data
4. How to collect data
5. Selection and limitation
6. Analysing
7. Quality assurance of the analysis
8. Discussion and presentation

1.2. DISCUSSION OF FINDINGS

Should all the questions be answered "Yes" for a study to be considered a scientific study or is possible to get some "No" or "Not sure" responses? That is a good question, and it will be discussed later in the paper. For example, if a study does not define its terms or its definitions go outside common usage, what value does it have to the field of reliability? In such cases, even if several factors indicate the study in general is done in a scientific way, **the conclusion is that it cannot be used to get a general view of reliability or on future probability**.

What can we say with scientific certainty about sprinklers based on the studies in question? Looking at **Table 21**, if we not know if the 49% assigned to "fires too small to activate" is correct, then we should basically use 51% as our starting point for calculation. Unfortunately, the studies include not only temperature activated equipment like sprinkler and water mist, but also detector activated systems like gas-systems (CO^2/Inergen) and foam. So, we must look at a newer study that only considers sprinklers, the 2017 NFPA research study (National Fire Protection Association Research, 2017).

Table 11 Automatic sprinkler system reliability and effectiveness, by property use 2010-2014 structure fires (excluding fires reported as confined fires)

A. All Sprinklers						
			When equipment was present, fire was large enough to activate equipment, and sprinklers were present in fire area			
Property Use	**Number of fires per year where sprinkler was present**	**Per Cent of fires (numbers) too small to activate sprinkler**	**Number of fires per year**	**Per Cent where sprinkler operated (A)**	**Per Cent effective of those that operated (B)**	**Per Cent where sprinkler operated effectively (A x B)**
All public assembly	1 220	48% (580)	640	90%	94%	85%
Educational property	590	70% (410)	180	87%	96%	84%
Health care property*	900	66% (590)	310	87%	97%	84%
Residential	6 630	38% (2 490)	4 140	93%	96%	89%
Store or office	2 070	50% (1 030)	1 040	91%	96%	87%
Manufacturing facility	1 360	44% (600)	1 030	91%	94%	85%
All storage	440	32% (140)	300	86%	96%	82%
All structures*	**13 210**	**44% (5 840)**	**7 640**	**92%****	**96%****	**88%****
* Nursing home, hospital, clinic, doctor's office, or development disability facility.						
** The per cent is taken from Table 6 in the 2017 report. Not checked.						

The conclusion is that 56% of the fires were large enough to activate the sprinklers, 92% were activated and 96% were effective. This gives a probability of 56 x 92 x 96 = **49%** that a sprinkler will perform efficiently when there is a fire in the building.

There are four areas that should be noted, as all studies had “No” for these areas.

A. The first one is the development of the problem and purpose (step 1). Only one study had a definition (Marryat, Rev. 1988), but not of reliability. The reason for not listing or discuss definition before in this article, is to stress: what is reliability?
   Simply stated, reliability is the ability to function as intended. More precisely it is the characteristic or expression of the ability of a component or system to perform an intended function. This also includes the lifetime probability distribution of failure, statistical life expectancy, expected number of failures per unit of time, a system or component's ability to function satisfactorily over time and the likelihood that it will work at a specific time (Aven, 2006). For a sprinkler system, intended means the likelihood of functioning as designed. This point is missed in every report or study mentioned in the thesis. With a clear definition, the probability of functioning as designed, data can be gathered.

B. The second problem area, how to collect data (step 4), derives directly from the first. What does the ability to function as designed mean for a sprinkler system? Well, that comes down to what kind of a sprinkler system we are talking about.

What do for example American standards says about this? According to NFPA 13D (National Fire Protection Association, 2010) Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes:

> *“1.2.1 The purpose of this standard shall be to provide a sprinkler system that* ***aids*** *in the detection and control of residential fires and thus* ***provides improved*** *protection* ***against injury and life loss.***
> *1.2.2 A sprinkler system designed and installed in accordance with this standard shall be* ***expected to prevent flashover*** *(total involvement) in the room of fire origin, where sprinklered, and* ***to improve the chance for occupants to escape or be evacuated*”***
> (*author’s highlight).

With a 7/10-minute rate for water demand for up to two residential sprinklers in the biggest room (ref. Chap. 6.1), a home sprinkler system is not designed to confine a fire in a room or design area, but to help people escape a fire by preventing flashover until the system has water and, thus, to extend the escape time.

The purposes of sprinklers are expanded in the NFPA standard for larger residential buildings. NFPA 13R (National Fire Protection Association, 2010) Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height specifies the following:

"1.2.1 The purpose of this standard shall be to provide a sprinkler system that ***aids*** *in the detection and control of residential fires and thus* ***provides improved*** *protection* ***against injury, life loss, and property damage****.*

1.2.2 A sprinkler system designed and installed in accordance with this standard shall be ***expected to prevent flashover*** *(total involvement) in the room of fire origin, where sprinklered, and* ***to improve the chance for occupants to escape or be evacuated*****"* (*author's highlight).

With a 30-minute rate for water demand for up to four residential sprinklers in the biggest room (ref. Chap. 7.1.1.3), the purpose is expanded to include some protection against property damage.

Standard NFPA 13 (National Fire Protection Association, 2016) Installation of Sprinkler Systems more clearly specifies protection of property:

"1.2.1 The purpose of this standard shall be to provide a ***reasonable degree of protection for life and property**** *from fire through standardization of design, installation, and testing requirements for sprinkler systems, including private fire service mains, based on sound engineering principles, test data, and field experience"* (*author's highlight).

Chapter 3 in NFPA 13 gives the following definitions of purposes and sprinkler types:

"3.3.11 ***Fire Control.*** *Limiting the size of a fire by distribution of water so as to decrease the heat release rate and pre-wet adjacent combustibles, while controlling ceiling gas temperatures to avoid structural damage.*

3.3.12 ***Fire Suppression.*** *Sharply reducing the heat release rate of a fire and preventing its regrowth by means of direct and sufficient application of water through the fire plume to the burning fuel surface.*

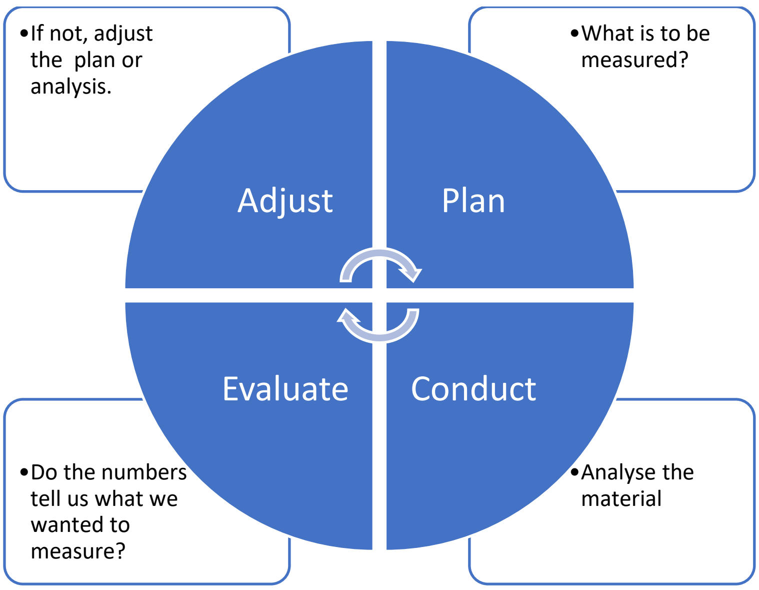
3.6.4.1 Control Mode Density/Area (CMDA) Sprinkler. A type of spray sprinkler intended*

*to provide **fire control*** in storage applications using the design density/area criteria described in this standard.*
3.6.4.3 Early Suppression Fast-Response (ESFR) Sprinkler. A type of fast-response sprinkler that has a thermal element with an RTI of 50 (meters-seconds)$^{1/2}$ or less and is listed for its capability to provide **fire suppression*** of specific high-challenge fire hazards.*

Importantly, The NFPA 13 standard defines the purposes of sprinklers differently, according to the sprinkler type. Given this lead, then, why do studies not try to determine the reliability of specific sprinkler designs? They are being designed, built, and inspected/maintained according to sprinkler standards, and it is not clear why there is no interest in monitoring, controlling, and adjusting the standards based on their reliability. Recall that the reliability of a sprinkler system is its ability to function as designed. What about activation and performance? These two parts is a natural part of reliability, but both meaning of words and use of them need to be discussed and defined. For example, is activation and operation the same?

C. The third area (step 7) is the quality assurance of the analysis. If there is no clear and measurable purpose, then is it hard to check if results give the answer that are searched. How this is done is illustrated in Figure I's depiction of a quality assurance wheel.

Figure 4 Quality assurance wheel



This concept is valid for planning in general; it can also be applied to data used in studies of reliability and to the management of quality. It is very important to check results for conceptual validity, contextual validity, external validity, and are the results trustworthy. If they do not have these qualities, it will be hard to trust them.

D. The fourth problem area is presentation (step 8). Discussions, comparisons to earlier or other studies, trends if possible, and honest views on uncertainty must indicate everything that could be a major issue. There is only one study in this literature review uses the word "*indicates*" when discussing the results (Optimal Economics, 2017).

1.2.1. HOW SCIENTIFIC IS THE USE OF DOCUMENT ANALYSIS?

The use of document analysis is a scientific method for the systematic analysis of documents, but two aspects require further attention.

First, how well does this method from the social sciences work when it is applied in the natural sciences, in this case, in Fire Safety and Fire Engineering? There is room for improvement and I hope that I can come back to this in my next article, where I will give suggestions on methodology and designs for scientific investigation/studies, with a focus on collecting, analysing, and presenting data on sprinkler reliability. These can, of course, be used in other areas as well.

Second, should all questions be answered "Yes" in the document analysis to make a study a scientific one, or is possible to score some "No" or "Not sure" without being "unscientific"? There are questions that are informative, but manly this depends on the purpose, sources, and resources available. For example, consider the three first questions under the

"*Development of problem and purpose (step 1):*

a) Is the issue clear?

b) Is it explanatory (causal) or descriptive?

c) Can it be generalized?"

a) If the purpose or issue of the study is not clear, this often means it suffers from a lack of definitions. Moreover, the purpose may not have been followed and adjusted to suit available sources and data. Lack of sources or data can be compensated and overcome. If a fire brigade report lacks central information, for example, a written inquiry, telephone contact and even a personal visit/investigation is possible, but this comes down to what kind of the resources the study team has. If there are not enough resources/time available, the purpose should be adjusted to reflect this.

b) A study can be both explanatory (causal) and descriptive. None of the studies examined in the literature review received a "Not passed" at question number 1, because it was either explanatory or descriptive. This is an informative question. The challenge is that the extent of the survey increases exponentially when a study changes from descriptive to explanatory. Are we more interested in *how* (descriptive) or *why* (explanatory)? As soon as the interest shifts from whether something works or not, to what makes it work, the purpose, data, and resources must be adjusted. This is often not the case, and the causes of interest are not redefined. Interestingly, few (perhaps no) studies look at why sprinklers work in different buildings, with different storage configurations and human behaviour.

c) If a study wants to define general reliability, the demand to generalize often pushes the benchmark up, not down. The most common fault in the studies examined is the assumption that all sprinkler systems have the same function. This is not the case; an NFPA 13D system cannot be compared to an ESFR system. If there has been a conscious generalization, not possible to gain the right data or this has happened because of a lack of study management, it is not possible to make conclusions from the studies.

1.3. SUMMARY

The sprinkler has been used for 150 years with great success. Its ability to improve fire safety for both building occupants and fire and rescue personnel has been noted for a long time. The producers of sprinkler systems and insurance companies express great interest in testing and validating these systems' components. The same could be said about sprinkler standards. They too should be tested and validated with field experience. Although there are regulations in place, there is little follow up on their usage and efficacy. Unfortunately, those making the decisions have not had sufficient interest or the knowledge required to conduct good studies. The need to know if a mandatory regulatory demand is working as expected or not and to collect good quantitative data for performed-based design, is of outmost importance. This data must be provided by the systems to the fire and rescue services, since they can give the impartiality required to such a study.

For the time being, the conclusion about the studies reviewed here is that they cannot be used to determine a general view of reliability of sprinkler systems or future probability. Fire or sprinkler organisations do most of the unthankful work of producing studies that give some insight. As a fire engineer, the lack of data on sprinkler reliability concerns me. Even more concerning, there are few data on other fire protecting system, both active and passive.

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6. ARTICLE "NEW METHODS FOR COLLECTING, ANALYSING, AND PRESENTING RELIABILITY DATA"

The first of two articles sent SFPE Journal.

6.1. ABSTRACT

In the previous article "How Reliable is Reliability Data for Sprinkler?", the conclusion was that the survey in question "*cannot be used as a general documentation on reliability for sprinkler systems to function as designed*". There are areas of improvement in methodology and design for surveys and this article give suggestion to this and a descriptive study.

Keywords: Sprinkler; Reliability; Critical review; Document analysis; How to conduct survey.

6.2. INTRODUCTION

The subject of my previous article "How Reliable is Reliability Data for Sprinkler?", where I combined critical review and analysed the surveys in question by asking, how are the surveys been done? This was done as a document analysis. This is helpful when:

a) It is impossible to get primary data
b) A researcher wishes to learn how others have interpreted a situation, event, or data
c) A researcher wishes to learn what has been done or said

The table under shows the different steps on a scientific survey that was applied for the surveys of interest and validated through document analysis:

Table 12 General overview for document analysis validation

Preparation and collecting		Analysing		Presentation	
1. Development of problem and purpose		6. Analysing		8. Discussion and presentation	
2. Choice of survey design		7. Quality assurance of the analyse			
3. Type of data					
4. How to collect data?					
5. Selection and limitation					

If surveys were to be used as a documented expected reliability, the demand to be done in an acceptable scientific way, must be met. This is not the case and "*the conclusion is that they cannot be used as a general documentation on reliability or on future probability for sprinkler systems to function as designed*".

Table 13 Overview of document analysis validation for the examined studies

Reference	1.	2.	3.	4.	5.	6.	7.	8.	SUM
Marryat (Marryat, Rev. 1988)	No	Yes	Yes	No	No	No	No	No	No
NFPA (National Fire Protection Association, 1970)	No	Yes	Yes	No	Yes	Yes	Not sure	No	No
NFPA (National Fire Protection Association Research, 2010)	No	Yes	Yes	No	Yes	Yes	No	No	No
NFPA (National Fire Protection Association Research, 2017)	No	Yes	Yes	No	Yes	Yes	No	No	No
NFSM (Optimal Economics, 2017)	No	Yes	Yes	No	No	Not sure	No	No	No

1. Development of problem and purpose
2. Choice of overall study design
3. Type of data
4. How to collect data
5. Selection and limitation
6. Analysis
7. Quality assurance of the analysis
8. Discussion and presentation

As mention in past article, there are areas of improvement in this field of Fire Engineering and this article is about suggestion on methodology and design of scientific survey for collecting, analysis and presentation of reliability.

This article can also be read as a supplement to better understand how the surveys in question failed on several areas.

6.3. METHODOLGY

Most of the sprinkler standards in the world say something like this: "*The purpose of this standard shall be to provide a sprinkler system that aids in the detection and control of fires*". This or a similar statement is written into the purpose of the standard or communicated throughout the standard. Since the beginning of sprinkler systems, the purpose of detecting and warning of fire has been a natural part of the system. Even today, a sprinkler control valve is called alarm valve. Therefore, those who plan to conduct studies of sprinkler systems should consider detection and warning. If this is of no interest, what is then the purpose of have this as part of designed and installing of sprinkler system in the future?

As mention in the previous appendices, certain areas in the field of Fire Engineering require improvement. This appendix should be of some help, as it offers suggestions for methodologies to collect, analyse and present reliability data for all types of safety systems, with a focus on sprinklers.

Many factors in how things are done affect both the quality of the data and the outcome of the analysis. One example is from the UK Incident Recording System (IRS) (DCLG, 2012). After the answer "*Yes"* is given to the question "*Did the safety system operate?*", a following question is "*Select the number of sprinkler heads that operated*". This can be answered by 1 to 5, more than 5 and "*Not known*". Why is "*Not known*" given as option at all? Is it assumed that visual inspection cannot find this? Furthermore, will this type of question improve the data or not? These and other questions must be asked. Data collection and analysis is a multi-discipline and multi-team efforts.

Based on the document analysis and the requirements of a scientific study, in **Table *49***, I suggest a new format for a scientific study.

Table 14 Division and steps in a study of sprinkler reliability

Main step*	Sub step	Explanation
Preparation and collecting		
	1.1. Is the issue clear or not?	If the purpose or problem of the study is not clear, this often means the purpose has not been revised over time, adjusted according to available sources and data.
Informative	1.2. Is it descriptive or explanatory (causal)?	Is the study more interested in how (descriptive) or why (explanatory)?
Informative	1.3. Is it desirable to generalize the findings?	If it is desirable to generalize the findings, this pushes the benchmark up.
1. Development of problem and purpose		**Does it have an understandable problem or purpose?**
Informative	2.1. Intensive (deep), extensive (width) study design or both?	Extensive designs have many units in the study, but few variables. Intensive designs have many variables, but few units. If both are selected, there will be many units and variables.
Informative	2.2. Descriptive or explanatory?	This of most interest if an explanatory design is selected. The following steps must be taken, as the extent increases exponentially when

		the study goes from descriptive to explanatory. 1. Correlation of cause and presumed effect. 2. Cause must precede effect in time. 3. Control of all other relevant factors.
2. Choice of overall study design		**Is there an understandable overall design?**
	3.1. Operationalization, how to make a concept measurable	Make abstract concepts, like reliability, operation, function, effect, and soon on, into something measurable.
	3.2. Design of the study	Does it use its own design or another study's design?
	3.3. Source and use of sources	Is it possible to use or change data collecting or design the study to accommodate fire brigades or must it be independent?
	3.4. Selection and limitation**	The selection of more than one extinguishing system will result in more than one study. The study must limit all types of events that don't control other relevant factors: e.g., ships vs. buildings; fully vs. partially protected; residential vs. ordinary hazard, and so on.
3. How to collect data?		**Does the study have a workable design?**
Analysis		
4. Analysis		**It is very important to do the analysis scientific methods, including control of the use of results.**
	5.1. Conceptual validity	After concretization of the concepts, it is very important to ask: Do the indicators measure what we are interested in?
	5.2. Validation of correlations	If an explanatory (causal) problem/design has been chosen, this places a strong demand on the study. Is it answered by the analysis?
	5.3. External validity	Is it possible to go from empirical evidence to known theory, based on the findings? If is desirable to generalize from selected units, it is important to ask if the study is wide enough and there is a representative selection in the analysis.
	5.4. Are the results trustworthy?	Can the way the study has been done be the reason for the results? There is a need to control the level, time frame, and causality.
5. Quality assurance of the analysis		**How good are the conclusions drawn from the analysis?**
Presentation		
	6.1. Methodological discussion	Methodological discussion includes the steps of quality assurance of the results (step 5 of this section) and how the study has been conducted.

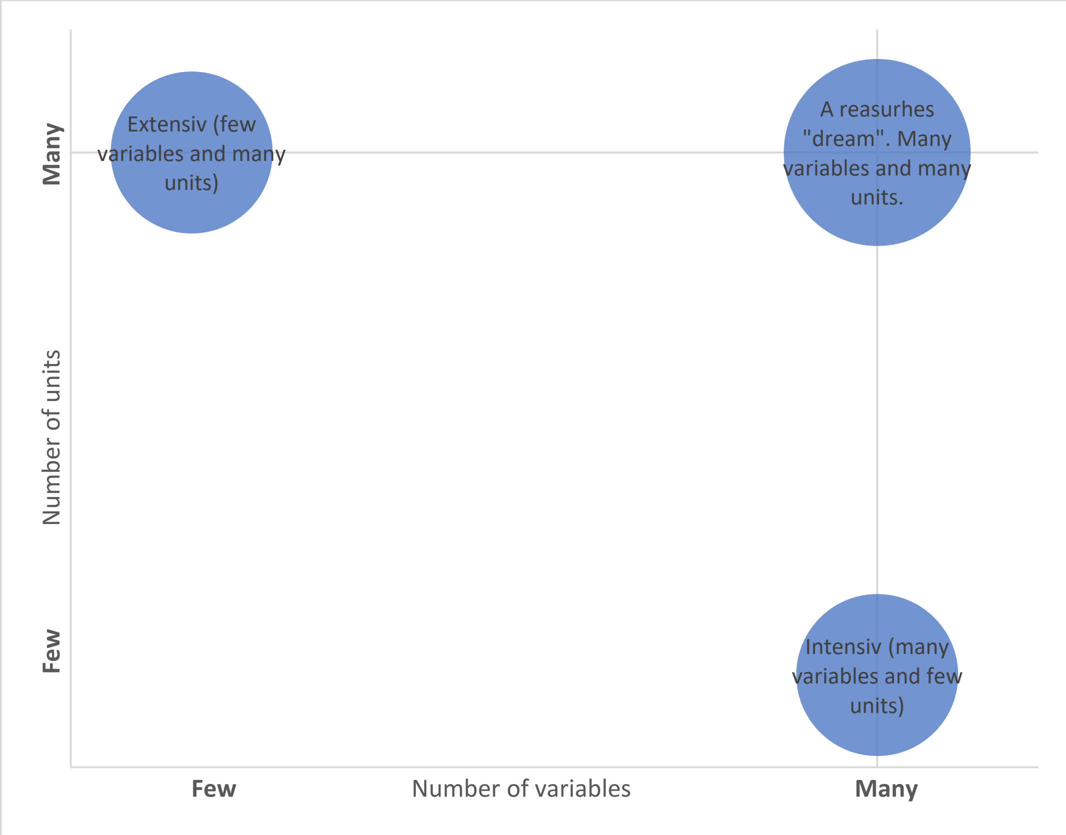
	6.2. Substantial discussion – connection of findings and theory	Is it empirically consistent or inconsistent with other like or similar studies in this field? What are the connections between the findings and how this should be theoretically understood?
	6.3. Presentation (also uncertainty)	Is it transparent, logical, and readable?
6. Discussion and presentation		**How good is the presentation of the conclusions?**
* Former step 3 Type of data (qualitative or quantitative) have has been removed in this table, because qualitative data, analysis and presentation is seldom of interest in Fire Safety. ** While this is step 5 in the document analysis, several aspects argue for inclusion in step 3. The need to select and limit the type of objects, systems, and so on when designing the study, does not exclude the possibility of excluding collected data that are obviously wrong or inadequate later in the process.		

Further comments on the suggested methodology:

1. Development of problem and purpose: It would be a major improvement if the international fire community could reach agreement on the terms used in reliability data. There are many different words used to describe reliability or part of reliability. Of real interest is a study that wishes to generalize the outcome. It is important to find out if this is possible. Are the sources available for the whole area of interest? If not, perhaps an indicative study could be used to illuminate the problem or to address the proper authorities for improved collecting data.

2. Choice of overall study design: The following figure shows the correlation between intensive and extensive study designs.

Figure 5 Classification of study design as intensive or extensive



An extensive study with many units and few variables is a very good foundation for a generalizable study.

3. Some of the steps are informative. There is no right or wrong choice, but the choices must be conscious. Every choice has consequences for collecting, analysing, and presenting.

6.4. HOW TO PERFORM A SIMPLE STUDY

Based on the overview in **Table 14**, I will suggest principles for two different studies, from the simplest to the more demanding, starting with the simplest.

STEP ONE

The first step is to determine the overall design and what is of interest. This requires a detailed plan of what kind of sprinkler systems are of interest, how, where, and over what time.

Table 15 Design of simple study

Main step	Sub step	Task
Preparation and collecting		
	1.1. Is the issue clear or not?	The purpose of this study is to find the reliability (to function as designed) of sprinkler systems in Norway. Design means the selected sprinkler system.
	1.2. Is it descriptive or explanatory (causal)?	This is a descriptive study and causal reasons (why the systems work or do not work as intended) will not be covered.
	1.3. Is it desirable to generalize?	It is desirable to generalize historical reliability, as this is a good indicator of future probability of the sprinkler systems being designed and installed under the conditions covered by the study.
1. Development of problem and purpose		**Conduct a descriptive study that generalizes the national reliability of sprinkler systems in Norway.**
	2.1. Intensive (deep) or extensive (width) study design	Based on the purpose, an extensive design with many units in the study and few variables is chosen.
	2.2. Descriptive or explanatory	Descriptive design is chosen.
2. Choice of overall study design		**Create an extensive and descriptive overall study design.**
	3.1. Operationalization, how to make a concept measurable	Definition: **Sprinkler system activation**; 1: the sprinkler control valve (alarm valve) opens, 2: the pump (if installed) starts and 3: the sprinkler alarm activates. **Fire controlled by sprinkler system**; the fire is contained/extinguished within the sprinkler system's design (number of activated sprinklers and square metres covered).
	3.2. Design of the study	Based on design and event tree analysis, create a form for the study.
	3.3. Source and use of sources	It is desirable to use the Norwegian BRIS (Brann, Redning, Innrapportering, Statistikk / Fire, Rescue, Reporting, Statistics[4]) for reporting fires.
	3.4. Selection and limitation	Only buildings fully protected by sprinklers or parts of building that are separated by fire section walls are of interest. Only sprinkler systems by NS-EN 12845:2004 and CEA 4001 will be examined. Data on system type will always be validated against the ESS (Elektronisk System for

[4] Norwegian incident reporting system used by all Norwegian fire and rescue personnel.

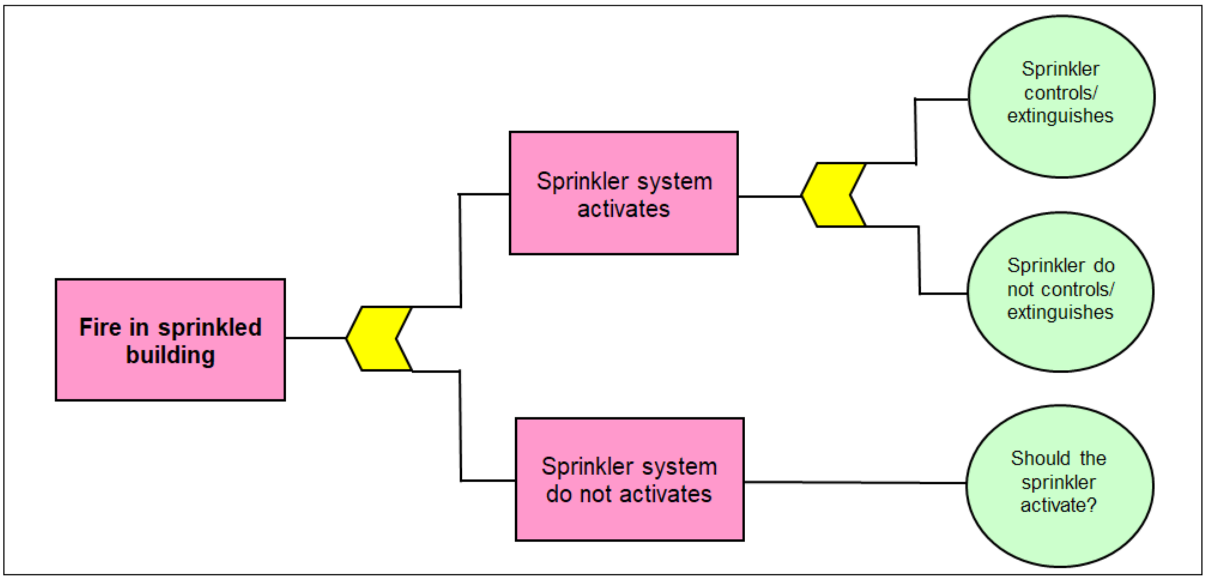
		Sprinkleranlegg / Electronic System for Sprinkler-system[5]). Fires from 2010-2014 will be examined.
3. How to collect data?		**The design of the study is based on Norwegian BRIS, looking at building fires from 2010 – 2014 in buildings protected following NS-EN 12845:2004 and CEA4001 rules. Details on sprinkler systems and hazard classes are validated using ESS.**

Before writing a new form to collect data, using earlier forms, or taking data directly from the BRIS, an event tree analysis of some nature must be performed to make sure the description is correct, and every aspect is thought out, to create tools for a form and to do a quality assurance of the analysis.

STEP TWO

In the event tree, the starting point is: Fire in sprinkled building.

Figure 6 Event tree simple design



Before writing the form, they three outcomes need discussion and clarification. We also need to discuss the use of the words activate/activation.

Activate/activation: In most of the literature and studies, the words operate/operating/operational are used about a system that starts to do something. This is

[5] ESS is the Norwegian insurance company's database for recording reports after inspections of sprinkler systems and for project reports when planning new sprinkler systems.

interesting, but a system should operate BECAUSE it was activated. If a system is activated, but does not operate, this has a cause. Even if the cause is not of interest in this case, the establishment of an accurate and precise vocabulary is necessary, and the word activate will be used herein.

Outcome 1: “Sprinkler system controls or extinguishes the fire.” There is interest in the number of sprinklers activated and the area damaged by the flames, since the hazard classes have an area of design and to quality assurance the number of activated sprinkler. The fire response team has no difficulty concluding that a fire has been put out or is under control, with only minor measures required to put out the fire. The number of activated sprinklers should relate to the area of flame damage. If not, this needs further investigation.

Outcome 2: “Sprinkler system does not control or extinguish the fire.” There is interest in the number of sprinklers activated and the area damaged by the flames, for same reason as outcome 1 (control on hazard class and quality assurance), and to ensure the right outcome has been chosen. It is possible that the fire team thinks, e.g., that 10 sprinklers and $100m^2$ do not indicate control, but for every hazard class over OH1 in EN 2845, this is less than design area for the sprinkler system. It is important to have control of all possible non-negative outcomes in the category of negative outcomes as well.

Outcome 3: “Sprinkler system does not activate.” As shown earlier, this outcome has been neglected when it comes to quality assurance. It is very important to find out two things. One, was the system activated, but did not operate? Two, should it have activated but did not?

One: To determine this with high degree of certainty, it is necessary to conduct an alarm test of the sprinkler valve. With an alarm, the system is intact, and the system was not activated. No alarm is a fault and indicates a problem with the system in general.

Two: Visual inspection of affected sprinklers. If the bulb/fusible link is intact and there is no suggestion that the heat was sufficient to activate the sprinkler, it can be concluded that the system should not have been activated. If there is uncertainty, this should be noted.

STEP THREE

Step three is writing the form to collect data. This is basic regardless of how it will be distributed or how information will be collected from databases. The main purpose is to have control of questions that are of interest and to use them in the quality assurance of the analysis.

Table 16 Inquiry form for fires in buildings protected by sprinkler systems

Form for fires in buildings protected by sprinkler systems		
Information about the building*		
1.	**Address:**	**Official identification number (Norway Gnr/Bnr)**
	Type of building:	**Is the building registered in ESS? If not, must the owner must do this?**
	Date and time of fire:	
	Installing year and latest inspection/maintenance:	**Data from documentation or from ESS.**
Information about the sprinkler system		
2.	**Type of sprinkler system:**	**CEA 4001** **NS-EN 12854** **NS-INSTA 900** **NFPA 13** **Other (specify)**
3.	**Hazard class**	**OH/HHP/HHS** **1 – 4**
Information about consequences of fire		
4.	**Did the sprinkler system activate alarm (by the fire alarm system or by external alarm bell)?**	**Yes/No**
5.	**Did the sprinkler system activate sprinkler pump if present?**	**Yes/No/Not present**
6.	**Did the sprinkler system control or extinguish the fire?**	**Yes/No**
7.	**If yes, how many sprinklers were activated and what was the area of flame damage?**	**Number:** **Area:** m^2
8.	**If no, how many sprinklers were activated and what was the area of flame damage?**	**Number:** **Area:** m^2
9.	**If the fire did not activate the sprinkler system, is the bulb or fusible link on sprinkler destroyed/damaged?**	**Yes/No**
10.	**If the fire did not activate the sprinkler system, does a test of the alarm show it works?**	**Yes/No**

11.	If the fire did not activate the sprinkler system, are there any indications that is should have been activated (size of fire, damage in the area, e.g.)?	Yes/No Affected area: m^2
*It must be possible to trace the data to the source, if needed.		

Even this simple study has 8 questions. By concretizing the activation/outcome in only yes/no answers, question 11 is changed from a qualitative question in **Outcome 3** to a quantitative question.

STEP FOUR

Step four is the analysis and this must be done by normal scientific methods.

STEP FIVE

By conducting a good quality assurance of the analysis in step five, the fundamental requirements for a solid presentation in the last step are mostly met. The importance of checking the answers given by analysing them against the purpose of the study cannot be stressed enough. The list in **Table 17** is a minimum layout for this form based on the purpose of the study; it can be extended.

Table 17 Design of simple study, step five

	5.1. Conceptual validity	**Overall question: Do the indicators measure what we are interested in?** 1. How many building fires are there per year during 2010 – 2014? 2. How many fires are in sprinkled buildings? 3. How many sprinkler systems were CEA 4001/ NS-EN 12845/ NS-INSTA 900/ NFPA 13/Other system?[1] 4. How many fires activated the sprinkler system (both overall and by alarm and pump)? 5. How many fires were indicated as controlled/ extinguished by the report? 6. How many sprinklers were activated on the different systems and hazard classes? This includes also non-controlled fires. 7. When the system did not activate, was sprinkler bulb/ fusible link destroyed/ damaged? 8. Are there indicators that the system should have activated/worked?

		9. Did the alarm test work on the non-activated sprinkler system?
	5.2. Validation of correlations[2]	1. How many fires were controlled/ extinguished according to the number of sprinklers/area of damage? 2. Is the area affected by the fire (flames/hot plume) correlated to the number of activated sprinklers?[3] 3. Are the area and number of sprinklers activated for a non-controlled fire correlated to the stated effect?[3]
	5.3. External validity[4]	1. Are some geographic areas or fire brigades excluded from this study? 2. Do the findings support known theory? 3. Is uncertainty quantified?
	5.4. Are the results trustworthy?	Once again, it is important to ask: is it the way the data are collected (e.g. the inquiry form) and analysed that produces the result? One example of **level failings** is when the results show that most fires are confined to the room of origin, and the conclusion is that sprinklers are designed to confine fire to the room of origin. Do we have data that support this, and this the design based on the standards and test protocols? When the conclusion takes the result up or down a level, these fallings occur. One example of a **time frame failing** is assuming a sprinkler system is no less reliable because of its age. This is based on a study that looks at a selected sprinkler system from where it was installed to 5 years later; it concludes there is no difference in reliability based on age. **Causality failings** will be discussed later under the explanatory study, but these affect all studies. One example is the reason a sprinkler system does not activate. With no cause for this, the conclusion can be that they should not activate, but there are no data to support such a conclusion. We have only certainly / uncertainty.
5. Quality assurance of the analysis		**Based on validation of concept, correlations, external information, level failings, time frame failings, and causal failings, how good are the conclusions drawn from the analysis?**

[1] Even if the CEA 4001/NS-EN 12845 system is of interest, it is possible to get some data on all types of system at this point. With data here, it is possible to get an idea of other types of systems in Norwegian buildings.

[2] Even if validating correlations must be done carefully for an explanatory (causal) study (this will be reviewed in more detail in the next example), several aspects in this study need to be validated against the collected data.
[3] When it comes to uncertainty, this can be handled strictly theoretically by only looking at the collected data or more favourably by investigating. Case studies give more insight into how fires and sprinklers are connected and generate more correct uncertainty data.
[4] When the study generalizes from collected data to a further probability, some areas need validation.

When conducting the quality assurance, the form may need to be corrected, and the analysis must be done over again in some areas, but all this is expected.

In some instances, this will indicate areas not previously thought of, but the data are collected and cannot be changed in an economical/ practical way. This suggests the need for comments on uncertainty to strengthen the sense that the study has been conducted in a scientific way.

STEP SIX

The last step is to write the report and present the results of the study. The areas listed in **Table 18** must be not be forgotten.

Table 18 Design of simple study, step six

Presentation		
	6.1. Methodological discussion	A theoretical review of the methodology of the study design, including data collection, analysis, and quality assurance of the results. 1. How good is the reliability of the data? 2. How good is conceptual validity? 3. How good is the internal validity? 4. How good is the external validity? These four constitute the total validity of the study.
	6.2. Substantial discussion – connection of findings and theory	**Findings:** Are the results consistent or inconsistent with earlier and other similar studies? When there are earlier studies, what are the long-time changes? **Theory:** What is the connection between results and known theory? What is unknown? Can some hypotheses be followed up in later or other studies? **N.B:** What do the findings tell us about the standards used?

		What are suggestions for **further work?**
	6.3. Presentation (also uncertainty)	There must be a definition list or presentation of key terms earlier in the report. The summary or abstract of findings helps the reader understand the report. With many options on how figures and tables can be designed, there is no need to use colours and shapes that take attention away from the facts. Make the report transparent, logical, and readable.
6. Discussion and presentation		**How well is the general presentation supported by the methodological and substantial discussion?**

If the presentation gives reliability answers to two decimal points but fails to have the same answer in different places, this give uncertainty to the study. The scientific way is to present the results with uncertainty, preferably quantified, hence giving reliability to the study.

6.5.SUMMARY

This has been a suggestion of how to establish a methodology and a design for a study to collect, analyse and present reliability data based my review of the literature and the scientific principles that need to be included in such a study. This has been concretized with a short review of the steps based on Norwegian conditions, rules/standards, and choices. Other choices give other answer and other areas need attention, but it must not be forgotten that a study in a larger geographical area (state or nation) must do so using proven scientific methods. Without a correct approach to the discipline of study TOGETHER with the discipline of fire science, this will only cast doubt on the discipline and the study.

For a suggestion on a more complex study, an explanatory (causal) study with a mix of intensive and extensive design with many units and many variables, can be found in

"*Collecting, Analysing, and Presenting Reliability Data for Automatic Sprinkler Systems*", a Master's Thesis in Fire Safety.

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7. APPENDIX 1: STUDIES IN THE UNITED STATES

This chapter takes a closer look at studies done by National Fire Protection Association; these provide the data used in the article.

7.1. EARLY STUDIES IN THE UNITED STATES

One of the major first studies is in the Fire Journal, entitled "*Automatic Sprinkler Performance Tables, 1970 Edition*" (National Fire Protection Association, 1970).

This report has some interesting statistics, findings, table, and figures; it goes back to 1897 and is one the first reports to present sprinkler performance over a longer period. The report is somewhat opinionated. For example, page 35 states:" *The tables present below summarize sprinkler performance by occupancy and point out those weakness in system* ***design, installation, and maintenance**** *that have so far prevented sprinkler from reaching the goal of 100 per cent reliability as a primary means of fire control*" (* author's highlight). Later, in Table 4 on page 38, it gives more reasons for unsatisfactory performance, for example, the failure of valves, faulty building construction, obstructions and so on. Whether the author thinks 100% reliability can be achieved is not clear.

7.1.1. RELIABILITY

The report starts by summarizing sprinkler performance in two columns, one for 1897 to 1924 and the second for 1925 to 1969.

Table 19 Summary of sprinkler performance: 1897-1969

	Fires 1897-1969		Fires 1925-1969*	
	Number	Per Cent	Number	Per Cent
Satisfactory	31 338	95.8%	78 291	96.2%
Unsatisfactory	1 390	4.2%	3 134	3.8%
Total	32 778	100%	81 425	100%

* *"For the five-year period 1965-1969 the ratio of satisfactory performance was 95.7 per cent. As is explained in the text, the NFPA now receives fewer reports of favourable performance, relatively, than in previous periods, because small losses are often not reported. Actual sprinkler performance in the five-year period was undoubtedly higher than 95.7 per cent."*

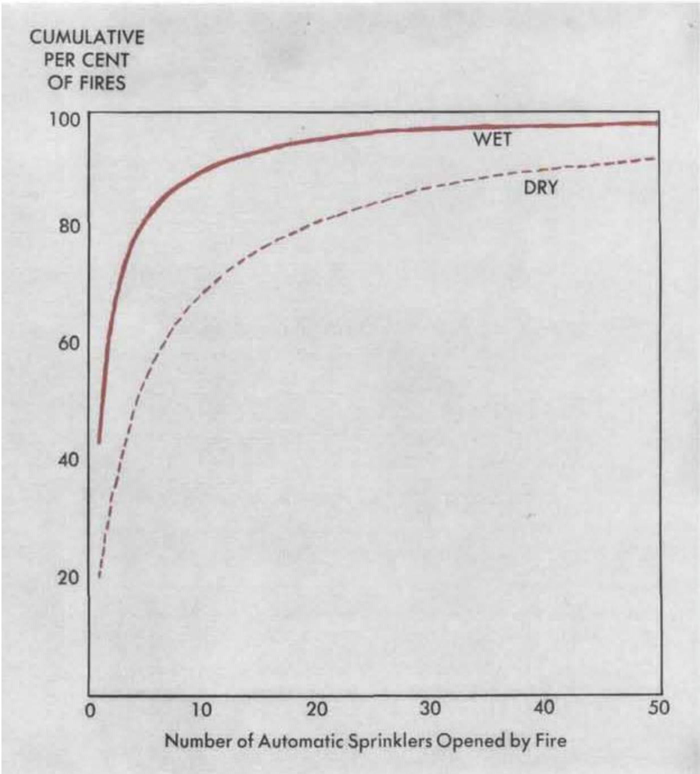
Of special interest is the term “fire control”. On page 25, the report states that “*sprinkler systems have successfully performed their two main functions -* ***control and notification**** *- in 96.2 per cent of the fires”* (* author’s highlight).

Historically has electric fire alarms and sprinklers were used side by side to signal fires. As mentioned earlier, the first practical sprinkler appeared in 1874. The first electric fire sensor to see commercial use, was designed by William B. Watkins in 1870 (National Fire Protection Association, u.d.). The report does not state how notification of fire in sprinkled buildings is incorporated into the findings.

At the end of page 35, the report states: “*The word control, as used above, means* ***prevention of excessive fire spread in light of the nature of the occupancy*****. In certain occupancies fewer than five sprinklers should establish control, while in other occupancies over 100 may be needed*” (* author’s highlight).

NFPA 13 (National Fire Protection Association, 2016) categorizes occupancy; for example, Light Hazard, Ordinary Hazard 1 and Ordinary Hazard 2 have the same area of operation (139 m2) and Extra Hazard 1 and Extra Hazard 2 have a larger area (232 m^2). It is not known when NFPA started to use hazard classes.
Since the report defines control “*in light of the nature of the occupancy*”, it would have been natural to present findings based on sprinkler activation within different classifications, but this is not done. Instead, there is a figure with the cumulative per cent of fires and the numbers of sprinklers operated.

Figure 7 Wet versus dry-pipe systems, 1925-1969



In **Figure 7**, the data clearly show that on average, more dry-pipe sprinklers open than wet-pipe sprinklers; the delay between the time of tripping the valve and water going through the pipe permits the fire to grow larger. This finding does not support the reason for the study, i.e., to find out if the sprinkler system controls the fire "*in light of the nature of the occupancy*".

The report goes on to take a more detailed look at performance in different occupancies, like residential, educational, office, and so on, shown here in **Table *20***. This is done as a percentage and not as perhaps expected, as the number of sprinklers activated per occupancy.

Table 20 Sprinkler performance summary and classification of unsatisfactory performance

TABLE 3. SPRINKLER PERFORMANCE SUMMARY AND CLASSIFICATION OF UNSATISFACTORY PERFORMANCE

	PERFORMANCE SUMMARY				CLASSIFICATION OF UNSATISFACTORY PERFORMANCE												
Occupancies	*Total No. of Fires*	*Total Unsatis-factory*	*Total Satis-factory*	*Total Satis-factory Per Cent*	*Water Shut Off*	*Partial Protection*	*Inadequate Water Supplies*	*System Frozen*	*Slow Operation*	*Defective Dry-Pipe Valve*	*Faulty Building Construction*	*Obstruction to Distribution*	*Hazard of Occupancy*	*Exposure Fire*	*Inadequate Maintenance*	*Antiquated System*	*Miscellaneous and Unknown*
Residential	1,073	48	1,025	95.5	13	9	5	1	...	...	11	3	1	...	2	2	1
Assembly	1,551	52	1,499	96.6	23	10	3	...	1	...	9	1	...	1	4	...	...
Educational	241	20	221	91.7	4	8	1	...	...	...	5	...	...	...	1	1	...
Institutional	305	12	293	96.1	3	3	2	...	...	...	1	...	1	...	...	...	2
Office	494	13	481	97.4	4	2	1	...	...	1	2	...	1	...	1	1	...
Mercantile	6,237	176	6,061	97.2	83	11	4	4	4	5	35	11	12	1	4	1	1
Industrial																	
Beverages, essential oils	543	64	479	88.2	17	4	9	...	...	1	2	1	18	3	3	5	1
Chemicals	4,147	198	3,949	95.2	33	11	19	...	3	3	1	13	95	2	12	1	5
Fiber products	539	25	514	95.3	6	...	4	1	...	2	...	5	4	...	2	1	...
Food products	2,484	133	2,351	94.6	43	11	8	1	2	1	7	9	29	4	12	1	5
Glass products	519	23	496	95.6	8	...	3	1	...	...	2	1	5	...	3	...	...
Leather, leather products	2,864	114	2,750	96.0	43	8	7	3	2	4	9	7	9	4	9	6	3
Metal, metal products	9,807	305	9,502	96.9	91	36	22	3	6	6	15	35	43	6	29	7	6
Mineral products	394	19	375	95.2	10	4	2	...	...	...	1	...	...	...	1	1	...
Paper, paper products	7,147	234	6,913	96.7	75	16	34	3	2	2	16	32	21	2	23	4	4
Rubber, rubber products	1,489	61	1,428	95.9	21	4	3	...	1	1	1	10	14	1	5	...	...
Textiles – manufacturing	16,119	291	15,828	98.2	109	15	32	3	5	3	11	27	18	1	50	9	8
Textiles – processing	6,527	127	6,400	98.1	52	6	11	...	5	1	8	13	15	2	7	1	6
Wood products	5,353	492	4,861	90.8	137	57	84	9	16	14	27	19	77	8	24	12	8
Miscellaneous industries	9,013	265	8,748	97.1	146	15	14	8	3	...	12	11	18	3	27	8	...
Total (Industrial)	66,945	2,351	64,594	96.5	791	187	252	32	45	38	112	183	366	36	207	56	46
Storage Occupanies	4,160	375	3,785	91.0	122	24	48	5	6	9	10	57	38	11	40	3	7
Other Occupancies	419	87	332	79.2	67	...	...	2	...	...	2	1	5	3	3	1	3
TOTAL (ALL OCCUPANCIES)	81,425	3,134	78,291	96.2	1,110	254	311	44	56	53	187	256	424	52	262	65	60

The table includes "*Total Satisfactory per cent*" and "*Total Unsatisfactory*". It is possible to track what "*unsatisfactory*" means, as part two of the table shows what constitutes this term. It is not possible to track what "*Total Satisfactory*" means.

"Other Occupancies" in **Table *20*** consist chiefly of idle or vacant buildings with a 79.2 % "*Total Satisfactory*" rate. The low findings designate buildings where sprinkler maintenance is likely to be substandard.

This contrasts with the 88.2 % found by Koffel (Koffel, 2006) and the even higher 90.8 % found by Budnick (Budnick, 2001). The gap between the NFPA report and their reports is quite high, 88.2 – 79.2 = 9 % and 90.8 –79.2 = 11.6 %, for Koffel and Budnick, respectively.

7.1.2. UNRELIABILITY

In **Table *20***, there is no differentiation between failed to operate or operating ineffectively under the column "**Classification of unsatisfactory performance**". The table lists 13 main reasons (corresponding to Table 4 on page 38 in the report). It gives four reasons why the system did not work, "*Water Shut Off, Partial Protection, Inadequate Water Supply and System Frozen*" before giving reasons that would probably be classified as not operating effectively, like "*Slow Operation*", and so on.

So even if differentiation is not given, the author was perhaps thinking about it. The problem is that *Inadequate Water Supply* is not a reason for not operating, but for not operating effectively. The following could be classified as "Failed to operate".

a) **Water Shut Off:** If the system is shut off, it can clearly not operate.

b) **Partial Protection:** If a system does not cover the whole building, there is no guarantee that there will be a sprinkler where a fire breaks out. A fire that starts outside the protected area will naturally not activate the system (at least at the start) and perhaps not work effectively.

c) **System Frozen**: If a system or part of the system is frozen, there will be no delivery of water.

d) **Defective Dry-Pipe Valve:** Dry valves are more exposed to faults, because of their design, but a semi-wet environment is the perfect place for rust. This system has a higher need of maintenance than a wet system. If the valve does not open, the system is in fact shut off.

Since there are no explanations of terms and classifications, some of these reasons are not easy to interpret with respect to operation and operating effectively.

The report says Water Shut Off is the main cause in 52% of the cases (1 110 cases out of 2 134 cases).

7.1.3. SUMMARY

This critical literature review has highlighted that there is a lack of definition, explanation, and substantiation of expressions used, for example, "*in light of the nature of the occupancy*". It would have been natural to present findings based on sprinkler activation within different classifications, but this is not done. Instead, we are given a figure that presents cumulative per cent of fires with the numbers of sprinklers operated.

Why Koffel (Koffel, 2006) uses the second lowest individual performance rate of 88.2% and not the lowest, 79.2%, without remarking on this choice in any way in his report, is not clear.

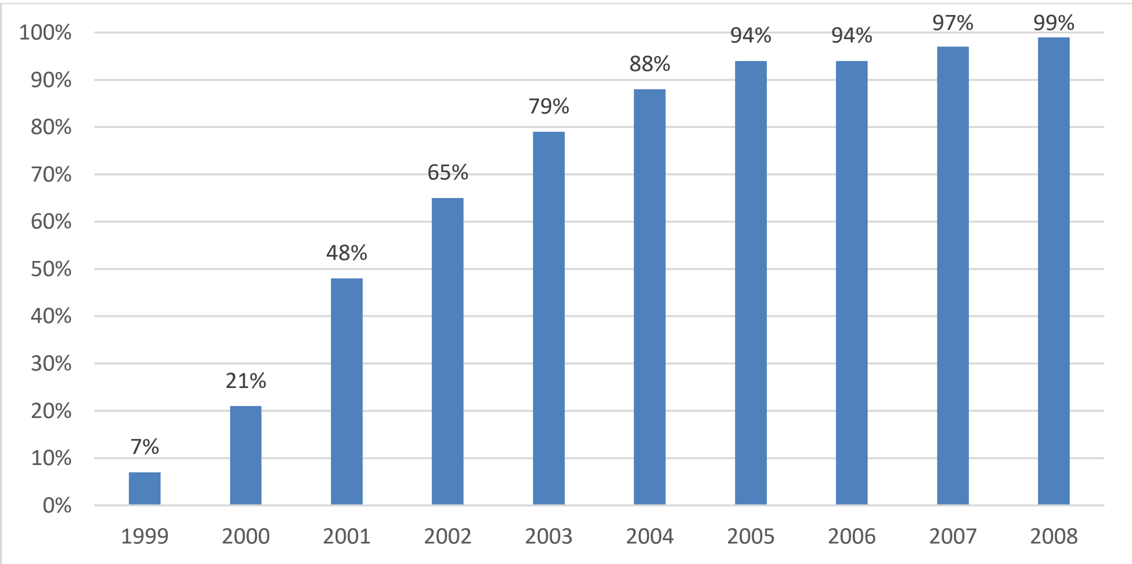
7.2.U.S. EXPERIENCE WITH SPRINKLERS: 2010

In September 2010, NFPA's Fire Analysis and Research Division released "*U.S. Experience with Sprinkler and Other Automatic Fire Extinguishing Equipment*" (National Fire Protection Association Research, 2010). As the report makes clear, there have been many changes since the "Automatic Sprinkler Performance Tables" were published in the NFPA *Fire Journal* in 1970 (National Fire Protection Association, 1970). Some of the changes are obvious; for example, the earlier article has five pages and the more recent one has 87 pages. More importantly, NFPA has made major changes in methodology and presentation.

1. The data used in this report not only come from NFPA's databank, but also from the detailed information available in Version 5.0 of the U.S. Fire Administration's National Fire Incident Reporting System (NFIRS 5.0). These fires are reported by the US municipal fire departments, so the report excludes fires reported only to federal or state agencies or industrial fire brigades.

2. NFIRS 5.0 was introduced in 1999 and brought major changes to fire incident data, including changes in definitions and coding rules. There were further changes in 2003. Data for 1999-2003 are not used in this report. This report is for 2004-2008.

Figure 8 Fires originally collected in NFIRS 5.0 by year: 1999-2008



3. As Appendix A in the report (National Fire Protection Association Research, 2010) states, the NFIRS is voluntary. Roughly two-thirds of the US municipal fire departments participate. To address this issue and to update the NFPA Fire Records, the annual NFPA Fire Department Experience is sent to all municipal departments protecting populations of 50 000 or more.
The study is used to project national estimates by scaling the ratios obtained by comparing NFPA's projected totals to data in NFIRS. Even though there are uncertainties in this method, it gives a far better picture from an analytical point of view.
Projection is based on the following equation:

$$\frac{NFPA\ survey\ projections}{NFIRS\ totals\ (Version\ 5.0)}$$

Appendix B in the report (National Fire Protection Association Research, 2010) shows a systematic approach to questions about Automatic Extinguishing Systems.

A. M1 Presence of Automatic Extinguishment System

N None Present

1 Present

U Undetermined

B. M2. Type of Automatic Extinguishment System

1 Wet pipe sprinkler

2 Dry pipe sprinkler

3 Other sprinkler system

4 Dry chemical system

5 Foam system

6 Halogen type system

7 Carbon dioxide system

0 Other special hazard system

U Undetermined

C. **M3. Automatic Extinguishment System Operation**

1 System operated and was effective

2 System operated and was not effective

3 Fire too small to activate the system

4 System did not operate

0 Other

U Undetermined

D. **M4. Number of Sprinklers Operating**

E. **M5. Automatic Extinguishment System Failure Reason**

1 System shut off

2 Not enough agent discharged [to control the fire]

3 Agent discharged but did not reach [the] fire

4 Wrong type of system [Inappropriate system for the type of fire]

5 Fire not in area protected [by the system]

6 System components damaged

7 Lack of maintenance [including corrosion or heads painted]

8 Manual intervention [defeated the system]

0 Other _____________ [Other reason system not effective]

U Undetermined

It seems that information about design requirements of the automatic extinguishment system is not collected.

7.2.1. RELIABILITY

On the basis on the findings, in Fact Sheet, page vii, the report states: "*In reported structure fires large enough to activate them, sprinklers operated in 91% of fires in sprinklered properties*." Furthermore, *"In reported structure fires large enough to activate them, sprinklers operated and were effective in 87% of fires in sprinklered properties"*. These findings are shown in Table 6 based on property use.

Table 21 Automatic extinguishing equipment reliability and effectiveness, by property use for 2004-2008 structure fires (excluding fires reported as confined fires)

A. All Sprinklers						
			When equipment was present, fire was large enough to activate equipment, and sprinklers were present in fire area			
Property Use	**Number of fires per year where extinguishing equipment was present**	**Per Cent of fires too small to activate equipment**	**Number of fires per year**	**Per Cent where equipment operated (A)**	**Per Cent effective of those that operated (B)**	**Per Cent where equipment operated effectively (A x B)**
All public assembly	1 350	50%	680	89%	92%	82%
Eating or drinking establishment	770	46%	410	90%	90%	81%
Educational property	810	71%	240	85%	96%	82%
Health care property*	1 320	69%	400	87%	97%	84%
Residential	6 760	44%	3 790	94%	97%	91%
Home (including apartment)	4 860	38%	3 000	94%	97%	92%
Hotel or motel	810	60%	330	91%	98%	89%
Dormitory or barracks	260	62%	100	91%	99%	90%
Rooming or boarding house	210	47%	110	93%	96%	90%
Board and care home	170	60%	70	91%	97%	89%
Store or office	2 590	54%	1 200	89%	97%	86%
Grocery or convenience store	510	60%	210	88%	95%	83%
Laundry or dry cleaning	240	47%	130	91%	95%	87%
Service station or motor vehicle sales or service	110	32%	80	93%	94%	87%
Department store	370	61%	150	88%	98%	86%
Office	520	62%	200	89%	97%	86%
Manufacturing facility	2 470	42%	1 420	90%	93%	84%
All storage	600	35%	390	80%	96%	76%
Warehouse excluding cold storage	340	34%	230	85%	97%	82%
All structures**	**16 600**	**49%**	**8 430**	**91%**	**96%**	**87%**

* Nursing home, hospital, clinic, doctor's office, or development disability facility.

** Includes some properties not listed separately above.

Table *21* states that 49% of all fires to which the fire department responded were too small to activate the extinguishing system. When an extinguishing system was present, the fire was large enough to activate the equipment in 51% of the cases; sprinklers were present in the fire area in 91% of the cases, and in 87% of these, the equipment operated effectively.

The reports do not have definitions or explanations of how central key questions are answered.
Example, 1: "*Percent of fires too small to activate equipment.*" How small is too small? Presumably a smouldering fire would, in many cases, not give off enough heat to activate a thermal bulb on a sprinkler head, but this is not defined, and there is no explanation of how the key findings were derived. This could also be applied to the Omega sprinkler failure, when studies discovered that roughly one-third of Omega sprinklers failed to operate under the required pressure (Fire engineering, 1997). Failure should be of interest for the fire community in general, including fire departments and regulatory agencies alike.

Example, 2: "*Equipment operated effectively*": What is effective? Is this fire control without manual interventions from residents, employers, or fire departments? A hint is given on page 17: "*As noted, for most rooms in most properties, **effective performance is indicated by confinement of fire to the room of origin*. For the few rooms where the design area is smaller than the room, a sprinkler system can be ineffective in terms of confining fire to the design area but still be successful in confining fire to the larger room of origin. Therefore, one might expect the percentage of fires with flame confined to room of origin to be slightly larger than the combined performance (operating effectively) for any given property use. Table B shows this is usually the case.*" (* author's highlight)

According to page 15 in the report (National Fire Protection Association Research, 2010), ***"Effectiveness should be measured relative to the design objectives for a particular system.** For most rooms in most properties, sprinklers are designed to confine fire to the room of origin."*
It seems there are some assumptions on room and fire spread. See 11.2.2 for more information on this.

Example 3: According to page 16-17, *"Table 6 provides direct measurement of sprinkler effect involving the first bulleted scenario on the previous page. For all structures combined, 73% have flame damage confined to room of origin when there is no automatic extinguishing equipment present. This rises to 95% of fires with flame damage confined to room of origin when any type of sprinkler is present."*

Table 22 Extent of flame damage, for sprinklers present vs. automatic extinguishing equipment absent for 2004-2008 structure fires

	Per cent of fires confined to room of origin excluding structures under construction and sprinklers not in fire area		
Property Use	**With no automatic extinguishing equipment**	**With sprinklers of any type**	**Difference (in percentage) points)**
Public assembly	76%	95%	19
Fixed-use amusement or recreation place	75%	96%	21
Variable-use amusement or recreation place	84%	97%	13
Religious property	72%	96%	24
Library or museum	83%	97%	14
Eating or drinking establishment	75%	94%	19
Educational	90%	98%	8
Health care property*	93%	99%	6
Residential	76%	97%	21
Home (including apartment)	76%	97%	21
Hotel or motel	86%	97%	11
Dormitory or barracks	96%	99%	3
Store or office	71%	93%	22
Grocery or convenience store	76%	96%	20
Laundry or dry cleaning or other professional supply or service	80%	92%	12
Service station or motor vehicle sales or service	61%	88%	27
Department store	73%	93%	20
Office building	76%	94%	18

Manufacturing facility	69%	86%	17
Storage	32%	80%	48
Warehouse excluding cold storage	53%	81%	28
All structures**	**73%**	**95%**	**22**
* Nursing home, hospital, clinic, doctor's office, or development disability facility. ** Includes some properties not listed separately above.			

For 27% of the fires with no sprinkler system present, the fire goes beyond the room of origin. The number is 5% for fires with a sprinkler system. Is a 95/73=30% increase in reducing fire spread when a sprinkler system is present a scientific proof of success for a sprinkler system, or is it something else? Perhaps it proves that fire barriers (every room is a fire barrier) together with sprinkler systems can prevent the spread of fire in 95% of the cases, even if the design area is smaller than the room in question.

Example 4: According to page 18, "***Effectiveness declines when more sprinklers operate****. When more than 1-2 sprinklers have to operate, this may be taken as an indication of less than ideal performance.*" Later, the report says: "*At the same time, the number of sprinklers operating should not be used as an independent indicator of effectiveness because sprinklers are deemed effective in most fires where sprinklers operate, no matter how many sprinklers operate.*" It is not clear what the author means.

Example 5: **Table *21*** indicates that 49% of all fires to which fire departments responded were too small to activate the extinguishing system: "*Percent of fires too small to activate equipment*".

1.1. It should be possible to only refer to sprinklers and not to extinguishing systems more generally, when it is the findings about sprinklers that are interesting in this case.
1.2. There is no definition of a "fire large enough" or a fire "too small to activate" the sprinkler. This one of the most important findings in this report, but it is not treated or discussed as one would expect. Of course, small fires can activate smoke detectors, fire alarms may be manually activated alerting the fire department,

people may intervene, or fires may be smouldering and not trigger the sprinkler system. The unanswered question is: how has evaluation if the system should activate or not been handled by the person reporting the fire?

7.2.2. UNRELIABILITY

As noted at the beginning of this chapter, NFPA has made a major shift in methodology and presentation. One is a clear differentiation between failed to operate or operated ineffectively, as stated above. What are the reasons for failure to activate?

Table 23 Reasons for failure to operate when fire was large enough to activate equipment and equipment was present in area of fire, by property use based on indicated estimated number of 2004-2008 structure fires per year (excluding fires reported as confined fires)

A. All Sprinklers						
Property Use	**System shut off**	**Manual intervention defeated system**	**Lack of maintenance**	**Inappropriate system for type of fire**	**System component damaged**	**Total fires per year**
All public assembly	61%	14%	12%	10%	2%	74
Eating or drinking establishment	15%	15%	21%	0%	0%	41
Residential	54%	20%	9%	9%	7%	234
Home (including apartment)	57%	15%	9%	11%	9%	167
Store or office	62%	20%	8%	6%	3%	131
Manufacturing facility	64%	17%	7%	4%	7%	141
Storage	84%	5%	5%	1%	4%	79
All structures*	**64%**	**17%**	**8%**	**6%**	**5%**	**801**
* Includes some properties not listed separately above.						

The 1970 report (National Fire Protection Association, 1970) gives at least 4 reasons for not operating (Water Shut Off, Partial Protection, System Frozen and Defective Dry-Pipe Valve). The following are explained on page 19 in the report.

a) **System Shut Off:** If the system is shut off, it can clearly not operate. This is called Water Shut Off in the report (National Fire Protection Association, 1970), but it includes, for example, pumps that are shut off/out of order.

b) **Manual intervention:** With a fire in the building, is very important that the system is shut off at the right time. Intervention should always be the responsibility of the fire department.

c) **Lack of maintenance:** It is important that valve, pipes, and sprinklers are maintained correctly according to standards and recommended procedures, so that the intended function is maintained.

d) **Inappropriate system:** "Inappropriate" system can refer to the wrong type of agent (e.g., water vs. chemical agent or carbon dioxide), the wrong type of system for the same agent (e.g., wet pipe vs. dry pipe), or the wrong design for the system and agent (e.g., a design adequate only for Class I commodities vs. a design adequate for any class of commodities). It is not clear how this is determined or how a fire in a room with e.g. a chemical agent or incorrect design will affect whether the system works or not.

e) **System component damaged:** "I*n the NFPA compilation of incidents of failure or ineffectiveness, the incidents involving component damage consist entirely of fires where automatic extinguishing equipment was damaged by explosions or by ceiling, roof, or building collapse,* ***nearly always as a consequence of fire****" (* author's highlight). Except for explosions (that could start a fire), this occurs after a fire breaks out. How can a fire that has already started and results in the collapse of a roof or a ceiling be the reason for the damaged component causing the system not to work? The system did not respond to the fire or did the fire start outside sprinkled area? Not clear.

Table *24* shows the combined failure and ineffective sprinkler performance (**Water discharged but did not reach fire** and **Not enough water discharged**). The report has a Table C, but this is only for wet sprinkler. The following two tables are based on Table 4 and Table 5 in the report.

Table 24 Reasons for failure or ineffectiveness as number of fires per year and percentages of all cases of failure or ineffectiveness, for all structures and all type sprinklers

Reason	Failure		Ineffectiveness		Combined	
	Number*	Per Cent	Number*	Per Cent	Number*	Per Cent
System shut off	513	45%	0	0%	513	45%
Manual interruption defeated system	136	12%	23	2%	159	14%
Water discharged but did not reach fire	0	0%	144	13%	144	13%
Not enough water discharged	0	0%	88	8%	88	8%
Lack of maintenance	64	6%	26	2%	90	8%
Wrong type of (inappropriate) system for type of fire	48	4%	20	2%	68	6%
System component damaged	40	4%	26	2%	66	6%
Total	**801**	**71%**	**327**	**29%**	**1 128**	**100%**
*The number are not given in the table but calculated on the bases of per cent on given total number.						

Alternatively, the per cent of failure and ineffectiveness be presented separate cases of failure and ineffectiveness per year.

Table 25 Reasons for failure or ineffectiveness as percentages of separated cases of failure or ineffectiveness, for all structures and all type sprinklers

Reason	Failure		Ineffectiveness		Combined	
	Number*	Per Cent	Number*	Per Cent	Number*	Per Cent
System shut off	513	64%	0	0%	513	45%
Manual interruption defeated system	136	17%	23	7%	159	14%
Water discharged but did not reach fire	0	0%	144	44%	144	13%
Not enough water discharged	0	0%	88	27%	88	8%
Lack of maintenance	64	8%	26	8%	90	8%
Wrong type of (inappropriate) system for type of fire	48	6%	20	6%	68	6%
System component damaged	40	5%	26	8%	66	6%
Total	**801**	**100%**	**327**	**100%**	**1 128**	**100%**
*The numbers are not given in the table but calculated as percentages of the given total number.						

As **Table *24*** shows, there is a drop in per cent of "**System shut off"**, from 52% in the 1970 report to 45% in this report; when it is combined with ineffectiveness.

7.2.3. SUMMARY

Compared to the 1970 article, this is a comprehensive report. Since then, there has been major shift in methodology and presentation. NFIRS is now the main source of data.

There is lack of definitions. For example, the following are not explained: "*fires large enough to activate them*" and why not performance should not be viewed "*in light of the nature of the occupancy*" as defined in the (National Fire Protection Association, 1970) report, but should be "*indicated by the confinement of fire to the room of origin*". The assumptions given have not been proven to be right.

The report's tables indicate reliability and effectiveness by property use, reasons for failure to operate and ineffectiveness.

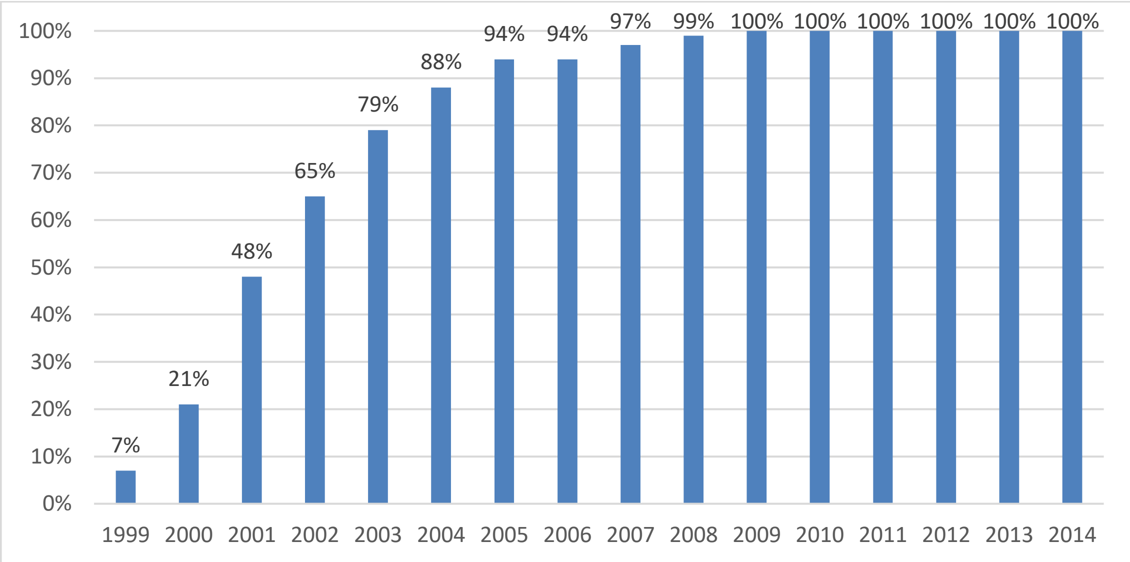
7.3.US EXPERIENCE WITH SPRINKLERS: 2017

In July 2017, NFPA Fire Research released "*U.S. Experience with Sprinklers*" (National Fire Protection Association Research, 2017) for 2010-2014.

The methodology from the 2010 report is continued. Data from NFIRS 5.0 are collected and derived by the NFPA annual Fire Department Experience Survey because "*Some states require fire departments to report all incidents or all fires, some have a loss threshold, and in other states, reporting is completely voluntary*" (page 1).

The numbers from the collected reports on fire from the NFIRS 5.0 are improved.

Figure 9 Fires originally collected in NFIRS 5.0 by year: 1999-2014



Now that all the data come from newest edition of NFIRS, the scaling ratios should be of greater interest. How much influence do they have on the numbers? In addition to estimating number of fires, fatalities, and fire losses, does this have an influence on sprinkler operating and effectiveness? The report says:

"*All estimates in this report exclude fires in properties under construction. Fires in which partial systems were present and fires in which sprinklers were present but failed to operate because they were not in the fire area were excluded from estimates related to presence and operation*" (page 1).

"Confined fires" are excluded from this report and the previous report. A confined fire is a fire within a chimney or flue, fuel burner or boiler, cooking vessel, incinerator, commercial compactor, or trash.

The report also excludes automatic fire extinguishing systems other than sprinklers and goes into in depth on the numbers of home fires.

7.3.1. RELIABILITY

For reliability, on page 5, the report states: "*Sprinklers operated in 92% of the fires in which sprinklers were present and the fire was considered large enough to activate them. They were effective at controlling the fire in 96% of fires in which they operated. Figure 8 shows that sprinklers operated effectively in 88% of the fires large enough to trigger them.*"

Table 26 Automatic sprinkler system reliability and effectiveness, by property use for 2010-2014 structure fires (excluding fires reported as confined fires)

A. All Sprinklers						
			When equipment was present, fire was large enough to activate equipment, and sprinklers were present in fire area			
Property Use	**Number of fires per year where sprinkler was present**	**Property Use**	**Number of fires per year where sprinkler was present**	**Property Use**	**Number of fires per year where sprinkler was present**	**Property Use**
All public assembly	1 220	48% (580)	640	90%	94%	85%
Eating or drinking establishment	710	46% (300)	410	90%	92%	83%
Educational property	590	70% (410)	180	87%	96%	84%
Health care property*	900	66% (590)	310	87%	97%	84%
Residential	6 630	38% (2 490)	4 140	93%	96%	89%
Home (including apartment)	5 470	35% (1 900)	3 570	94%	96%	91%
Hotel or motel	680	52% (350)	330	90%	98%	89%
Store or office	2 070	50% (1 030)	1 040	91%	96%	87%
Grocery or convenience store	430	56% (240)	190	89%	93%	83%
Department store	270	56% (150)	120	90%	98%	88%
Office	400	55% (220)	180	91%	96%	87%
Manufacturing facility	1 360	44% (600)	1 030	91%	94%	85%
All storage	440	32% (140)	300	86%	96%	82%
Warehouse excluding cold storage	270	33% (90)	180	84%	97%	81%
All structures*	**13 210**	**44% (5 840)**	**7 640**	**92%****	**96%****	**88%****

* Nursing home, hospital, clinic, doctor's office, or development disability facility.

** The per cent is taken from Table 6 in the 2017 report. Note: this was not checked.

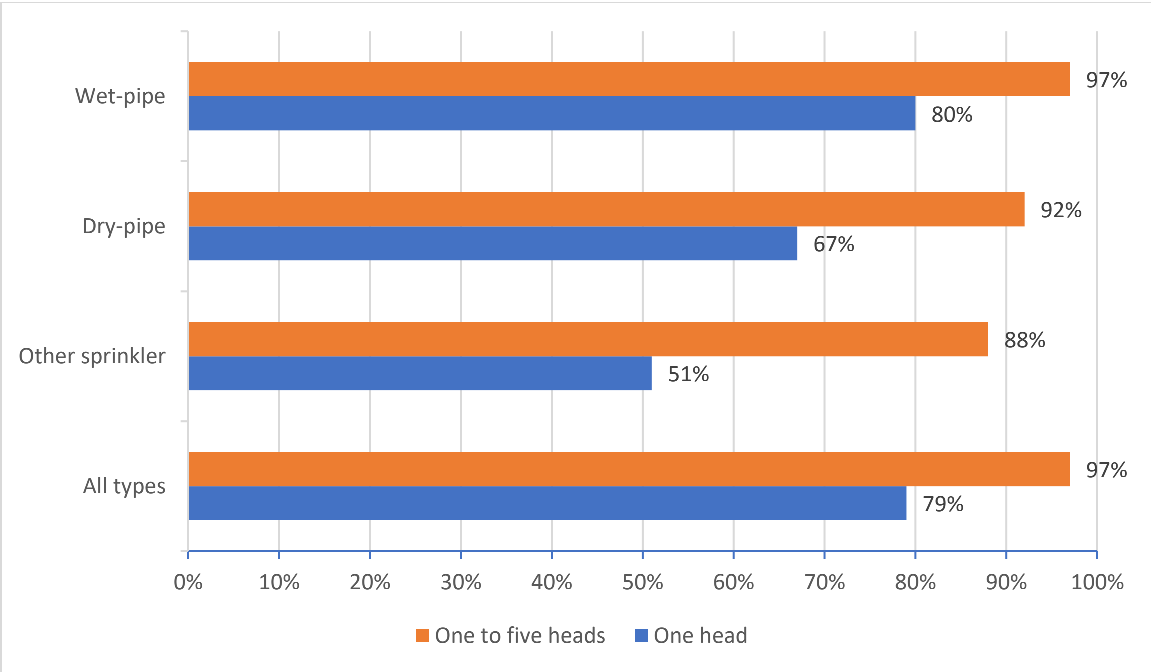
Table *21* set the percentage of fires too small to activate equipment at 49%, but the percentage has now dropped to 44%. The numbers in the 2010 report (National Fire Protection Association Research, 2010) included all extinguishing equipment, but this newer report only looks at sprinklers; this could be the reason for the drop in the numbers of too small fires from 16 600 to 13 210.

Unfortunately, 7 of 14 numbers in the column "**Non-confined fires too small to activate or unclassified operation**" do not match. The first example, "**All public assembly**", says there were 3 760 fires where a sprinkler was present, and 2 540 of these were classified as "**Confined fires**". This means that for 3 670 – 2 540 = 1 220 non-confined fires, a sprinkler was present. If 640 fires were coded as large enough to activate sprinklers, then 1 220 – 640

= 580 were too small to activate sprinklers. The problem is that Table 6 in the report states that 590 fires were too small to activate sprinklers or were unclassified operations.

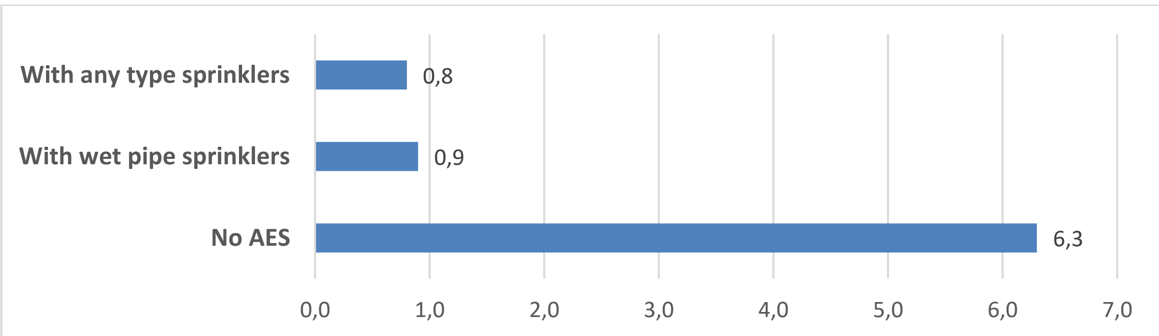
Out of five fires, only one head activated in four cases (79%).

Figure 10 Per cent of fires in which one or five sprinkler heads operated by type: 2010-2014



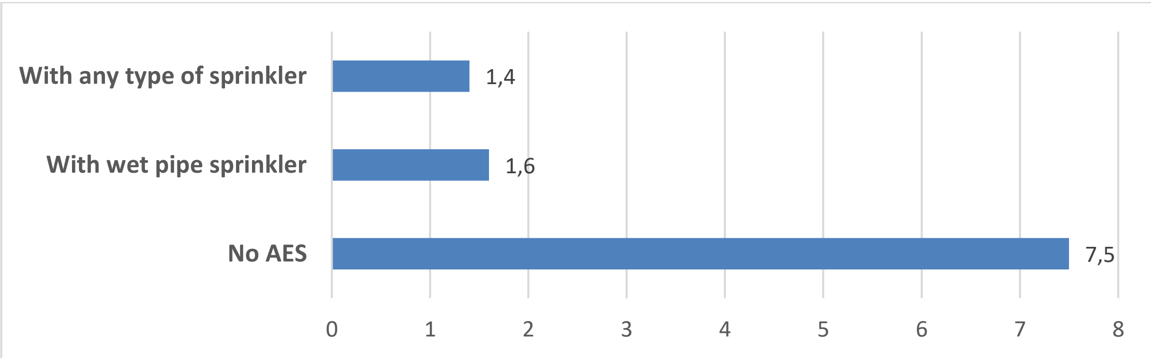
Some type of sprinkler was present in an average of 49 840 fires per year (including confined fires). These fires caused in annual average of 42 deaths, representing 2% of all fire deaths. **Figure 11** shows in percentages the difference in death rates for buildings where a sprinkler was present and those without an AES.

Figure 11 Civilian death rates per 1,000 fires in properties with sprinklers and with no AES: 2010-2014



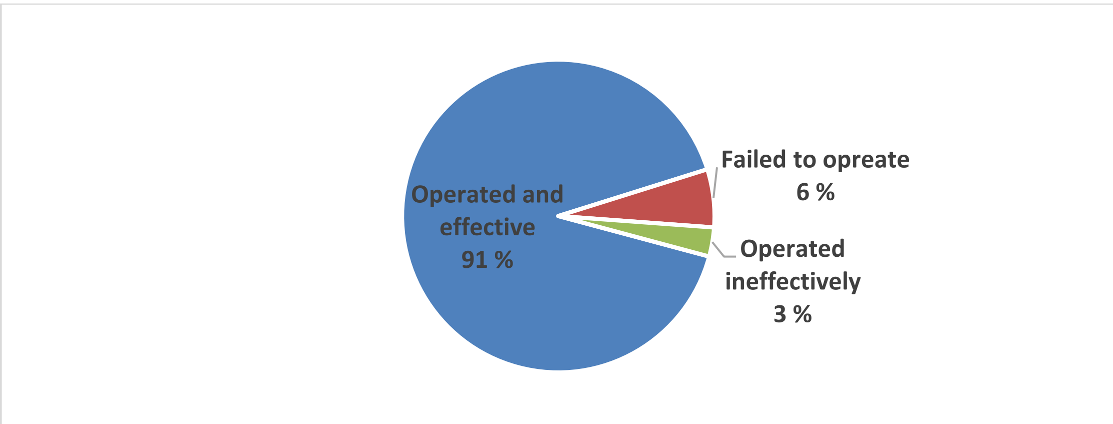
Some type of sprinkler was present in an average of 24 440 home fires per year. These fires caused an average of 35 deaths. One percent of the home fire deaths happened in houses with sprinklers; 7 percent occurred in houses without sprinklers. According to another NFPA study (National Fire Protection Association Research, 2017) the number of deaths was 81% lower when sprinkler systems were present than when there were no automatic extinguishing systems.

Figure 12 Civilian death rates per 1,000 fires in homes with sprinklers and with no AES: 2010-2014



After looking at death and injures, the report shifts to sprinkler operation and effectiveness in home fires. As stated earlier, the general operating effectivity is 88%, and for home fires, it is 91%.

Figure 13 Sprinkler operation and effectiveness in home fires: 2010-2014



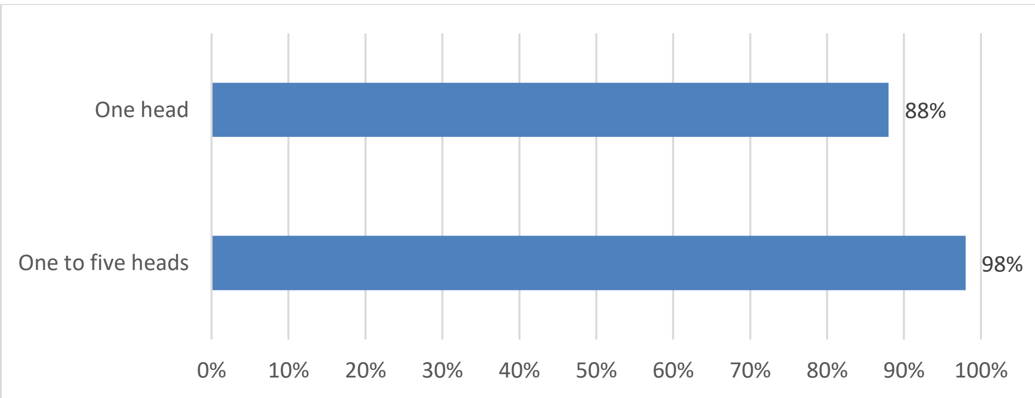
There are no definitions in this report, and it is not clear if homes are separated from other residential structures. According to page 2 of the "FACT SHEET": "*Although the majority of structure fires, civilian fire deaths and injuries, and property damage occurred in residential properties, **particularly homes***, only 8% of the reported residential fires were in properties with sprinklers*" (* author's highlight). On page 3 of the "FACT SHEET", the following explanation is given: "*Homes include one- or two-family homes and apartments or other multi-family homes.*" If this means that, for example, nursing homes are not homes but are residential, is not clear.

The chapter "Sprinkler in Home Fires" says the sprinklers are found in 7% of homes, compared to all types of buildings, at 12%.

"***In 98% of home fires with operating sprinklers, five or fewer heads operated***" (page 12). The (normal) design numbers of residential sprinklers is up to 2, with 4 suggested for the biggest rooms, and 4 for the most hydraulically demanding areas (more about this at 11.2.2 How to collect data). It is not clear if the reported sprinklers are only residential sprinklers or include other types. It is not clear what the purpose is for including 5 sprinkler heads, when normal design criteria are fewer for residential buildings/homes.

What is clear is that in 88% of the cases, only one head activated.

Figure 14 When sprinklers operated, percentage of home fires in which one or one to five heads operated: 2010-2014



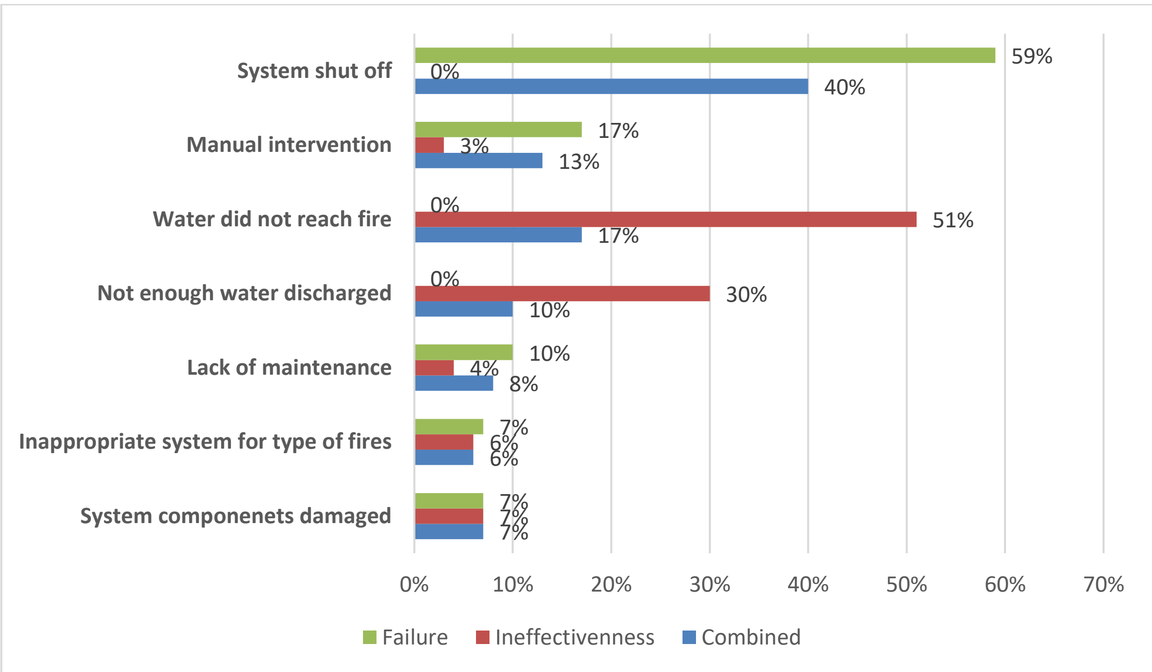
There is also a lack of clarity in the following:

A. **Too small vs. large enough**: The report does not supply objective criteria to separate them.
B. **Sprinkler operated effectively**: Have been commented regarding design criteria in 7.1.2 Unreliability.
C. **Confined to room with start fire**: Fires confined to room of origin represent 96% with sprinklers and 71% with no AES. It is not clear if this is a success criterion.

7.3.2. UNRELIABILITY

According to **Figure 15** (Figure 13 in the report), there is a drop in "**System shut off"** from 52% in the 1970 report (National Fire Protection Association, 1970) to 45% in the 2010 report (National Fire Protection Association Research, 2010), to 40% in this report in combination with ineffectiveness.

Figure 15 Reasons for combined sprinkler failure and ineffectiveness: 2010-2014



When looking at the bar graph, it is hard to see the difference from the 2010 report (National Fire Protection Association Research, 2010) and for this reason, "**Table *25* Reasons for failure or ineffectiveness as percentages of separated cases of failure or ineffectiveness, for all structures and all type sprinklers**" is compared with the known data from the 2010-14 bar graph, to create **Table *27***.

Table 27 Comparing reasons for failure or ineffectiveness as percentages of separate cases of failure or ineffectiveness from 2004-2008 to 2010-2014

Reason	Failure		Ineffectiveness		Combined	
Year	2004-08	2010-14	2004-08	2010-14	2004-08	2010-14
System shut off	64%	59%	0%	0%	45%	40%
Manual intervention*	17%	17%	7%	3%	14%	13%
Water did not reach fire*	0%	0%	44%	51%	13%	17%
Not enough water discharged	0%	0%	27%	30%	8%	10%
Lack of maintenance	8%	10%	8%	4%	8%	8%
Inappropriate system for type of fire*	6%	7%	6%	6%	6%	6%
System component damaged	5%	7%	8%	7%	6%	7%
Total	**100%**	**100%**	**100%**	**101%**	**100%**	**101%**
*The names are changed name in this report, compared to the 2010 report.						

When the columns "Ineffectiveness" and "Combined" are summed for 2010-2014, the total passes 100%, suggesting the rounding has been done wrong somewhere. What is important is that "**System shut off**" continues to drop and "**Water did not reach fire**" increases.

Long-time trends and changes over a shorter time are not included, and this lack is an important missing tool for fire engineers, fire departments and others concerned with fire safety.

There seem to be some mixing of terms in this NFPA reports. Both reasons and causes are used.

7.3.3. SUMMARY

In this report, 100 % of the data now come from the NFIRS databank but have been scaled by an unknown ratio based on the NFPA annual Fire department Experience Survey.

The major focus is on fires in homes, and the probability of death is over 6 times higher in a home without AES, then in a home with sprinklers. The report does not explain why it focuses on 5 or fewer operated sprinklers, when the design for residential buildings is 2 and up to 4.

No long-time trends and changes are included in the report, but they have been incorporated in to this review.

8. APPENDIX 2: STUDIES IN AUSTRALIA AND NEW ZEALAND

This chapter takes a closer look at a study done in Australia and New Zealand.

8.1. AUSTRALIA AND NEW ZEALAND'S EXPERIENCES WITH SPRINKLERS

One of the report that have been given most credit when it comes to success for sprinkler system, is the comprehensive work by Henry William (Harry) Marryatt, *Fire – A Century of Automatic Sprinkler Protection in Australia and New Zealand – 1886-1986* (Marryat, Rev. 1988). This 478 page book takes a close look at the history of sprinklers in Australia and New Zealand, including technical aspects of discharging water and water damage, performance analysis (both general and detailed), safeguarding life, causes of fire, incendiarism[6], the operation of sprinklers on flammable liquids, electrical equipment, explosions, fires involving high piled storage, smoke and heat venting in relation to sprinklers, fires with large numbers of sprinklers operated, exposure fires, partial protection, fires not controlled by sprinklers, fires involving multiple-jet controls[7] and economic considerations and cost-benefit analysis.

This book is now in its second edition. It comes with definitions, abbreviations, conversion rates and explanatory notes.

8.1.1. RELIABILITY

The Introduction says, "*The record which is detailed in this book show that except under the most extraordinary conditions, it is possible to control fire automatically with a minimum loss of life and property. The evidence suggests that probably there can no better way of safeguarding life and property in the majority of buildings than by equipping them with automatic sprinkler system.*" Since the first edition, the term satisfactory performance has been changed to "fires extinguished and/or controlled".

According to the book's definition, "*Fires controlled = Fires which have either been completely extinguished or controlled by automatic sprinkler system to the point that they*

[6] The act or practice of an arsonist; malicious burning or inflammatory behaviour; agitation

[7] Multiple jet or spray controls is at thermic controlled valve, often bulb equipped, that release water from more than one open jet, spray, or sprinkler heads over a design area.

would be extinguished even if the supplementary action had not been taken by fire brigades or others."

It covers 9 022 fires in 231 occupancies, of which 99.46% were controlled (Preface to the book).

In Chapter 4, "Overall Performance Analysis", gives a detailed analysis of number of sprinklers activated from 1 to 113 sprinklers operating and controlling fires (page 90, Table 3). This adds up to 8 973 fires, which gives a performance/ controlling rate of 99.46%. The number not controlled is 49 or 0.54%. The book says: "*The following table 3 gives the numbers of sprinkler heads operating on all fires except the 49 fires not controlled. Multiple jet controls and spray controls have been counted as each being equivalent to one sprinkler head and these have not been shown separately as full details of the fires in which this specialized equipment was involved are given in chapter 19. (page 90)*

On the next page and in the next table, the author compares these to US numbers. I will not use the NFPA numbers from the 1925-1964 period from this table, but the numbers from the Automatic Sprinkler Performance Tables (National Fire Protection Association, 1970); these are from the period of 1925-1969 and are therefore somewhat closer for comparative purposes.

Table 28 Number of sprinklers operating in US and Australia/New Zealand as a per cent

Number of Sprinklers Operating	United States[1]				Australia and New Zealand		
	Wet System Per Cent	Dry System Per Cent	Total Numbers of Fires	Total System Per Cent	Number of Fires	Total Numbers of Fires	Total System Per Cent
1	42.6%	20.1%	29 733	37.4%	5 816	5 816	64.55%
2 or fewer	61.0%	32.7%	43 396	54.6%	1 431	7 247	80.41%
3 or fewer	70.2%	41.5%	50 769	63.8%	553	7 800	86.54%
4 or fewer	76.2%	48.7%	55 795	70.1%	290	8 090	89.79%
5 or fewer	80.2%	53.7%	59 156	73.4%	189	8 279	91.84%
6 or fewer	83.2%	57.8%	61 814	77.7%	144	8 423	**93.44%**
7 or fewer	85.2%	61.3%	63 724	80.1%	87	8 510	94.40%
8 or fewer	87.0%	64.2%	65 348	82.2%	76	8 586	95.24%
9 or fewer	88.3%	66.4%	66 571	83.7%	50	8 636	95.79%
10 or fewer	89.4%	68.5%	67 629	85.0%	47	8 683	**96.31%**
11 or fewer	90.4%	70.3%	68 533	86.2%	22	8 705	96.55%
12 or fewer	91.2%	72.4%	69 464	87.3%	24	8 729	96.82%
13 or fewer	91.7%	73.8%	69 990	88.0%	31	8 760	97.16%*
14 or fewer	92.6%	75.3%	70 788	89.0%	32	8 792	97.51%
15 or fewer	93.1%	76.2%	71 313	89.7%	22	8 814	97.75%
20 or fewer	95.0%	81.0%	73 347	92.2%	59	8 873	98.39%
25 or fewer	96.0%	84.3%	74 464	93.6%	36	8 909	98.79%
30 or fewer	96.9%	86.7%	75 411	94.8%	23	8 932	99.05%
35 or fewer	97.3%	88.6%	75 976	95.5%	12	8 944	99.17%
40 or fewer	97.7%	90.0%	76 472	96.2%	8	8 952	99.25%
50 or fewer	98.1%	91.9%	77 079	96.9%	6	8 958	99.31%
75 or fewer	98.9%	94.7%	77 995	98.1%	10	8 968	99.41%
100 or fewer	99.4%	96.3%	78 533	98.7%	4	8 972	99.45%
200 or fewer	99.8%	99.7%	79 384	99.8%	1	8 973	99.46%
All fires	100.0%	100.0%	79 544	100.0%	49	9 022	100.00%

[1] These numbers have been updated to 1925-1969 numbers from the Automatic Sprinkler Performance Tables (National Fire Protection Association, 1970) and are not the original version of 1925-1964 shown in Table 4.

*This is specified as 96.16 in the original table. This cannot be true and has been changed.

This table points out the following.

1. The book states before the table on page 91: "*It will be seen from Table 4 which follows that one sprinkler head in operation was required in 64.55% of fires, while 6 sprinkler heads or fewer were required in **93.36%*** of fires, and 10 sprinkler heads or fewer were required in **96.16%*** of fires*". The problem is that the table gives **93.44%** and **96.31%** respectively (and this number has been checked against a previous table in the book that gives the precise per cent against number of sprinkler heads operating) (* author's highlight). Both text and table cannot be correct.

Chapter 15, “Fires in which large numbers of sprinkler heads operated”, takes a closer look at fires with a large number of sprinkler heads, more specifically, fires with more than 10 sprinkler heads operating: “*It has already been shown in Chapter 4 that the percentage of fires in Australia and New Zealand controlled with six (6) or less sprinkler heads in operation, and ten (10) or less respectively, were as follows*:

Table 29 Fires in which 6 or less and 10 or less sprinklers were in operation

6 or less sprinklers in operation		
1886-1968	**1968-1986**	**100 Years**
94%	91.69%	**93.39%***
10 or less sprinklers in operation		
1886-1968	**1968-1986**	**100 Years**
96,7%	95.13%	**96.60%***

***** This is the third place where we see a difference in the number of sprinkler heads in operation. If this includes “*not controlled*”, both numbers should be higher than 93.44% and 96.31%.

2. While the NFPA table separates wet and dry systems, this book does not. Under “Dry pipe and marine automatic sprinkler system” in the same chapter, the author says that “*one of the important differences in results when comparing the number of sprinkler heads in operation on fires in Australia and New Zealand with those in the United States is that there are very few dry pipe systems in these two countries, so few that* ***no fires**** *have been recorded for this type of installation*. *However, four fires in marine automatic sprinkler systems have been recorded*” (* author’s highlight).

3. The third finding is that one activation in row “200 or fewer”, was 113 sprinklers (according to Table 3 in the book), giving an overall performance rate of 99.46 ≈ 99.5%. This indicates that 49 fires not controlled, is fires with more than 200 sprinklers operated. This is completely in according to **Table 28** which in last line “All fires” have the number of fires 49 and per cent 0,54.
   But this cannot be the case. In Chapter 15 “**Fires in which large numbers of sprinklers heads operated**”, the author *“…. analyses the fires in which more than ten (10) sprinkler heads operated, other than those in which exposure was involved, and where fires were not controlled.”*

Table 30 Comparison of the numbers from Table 28 and Table 50 in the book

Number of sprinklers operated	**Table 28**	Table 50 in the book	Difference
11	22	20	2
12	24	22	2
13	31	29	2
14	32	29	3
15	22	19	3
16-20	59	54	5
21-25	36	38	-2

Table 50 in the book also lists cases where 124, 126, 140, 150, 156, 179, 220, 240, 256, 278, 290 and 361 sprinkler heads were activated. These are not included in **Table 28**. Does this mean that Table 10 in the book includes exposure sprinkler systems and multiple jet controls and spray controls?

Table 31 Summary of different tables

Number of sprinklers	Table 28	Table 50 in the book	Multiple jet*	Exposure sprinkler**	Total number (table 50 + MJ+ES)
11	22	20	1	1	22
12	24	22	1	1	24
13	31	29		1	30
14	32	29	1	2	32
15	22	19	1	2	22
16-20	59	54	2	3	59
21-25	36	38		2	40
* Tables 79 to 81 in the book ** Table 56 in the book					

This does not add up, even if it is close for some of the numbers. When 21 to 25 sprinklers were operated, the gap between all sprinklers, including exposure sprinkler systems and multiple jet controls and spray controls, increases when adding those systems to normal sprinkler systems (if I understood the book correctly).

4. There is no explanation why the 113 sprinklers were considered “fires controlled”. For example, the operating area for 113 sprinkler heads is around 113 x $9m^2$= 1 $017m^2$. This is far more than even the biggest design area ($360m^2$) for sprinkler systems according to Australian standards. This could perhaps be an exposure system, but this is not known.

5. The book has one chapter on partial protection, but there is no evidence of how this is incorporated into performance analysis.

   This opens a question on methodology. This has not been presented in the book, but there is some clue to this. On page 14 of the Introduction, the author writes: "*289 fires were identified from Fire Brigade records in which automatic sprinkler system operated satisfactorily, but for which no detailed reports were available.*" And further down on the page, he says: "*This edition has been dedicated to Wormald International Limited*[8]*, one of world's largest organizations in the field of Fire Protection and Security and a Company which had the foresight to keep the records which have been so important for so many years.*"

   More information is not found until Chapter 21 "Summary", where the author writes: "*Regrettably, this claim could not be sustained for 100 years, because of declining interest in making detailed reports available, the Wormald International Group of Companies being* ***the only**** *organization which continued to submit reports to the end of 1986*" (* author's highlight).

   It therefore appears that the main source of reports is the largest sprinkler company in Australia and New Zealand. There is no information on scientific independence or how results are tested.

6. Because all systems investigated in Australia and New Zealand were wet systems, I now compare them with NFPA reports. First, I will look at the per cent difference between total number (both wet and dry) and only wet sprinkler systems from the 1970 report (National Fire Protection Association, 1970) and compare the results to this report.

[8] The American conglomerate Tyco International, acquired the company in 1990.

Table 32 Percentage difference between operation of all systems and only wet sprinkler systems

Number of Sprinkler Operating	United States Total System Per Cent	Australia and New Zealand Total System Per Cent	Difference Per Cent	United States Wet System Per Cent	Australia and New Zealand Wet System Per Cent	Difference Per Cent	Difference between total and wet Per Cent
1	37.4	64.55	27.2	42.6	64.55	22.0	5.2
2 or fewer	54.6	80.41	25.8	61.0	80.41	19.4	6.4
3 or fewer	63.8	86.54	22.7	70.2	86.54	16.3	6.4
4 or fewer	70.1	89.79	19.7	76.2	89.79	13.6	6.1
5 or fewer	73.4	91.84	18.4	80.2	91.84	11.6	6.8
6 or fewer	77.7	93.44	15.7	83.2	93.44	10.2	5.5
7 or fewer	80.1	94.40	14.3	85.2	94.40	9.2	5.1
8 or fewer	82.2	95.24	13.0	87.0	95.24	8.2	4.8
9 or fewer	83.7	95.79	12.1	88.3	95.79	7.5	4.6
10 or fewer	85.0	96.31	11.3	89.4	96.31	6.9	4.4
11 or fewer	86.2	96.55	10.4	90.4	96.55	6.1	4.2
12 or fewer	87.3	96.82	9.5	91.2	96.82	5.6	3.9
13 or fewer	88.0	97.16*	9.2	91.7	97.16*	5.5	3.7
14 or fewer	89.0	97.51	8.5	92.6	97.51	4.9	3.6
15 or fewer	89.7	97.75	8.1	93.1	97.75	4.7	3.4
20 or fewer	92.2	98.39	6.2	95.0	98.39	3.4	2.8
Average			**14.5**			**9.7**	**4.8**
*This is specified as 96.16 in the original table. This cannot be true and has been changed.							

The average difference between reports for only wet systems is 9.7%. There is an average difference between total percentage and between percentage for only wet sprinkler systems of 4.8%. This explains some of the difference between US and Australia/New Zealand numbers, but not all.

Since the numbers from NFPA are based on the 1970 report that covers the period between 1925-1969, I include the numbers from the 2010 NFPA report (National Fire Protection Association Research, 2010). I take the mean value for only wet sprinkler systems from both NFPA reports and compare it to this report. This number is probably being more relevant to the numbers from Australia and New Zealand, as their numbers go 17 years longer into the period than the 1970 NFPA report.

Table 33 Per cent difference between sprinklers operated using updated NFPA numbers and only wet sprinkler systems

Number of Sprinkler Operating*	NFPA reports 1925-1969 Wet System	2004-2008 Wet System	Mean value	Australia 1886-1986 Wet system	Difference table 14	Difference	Difference table 14 vs updated wet system
1	42.6	52	47.3	64.6	22.0	17.3	4.7
2 or fewer	61	71	66.0	80.4	19.4	14.4	5.0
3 or fewer	70.2	76	73.1	86.5	16.3	13.4	2.9
4 or fewer	76.2	79	77.6	89.8	13.6	12.2	1.4
5 or fewer	80.2	91	85.6	91.8	11.6	6.2	5.4
6 or fewer	83.2	93	88.1	93.4	10.2	5.3	4.9
7 or fewer	85.2	94	89.6	94.4	9.2	4.8	4.4
8 or fewer	87	94	90.5	95.2	8.2	4.7	3.5
9 or fewer	88.3	95	91.7	95.8	7.5	4.1	3.4
10 or fewer	89.4	96	92.7	96.3	6.9	3.6	3.3
20 or fewer	95	97	96.0	98.4	3.4	2.4	1.0
Average					**11.7**	**8.1**	**3.6**
*The 2010 report does not have 11-15 sprinklers or fewer sprinklers.							

The average difference between countries for only wet systems is 8.1%. There is an average difference between total mean value for the updated per cent and the per cent for only wet sprinkler systems of 3.6%. This means that the updated NFPA numbers only reduce the average gap by 4.8% – 3.6% = 1.2%.

It does explain some of the difference, but not all.

8.1.2. UNRELIABILITY

Chapter 18 on “failure or none-operating sprinkler systems or on ineffectiveness” is called “Fires not controlled by automatic sprinkler system”. It was called “Fires in which automatic sprinkler performance was unsatisfactory” in the earlier edition.

The chapter starts with the 1886-1968 period and list 14 different cases where the sprinkler system did not operate as expected. Then it lists 23 cases for the period of 1968-1986. It adds 15 fires that were classified as “Satisfactory” in the earlier edition. The problem is that adding them gets 52 fires that were “Not controlled”. According to Chapter 4, “Overall performance analysis”, this should have been 49.

The chapter lists up to 8 causes for 49 fires. I tried to catalogue the 52 separate cases, but could not, because of missing information in the classification of each case.

Table 34 Causes of not controlling fires as per cent of separate cases of failure or ineffectiveness for all structures and wet pipe sprinklers

Reason	**Failure**	
	Number	Per Cent
Severe external exposure	5	10%
Unprotected area within or attached to the building	12	25%
Explosions	4	8%
Severity of internal hazard and high fire loading	16	33%
Inadequate water supplies	2	4%
Incendiarism	2	4%
Flash fires and flammable liquids	4	8%
Other factors*	4	8%
Total	**49**	**100%**
*This includes 3 cases were the sprinkler system was shut off.		

Compared to reasons given in the NFPA reports, this stands out for several reasons. The first is the different name and that some of the definitions have two of the reasons from the Australian report incorporated into one reason. For example, "**Severe external exposure**" and "**Unprotected area within or attached to the building**" could both be incorporated into the NFPA reason "**Fire not in area protected**". These fires are not included in the NFPA failure or ineffectiveness analysis, as the fires were outside protected areas.

"**System component damaged**" consists entirely of fires where automatic extinguishing equipment was damaged by "**Explosions**" or by ceiling, roof or building collapse. "**Inappropriate system**" can refer to the wrong type of agent, the wrong type of system for an agent or the wrong design for the system and agent, such as "**Severity of internal hazard and high fire loading**" and "**Flash fires and flammable liquids**".
"**Not enough water discharged**" is the same as "**Inadequate water supplies**".

The overview in the ***Table 34*** does not have the following four reasons from the NFPA reports.

1. **Water did not reach fire**: The largest category for ineffectiveness in the NFPA reports is not listed. Typically, this can be the shielding of the sprinkler by obstructions or the shielding of the area where the fire started. For example, case

study number 44*, "Rubber Works and Warehouse" is a fire that starts under a temporary cover over a stack of foamed plastic (*author's numbering). There is no explanation of why this has been added.

The book does not discuss whether obstruction or shielding could be reasons for the number of sprinklers operated.

2. **Manual intervention**: Two case studies involved manual intervention. Case study number 18*, "Department Store" is a fire where an unauthorized person or persons closed two main stop valves. Case study number 28*, "Furniture Factory", is a fire where the fire brigade shut off the sprinkler system too early (*author's numbering). There is no explanation of why they have been added.

3. **Lack of maintenance**: There are no cases of lack of maintenance in the case studies.

4. **System shut off**: This is largest reason for failure in the three NFPA reports reviewed in this dissertation. There is a drop from 52% in the 1970 report, to 43% in the 2010 report and 40% in the 2017 report. At least 7 cases in the Australian/New Zealand study that could be classified under this heading. They are case study number* 15, 23, 26, 31, 36, 39 and 51 (*author's numbering). They have mainly been classified as "**Incendiarism**" and "**Other factors**".

   At the beginning of Chapter 18, the following elaboration is given for systems shut off: "*As in the first edition, the several cases where buildings and contents where destroyed by fire when the building concerned were equipped with automatic sprinkler system, but from which water supplies had been **disconnected permanently, have not been included in the records***, since these buildings did not in fact have automatic sprinkler system available to operate at the time of the fire*" (* author's highlight).
   The author does not explain why there are no separate classes between permanently closed systems, such as buildings that are vacant, being remodelled, still under construction, or cases when systems are temporarily shut off because of

system problems like leaks in the system, problems with dirt or pollution of water, damage to pipes or heads.

There seems to be some mixing of terms in this chapter. Both reasons and causes are used. Instead of using the term "**System shut off**" as a cause, the author uses the reason the system is shut off. For example, arsonists shut the system off as part of incendiarism. Incendiarism is not a cause; it is a reason.
In other places, he gives the cause, for example, "**Inadequate water supplies**". There are many reasons for this, but they are not investigated.

8.1.3. SUMMARY

The comprehensive book provides an in-depth look at the 100-year experience with sprinklers in Australian and New Zealand. Different numbers are given for the same result and there are several calculation errors.

Attempts to compare the numbers against newer NFPA numbers and just look at the corresponding numbers for wet sprinklers do not explain the big difference between this study and others from around the world. This difference is not commented in the book.

(Bukowski. R. W., 1999) gives the following explanation of high reliability: "*Inspection, testing, and maintenance exceeded normal expectations, and higher pressures*". However, the systems in this study are wet systems (dry systems have larger fire growth because of the time water must travel from the sprinkler alarm valve to the area of fire; the fact that dry systems have more inherent possibility of failure is another factor), all fires where sprinklers were shut off (except where arson was involved) are excluded, the fact that most of the cases come from Wormald International Group of Companies (which may have a self-interest in collecting good reports) and the fact that 99,5% reliability is referring up to 113 sprinklers operating, may explain the high reliability.

9. APPENDIX 3: STUDIES IN UNITED KINGDOM

This chapter takes a closer look at the study done in UK.

9.1. EARLY STUDIES IN UNITED KINGDOM

As mentioned in 4.1, the study by Finucane M, Pinkney D (1988) is Reliability of fire protection and detection systems. Report Number SRD R431 United Kingdom Atomic Energy Authority Safety and Reliability Directorate, University of Edinburgh, Scotland, p 15.

I have only been able to find: Finucane M, Pinkney D (1987). Reliability of Fire Protection and Detection Systems. Recent Developments in Fire Detection and Suppression systems (p. 20). Edinburgh, Scotland: University of Edinburgh, Unit of Fire Safety Engineering.

In the edition that I found, there is no mention of 96.9 – 97.9% reliability for sprinkler systems in the United Kingdom. There is a reference to a study by the Home Office where sprinkler reliability is given as 95%. I do not know if there are two reports from Finucane and Pinkney with the same name, or if there is only one, with a first edition and a second more extended edition.

9.2.U.K. EXPERIENCE WITH SPRINKLERS: 2017

The report "*Efficiency and Effectiveness of Sprinkler Systems in the United Kingdom: An Analyse from Fire Service Data*" (Optimal Economics, 2017) was prepared for the Chief Fire Officers Association (CFOA) and the National Fire Sprinkler Network (NFSN) by Optimal Economics[9] (OE). OE analysed data on the activation and performance of sprinkler systems to control fires in buildings.

The data were collected from 47 of 52 fire and rescue services through the Incident Recording System (IRS) in the UK by CFOA and NFSN, for the years 2011 to 2015/16. Three were not fires with sprinkler systems. Some services reports are by financial year (2011/12 to 2015/16), but most are by calendar year. This have been adjusted in my presentation to 2011 to 2015.

The report looks at Data and Analysis Framework, and Analysis and Results.

9.2.1. RELIABILITY

From 2011 to 2015 (including 26 fires in from January to March 2016 for 11 fire and rescue services in 2016) there were 2 294 fires. Most of the fires, 75%, were in non-residential buildings and 18% were in dwellings.

In the Summary, point 3 says: "*The aim of the analysis was to provide an authoritative assessment of the **reliability and effectiveness*** *of sprinkler systems in controlling and extinguishing fires and in preventing damage*" (author's highlight). There are no definitions.

Point 4 says: "*The **effectiveness and reliability*** *of sprinklers has been assessed with regard to two key criteria:*

■ *When sprinklers operate how effective are they in extinguishing or controlling fires and thus preventing damage? (**performance effectiveness***)*

…, the performance effectiveness of sprinkler system was 99% across all building types.

■ *How reliable are sprinklers in coming into operation when a fire breaks out? (**operational reliability***)*" (author's highlight).

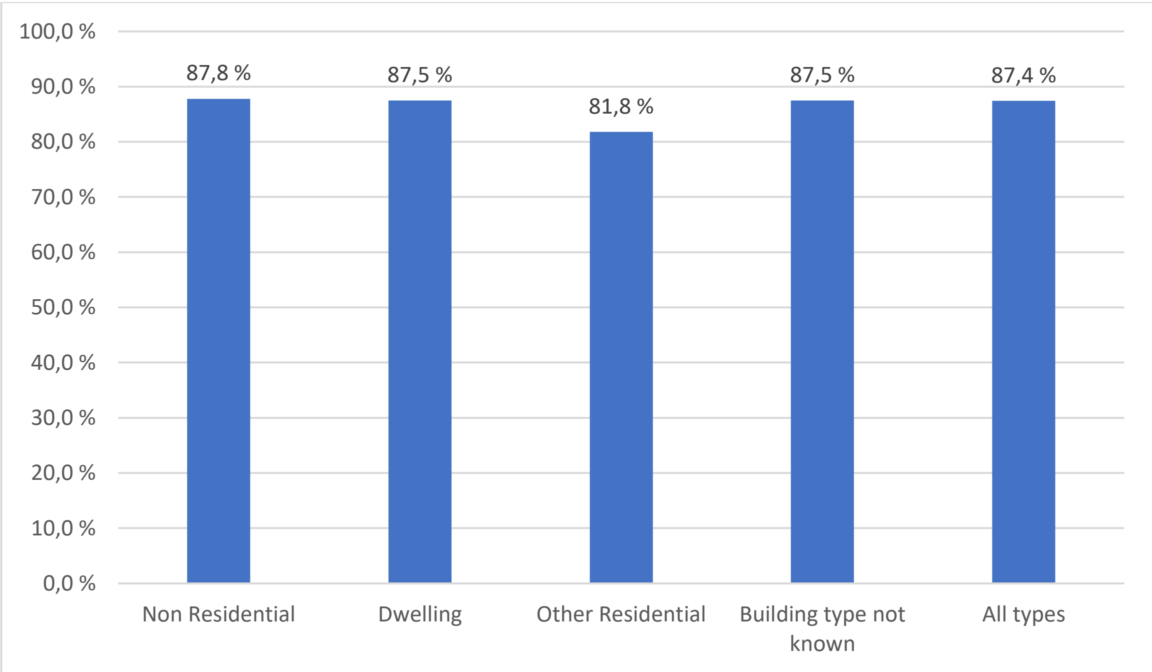
[9] Optimal Economics is a U.K. based analyst firm in economics, financial appraisal, and policy.

"This indicates that the operational reliability of the system was 94%."

There seems to be an assumption that efficiency (title of the report), reliability (point 3 in summery) and operational reliability (point 4 in summary) are the same. The report does not explain why this is the same or why there is a need to use three different words for the same thing.

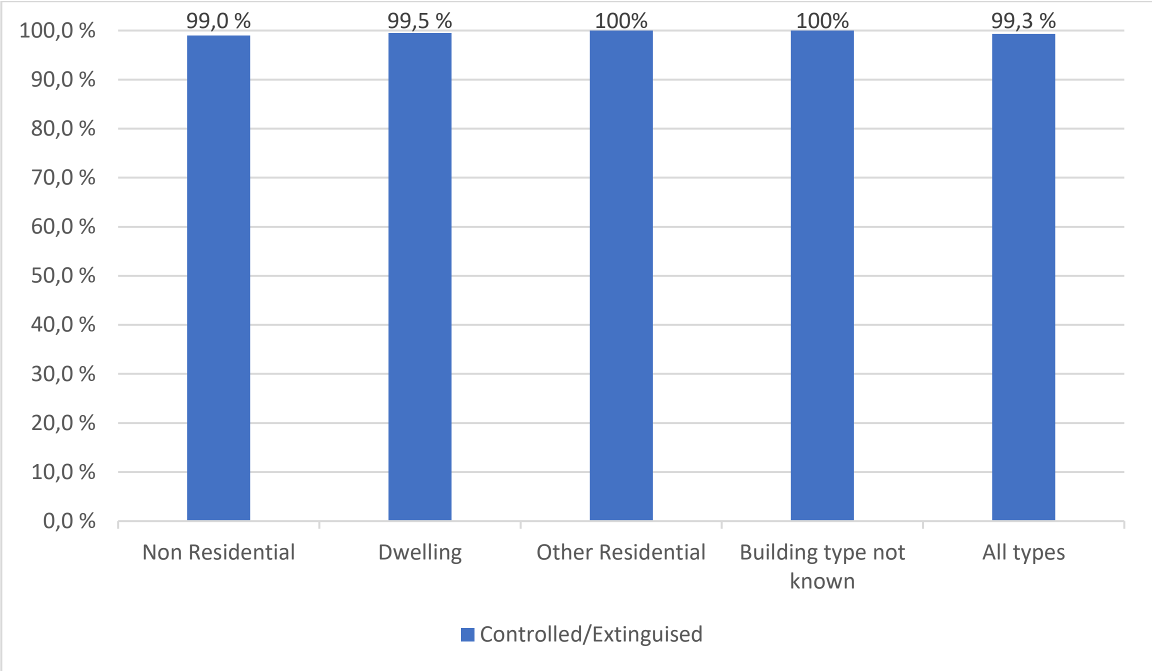
Of the 945 cases of sprinklers operated, data are only available for 532 cases. There is no explanation of whether the 532 cases are representative of all the cases.
Figure *16* (Figure 5 in the report) shows how often sprinklers were in the room of fire origin.

Figure 16 Operating sprinkler system in room of origin by building type



Two other categories are "On the same floor" and "Different floor". It is not clear whether this means there was sprinkler or not in the room of origin or that there was a sprinkler, but it did not operate. If there was no sprinkler in the room of origin, why are partial protection of interest? This is not explained.

Figure 17 Impact on fires where system operated by building type



The report does not explain how a system can extinguish or control a fire up to 100% when it is not present in the room of origin but is only on the same floor or even on a different floor. There is no explanation why performance reliability improved from 532 cases, the basis for **Figure *16*** for known locations of the sprinkler system, to 677 cases in **Figure *17*** (figure 8 in the report). Why can the performance data for the 532 cases not be used?

Under the assumption that sprinklers in the room of fire origin can extinguish or control the fire as **Figure *17*** indicates, there is a possibility of determining the percentage of times when sprinklers operated effectively. The number of sprinkler fires in buildings was 2 268 from 2011 to 2015; this number was adjusted for the number of fires in 2016.

Table 35 Automatic sprinkler system reliability and effectiveness, by property use for 2011-2015 structure fires

A. All Sprinklers (Based on Fig. 1, 2, 5, 8 and Table 1, 4, 5 in the report)						
			When equipment was present, fire was large enough to activate equipment, and sprinklers were present in fire area			
Property Use	**Number of fires where sprinkler was present***	**Per cent of fires not activating sprinkler****	**Per cent (numbers) of fires per year**	**Per cent where sprinkler operated in room of origin (A)*****	**Per cent effective of those that operated (B)**	**Per cent where sprinkler operated effectively (A x B)**
Non- Residential	1 705	65%	35% (603)	88%	99%	87%
Dwellings	409	33%	67% (273)	88%	100%	87%
Other Residential	117	65%	35% (41)	82%	100%	82%
Not Known	37	54%	46% (17)	88%	100%	88%
All fires	**2 268**	**59%**	**41% (934)**	**87%**	**99%**	**87%**

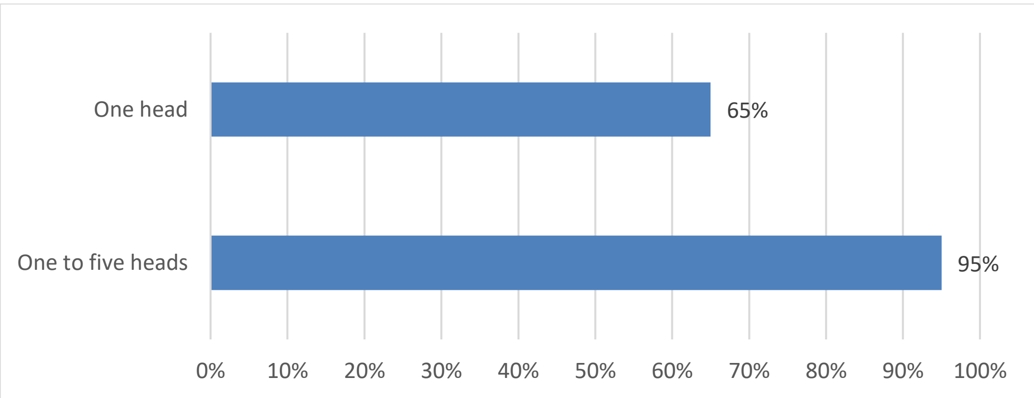
*These numbers are based on the total numbers of fires (2 294 minus 26 for 2016) and given in percentages.
**The report uses one decimal in the tables and none in the presentation of findings. No decimal is used to be more in line with rest of the reports reviewed.
***The rest of the reports reviewed are only interested in systems present in area of fire. A system that does not operate in area of the origin fire, cannot under any conditions be accepted as successful.

There is no explanation of why only 41% of the fires activated the sprinkler in the room. This is especially interesting, as 12.8% of the fires activated sprinklers on the same floor or a different floor, but not in the room where the fire started. There is no explanation of how it was determined there was insufficient heat to activate sprinklers.

The report rates performance effectiveness at 99.3% and operational reliability at 94.3%. This gives total reliability of 99.3 x 94.3 = 93.6%. This contrasts with the finding of 87% in the above table.

The report has data on the number of sprinklers activated for 788 of the 945 fires.

Figure 18 Per cent of fires where one or five or fewer sprinklers are activated



The 2017 NFPA report (National Fire Protection Association Research, 2017) cites the percentages for one and one to five sprinklers as 79% and 97%, respectively. It concludes that reliability is 88%. Since it has a higher percentage for one and five or less sprinklers, this suggests the finding in **Table *35*** is more accurate.

9.2.2. UNRELIABILITY

According to Figure 9 in the report, 62% of all fires where a sprinkler did not operate, sprinkler systems were located in the room of the fire origin. This means sprinkler systems were outside the room 38% of the time. But according to Figure 10 in the report, 42.1% of the fires were in areas not covered by a sprinkler system.

There is no explanation of this.

Table 36 Reasons for combined sprinkler failure and ineffectiveness: 2011-2015

Reason	**Failure**	
	Number	Per Cent
Fault in the system	12	26%
System not set up properly	4	9%
System damaged by fire	7	15%
System turned off	18	39%
Operating failure	3	7%
Human error	1	2%
Flash fires	1	2%
Total	**46**	**100%**

*There is no reason given in ***Figure 17*** for systems not operating in the room of origin of fire. This represents 121 cases; the reasons would have an impact on this table.
**There is no explanation in the report of the 0.7% sprinkler not controlling the fire (Figure 8). The numbers are taken from Figure 10 and Table 5. All reasons when the system should not operate have been excluded.

According to the report (page 7) the system operated in 945 cases and did not operate in 1 316 cases (page 13). This represents 945 + 1 316 = 2 261 total cases. According to the report, in 2 294 cases, a sprinkler system was present. There is no explanation of why the 33 cases are not included in the two subcategories; perhaps this is just an incorrect summary.

9.2.3. SUMMARY

The UK study does not provide definitions and the assumptions are not explained to the reader.

In addition, there are calculation errors, and there are no explanations of the differences in numbers from one case to another. There are different numbers in each case, and the selection of cases seems random.

However, this is the only report to use the word “indicates” about its findings.

10. APPENDIX 4: STUDIES IN NORWAY

This chapter looks at a study done in Norway. It is included in the dissertation to provide data for Norwegian readers.

10.1. NORWEGIAN EXPERIENCE WITH SPRINKLERS

Few studies have been done in Norway. Most look at the literature from around the world. One example of this is the study of (Opstad, 2002), were the study from (Bukowski. R. W., 1999) is the main source for reliability data.

One report that looks at raw data is the "*Reliability of Automatic Sprinkler Systems – an Analysis of Available Statistics*" by (Malm, 2008). Statistics from Sweden, Finland, Norway, England, New Zealand, Australia, and the US are used in this report. About 1.5 pages out of 52 are on Norway. Incident statistics come from Direktoratet for samfunnssikkerhet og beredskap (DSB) (The Directorate for Civil Protection and Emergency Planning) from 1998 to 2007.

10.1.1. RELIABILITY

The report has the following definition: "*Reliability refers to the probability that a sprinkler system will perform as expected. Reliability is the product of operational reliability and performance reliability.*"
"*Perform as expected expresses that a sprinkler system activates and contains, controls or extinguishes a fire*". The origin of the definitions and the difference between contain and control are not clear.

Mathematical expression for reliability is given as:

$$Reliability\ =\ Operational\ reliability\ x\ Performance\ reliability$$

The study for Norway uses the following mathematical expression without explanation:

$$Reliability = \frac{Number\ of\ incidents\ that\ functioned}{Total\ number\ of\ incidents}$$

The incident reports identify 1 262 fires in buildings with an extinguishing system. Out of these, 732 are identified as fires with sprinkler systems and the effect of the sprinkler systems is given for 453 cases. Four cases, including fire in boats, are removed from my discussion.

Table 37 Automatic sprinkler system reliability by property use for 1998-2007 structure fires

All Sprinklers					
			When sprinkler was present, effect known, and sprinklers operated effectively		
Property Use	Number of fires per year where extinguishing equipment was present	Per cent (number) of fires with known sprinkler system	Per Cent (number) of fires with known effect (A)	Number of fires where sprinkler operated effectively (A x B)	Per cent where sprinkler operated effectively (A x B)
All structures	1 258	58% (732)	36% (453)	334	74%

The report states that only 58% of fires with extinguishing systems were known to be sprinkler systems. The report does not explain if there was contact with fire departments to clarify what type of extinguishing systems they were, if they functioned and the outcome.

There is no explanation if extinguishing system is listed, there is no explanation of whether the fire was too small to activate the system.

I received the raw data from DSB and this raised more fundamental questions.

a) What value do the collected data have, when for over 25% of the registered fires, it is not known whether there was an extinguishing system present or not?
b) What value do the collected data have, when the data indicate there was sprinklers but not sure if it functioned?
c) "*The effect of the sprinkler systems is stated in 457 of the 736 incidents.*" In the data all incidents were given as having one cause. What value does this bring to the report?
d) In the incident reports, the fire brigade must indicate "*What stopped the fire spread*". If a sprinkler system performs as expected to contain/control the fire, how is this analysed and incorporated in the report if it is only possible to list one cause for stopping the fire spread?

10.1.2. UNRELIABILITY

The cause of failure is only known in 17 of the 118 incidents. These are shown in **Table *38***.

Table 38 Reasons for combined sprinkler failure and ineffectiveness: 1998-2007

Reason	**Failure**	
	Number	Per Cent
Not activated	8	47%
Out of order	6	35%
Insufficient amount of water	2	12%
Building partially sprinklered with deficient fire compartmentation	1	6%
Total	**17**	**100%**

The meanings are unclear. Does "Not activated" mean "System shut off", "Fire is large enough to activate sprinkler, but did not" or something else?

What value does "Not activated" give to the report, if we are not sure if the sprinkler system should have been activated because the fire was too small?

10.1.3. SUMMARY

This study has a definition for reliability that is not used for the section Norway. Instead, another expression is used.

The use of raw data is problematic, since the report do not deal with uncertainty in the data.

11.APPENDIX 5: DATA COLLECTION, ANALYSIS, AND REPORTING

A critical review of the selected literature leads to many questions and few answers. Could there be some more fundamental issues at stake here, and, if so, how should they be reviewed? Within the social sciences, including history, social anthropology, political science, socioeconomics, psychology, and so on, there is developed social science methodology on this matter. Two methodologies are of particular interest her: how to conduct studies and how to analyse documents (Jacobsen, 2015).

11.1. DOCUMENT ANALYSIS

Document analysis or source examination is the analysis of documents (secondary data) to answer the research question (problem) by collecting and analysing other words, phrases, stories on a topic, and reports. While a literature review tries to find theories or practices hole (or abundance), document examination is a systematic tool to examine all types of documents to find the answer to the question(s). This is helpful when:

d) It is impossible to get primary data
e) A researcher wishes to learn how others have interpreted a situation, event, or data
f) A researcher wishes to learn what has been done or said

Many different words are used to describe reliability (success, performance, performance effectiveness, operating, operating reliability, effectivity, operational effectively), and there are large gaps between the different levels or scores of reliabilities from one study to another. In addition, key findings are not always explained in a satisfactory way. Thus, the question is: are the studies done in a satisfactory, scientific way? Are the results trustworthy? Can they be applied as documented expected reliability within the area of the study?

Several steps are required in good scientific studies.

2. Development of problem and purpose
    2.1. Is the issue clear?
    2.2. Is it descriptive or explanatory (causal)?
    2.3. Can it be generalized?
3. Choice of design
    3.1. Intensive (deep) or extensive (width) study design
    3.2. Descriptive or explanatory
4. Type of data (qualitative or quantitative)
5. Method of data collection
    5.1. Operationalization: how to make a concept measurable
    5.2. Design of the study
    5.3. Sources and use of sources
6. Selection and limitation of data
7. Analysis of data
8. Quality assurance of the analysis
    8.1. Conceptual validity
    8.2. Validation of contexts
    8.3. External validity
    8.4. Are the results trustworthy?
9. Discussion and presentation of results
    9.1. Methodological discussion
    9.2. Substantial discussion – connection of findings and theory
    9.3. Presentation (also uncertainty)

Some of the key areas are discussed in 10.2: Discussion of findings.

10.2. DOCUMENT ANALYSIS VALIDATION

The best way to do a systematic validation is to visualize and put the components that must be present into a table based on the three phases of a survey.

Table 39 Systematic overview of document analysis validation

Preparation and collection		Analysis		Presentation	
1. Development of problem and purpose		6. Analysis		8. Discussion and presentation	
a) Is the issue clear?				a) Methodological discussion	
b) Is it explanatory (causal) or descriptive?				b) Substantial discussion (connection of findings and theory)	
c) Can it be generalized?				c) Presentation (also uncertainty)	
2. Choice of design		7. Quality assurance of the analysis			
a) Intensive (deep) or extensive (width) study design		a) Conceptual validity			
		b) Validation of contexts			
b) Descriptive or explanatory		c) External validity			
		d) Are the results trustworthy?			
3. Type of data (qualitative or quantitative)					
4. Method of data collection					
a) Operationalization: how to make a concept measurable					
b) Design of the study c) Sources and use of sources					
5. Selection and limitation					

Each can be answered by Yes, No or Not sure. **Table *40*** gives a general overview of the steps in a scientific study that should be analysed in a document validation.

Table 40 General overview of document analysis validation

Preparation and collection		Analysis		Presentation	
1. Development of problem and purpose		6. Analysis		8. Discussion and presentation	
2. Choice of design		7. Quality assurance of the analysis			
3. Type of data					
4. Method of data collection					
5. Selection and limitation					

The content is checked according to the template in **Table *41***.

Table 41 Quality assurance of the steps in the document analysis

Main step	Sub step	Explanation
Preparation and collection		
	1.1. Is the issue clear or not?	If the purpose of the study is not clear, this means the purpose has not been revised over time, adjusted according to available sources and data.
	1.2. Is it descriptive or explanatory (causal)?	Is the study more interested in how (descriptive) or why (explanatory)?
	1.3. Is it desirable to generalize the findings?	If it is desirable to generalize the findings, this pushes the benchmark up.
1. Development of problem and purpose		**Is there an understandable problem and purpose?**
	2.1. Intensive (deep) or extensive (width) study design	Extensive designs have many units in the study, but few variables. Intensive designs have many variables, but few units.
	2.2. Descriptive or explanatory	The extent of the study increases exponentially when it goes from descriptive to explanatory. 1. Correlation of cause and presumed effect. 2. Cause must precede effect in time. 3. Control of all other relevant factors
2. Choice of overall study design		**Is the overall study design understandable?**
3. Type of data (qualitative or quantitative)		**Can be of interest to have this as a separate point in some studies (e.g., social sciences), but not in this type of study. We need quantitative answers.**
	4.1. Operationalization, how to make a concept measurable	Make abstract concepts, like reliability, operation, function, effect, and so on, into something measurable.
	4.2. Design of the study	Does the study use its own design or another study's design?
	4.3. Source and use of sources	Is it possible to use or change data collecting or design the study to accommodate fire brigades or must it be independent?
4. How to collect data?		**Does the study have a workable detail design?**
5. Selection and limitation		**Selecting more than one system leads to more than one study. The study must limit all types of events that don't control over other relevant factors: for example, ship vs. buildings or fully vs. partially protected.**

Analysis		
6. Analysis		**Very important to do the analysis using scientific methods, including the use of results.**
	7.1. Conceptual validity	After concretization of the concepts, it is very important to ask: Do the indicators measure what we are interested in?
	7.2. Validation of correlations	If an explanatory (causal) problem/design is chosen, this puts a strong demand on the study. Is the question answered by the analysis?
	7.3. External validity	When we wish to generalize, it is important to ask if the analysis is wide enough and representative.
	7.4. Are the results trustworthy?	Can the way the study has been done be the reason for the result? Consider the level, time, and causality.
7. Quality assurance of the analysis		**How good are the conclusions drawn from the analysis?**
Presentation		
	8.1. Methodological discussion	Methodological discussion goes through the steps for quality assurance of the results, step 7 of this section, and examines how the study was conducted.
	8.2. Substantial discussion – connection of findings and theory	Is this empirically consistent or inconsistent with other like or similar studies in this field? What are the connections between the findings and how they should be theoretically understood?
	8.3. Presentation (also uncertainty)	Is it transparent, logical, and readable?
8. Discussion and presentation		**How good is the presentation of conclusions?**

The systematic tool of document analysing can now be used on the respective reports and studies.

11.1.1. USA

In this thesis, there are three US studies are of interest. They are: (National Fire Protection Association, 1970), (National Fire Protection Association Research, 2010) and (National Fire Protection Association Research, 2017).

Table 42 Overview of US studies of interest for document analysis

Reference	Success, individually and average (%)	Applied area/ Focus/Comments	Comments
NFPA (National Fire Protection Association, 1970)	79.2 – 98.2 96.2	Data from 1897 – 1969 were 95.8% on average.	Data from 1897 – 1924 and 1925 - 1969
NFPA (National Fire Protection Association Research, 2010)	80 – 94 91	This study was done on sprinklers and other automatic fire extinguishing equipment	Data from NFIRS 2004 – 2008
NFPA (National Fire Protection Association Research, 2017)	81 – 91 88	This study was done only for sprinklers	Data from NFIRS 2010 – 2014

The first study is National Fire Protection Association. (1970, July). Automatic Sprinkler Performance Tables 1970 Edition. Fire Journal, 64(4), 5 (35-39).

Table 43 Document analysis of automatic sprinkler performance tables, 1970 Edition

Preparation and collection		Analysis		Presentation	
1. Development of problem and purpose	No[4]	6. Analysis	Yes[14]	8. Discussion and presentation	No[19]
a) Is the issue clear?	No[1]			a) Methodological discussion	No[16]
b) Is it explanatory (causal) or descriptive?	No[2]			b) Substantial discussion (connection of findings and theory)	No[17]
c) Can it be generalized?	Yes[3]			c) Presentation (also uncertainty)	No[18]
2. Choice of design	Yes[7]	7. Quality assurance of the analysis	Not sure[15]		
a) Intensive (deep) or extensive (width) study design.	No[5]	a) Conceptual validity	Not sure		
		b) Validation of contexts	Not sure		
b) Descriptive or explanatory	Yes[6]	c) External validity	Not sure		
		d) Are the results trustworthy?	Not sure		
3. Type of data (qualitative or quantitative)	Yes[8]				
4. Method of data collection	No[12]				
a) Operationalization: make a concept measurable	No[9]				
b) Design of the study	No[10]				
c) Source and use of sources	Yes[11]				
5. Selection and limitation	Yes[13]				

[1] It is not clear what sprinkler performance is. No definition.
[2] The study is both.
[3] The first line is "…an over-all record…". This is generalizing.
[4] The sum of a, b, and c.
[5] Both. Extensive when using the NFPA Fire Record Department and over 75 000 fires and intensive when having many variables.
[6] Explanatory. Not only low performance, but also causes/reasons (Table 3).
[7] The sum of a and b.
[8] Quantitative.
[9] Even if performance/effectiveness/reliability could be objectively measured, it is how the person filling in the form perceives performance/effectiveness/reliability that is noted and used in the analysis.

[10] Study design does not consider type of system.
[11] Insurance company and inspection bureau (most be considered impartial).
[12] The sum of a, b, and c.
[13] Only buildings.
[14] The report.
[15] The sum of a, b, and c.
[16] No
[17] No
[18] Only positive uncertainty. It is argued that a great number of small fires are not reported, and that if they were included, this would have given higher performance.
[19] The sum of a, b, and c.

The second study is National Fire Protection Association Research. (2010). U.S. Experience with Sprinkler and Other Automatic Fire Extinguishing Equipment 2004-08. Quincy, MA: NFPA.

Table 44 Document analysis of US experience with sprinklers and other automatic fire extinguishing equipment, 2010

Preparation and collection		Analysis		Presentation	
1. Development of problem and purpose	No[4]	6. Analysis	Yes[14]	8. Discussion and presentation	No[21]
a) Is the issue clear?	No[1]			a) Methodological discussion	Yes[18]
b) Is it explanatory (causal) or descriptive?	No[2]			b) Substantial discussion (connection of findings and theory)	No[19]
c) Can it be generalized?	Yes[3]			c) Presentation (also uncertainty)	No[20]
2. Choice of design	Yes[7]	7. Quality assurance of the analysis	No[17]		
a) Intensive (deep) or extensive (width) study design.	No[5]	a) Conceptual validity	No[15]		
b) Descriptive or explanatory	Yes[6]	b) Validation of contexts	Yes[16]		
		c) External validity	Not sure		
		d) Are the results trustworthy?	Not sure		
3. Type of data (qualitative or quantitative)	Yes[8]				
4. Method of data collection	No[12]				
a) Operationalization: make a concept measurable	No[9]				
b) Design of the study	No[10]				
c) Source and use of sources	Yes[11]				
5. Selection and limitation	Yes[13]				

[1] It is not clear what sprinkler reliability and effectiveness are. Even if there is no definition, there is a statement that effectiveness should be measured relative to design objectives and the design purpose is to confine a fire to the room of origin. This has not been proved to be right.
[2] It studies both.
[3] The first line is "Sprinklers are a highly effective and reliable part...". This is generalizing.
[4] The sum of a, b, and c.
[5] Both. Extensive when using the US Fire Administration's National Fire Incident Reporting System (NFIRS 5,0) corrected with NFPA Fire Record Department and over 57 000 fires and intensive when there are many variables.
[6] Explanatory. Not only low ineffectiveness, but also causes/reasons (Figure 11 to 13).
[7] The sum of a and b.

[8] Quantitative.
[9] Even if performance/effectiveness/reliability could be objectively measured, it is how the person filling in the form perceives performance/effectiveness/reliability that is noted and used in the analysis.
[10] Design of study does not consider type of system.
[11] NFPA study uses NFIRS to scale the numbers, but NFIRS is a voluntary system.
[12] The sum of a, b, and c.
[13] Only buildings and excluding partially protected buildings.
[14] The report.
[15] Even if 49% of the fires were too small to activate equipment, there is no discussion or validation of how this affected performance/reliability.
[16] Tables 4 and 5 show correlation; cause comes before effect in time and control on other conditions. The fact that “Fires too small to activate” is not supported by either qualitative or quantitative data is not considered.
[17] The sum of a, b, and c.
[18] Section 1 and Appendix A.
[19] Either fire theory (including extinguishing) or reliability theory is discussed or defined.
[20] Appendix A has a discussion of uncertainty, but this is not specified in numbers. Lack of uncertainty analysis.
[21] The sum of a, b, and c.

The third study is National Fire Protection Association Research. (2017). U.S: Experience with Sprinklers 2010-14. Quincy, MA: NFPA.

Table 45 Document analysis of US experience with sprinklers, 2017

Preparation and collection		Analysis		Presentation	
1. Development of problem and purpose	No[4]	6. Analysis	Yes[14]	8. Discussion and presentation	No[21]
a) Is the issue clear?	No[1]			a) Methodological discussion	Yes[18]
b) Is it explanatory (causal) or descriptive?	No[2]			b) Substantial discussion (connection of findings and theory)	No[19]
c) Can it be generalized?	Yes[3]			c) Presentation (also uncertainty)	No[20]
2. Choice of design	Yes[7]	7. Quality assurance of the analysis	No[17]		
a) Intensive (deep) or extensive (width) study design.	No[5]	a) Conceptual validity	No[15]		
		b) Validation of correlations	Yes[16]		
b) Descriptive or explanatory	Yes[6]	c) External validity	Not sure		
		d) Are the results trustworthy?	Not sure		
3. Type of data (qualitative or quantitative)	Yes[8]				
4. Method of data collection	No[12]				
a) Operationalization: make a concept measurable	No[9]				
b) Design of the study	No[10]				
c) Source and use of sources	Yes[11]				
5. Selection and limitation	Yes[13]				

[1] It is not clear what sprinkler reliability and effectiveness is. Even if there is no definition, there is a statement that effectiveness should be measured relative to design objectives and that the design is to confine a fire to the room of origin. This has not been proven to be right.
[2] The study is both.
[3] The first line is "Automatic sprinklers are highly effective". This is generalizing.
[4] The sum of a, b, and c.
[5] Both. Extensive when using the U.S. Fire Administration's National Fire Incident Reporting System (NFIRS 5,0) corrected with NFPA Fire Record Department and over 46 000 fires and intensive when having many variables.
[6] Explanatory. Not only low performance, but also causes/reasons (Table 4 and 5).
[7] The sum of a and b.

[8] Quantitative.
[9] Even if performance/reliability could be objectively measured, it is how the person filling in the form perceives performance/reliability that is noted and used in the analysis.
[10] Study design does not consider type of system.
[11] NFPA study uses NFIRS, but NFIRS is a voluntary system.
[12] The sum of a, b, and c.
[13] Only buildings and excluding partially protected buildings.
[14] The report.
[15] Even if 44% of the fires were to be too small to activate equipment, there is no discussion or validation of how this affected performance/reliability.
[16] Tables 8 and 9 show correlation; cause comes before effect in time and control on other conditions. The fact that "Fires too small to activate" is not supported with either qualitative or quantitative data is not considered.
[17] The sum of a, b, and c.
[18] Section 1 and appendix A.
[19] Either fire theory (including extinguishing) or reliability theory is discussed or defined.
[20] Appendix A has a discussion of uncertainty, but this is not specified in numbers. Lack of uncertainty analysis.
[21] The sum of a, b, and c.

11.1.2. AUSTRAILIA AND NEW ZEALAND

In this thesis, the Marryat, H. W. (Rev. 1988). *Fire - A Century of Automatic Sprinkler Protection in Australia and New Zealand - 1886-1986*, North Melbourne, Victoria: Australian Fire Protection Association is of interest.

Reference	Success, individually and average (%)	Applied area/ Focus/Comments	Comments
Marryat (Marryat, Rev. 1988)	95.3 – 100 99.5	Inspection, testing, and maintenance exceeded normal expectations, and higher pressures.	Data from 1886 – 1986.

Table 46 Document analysis of *Fire - A Century of Automatic Sprinkler Protection in Australia and New Zealand - 1886-1986*

Preparation and collection		Analysis		Presentation	
1. Development of problem and purpose	No[4]	6. Analysing	No[14]	8. Discussion and presentation	No[23]
a) Is the issue clear?	No[1]			a) Methodological discussion	No[20]
b) Is it explanatory (causal) or descriptive?	No[2]			b) Substantial discussion (connection of findings and theory)	No[21]
c) Can it be generalized?	Yes[3]			c) Presentation (also uncertainty)	No[22]
2. Choice of overall study design	Yes[7]	7. Quality assurance of the analysis	No[19]		
a) Intensive (deep) or extensive (width) study design.	No[5]	a) Conceptual validity	No[15]		
		b) Validation of correlations	No[16]		
b) Descriptive or explanatory	Yes[6]	c) External validity	Yes[17]		
		d) Are the results trustworthy?	No[18]		
3. Type of data (qualitative or quantitative)	Yes[8]				
4. Method of data collection	No[12]				
a) Operationalization: make a concept measurable	Yes[9]				
b) Design of the study	No[10]				
c) Source and use of sources	No[11]				
5. Selection and limitation	No[13]				

[1] It is not clear what satisfactory performance is. Even if there is a definition, this is not in accordance with the statistics used in the book. Definition: "*Fires which have either been completely extinguished, or controlled by the automatic sprinkler system to the point that they would by extinguished even if supplementary action had not been taken by fires brigades or others.*" Table 4 on overall performance says: "*Fires which were completely extinguished by action of automatic sprinklers, fires in which hand extinguishers were used, and fires in which there was Fire Brigade action.*"
[2] The study is both.
[3] The first line is "*…of this book, which covered the experience with automatic sprinkler system in Australia and New Zealand…*" This is generalizing.
[4] The sum of a, b, and c.
[5] Both. Extensive when using around 9 000 fires with working sprinkler in this study and intensive when having many variables.
[6] Explanatory. Not only not controlled, but also causes/reasons (Chapter 18).
[7] The sum of a and b.
[8] Quantitative.
[9] Either is extinguished or on its way to being extinguished by the sprinkler system without interference.
[10] Study design does not measure this, but interference included hand extinguishers and fires in which there was Fire Brigade action.
[11] It is not clear if Wormald International Group of Companies is the only supplier of records.
[12] The sum of a, b, and c.
[13] It is not clear if partially protected buildings are included, why four fires in marine automatic sprinkler system are included, and why fires with water supplies shut off are taken out.
[14] The report has several incorrect calculations, including summation of the number of events.
[15] There is no discussion or validation of how results answer the question.
[16] There is no discussion of correlation, i.e., that cause comes before effect in time and controls other conditions.
[17] Compared to NFPA.
[18] The results are so different from other studies because of the lack of proper discussion and incorrect calculations that they appear untrustworthy.
[19] The sum of a, b, and c.
[20] Chapter 21 only touches on this subject.
[21] Either fire theory (including extinguishing) or reliability theory is discussed or defined.
[22] Lack of uncertainty analysis.
[23] The sum of a, b, and c.

11.1.3. UNITED KINGDOM

In this thesis, the (Optimal Economics, 2017) Efficiency and Effectiveness of Sprinkler Systems in the United Kingdom: An Analysis from Fire Service Data. Chief Fire Officers Association, National Fire Sprinkler Network, is of interest.

Reference	**Success, individually and average (%)**	**Applied area/ Focus/Comments**	**Comments**
NFSM (Optimal Economics, 2017)	92 – 97.7 93.6	United Kingdom	2017

Table 47 Document analysis of Efficiency and Effectiveness of Sprinkler Systems in the United Kingdom

Preparation and collection		**Analysis**		**Presentation**	
1. Development of problem and purpose	No[4]	6. Analysis	Not sure[14]	8. Discussion and presentation	No[23]
a) Is the issue clear?	No[1]			a) Methodological discussion	No[20]
b) Is it explanatory (causal) or descriptive?	No[2]			b) Substantial discussion (connection of findings and theory)	No[21]
c) Can it be generalized?	Yes[3]			c) Presentation (also uncertainty)	No[22]
2. Choice of overall study design	Yes[7]	7. Quality assurance of the analysis	No[19]		
a) Intensive (deep) or extensive (width) study design.	Yes[5]	a) Conceptual validity	No[15]		
b) Descriptive or explanatory	Yes[6]	b) Validation of correlations	No[16]		
3. Type of data (qualitative or quantitative)	Yes[8]	c) External validity	No[17]		
4. How to collect data	No[12]	d) Are the results trustworthy?	No[18]		
a) Operationalization: make a concept measurable	No[9]				
b) Design of the study	No[10]				
c) Source and use of sources	Yes[11]				
5. Selection and limitation	No[13]				

[1] Five key questions are in 2.2 but there are no definitions and they conflict with Summary.
[2] The study is both.
[3] Summary: "*The aim of the analysis was to provide an authoritative assessment of the reliability and effectiveness of sprinkler systems in controlling and extinguishing fires and in preventing damage.*"
[4] The sum of a, b, and c.
[5] Extensive design with many units (around 2 300 fires), but few variables (Fig. 4).
[6] Explanatory. Not only not controlled, but also causes/reasons for not operating (Chapter 3.3).
[7] The sum of a and b.
[8] Quantitative.
[9] Even if performance/operational could be objectively measured, it is how the person filling in the form perceives it that is noted and used in the analysis.
[10] Design gives "Not known" to measurable questions.
[11] The reports come from 47 Fire and Rescue Services across the UK.
[12] The sum of a, b, and c.
[13] The reason for incorporating systems not present in room of fire origin or same floor is not clear. The reason for different numbers of fires in each figure and table is not clear.
[14] It is not clear how the analysing is done. Only 2 261 cases are presented, when there should be 2 294, and the use of data from one question to another is not clear.
[15] There is no discussion or validation of how results answer the question.
[16] There is no discussion of correlation, i.e., that cause comes before effect in time and controls other conditions.
[17] There is no discussion about fires with such low heat that the sprinkler does not activate the sprinkler, or sprinklers not present in area of fire (partial protection), or fires that are large enough activate the sprinkler, but do not. Many other studies consider these.
18 Because the study includes systems that operate on different floors and outside room of origin without discussing the reason for doing so, the results seem untrustworthy.
[19] The sum of a, b, and c.
[20] Chapter 3.4 only touches on this subject.
[21] Either fire theory (including extinguishing) or reliability theory is discussed or defined.
[22] Lack of uncertainty analysis. The fourth conclusion states: "*Operational reliability measures the probability that a system will operate as designed when required.*" There is no definition, discussion or presentation of the design or the individual results.
[23] The sum of a, b, and c.

11.1.4. NORWAY

Document analysis is useful when it is impossible to collect primary data. In this case, this was possible and, therefore, there is no reason for the analysis. The conclusion of the literature review on the (Malm, 2008) report is that it cannot be taken as historically reliable and cannot predict the reliability of sprinkler systems in Norway.

11.1.5. SUMMARY OF THE DOCUMENT ANALYSIS

The basis for choosing these studies for analysis is whether they can be used in a scientific way as a general basis for predicting the reliability of sprinkler systems. It must be stressed that this analysis does not attempt to judge the value of the studies. **Table *48*** gives an overview of the findings.

Table 48 Overview of document analysis validation for the examined studies

Reference	1.	2.	3.	4.	5.	6.	7.	8.	SUM
Marryat (Marryat, Rev. 1988)	No	Yes	Yes	No	No	No	No	No	**No**
NFPA (National Fire Protection Association, 1970)	No	Yes	Yes	No	Yes	Yes	Not sure	No	**No**
NFPA (National Fire Protection Association Research, 2010)	No	Yes	Yes	No	Yes	Yes	No	No	**No**
NFPA (National Fire Protection Association Research, 2017)	No	Yes	Yes	No	Yes	Yes	No	No	**No**
NFSM (Optimal Economics, 2017)	No	Yes	Yes	No	No	Not sure	No	No	**No**

1. Development of problem and purpose
2. Choice of overall study design
3. Type of data
4. How to collect data
5. Selection and limitation
6. Analysis
7. Quality assurance of the analysis
8. Discussion and presentation

Should all the questions be answered "Yes" for a study to be considered a scientific study or is possible to get some "No" or "Not sure" responses? That is a good question, and it will be discussed later in the thesis. In addition, if a study does not define its terms or its definitions go outside common usage, what value does it have to the field of reliability? In these cases, even if several factors indicate the study in general is done in a scientific way, **the conclusion is that they cannot be used as a general documentation on reliability or on future probability for sprinkler systems to function as designed.**

11.2. DISCUSSION OF FINDINGS

Are sprinkler systems the same in USA, United Kingdom, Australia/New Zealand, and Norway? Are they engineered in the same way, are Planning and Building Acts the same when it comes requirements regarding engineering and installation, and are the control and maintenance regimes after the system is put into operation the same? They are not, and this explains some of the differences in the reliability in the different countries, but the main finding of the document analysis is that all studies have problems in 4 areas: development of problem and purpose (including definition), how to collect data, quality assurance of the analysis and discussion and presentation.

11.2.1. DEVELOPMENT OF PROBLEM AND PURPOSE

The first problem area is the development of the problem and purpose (step 1). Only one study has a definition (Marryat, Rev. 1988), but not of reliability.
Simply stated, reliability is the ability to function as intended. More precisely, it is the characteristic or expression of the ability of a component or system to perform an intended function. This includes the lifetime probability distribution of failure, statistical life expectancy, expected number of failures per unit of time, a system or component's ability to function satisfactorily over time and the likelihood that it will work at a specific time (Aven, 2006). For a sprinkler system, intended means the likelihood of functioning as **designed**. This includes correct or proper design following a sprinkler standard. This point is missed in every report or study mentioned in the thesis. With a clear definition of the probability of functioning as designed, the correct data can be gathered.

11.2.2. HOW TO COLLECT DATA

The second problem area, how to collect data (step 4), derives directly from the first. What does the ability to function as designed mean for a sprinkler system? Well, that comes down to what kind of a sprinkler system we are talking about.

What do American standards say about this? According to NFPA 13D (National Fire Protection Association, 2010) Standard for the Installation of Sprinkler Systems in One- and Two-Family Dwellings and Manufactured Homes:

*"1.2.1 The purpose of this standard shall be to provide a sprinkler system that **aids** in the detection and control of residential fires and thus **provides improved** protection **against injury and life loss.***

> *1.2.2 A sprinkler system designed and installed in accordance with this standard shall be **expected to prevent flashover** (total involvement) in the room of fire origin, where sprinklered, and **to improve the chance for occupants to escape or be evacuated*."*** (* authors highlight)

With a 7/10-minute rate for water demand for up to 2 residential sprinklers in the biggest room (ref. Chap. 6.1), the sprinkler system is not designed to confine a fire in the room or design area, but to help people to escape from a fire by preventing flashover during the time the system has water and extending the escape time.

The purposes of sprinklers are expanded in the NFPA standard for larger residential buildings. NFPA 13R (National Fire Protection Association, 2010) Standard for the Installation of Sprinkler Systems in Residential Occupancies up to and Including Four Stories in Height specifies the following:

> *"1.2.1 The purpose of this standard shall be to provide a sprinkler system that **aids** in the detection and control of residential fires and thus **provides improved** protection **against injury, life loss, and property damage**.*
>
> *1.2.2 A sprinkler system designed and installed in accordance with this standard shall be **expected to prevent flashover** (total involvement) in the room of fire origin, where sprinklered, and **to improve the chance for occupants to escape or be evacuated*."*** (* authors highlight)

With a 30-minute rate for water demand for up to 4 residential sprinklers in the biggest room (ref. Chap. 7.1.1.3), the purpose is extended to property damage. This does not mean confined fires, just improved protection against property damage.

Standard NFPA 13 (National Fire Protection Association, 2016) Installation of Sprinkler Systems more clearly specifies protection of property:

*"1.2.1 The purpose of this standard shall be to provide a **reasonable degree of protection for life and property*** from fire through standardization of design, installation, and testing requirements for sprinkler systems, including private fire service mains, based on sound engineering principles, test data, and field experience."* (* authors highlight)

Chapter 3 in NFPA 13 gives the following definitions of purposes and sprinkler types:

*"3.3.11 **Fire Control.** Limiting the size of a fire by distribution of water so as to decrease the heat release rate and pre-wet adjacent combustibles, while controlling ceiling gas temperatures to avoid structural damage.*

*3.3.12 **Fire Suppression.** Sharply reducing the heat release rate of a fire and preventing its regrowth by means of direct and sufficient application of water through the fire plume to the burning fuel surface.*

3.6.4.1 Control Mode Density/Area (CMDA) Sprinkler. A type of spray sprinkler intended to provide **fire control*** in storage applications using the design density/area criteria described in this standard.*

3.6.4.3 Early Suppression Fast-Response (ESFR) Sprinkler. A type of fast-response sprinkler that has a thermal element with an RTI of 50 (meters-seconds)$^{1/2}$ or less and is listed for its capability to provide **fire suppression*** of specific high-challenge fire hazards.*

*3.6.4.9 Residential Sprinkler. A type of fast-response sprinkler having a thermal element with an RTI of 50 (meters-seconds)$^{1/2}$ or less that has been specifically investigated for its ability to **enhance survivability in the room of fire origin***, and that is listed for use in the protection of dwelling units"* (* author's highlight).

It should also be noted that residential sprinklers in NFPA 13 have the 4 most hydraulically demanding sprinklers, regardless of room size, and water density should be double.

There is even a possibility of reducing area of operation when using quick-response sprinklers and designing the sprinkler system to suit the room design method, in NFPA 13 (Chapter 11).

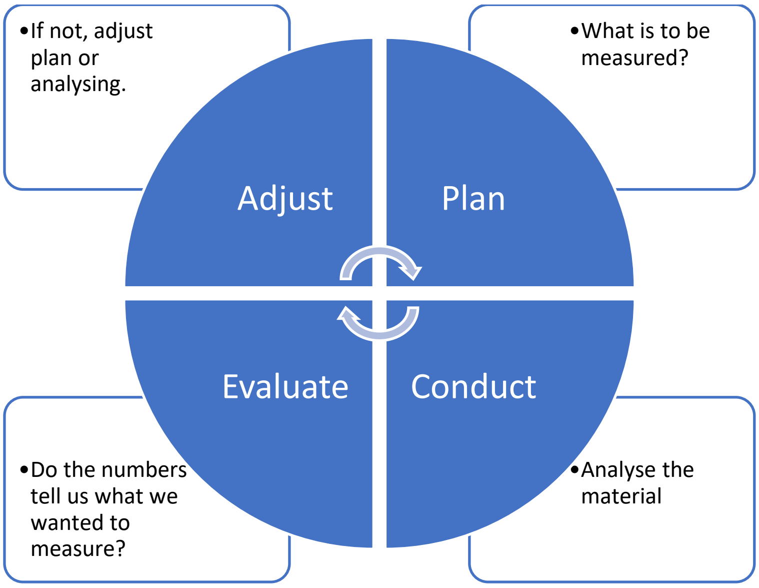
The NFPA 13 standard defines the purposes of sprinklers differently, according to the sprinkler type. Given this lead, then, why do studies not try to determine the reliability of specific sprinkler designs? They are being designed, built, and inspected/maintained according to sprinkler standards, and it is not clear why there is no interest in monitoring, controlling, and adjusting the standards based on their reliability. Recall that the reliability of a sprinkler system is its ability to function as designed.
What about activation and performance? These are a natural part of reliability, but both the meaning of the words and their use need to be discussed and defined. Are activation and operation the same?

Not only must the number of triggered sprinklers be counted (and analysed) for the sprinkler system in question, but two further areas also need attention. This is discussed in Appendix 6: Suggestions for methodology and future studies.

11.2.3. QUALITY ASSURANCE OF THE ANALYSIS

The third area, step 7, is quality assurance of the analysis. If there is no clear and measurable purpose, it is hard to check whether the results give the answer to the question. This can be Illustrated with a quality assurance wheel.

Figure 19 Quality assurance wheel



This concept is valid for planning in general; it can also be applied to data used in studies of reliability and to the management of quality. It is very important to check results for conceptual validity, contextual validity, external validity, and trustworthiness. If they do not have these qualities, it will be hard to trust them.

11.2.4. DISCUSSION AND PRESENTATION

The fourth problem area is presentation (step 8). Discussions, comparisons to earlier or other studies, trends if possible, and honest views on uncertainty must indicate everything that could be a major issue. There is only one study in this literature review uses the word "*indicates*" when discussing the results (Optimal Economics, 2017).

11.3. HOW SCIENTIFIC IS THE USE OF DOCUMENT ANALYSIS?

The use of document analysis is a scientific method for the systematic analysis of documents, but two aspects require further attention.

First, how well does this method from the social sciences work when it is applied in the natural sciences, in this case, in Fire Safety and Fire Engineering? As the holder of a bachelor's degree on my way to a master's, I am in no position to change an established method, even if I see areas for improvement. In my next article, "New Methods for

Collecting, Analysing, and Presenting Reliability Data", I will give suggestions on methodology and designs for scientific investigation/studies, with a focus on collecting, analysing, and presenting data on sprinkler reliability. These can, of course, be used in other areas as well. Adaptation must be transparent, so that if others are doing the same type of study, they will come to the same result.

Second, should all questions be answered "Yes" in the document analysis to make a study a scientific one, or is possible to score some "No" or "Not sure" without being "unscientific"? Mainly this depends on the purpose, sources, and resources available. For example, consider the three first questions under "*Development of problem and purpose (step 1):*
a) Is the issue clear?
b) Is it explanatory (causal) or descriptive (descriptive)?
c) Can it be generalized?

d) If the purpose or issue of the study is not clear, this often means it suffers from a lack of definitions. Moreover, the purpose may not have been followed and adjusted to suit available sources and data. Lack of sources or data can be compensated for and overcome. If a fire brigade report lacks central information, for example, a written inquiry, telephone contact and even a personal visit/investigation is possible, but this comes down to what kind of the resources the study team has. If there are not enough resources/time available, the purpose should be adjusted to reflect this.

e) A study can be both explanatory (causal) and descriptive. None of the studies examined in the literature review received a "Not passed" for question number 1, because it was either explanatory or descriptive. The challenge is that the extent increases exponentially when a study changes from descriptive to explanatory. Are we more interested in how (descriptive) or why (explanatory)? As soon as the interest shifts from whether something works or not to what makes it work or not, the purpose, data, and resources must be adjusted. This is often not the case, and the causes of interest are not redefined. Interestingly, few (perhaps no) studies look at why sprinklers work in different buildings, with different storage configurations and human behaviour.

f) If a study wants to define general reliability, the demand to generalize often pushes the benchmark up, not down. The most common fault in the studies examined is the assumption that all sprinkler systems have the same function. This is not the case; an NFPA 13D system cannot be compared to an ESFR system. If there has been a conscious generalization or this has happened because of a lack of study management, it is not possible to make conclusions from this study.

12. APPENDIX 6: SUGGESTIONS FOR METHODOLOGY AND FUTURE STUDIES

Most of the sprinkler standards in the world say something like: "*The purpose of this standard shall be to provide a sprinkler system that aids in the detection and control of fires*". This or a similar statement is written into the purpose of the standard or communicated throughout the standard. Since the beginning of sprinkler systems, the purpose of detecting and warning of fire has been a natural part of the system. Even today, a sprinkler control valve is called alarm valve. Therefore, those who plan to conduct studies of sprinkler systems should consider detection and warning. If this is of no interest, what is then the purpose of have this as part of designed and installing of sprinkler system in the future?

As mention in the previous appendices, certain areas in the field of Fire Engineering require improvement. This appendix should be of some help, as it offers suggestions for methodologies to collect, analyse and present reliability data for all types of safety systems, with a focus on sprinklers.

12.1. METHODOLOGY

Many factors in how things are done affect both the quality of the data and the outcome of the analysis. One example is from the UK Incident Recording System (IRS) (DCLG, 2012). After the answer "*Yes"* is given to the question "*Did the safety system operate?*", a following question is "*Select the number of sprinkler heads that operated*". This can be answered by 1 to 5, more than 5 and "*Not known*". Why is "*Not known*" given as option at all? Is it assumed that visual inspection cannot find this? Furthermore, will this type of question improve the data or not? These and other questions must be asked. Data collection and analysis is a multi-discipline and multi-team efforts.

Based on the document analysis and the requirements of a scientific study, in **Table *49***, I suggest a new format for a scientific study.

Table 49 Division and steps in a study of sprinkler reliability

Main step*	Sub step	Explanation
Preparation and collecting		
	1.1. Is the issue clear or not?	If the purpose or problem of the study is not clear, this often means the purpose has not been revised over time, adjusted according to available sources and data.
Informative	1.2. Is it descriptive or explanatory (causal)?	Is the study more interested in how (descriptive) or why (explanatory)?
Informative	1.3. Is it desirable to generalize the findings?	If it is desirable to generalize the findings, this pushes the benchmark up.
1. Development of problem and purpose		**Does it have an understandable problem or purpose?**
Informative	2.1. Intensive (deep), extensive (width) study design or both?	Extensive designs have many units in the study, but few variables. Intensive designs have many variables, but few units. If both are selected, there will be many units and variables.
Informative	2.2. Descriptive or explanatory?	This of most interest if an explanatory design is selected. The following steps must be taken, as the extent increases exponentially when the study goes from descriptive to explanatory. 1. Correlation of cause and presumed effect. 2. Cause must precede effect in time. 3. Control of all other relevant factors.
2. Choice of overall study design		**Is there an understandable overall design?**
	3.1. Operationalization, how to make a concept measurable	Make abstract concepts, like reliability, operation, function, effect, and soon on, into something measurable.
	3.2. Design of the study	Does it use its own design or another study's design?
	3.3. Source and use of sources	Is it possible to use or change data collecting or design the study to accommodate fire brigades or must it be independent?
	3.4. Selection and limitation**	The selection of more than one extinguishing system will result in more than one study. The study must limit all types of events that don't control other relevant factors: e.g., ships vs. buildings; fully vs. partially protected; residential vs. ordinary hazard, and so on.
3. How to collect data?		**Does the study have a workable design?**

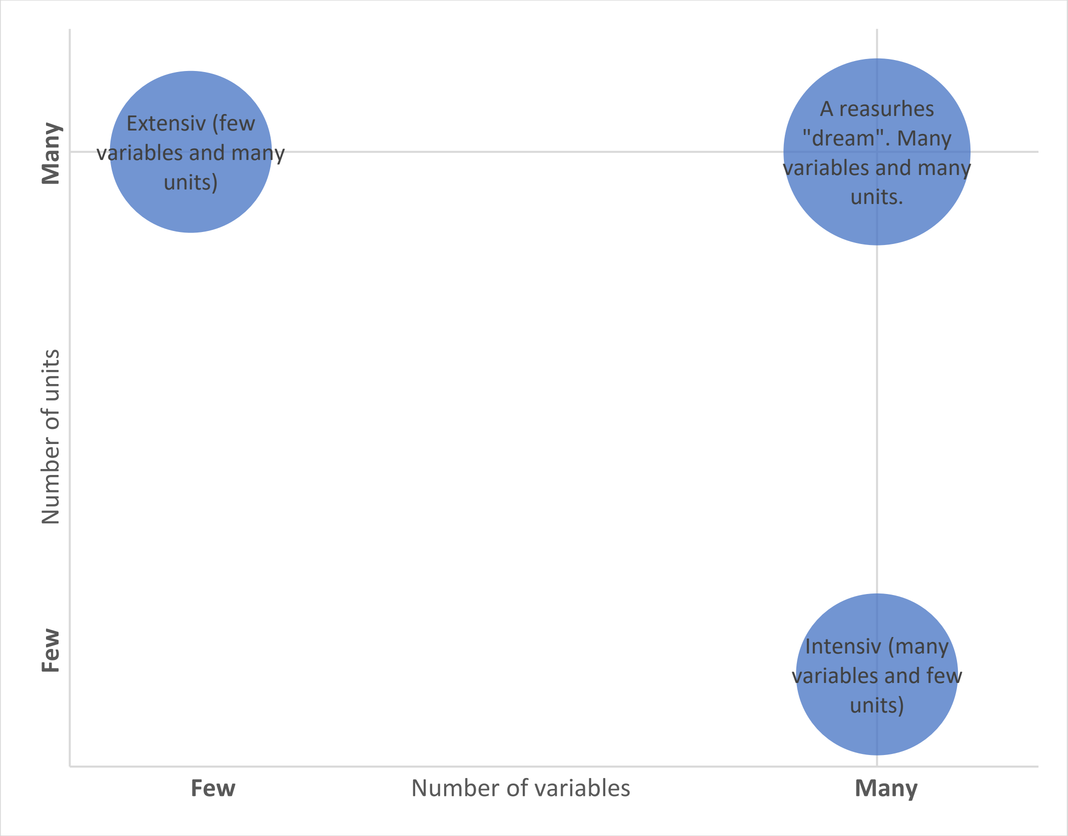
Analysis		
4. Analysis		**It is very important to do the analysis scientific methods, including control of the use of results.**
	5.1. Conceptual validity	After concretization of the concepts, it is very important to ask: Do the indicators measure what we are interested in?
	5.2. Validation of correlations	If an explanatory (causal) problem/design has been chosen, this places a strong demand on the study. Is it answered by the analysis?
	5.3. External validity	Is it possible to go from empirical evidence to known theory, based on the findings? If is desirable to generalize from selected units, it is important to ask if the study is wide enough and there is a representative selection in the analysis.
	5.4. Are the results trustworthy?	Can the way the study has been done be the reason for the results? There is a need to control the level, time frame, and causality.
5. Quality assurance of the analysis		**How good are the conclusions drawn from the analysis?**
Presentation		
	6.1. Methodological discussion	Methodological discussion includes the steps of quality assurance of the results (step 5 of this section) and how the study has been conducted.
	6.2. Substantial discussion – connection of findings and theory	Is it empirically consistent or inconsistent with other like or similar studies in this field? What are the connections between the findings and how this should be theoretically understood?
	6.3. Presentation (also uncertainty)	Is it transparent, logical, and readable?
6. Discussion and presentation		**How good is the presentation of the conclusions?**
* Former step 3 Type of data (qualitative or quantitative) have has been removed in this table, because qualitative data, analysis and presentation is seldom of interest in Fire Safety. ** While this is step 5 in the document analysis, several aspects argue for inclusion in step 3. The need to select and limit the type of objects, systems, and so on when designing the study, does not exclude the possibility of excluding collected data that are obviously wrong or inadequate later in the process.		

Further comments on the suggested methodology:

4. Development of problem and purpose: It would be a major improvement if the international fire community could reach agreement on the terms used in reliability data. There are many different words used to describe reliability or part of reliability. Of real interest is a study that wishes to generalize the outcome. It is important to find out if this is possible. Are the sources available for the whole area of interest? If not, perhaps an indicative study could be used to illuminate the problem or to address the proper authorities for improved collecting data.

5. Choice of overall study design: The following figure shows the correlation between intensive and extensive study designs.

Figure 20 Classification of study design as intensive or extensive



An extensive study with many units and few variables is a very good foundation for a generalizable study.

6. Some of the steps are informative. There is no right or wrong choice, but the choices must be conscious. Every choice has consequences for collecting, analysing, and presenting.

12.2. HOW TO PERFORM A SIMPLE STUDY

Based on the overview in **Table *49***, I will suggest principles for two different studies, from the simplest to the more demanding, starting with the simplest.

12.2.1. STEP ONE

The first step is to determine the overall design and what is of interest. This requires a detailed plan of what kind of sprinkler systems are of interest, how, where, and over what time.

Table 50 Design of simple study

Main step	Sub step	Task
Preparation and collecting		
	1.1. Is the issue clear or not?	The purpose of this study is to find the reliability (to function as designed) of sprinkler systems in Norway. Design means the selected sprinkler system.
	1.2. Is it descriptive or explanatory (causal)?	This is a descriptive study and causal reasons (why the systems work or do not work as intended) will not be covered.
	1.3. Is it desirable to generalize?	It is desirable to generalize historical reliability, as this is a good indicator of future probability of the sprinkler systems being designed and installed under the conditions covered by the study.
1. Development of problem and purpose		**Conduct a descriptive study that generalizes the national reliability of sprinkler systems in Norway.**
	2.1. Intensive (deep) or extensive (width) study design	Based on the purpose, an extensive design with many units in the study and few variables is chosen.
	2.2. Descriptive or explanatory	Descriptive design is chosen.
2. Choice of overall study design		**Create an extensive and descriptive overall study design.**
	3.1. Operationalization, how to make a concept measurable	Definition: **Sprinkler system activation**; 1: the sprinkler control valve (alarm valve) opens, 2: the pump (if installed) starts and 3: the sprinkler alarm activates. **Fire controlled by sprinkler system**; the fire is contained/extinguished within the sprinkler system's design (number of activated sprinklers and square metres covered).

	3.2. Design of the study	Based on design and event tree analysis, create a form for the study.
	3.3. Source and use of sources	It is desirable to use the Norwegian BRIS (Brann, Redning, Innrapportering, Statistikk / Fire, Rescue, Reporting, Statistics[10]) for reporting fires.
	3.4. Selection and limitation	Only buildings fully protected by sprinklers or parts of building that are separated by fire section walls are of interest. Only sprinkler systems by NS-EN 12845:2004 and CEA 4001 will be examined. Data on system type will always be validated against the ESS (Elektronisk System for Sprinkleranlegg / Electronic System for Sprinkler-system[11]). Fires from 2010-2014 will be examined.
3. How to collect data?		**The design of the study is based on Norwegian BRIS, looking at building fires from 2010 – 2014 in buildings protected following NS-EN 12845:2004 and CEA4001 rules. Details on sprinkler systems and hazard classes are validated using ESS.**

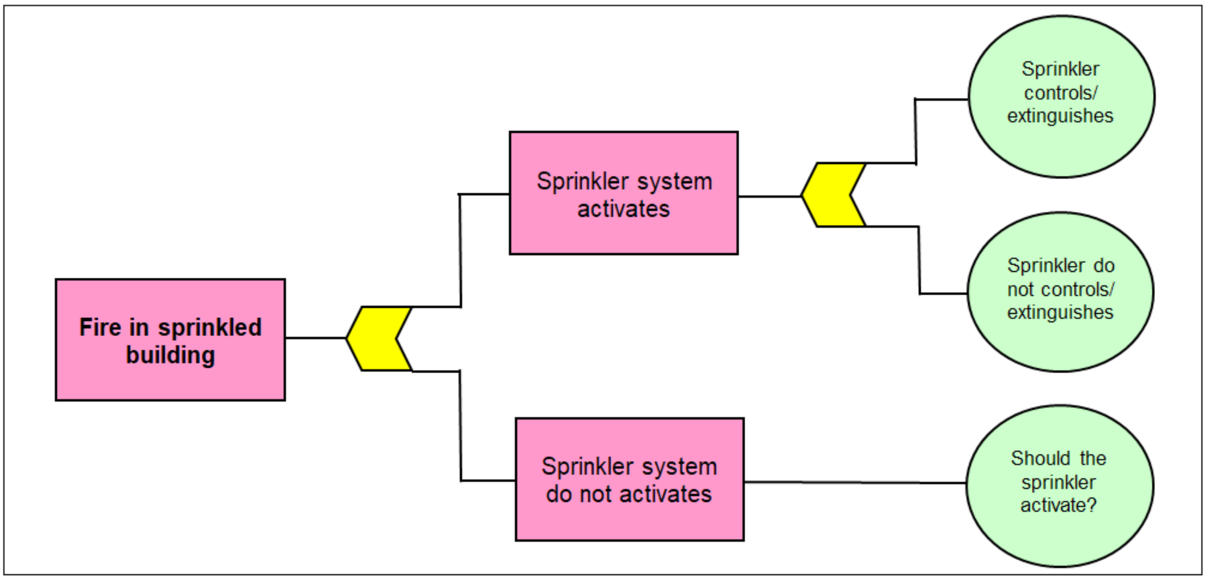
Before writing a new form to collect data, using earlier forms, or taking data directly from the BRIS, an event tree analysis of some nature must be performed to make sure the description is correct, and every aspect is thought out, to create tools for a form and to do a quality assurance of the analysis.

[10] Norwegian incident reporting system used by all Norwegian fire and rescue personnel.
[11] ESS is the Norwegian insurance company's database for recording reports after inspections of sprinkler systems and for project reports when planning new sprinkler systems.

12.2.2. STEP TWO

In the event tree, the starting point is: Fire in sprinkled building.

Figure 21 Event tree simple design



Before writing the form, they three outcomes need discussion and clarification. We also need to discuss the use of the words activate/activation.

Activate/activation: In most of the literature and studies, the words operate/operating/operational are used about a system that starts to do something. This is interesting, but a system should operate BECAUSE it was activated. If a system is activated, but does not operate, this has a cause. Even if the cause is not of interest in this case, the establishment of an accurate and precise vocabulary is necessary, and the word activate will be used herein.

Outcome 1: “Sprinkler system controls or extinguishes the fire.” There is interest in the number of sprinklers activated and the area damaged by the flames, since the hazard classes have an area of design and to quality assurance the number of activated sprinkler. The fire response team has no difficulty concluding that a fire has been put out or is under control, with only minor measures required to put out the fire. The number of activated sprinklers should relate to the area of flame damage. If not, this needs further investigation.

Outcome 2: "Sprinkler system does not control or extinguish the fire." There is interest in the number of sprinklers activated and the area damaged by the flames, for same reason as outcome 1 (control on hazard class and quality assurance), and to ensure the right outcome has been chosen. It is possible that the fire team thinks, e.g., that 10 sprinklers and 100m^2 do not indicate control, but for every hazard class over OH1 in EN 2845, this is less than design area for the sprinkler system. It is important to have control of all possible non-negative outcomes in the category of negative outcomes as well.

Outcome 3: "Sprinkler system does not activate." As shown earlier, this outcome has been neglected when it comes to quality assurance. It is very important to find out two things. One, was the system activated, but did not operate? Two, should it have activated but did not?
One: To determine this with high degree of certainty, it is necessary to conduct an alarm test of the sprinkler valve. With an alarm, the system is intact, and the system was not activated. No alarm is a fault and indicates a problem with the system in general.
Two: Visual inspection of affected sprinklers. If the bulb/fusible link is intact and there is no suggestion that the heat was sufficient to activate the sprinkler, it can be concluded that the system should not have been activated. If there is uncertainty, this should be noted.

12.2.3. STEP THREE

Step three is writing the form to collect data. This is basic regardless of how it will be distributed or how information will be collected from databases. The main purpose is to have control of questions that are of interest and to use them in the quality assurance of the analysis.

Table 51 Inquiry form for fires in buildings protected by sprinkler systems

Form for fires in buildings protected by sprinkler systems		
Information about the building*		
12.	Address:	Official identification number (Norway Gnr/Bnr)
	Type of building:	Is the building registered in ESS? If not, must the owner must do this?
	Date and time of fire:	
	Installing year and latest inspection/maintenance:	Data from documentation or from ESS.
Information about the sprinkler system		
13.	Type of sprinkler system:	CEA 4001 NS-EN 12854 NS-INSTA 900 NFPA 13 Other (specify)
14.	Hazard class	OH/HHP/HHS 1 – 4
Information about consequences of fire		
15.	Did the sprinkler system activate alarm (by the fire alarm system or by external alarm bell)?	Yes/No
16.	Did the sprinkler system activate sprinkler pump if present?	Yes/No/Not present
17.	Did the sprinkler system control or extinguish the fire?	Yes/No
18.	If yes, how many sprinklers were activated and what was the area of flame damage?	Number: Area: m^2
19.	If no, how many sprinklers were activated and what was the area of flame damage?	Number: Area: m^2
20.	If the fire did not activate the sprinkler system, is the bulb or fusible link on sprinkler destroyed/damaged?	Yes/No
21.	If the fire did not activate the sprinkler system, does a test of the alarm show it works?	Yes/No
22.	If the fire did not activate the sprinkler system, are there any indications that is should have been activated (size of fire, damage in the area, e.g.)?	Yes/No Affected area: m^2
*It must be possible to trace the data to the source, if needed.		

Even this simple study has 8 questions. By concretizing the activation/outcome in only yes/no answers, question 11 is changed from a qualitative question in **Outcome 3** to a quantitative question.

12.2.4. STEP FOUR

Step four is the analysis and this must be done by normal scientific methods.

12.2.5. STEP FIVE

By conducting a good quality assurance of the analysis in step five, the fundamental requirements for a solid presentation in the last step are mostly met. The importance of checking the answers given by analysing them against the purpose of the study cannot be stressed enough. The list in **Table *52*** is a minimum layout for this form based on the purpose of the study; it can be extended.

Table 52 Design of simple study, step five

	5.1. Conceptual validity	**Overall question: Do the indicators measure what we are interested in?** 1. How many building fires are there per year during 2010 – 2014? 2. How many fires are in sprinkled buildings? 3. How many sprinkler systems were CEA 4001/ NS-EN 12845/ NS-INSTA 900/ NFPA 13/Other system?[1] 4. How many fires activated the sprinkler system (both overall and by alarm and pump)? 5. How many fires were indicated as controlled/ extinguished by the report? 6. How many sprinklers were activated on the different systems and hazard classes? This includes also non-controlled fires. 7. When the system did not activate, was sprinkler bulb/ fusible link destroyed/ damaged? 8. Are there indicators that the system should have activated/worked? 9. Did the alarm test work on the non-activated sprinkler system?
	5.2. Validation of correlations[2]	1. How many fires were controlled/ extinguished according to the number of sprinklers/area of damage? 2. Is the area affected by the fire (flames/hot plume) correlated to the number of activated sprinklers?[3] 3. Are the area and number of sprinklers activated for a non-controlled fire correlated to the stated effect?[3]

	5.3. External validity[4]	1. Are some geographic areas or fire brigades excluded from this study? 2. Do the findings support known theory? 3. Is uncertainty quantified?
	5.4. Are the results trustworthy?	Once again, it is important to ask: is it the way the data are collected (e.g. the inquiry form) and analysed that produces the result? One example of **level failings** is when the results show that most fires are confined to the room of origin, and the conclusion is that sprinklers are designed to confine fire to the room of origin. Do we have data that support this, and this the design based on the standards and test protocols? When the conclusion takes the result up or down a level, these fallings occur. One example of a **time frame failing** is assuming a sprinkler system is no less reliable because of its age. This is based on a study that looks at a selected sprinkler system from where it was installed to 5 years later; it concludes there is no difference in reliability based on age. **Causality failings** will be discussed later under the explanatory study, but these affect all studies. One example is the reason a sprinkler system does not activate. With no cause for this, the conclusion can be that they should not activate, but there are no data to support such a conclusion. We have only certainly / uncertainty.
5. Quality assurance of the analysis		**Based on validation of concept, correlations, external information, level failings, time frame failings, and causal failings, how good are the conclusions drawn from the analysis?**

[1] Even if the CEA 4001/NS-EN 12845 system is of interest, it is possible to get some data on all types of system at this point. With data here, it is possible to get an idea of other types of systems in Norwegian buildings.
[2] Even if validating correlations must be done carefully for an explanatory (causal) study (this will be reviewed in more detail in the next example), several aspects in this study need to be validated against the collected data.
[3] When it comes to uncertainty, this can be handled strictly theoretically by only looking at the collected data or more favourably by investigating. Case studies give more insight into how fires and sprinklers are connected and generate more correct uncertainty data.
[4] When the study generalizes from collected data to a further probability, some areas need validation.

When conducting the quality assurance, the form may need to be corrected, and the analysis must be done over again in some areas, but all this is expected.

In some instances, this will indicate areas not previously thought of, but the data are collected and cannot be changed in an economical/ practical way. This suggests the need for comments on uncertainty to strengthen the sense that the study has been conducted in a scientific way.

12.2.6. STEP SIX

The last step is to write the report and present the results of the study. The areas listed in **Table *53*** must be not be forgotten.

Table 53 Design of simple study, step six

Presentation		
	6.1. Methodological discussion	A theoretical review of the methodology of the study design, including data collection, analysis, and quality assurance of the results. 1. How good is the reliability of the data? 2. How good is conceptual validity? 3. How good is the internal validity? 4. How good is the external validity? These four constitute the total validity of the study.
	6.2. Substantial discussion – connection of findings and theory	**Findings:** Are the results consistent or inconsistent with earlier and other similar studies? When there are earlier studies, what are the long-time changes? **Theory:** What is the connection between results and known theory? What is unknown? Can some hypotheses be followed up in later or other studies? **N.B:** What do the findings tell us about the standards used? What are suggestions for **further work?**
	6.3. Presentation (also uncertainty)	There must be a definition list or presentation of key terms earlier in the report. The summary or abstract of findings helps the reader understand the report. With many options on how figures and tables can be designed, there is no need to use colours and shapes that take attention away from the facts. Make the report transparent, logical, and readable.
6. Discussion and presentation		**How well is the general presentation supported by the methodological and substantial discussion?**

If the presentation gives reliability answers to two decimal points but fails to have the same answer in different places, this give uncertainty to the study. The scientific way is to present the results with uncertainty, preferably quantified, hence giving reliability to the study.

12.2.7. SUMMARY OF CONDUCTING A SIMPLE STUDY

This has been a suggestion of how to establish a methodology and a design for a study to collect, analyse and present reliability data based my review of the literature and the scientific principles that need to be included in such a study. This has been concretized with a short review of the steps based on Norwegian conditions, rules/standards, and choices. Other choices give other answer and other areas need attention, but it must not be forgotten that a study in a larger geographical area (state or nation) must do so using proven scientific methods. Without a correct approach to the discipline of study TOGETHER with the discipline of fire science, this will only cast doubt on the discipline and the study.

12.3. HOW TO CONDUCT A COMPLEX STUDY

Based on the overview in **Table *49***, in this section I make suggestions for a complex study. The steps in a descriptive study are also a part of an explanatory study. The steps are not commented on more than necessary, simply to get the meaning and the general idea for a complex study.

12.3.1. STEP ONE

The first step is to find the overall design and define what is of interest in the study. This includes a detailed plan of what kinds of sprinkler systems are of interest, how, where, and over what time, as well as reasons for sprinkler systems not to function as designed.

Table 54 Design of complex study

Main step	Sub step	Task
Preparation and collection		
	1.1. Is the issue clear or not?	The purpose of the study is to find the reliability (to function as designed) for sprinkler systems in Norway and the reasons for not functioning as designed. Design means by chosen sprinkler systems.
	1.2. Is it descriptive or explanatory (causal)?	This is both a descriptive and explanatory study. We wish to determine the reasons why sprinkler systems sometimes do not work as designed.
	1.3. Is it desirable to generalize or not?	It is desirable to generalize from a historical reliability, as this is a good indicator of future probability, if the sprinkler systems are designed and installed under the same conditions as those in the study.
1. Development of problem and purpose		**Conduct a descriptive and explanatory study that generalizes the national reliability and reasons why Norwegian sprinkler systems do not work as designed.** **The reason for a causal study is to be able to make suggestions for improvement.**
	2.1. Intensive (deep) or extensive (width) study design	Based on the purpose, a mix of intensive and extensive design with many units and many variables is chosen.
	2.2. Descriptive or explanatory	An explanatory design is chosen; this makes some demands on how the study is conducted. 1. Correlation between cause and presumed effect. 2. Cause must precede effect in time. 3. Control of all other relevant factors.

2. Choice of overall study design		**Create a mix of an intensive and an extensive study with a descriptive overall study design, based on three steps of correlation.**
	3.1. Operationalization, how to make a concept measurable	Definition: **Sprinkler system activation**: 1: the sprinkler control valve (alarm valve) opens, 2: the pump (if installed) starts and 3: the sprinkler alarm activates. **Fire controlled by sprinkler system**: the fire is contained by the sprinkler system's design (number of activated sprinklers and square metres they cover) or improved protection against injury and life loss is gained for residential systems. Improved protection is quantified as the possibility to escape (alone or with help) within 15 min of the start of a fire.[1] **Fire not controlled by sprinkler system**: a fire in not contained within design area for the chosen sprinkler design or improved protection against injury and life loss is not gained for residential systems. Not gained improved protection is quantified as the inability to escape (alone or with help) within 15 min of the start of a fire.[1] **Cause and reason**: this is always of interest, but the form should only look at reasons. E.g. can a valve be closed because maintenance is done at the time of a fire or because of a lack of maintenance (it does not work)? To make the form as manageable as possible, interviews/ investigations will follow reports of faults to find the causes.
	3.2. Design of the study	Based on design and event tree analysis, a form is created.
	3.3. Source and use of sources	It is desirable to use the Norwegian BRIS (Brann, Redning, Innrapportering, Statistikk / Fire, Rescue, Reporting, Statistics) for reporting fires.
	3.4. Selection and limitation	Only buildings fully protected by sprinklers or parts of buildings that are separated by fire section walls are of interest. All systems (NS-EN 12845:2004, CEA 4001, NFPA 13 and INSTA 900-1 and 2) will be examined in this study. Data of system type will always be validated against the ESS (Elektronisk System for Sprinkleranlegg / Electronic System for Sprinkler-system). Fires from 2015-2020 will be examined.

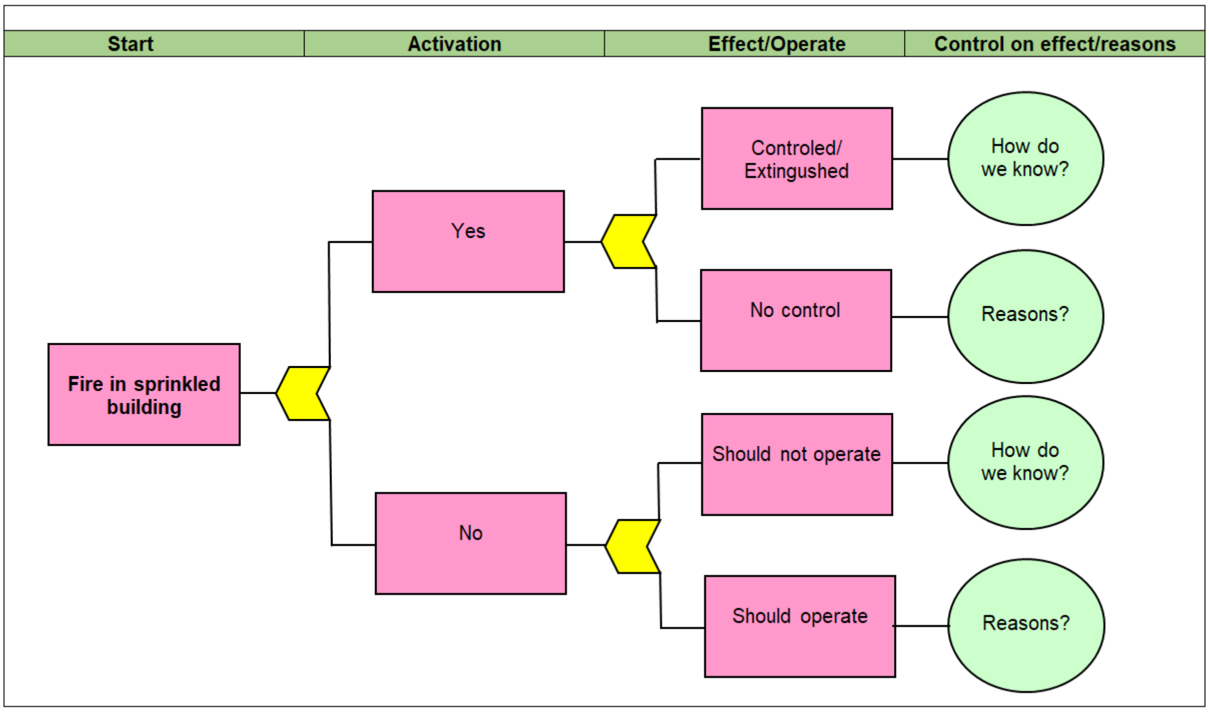
<table>
<tr><td>3. How to collect data?</td><td></td><td>The detailed design of the study is based on Norwegian BRIS, looking at building fires from 2015 - 2020 in buildings protected following NS-EN 12845:2004, CEA 4001, NFPA 13 and INSTA 900-1 and 2. Details on sprinkler systems and hazard classes are validated against ESS.</td></tr>
<tr><td colspan="3">[1] Since there is no known study or report on time from fire start in residential buildings with sprinklers, to the time of improved protection against injury and life loss (however this is quantified), both the time frame, and measurement of injury should probably by adjusted at some point in the process of the study.
For example, if the collected data indicate that 80% of the people in the buildings made following Norwegian regulations escaped within 15 min, but 98% escaped within 20 min when the sprinkler system operated as designed, the design of study should be adjusted. The overall fire design of a building with a sprinkler system that operates as designed has fulfilled its function in 98% of the cases within 20 min and the authorities can use these data. There is also the possibility of controlling a fire if there is development over time and the authorities can adjust or accept the demand for fire safety.</td></tr>
</table>

With a specific overall design in place, an event tree analysis can be performed.

12.3.2. STEP TWO

In the event tree, the starting point is: Fire in sprinkled building. Even if we are not totally sure what each outcome will bring, this can be handled in a review (analysis in **Table *55***) of each outcome.

Figure 22 Event tree complex design



Outcome 1 (How do we know?): To make sure the person filling out the form has understood the outcome as success (controlled/extinguished) and to find out how many sprinkler heads were activated/operated in each hazard class, the number of heads and the number of fire affected area must both be collected.

Outcome 2 (Reasons?): There are several reasons why a sprinkler system is unable to control a fire (or extinguish a fire, as for example, ESFR systems), either as sole reasons or in combination. The list in **Table *55*** gives various options.

Table 55 Review of reasons for fire not controlled/not extinguished when system has operated

Nr.	Reason	Comments	In form or not?
1.	Inspection and maintenance.	Lack of inspection and maintenance (both that done by the owner and external ones) is perhaps the most common fault. This is the probably the most under-reported area in most studies today, because it is difficult to separate from faults/damage. When an inspection and maintenance program is followed, most faults and damage on sprinkler heads, pipes, valves, closed or semi-closed valves, alarms, and pumps can be discovered and fixed. So where do we draw the line between component faults and maintenance? Why do we collect data on component faults, if they are finally seen as a failure of maintenance? These are difficult questions, but for this study, both data about component faults and data about maintenance will be collected and analysed.	A question already asks about maintenance, so further questions will not be asked in this study.
2.	Damage to sprinkler heads.	This is a common fault of sprinkler systems discovered in inspections, especially in buildings with some sort of storage. A sprinkler head that is damaged will have incomplete and / or disturbed water acquisition; this influences the process of getting control or extinguishing the fire. One challenge is that on a standard system, one or perhaps a few (we don't know) damaged sprinklers should have little influence on controlling the fire within the design area. The reason for having different design areas is to provide a robust design that can handle small faults. A second challenge is that if we only look for damaged heads where there was no control, we may reach the wrong conclusion. If this is to have scientific value (point 2.2 in ***Table 54*** Design of complex study), it should be collected on all systems.	In most cases, it will be possible to learn this from rescue personnel on site. This should therefore be included in the form.
3.	System components damaged.	In addition to damage to sprinkler heads, this could include pipes, valves, or pumps. Since this often less obvious, they will be included as indicative question.	Indicative question, where the different component is listed (need follow-up).
4.	Obstacles for water distribution.	Another common fault is an obstacle so that water does not reach the fire. This can be an obstacle to spray pattern in the ceiling (beams, fixtures, signs, and so on) or a shield over the flammable material. Shelves and covers of different types are the most common.	This will be divided into two questions: Are there obstacles in the ceiling that influence water distribution to the sprinkler?

		While obstacles in the ceilings have the same challenges as discussed above, obstacles over the flammable material have different challenges. Obstacles in the ceiling prevent some water from reaching the fire but new sprinklers activate and surround the fire (at least in theory). However, a dense shelf in a rack will not only shield the fire from water but will also contribute to the fire growth (reflecting the heat and leading the fire plume out to the sides, preheating the material stored beside the fire). This can overcome the sprinkler system (depending on affected area). If the dense shelf is made of flammable material (e.g. chipboard), there is reason to assume that it will disappear to a greater or lesser extent.	Are there reasons to think that there have been obstacles like a dense shelf over the area with flammable material? Both questions can be included in the form; the second needs follow-up.
5.	Inappropriate system for type of fire.	An inappropriate system can be a sprinkler system, where the storage method is not in consensus with the sprinkler standards, e.g. tire storage, and another system should have been chosen, e.g., a foam system. Alternatively, there may have been a change of use or storage, and the hazard class has gone up, without the design criterion for the sprinkler system have being changed. Even if there can be indicative clues for rescue personnel, there is no reason to demand that they should notice them or understand all parameters that must be considered to determine the correct system for type of fire. Even if data on this are interesting, they have nothing to do with unreliability. Sprinkler reliability is the ability to function as designed. If the system is designed incorrectly or is not redesigned after changes in use/storage, this has nothing to do with the ability of the system.	Indicative question used if there are reasons to think an inappropriate system was present at the time of fire.
6.	Not enough water discharged.	Three situations that can result in not enough water discharging. One; the sprinkler system is inappropriate for the present hazard class (designed for a lower hazard class with lower water density). Two: not enough water for the design. This is something that should be noted at the time of installing/ commissioning or inspection; maintenance should have revealed it, if changes to available water occurred after commissioning. Three: not enough water for the sprinkler and the fire fighters. Norwegian regulations do not demand water for both.	This is covered in point 5 above.

7.	Manual intervention.	Manual intervention, like closing valves, have an effect if it is done at the wrong time. This does not have anything to do with a properly designed system but is a “fault” that lies outside the design area.	This is covered in point 5 above.
8.	Not installed as designed	What if the sprinkler system is not engineered and/or installed as designed? What if the main valve is not supervised as demanded in the design? What if the hydraulic calculations have not included sprinkler fittings (flexible hose) and so on?[1]	Include in the form, with follow up.
9.	Other.	We must keep an open mind and acknowledge that science is the pursuit to understand what we do not yet know. Without being able to list what we have not yet thought about, progress is not easy.	Include in the form, with follow up.
[1] Should a system be rated based on “wrong” design or should we assume some robustness? Perhaps some of each? Perhaps some functions should not be treated as if the system has been in operation over one year and faults should have been discovered during inspection/maintenance, for example, if a valve is not supervised and is closed outside working hours. The big challenge is that we don’t know much about this, since we do not have a platform to look at these things. This platform is reliability.			

Summary: “Damage to sprinkler heads” and “Obstacles to water distribution” will be incorporated into the form so that the person filling in the form must answer them in both controlled/extinguished and not controlled. There will be indicative question about “System components damaged (pipe, valve, or pump)” and “Inappropriate system for type of fire (wrong type or wrong hazard class). Collecting data on inspection and maintenance will be of most importance.

Outcome 3 (How do we know?): See 12.2.2 Step two.

Outcome 4 (Reasons?): It is important to understand the reason for this “academic exercise”, both here and at Outcome 1. If we do not understand the reason for a fault and if it belongs under sprinkler fault or human/technical fault outside of what a sprinkler system is designed for, the outcome will be placed in the wrong category. It is not within the design of a sprinkler system to overcome manual intervention, with e.g. closing the main valve, and therefore, this has nothing to do with unreliability.

Table *56* reviews the reasons a sprinkler system does not activate and operate but should.

Table 56 Review of reasons for system not activated/operated when it should have operated

Nr.	Reason	Comments	In form or not?
1.	Inspection and maintenance.	See point 1 in the list under Outcome 1.	Already included
2.	Sprinkler head.	Both the Omega failure and counterfeit sprinklers clearly show this can affect both activating and operating. Furthermore, there is little knowledge about how sprinklers over a given age (if any) react to temperature and if this affects the RTI-factor.	Included in form, even if there are not enough resources to inspect affected sprinklers in test laboratory.
3.	Pipe	If a sprinkler activates, but there is no water or visible low flow of water, there are reasons to examine the state of the pipe. Rust, MIC[12] or physical damage to pipes could explain why sprinklers do not function as designed.	Include in the form, with follow up.
4.	Valve/pump.	Valves may fail for several reasons: lack of maintenance; closed; no supervision/ monitoring; sabotage. Without collecting and separating reasons that should and should not be included in unreliability and separating the types of valves (dry, wet, pre-action/deluge), it is not possible to have built-in reliability/unreliability. The same could be said for pumps, but there is also the question about power supply or the use of diesel pumps.	Include in the form, with follow up. Collection of data on types of pumps must also be done.
5.	Other	Without being able to list what we do have not yet thought about, progress is not easy.	Include in the form, with follow up.

Summary: All six reasons for not activated/operated will be incorporated as indicative questions with follow up.

12.3.3. STEP THREE

Step three is to write the form. This is basic regardless of how the form is distributed or how information is collected from databases. The main purpose is to have control of questions that are of interest and to use them in the quality assurance of the analysis.

[12] Microbiologically influenced corrosion is a form of localized corrosion. Material is lost at discrete points, instead of universally across an entire surface.

Table 57 Complex inquiry form for fires in buildings protected by sprinkler systems

Form for fires in buildings protected by sprinkler systems		
1.	Address:	Official identification number (Norway Gnr/Bnr)
	Type of building:	Is the building registered in ESS? If not, must the owner do this?
	Date and time of fire:	
	Installing year and latest inspection/maintenance:	Data from documentation or from ESS.
Information about the sprinkler system		
2.	Type of sprinkler system and type of main water supply:	CEA 4001 NS-EN 12854 NS-INSTA 900 NFPA 13 Other (specify) Water tank
3.	Hazard class	OH/HHP/HHS 1 – 4
Information about consequences of fire		
4.	Did the fire activate the sprinkler system?	Yes (point 5/6)/ No (point 9)
5.	If yes, did the sprinkler system activate the alarm or the pump?	Alarm (internal or external) Pump (if present)
6.	If yes, did the sprinkler system control/extinguish the fire?	Yes (point 7/8)/ No
7.	If yes, how many sprinklers were activated, what was the area of flame damage and was there any damage to the sprinkler head?	Number: m^2: Damaged sprinkler:
8.	If yes, are there any indications of obstacles in the ceiling and/or over the flammable material?	Ceiling: _________________* Stored material: _________________
9.	If no, what is the area of flame damage?	m^2: (point 10)
10.	If no, are there any indications that the system should have operated?	Yes (point 11/12/13) / No (point 14/15/16)

11.	**If yes, are there any indications of faults/damage to the sprinkler, pipe, valve, pump, or anything else?**	**Sprinkler: Yes (Number)/No** **Pipe: Yes (______)/No** **Valve: Yes (_____)/No** **Pump (if present: Yes (________)/No** **Other: ______________**
12.	**If yes, are there any obstacles in the ceiling and/or over the flammable material?**	**Yes (_________)/No**
13.	**If yes, does the alarm test of the sprinkler system work?**	**Yes/No**
14.	**If no, are there any indications or faults/damage to sprinkler, pipe, valve, pump, or anything else?**	**Sprinkler: Yes (Number)/No** **Pipe: Yes (______)/No** **Valve: Yes (_____)/No** **Pump (if present: Yes (________)/No** **Other: ______________**
15.	**If no, are there any obstacles in the ceiling and/or over the flammable material?**	**Yes (_________)/No**
16.	**If no, does the alarm test of the sprinkler system work?**	**Yes/No**

*(_____) Written comments.

12.3.4. STEP FOUR

Step four is the analysis using normal scientific methods.

12.3.5. STEP FIVE

By conducting a good quality assurance of the analysis in step five, the fundamental requirements for a solid presentation in the last step are mostly met. The importance of checking the answers given by the analysis against the purpose of the study cannot be stressed enough. **Table *58*** gives a minimum layout for the form based on the purpose of the study; it can be extended as needed.

Table 58 Design of complex study, step five

	5.1. Conceptual validity	**Overall question: Do the indicators measure what we are interested in?** 1. How many building fires were there per year during 2015 – 2020? 2. How many fires were in sprinkled buildings? 3. How many sprinkler systems were CEA 4001/ NS-EN 12845/ NS-INSTA 900/ NFPA 13/Other system? 4. How many fires activated the sprinkler system (both overall and by alarms and pumps)? 5. How many fires were reported as controlled/ extinguished? 6. How many sprinklers were activated for different systems and hazard classes? This include also they that is stated as non-controlled, if they in fact was controlled. 7. When the system did not activate, was this linked to sprinkler bulb/ fusible link destroyed/ damaged, fault/damage to pipe, valve, or pump (if present)? 8. Are there indicators that the system should have activated/worked? 9. Did the alarm test work on the non-activated sprinkler system?
	5.2. Validation of correlations[1]	1. How many fires were controlled/ extinguished according to number of sprinklers/area of damage? 2. Is the area affected by the fire (flames/hot plume) correlated to the number of activated sprinklers? 3. Is the area and the number of sprinklers activated for a non-controlled fire correlated to the stated effect?[1] 4. What influence do obstacles in the ceiling have? 5. What influence do obstacles over stored material have?
	5.3. External validity	1. Are some geographic areas or fire brigades excluded from this study? 2. Do the findings support known theory? 3. Is uncertainty quantified?
	5.4. Are the results trustworthy?	Once again it is important to ask: does the way the data are collected (e.g. the inquiry form) and analysed produce the result? An example of a **level failing** is when the results show that most fires are confined to the room of origin, and the conclusion is that sprinklers are designed to confine fires to the room of origin.

		Do we have data that support this and does the design follow standards and test protocols? When the conclusion takes the result up or down a level, these failings occur. An example of a **time frame failing** is the assumption that a sprinkler system is no less reliable because of its age. This is based on a study that looks at a selected sprinkler system from installation to 5 years later; it concludes there is no difference in reliability based on age. One example of a **causality failing**[2] is the lack of a cause of the failure to activate. The conclusion may be that it should not activate, with no data to support this conclusion.
5. Quality assurance of the analysis		**Based on validation of concept, correlations, external validity, level failings, time frame failings, and causal failings, how good are the conclusions drawn from the analysis?**
[1] Uncertainty can be handled strictly theoretically by only look at the collected data or more favourably by further investigation. Case studies (in fact, these are follow ups) give more insight into how fires and sprinklers are connected and yield more correct uncertainty data. [2] In 12.3.1 Step One 2.2, I concluded causality is based on all three conditions: 1. correlation of cause and presumed effect; 2. cause precedes effect in time; 3. control of all other relevant factors. It is not enough to have just the first two.		

When conducting the quality assurance (QA), it often happens that the form must be corrected, and the analysis must be done over again in some areas, but all this is to be expected. It may reveal areas not previously thought about, but the data are collected and cannot be changed in an economical/ practical way. In these cases, comments about uncertainty will strengthen the sense that the study has been conducted in a scientific way.

12.3.6. STEP SIX

The last step is to write the report and present the results of the study. The areas shown in **Table *59*** must be not be forgotten.

Table 59 Design of complex study, step six

Presentation		
	6.1. Methodological discussion	A theoretical review of the methodology, including study design, data collection, analysis, and quality assurance of the results. 1. How good is the reliability of the data? 2. How good is the conceptual validity? 3. How good is the internal validity? 4. How good is the external validity?
	6.2. Substantial discussion – connection of findings and theory	**Findings:** Are the results consistent or inconsistent with earlier and other similar studies? When there are earlier studies, what are the long-time changes? **Theory:** What is the connection between results and known theory? What is unknown? Could some hypotheses be followed up in later studies? **N.B:** What do the findings tell about the sprinkler standards that have been used?
	6.3. Presentation (also uncertainty)	There must be a definition list or presentation of key terms earlier in the report. A summary or abstract of findings helps the reader understand the report. Present the results with quantified uncertainty. Make the report transparent, logical, and readable.
6. Discussion and presentation		**How well is the general presentation supported by the methodological and substantial discussion?**

12.3.7. SUMMARY OF CONDUCTING A COMPLEX STUDY

As in 12.2 How to perform a simple , this section suggests six steps for a causal study, based on Norwegian conditions and my knowledge of sprinkler systems. This kind of work needs a thoughtful and systematic approach, and this cannot be stressed enough.

Since this has been an explanatory study and reliability is defined as the ability to work as designed, I have also touched on unreliability/ failure. More information is given in the next chapter.

It is important to make forms manageable for those filling them out. If they find the forms long and difficult, the quality of the answers will probably drop.

The type of study described here will give lasting scientific value.

13. APPENDIX 7: CONCLUSION

In this section of the thesis, I sum up some of the issues I discovered, the kind of data I investigated to answer my research questions, my findings and their importance, my conclusions, possible explanations of the findings, implications of the findings, limitations of my work, and suggestions for further work.

13.1. SUMMARY

I started with a desire to learn the reasons for the diversity in the key terms and level of reliability from one report to another, both within countries and between countries. After reviewing the literature, I had 5 publications that I wanted to examine more closely: NFPA (1970, 2010 and 2017), Marryat (Marryat, Rev. 1988) and NFSM (Optimal Economics, 2017).

In the "Automatic Sprinkler Performance Tables, 1970 Edition" (National Fire Protection Association, 1970), the original data from 1897 to 1924 are updated to include data from 1925 to 1969. Key definitions like control, "*prevention of excessive fire spread in light of the nature of the occupancy*," are illustrated in a graph showing the differences in the number of sprinklers operated in wet and dry systems. The fact that it does not use the lowest performance rate raises some questions.

In the "U.S. Experience with Sprinkler and Other Automatic Fire Extinguishing Equipment" (National Fire Protection Association Research, 2010), there are major changes in the area of interest (all extinguishing systems) and the methodology. The use of NFIRS 5.0 as a prime data source leads to the conclusion in the report that 49% of all fires were too small to activate the systems. The report also states that effective performance is indicated by confinement of fire to the room of origin and effectiveness declines when more sprinklers operate. None of these conclusions is proven or substantiated.

In the more recent "U.S. Experience with Sprinklers" (National Fire Protection Association Research, 2017) the focus is again on sprinklers, and home fires are given special attention. All data are from NIRS 5.0. The report focuses on five or fewer heads operated when the sprinkler design for such buildings is 2 or up to 4, but there is no explanation of the reason for this. As in the two previous reports, no long-term trends are included.

The comprehensive book by Marryat (Marryat, Rev. 1988) *Fire – A Century of Automatic Sprinkler Protection in Australia and New Zealand – 1886-1986* have been given the following explanation of high reliability: "*Inspection, testing, and maintenance exceeded normal expectations, and higher pressures*". However, all the systems in this study are wet systems; it excludes all fires where sprinklers were shut off. The fact that most of the cases come from Wormald International Group of Companies and the fact that 99.5% reliability refers to up to 113 sprinklers operating may explain the high reliability.

The last publication is from the U.K., "Efficiency and Effectiveness of Sprinkler Systems in the United Kingdom: An Analysis from Fire Service Data" (Optimal Economics, 2017). There are calculation errors, and there are no explanations of the inconsistent numbers. Different numbers seem to be used in each case. This is the only report to use the word "indicates" about its findings.

The review triggered my quest to understand how these reliability data were collected, analysed, and presented. I needed a systematic tool to validate the studies. I opted for document analysis, basing the analysis on how a scientific investigation should be carried out. I discovered that all the publications had problems in four out of seven possible areas.

Document analysis is primarily a tool for social science, but as this thesis shows, it is very useful in the field of fire science. Therefore, I propose a modified methodology adapted to the scientific principles of fire science. I make two proposals for future study using the suggested methodology, the first descriptive and the second explanatory.

13.2. CONCLUSION

A cautionary line appears at the start of this thesis and continues to the end. Even in the introduction to fire and extinguishing theory and the relevant publications, it becomes clear that there is a lack of knowledge of what an extinguishing system is (does it extinguish or control a fire or both?). Moreover, there are different types of sprinkler systems, including several different types of residential systems, systems for ordinary hazards, storage, and special systems, but there is little trace of this in literature. Finally, different sprinkler systems perform differently, and this is not acknowledged. A recognised comprehensive book on fire science has much more about hydraulic calculations than on extinguishing theory or the use of different system.

The same can be said about reliability. None of the publications has a definition of reliability or supports its views by referring to the science of reliability. This is a major finding. None of the publications communicates or works with the fact that reliability is the system's ability to function as designed.

More surprising is the "circle of trust". Even if there is a reference to sources, it does not mean it exists or is available. It is not certain that the authors have the correct result. It is not certain that they have even read the reference. Because some studies are comparative, there is an appearance of much data, but this is not the case.

In my validation of the studies using document analysis, it became clear that they all had problems in four out of seven possible areas: 1. unclear issues, including missing definitions and intentions of the investigations; 2. uncertain data collection process; 3. varying quality of analysis and lack of quality assurance; 4. lack of systematic presentation and discussion. Based on this finding, I concluded that none of the reports on sprinkler reliability could be used as a general documentation of reliability or future probability for sprinkler systems to function as designed.

Are these findings and conclusion supported by other scientific evidence? The overall evidence is that these findings are correct. First, the list of the literature is much shorter when I remove references that are impossible to find, comparative studies that use incorrect findings, studies with a small or limited time frame, and older studies.

Second, the critical review and the analysis of the selected publications showed most were not done following recognized scientific principles.

Third, both government publications (Department of Building and Housing, 2005) and other publications (Frank, Gravestock, Spearpoint, & Fleischmann, 2013) have understood that there is a lack of information. Their conclusions and methods are not clear.

Why are these findings important? We know little about sprinklers and their effect on live fires outside a test facility, the kind of protection they give, or the time before a flashover in different types of buildings. Furthermore, the criteria for selecting the right type of sprinkler system do not seem to be established, and there is no known reliability for each system or hazard class.

We know now that we do not have data on the reliability of the different types of sprinkler systems. We do not know the reliability measured in operationality and efficiency given by the various sprinkler standards. We do not know if today's division into hazard classes, with design area and water density, is adequate. We do know that standards are not revised using data on how sprinklers behave under fire. Revisions come from studies of single cases and tests done in laboratories.

The last important finding is the new methodology developed in this thesis for validation of any scientific survey. At last there is a possibility to work systematic in both validation and how to conduct survey.

Sprinklers have been around for 132 years (1886 to 2018), so why do we not know more? This is a good question. I have some but not all the answers. The first answer is probably the most surprising one: sprinklers work. Most of our experience with this kind of system tells us that they do work. The problem is that we do not know the overall reliability of all sprinkler systems over their lifetime or the reliability of each type or according to its age.

It seems the changes in methodology have been small. Without a systematic and critical look at methodology, which is the basis of science, improvement is difficult. The fact that large and important organisations can conduct their research without outside influence and have their own interest in publishing good results stresses the importance of independence.

Another problem is the lack of team work. Good scientific work in collecting, analysing, and presenting reliability demands a broad understanding from the people involved, for example, detailed knowledge about fire science, sprinklers, how to conduct studies, how to understand the collected data, how to analyse the data, including uncertainty calculations, and how to present the findings. In addition, there is a need to cooperate with the proper authorities to get the right data or adapt data to the research.

Finally, decision makers seem to know little about the area. They question the use of time and money to improve an area they erroneously think they know. The reel question is if they will do this now?

13.3. SUGGESTIONS FOR FURTHER WORK

What are the implications of my work?

1. The fact that 29% of the references were either incorrect or non-existent indicates the need for authors to conduct basic research in a proper way and, sadly, for readers to avoid assumptions that presented data are correct.

2. The fact that there are no reliable data on sprinkler reliability means that we are still far from the accuracy we need in fire safety engineering.

3. Even if I have not examined the reliability data for other active and passive fire protection measures in my research, is it clear that that no other measures have the amount of data and studies. Available data suggest strongly that the situation is not better for them; it is likely worse.

4. Performance-Based Fire Protection Design says: "*In the analysis of an existing building, the type (smoke detection, heat detection, UV/IR) of an automatic detection system must be documented. …… Similarly, whether in an analysis of an existing building or in the design of a new building, the characteristics of automatic suppression systems must be documented*" (Society of Fire Protection Engineers, 2016) Chapter 38: Fire scenarios, page 1265.
   The design's close links to quantitative and qualitative data have several implications:

Comparative criteria: Since there is no knowledge of the performance of sprinkler systems either in general or for specific types, how should comparisons be done?

Deterministic criteria: How can it be shown that the object (usually the worst case scenario) will not happen, when is not possible to prove that, e.g., the sprinkler will not work in more 50% of the cases?

Probabilistic criteria: How is it possible to set the probability of a given event acceptably low, when it is now clear that data are limited and unreliable?

There are, of course, many limitations to my work. This is a subject that could be investigated in much greater depth, but I have a time limit. Many articles and studies have key words like sprinkler and reliability, even if the briefly touched the theme, make it hard to track and find the right publications. Some can be missed just because of the sheer number of hits in an online search. It was also surprisingly difficult to get data and literature from some major world contributors within the fire community; to the point that I did not receive any from some. The fact that also some authorities stopped communicate at the first question on scientific value on how data is obtained, illustrate the difficulty in getting god dialog. The fact that I am not a statistician and do not work with reliability in general are final limitations.

Suggestion for further work

1. There is an urgent need to start all over again with basic research on fire protection measures (active and passive) and their reliability.

2. There is a need to develop fire and extinguishing theory, based on proper research, both under laboratory conditions for real fires.

3. In anticipation of that the new collection methods based on the principles show in this thesis, methods must be developed to use today's collected data on reliability and use them in such way that they give scientific value. It is better to get out some reliable data out of collect data, then to wait for the next time. We do not have time for waiting much longer.

4. Improve the methodology presented in this thesis, also for the other active and passive fire protection measures.

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