Riksantikvaren - The Norwegian Directorate for Cultural Heritage (RNDCH)

Analysis of Sprinkler Failures in Listed Heritage Buildings

Analysis of unintended activations of water based extinguishing systems in Norwegian heritage buildings

by

COWI

on behalf of

RIKSANTIKVAREN

in support of

COST

February 2006

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COST – the European CO-operation in the field of Scientific and Technical Research –
Action C17 Built Heritage: Fire Loss to Historic Buildings

Report no.	1
Issue no.	A
Date of issue	10. February 2006

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1 Background

In 2005 a record of known incidents in heritage buildings was made - where water based extinguishing systems caused unintentional activation or water leakage. The memo[1] is attached in full with this report, see Appendix A.

The recorded incidents occurred from 1986 to 2005. During that period an extensive maintenance scheme was in force by RNDCH for the stave churches, and relevant reports of incidents in other buildings were collected.

The incident reports contain valuable information beyond that of a classical record of sprinkler failures, and allow for unconvential analysis of failure modes.

2 Classical Breakdown of Failure Modes

None of these references are specific to heritage applications, they are general.

Our report is devoted to "unintended activations", i.e. activation when there is no fire. The references below, however, except the St Paul reference, focuses on "failure on demand", i.e. failed activation in real fires. In lack of comparable studies, we found that a very brief summary of each are still relevant.

NFPA on Sprinkler Reliability[4]

NFPA conclude that:

- System shut-offs and other human errors were responsible for nearly all the failures.
- Sprinklers failed to operate in only 7% of structure fires large enough to activate them.

(Important, but less related to this report, NFPA conclude on sprinkler abilities:

- In fires with sprinklers present, the chances of dying in a fire are reduced by one-half to three fourths and the average property loss is cut by one-half to two thirds, compared to fires where sprinklers are not present.)

NFPA on "Automatic Extinguishment System Failure Reason"[4]

Extracted from reference[4] as NFPA discusses the US Fire Administration fire reporting form with instructions relating to sprinkler, NFIRS 5.0:

> This is designed to capture the (one) reason why the system "failed to operate or did not operate properly." The instructions also say that this data element provides information on the "effectiveness" of the equipment. It is not clear whether this is to be completed if the system operated properly but was not effective.

Text shown in brackets is text shown in the instructions but not on the form. Note that for code 4, the phrase “wrong” is replaced by “inappropriate” in the instructions; the latter term is more precise and appropriate, although it is possible for the type of fire to be unexpected in a given occupancy.

Codes:

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

SFPE[5]

The SFPE reference does not break down failure modes for comparison with ours.

SFPE offer a systematic approach for calculating reliability of sprinklers, and include the very simplified illustration at right.

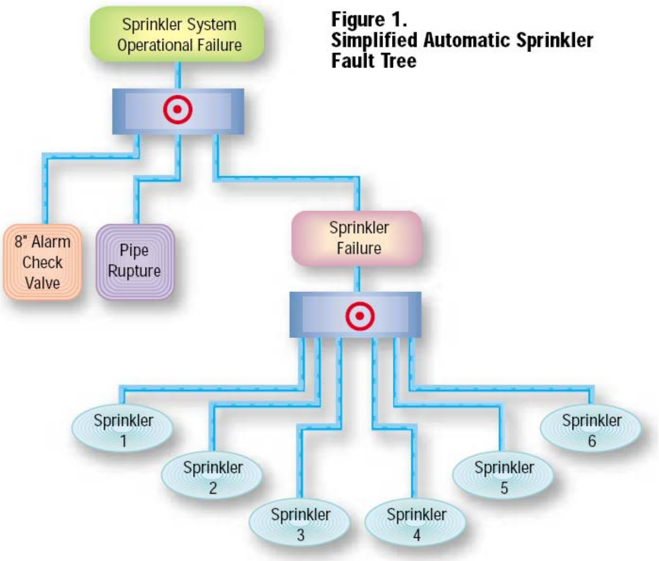

Figure 1.
Simplified Automatic Sprinkler Fault Tree

St Paul Fire Department (US)[6]

St Paul Fire Department reported these figures informally in January of 2003:

Physical Contact	11
Freezing	8
Fire	8
Ageing	2
Design Flaw	1
Tamper	1
Failure of Equipment	1

3 Alternative Breakdown of Failure Modes

The following categorizations of failure modes are proposed in order to make informed decisions on actions to improve reliability of water based extinguishing systems while minimizing cost and invasive measures in heritage buildings.

Installed sprinkler and water mist systems in heritage buildings in Norway sometimes deviate from standard designs, either to increase the safety level of particular buildings or to avoid parts of the systems required for industry or general applications only. Special designs are tailored to fit where installations require irreversible measures into fabric or unacceptable aesthetical invasions.

To make the new breakdown most useful, single incidents have multiple entries where applicable. This is because incidents typically are incurred by a set of conditions rather than single causes, and to provide the best overall evaluation.

The objectives of the new approach were to answer questions like:

- Are failures related to systems being adapted to fit the heritage environment?
- Are failures related to equipment or functions which are merely required by standard rules and not relevant to retain in heritage environment? And, are such equipment or functions not only cause of failure but also damaging to the heritage environment?

Alternative breakdown of failure modes (results in Table 1)

1. Dispensable part of system, retained to comply with standard
2. Dispensable function of system, retained to comply with standard
3. Dispensable maintenance procedure, retained to comply with standard
4. Indispensable part added, to cater for heritage demand
5. Indispensable part missing, left out to reduce cost or maintenance

6. Indispensable part missing, left out to minimize invasion

7. Unexpected condition, unforeseen and unlikely to reoccur at such building

8. Condition typical in heritage, but not addressed by standard or engineering of the system

9. System design require more skill to operate than local support offer

10. Support (drainage, plumbers, response to faults, frequency of inspections) assumed to be in place by standard, but not available at site

11. Complicated system, installation or procedures

12. Fault in system engineering design

13. Fault in system installation

14. Fault in professional maintenance

15. Fault in manufactured part

16. Human error (not system design)

17. Physical contact

18. Freezing

19. Ageing

20. Tamper

Entries 17 to 20 are adopted from the St Paul statistics[6].

For each incident measures to prevent reoccurrence are discussed (table 2):

A What specific remedy will prevent this failure from reoccurring?
B What general design approach will prevent this failure from reoccurring?

4 Results

The Norwegian record of unintentional activations of water sprinkler or mist systems 1986-2005 have been made subject to both the classical and the new approach of breakdown of failure modes, and is presented in Tables 1 and 2.

A summary of result deducted from the tables are presented in Chapter 5.

Two main factors of failures are dealt with below: complexity and freezing.

Freezing

Problems relating directly or indirectly to freezing are many. This is a main cause of failures word-wide in sprinkler systems in general. Rules for installation of sprinkler systems clearly specify how to avoid freezing problems. They are extensive in detail, parts expensive and sometimes appear invasive in heritage. Still, even if adhered to, failures are frequent, not only in the recorded incidents but in sprinkler systems subject to freezing in general. By our experience the reasons are in the many details, cumbersome maintenance procedures, dependence on power supply to compressors and the many parts required. Furthermore, in old buildings pitching pipes to drains challenge installers. It is easy to overlook one of the many draining drops to evacuate condensed water. Design wise, it is a challenge to specify the correct nozzles and fittings to avoid condensed water accumulation.

Some line heat detection systems and actuating systems are pneumatic, hence several incidents relate to freezing of condensed water in these, either by deluge systems or by water becoming trapped in dry pipes which subsequently froze. In two cases double knock point smoke detectors were used. In at least one case white frost caused multiple detectors to alarm whereupon activating sprinklers.

Since this is a very old world-wide problem, and well addressed in installation standards, there are no obvious cure to the problem. One may conclude that no water based extinguishing system should be used, but there is no other option.

More strict installation and maintenance may be advised, but the instructions are strict in the first place and may only marginally improve reliability.

Anti-freeze systems are not wide-spread in use in heritage objects due to the potential risk of chemical impact. It is known from experience on non-heritage sprinkler applications though, that anti-freeze systems are as likely to inadvertent leakage as dry sprinkler systems.

Recommendation to improve freeze protection design – including detection

Our current recommendation is to maintain use of water based extinguishing systems but avoid dry systems and anti-freeze systems in favour of special preaction systems: The preaction systems shall have automatic bulb sprinklers, dry piping and no pressure monitoring. Checks for tightness shall be done manually by routine, using a compressor, a connector and a pressure monitor. The manual check equipment may be designed for routinely drying the pipe system. This recommended system design allow for most parts to remain as designed, and in particular the detection systems: With double knock detection – say by one line heat detector signal plus one aspirating smoke detector signal - and the automatic nozzles, effectively a triple knock system is provided. This ensures high reliability against unintended water release without significantly sacrificing reliability to activate on demand. It is very important that detection systems are emergency powered and failsafe and that the pressure check for tightness is routinely performed. Note that *preaction systems in general should be avoided* because they depend on fairly complex detection systems and power supplies.

Complexity

It is generally well known that complexity translates to reduced reliability. Countermeasures are well proven advanced techniques or strict maintenance.

The incidents evaluated in this report quite clearly demonstrate that even fairly simple sprinkler systems overwhelm local attendants and installers. The maintenance schemes are high standard, but still they do not prevent incidents.

The incidents proved that the fire detection systems which activates extinguishing deluge systems are often unacceptably complex to attend, and prone to fail. Some of them have unique features and designs, like non-electric signal conductors to avoid arcs from lightning, hence introduce problems not known before.

Water based extinguishing systems are still the best overall option for most of the objects which were involved in this study. It is important to keep them as simple as possible and robust to harsh climate and to limited local maintenance.

The recommended practice to prevent water leakage and freezing problems presented above is one way of simplifying and making systems robust to failure.

	SPRINKLER																						WATER MIST				
FAILURE MODE / INCIDENT	1 Røldal	2 Høre	3 Høre	4 Urnes	5 Høre	6 Høre	7 Høre	8 Kaupanger	9 Flesberg	10 Nore	11 Hopperstad	12 Lomen	13 Hegge	14 Torpo	15 Borgund	16 Hedalen	17 Hedalen	18 Eidsborg	19 Heddal	20 Lom	21 Rein	22 Finneloftet	23 Rollag	24 Kong Carl	25 Bibsys	26 Gol	27 Tanum
1 Dispensable part of system, retained to comply with standard																											
2 Dispensable function of system, retained to comply with standard																											
3 Dispensable maintenance procedure, retained to comply with standard																											
4 Indispensible part added, to cater for heritage demand									x		x	x		x	x	x		x	x	x		x	x		x	x	x
5 Indispensible part missing, left out to reduce cost or maintenance																											
6 Indispensible part missing, left out to minimize invasion																											
7 Unexpected condition, unforeseen and unlikely to reoccur at such building	x	x				x	x		x			x					x										
8 Condition, typical in heritage but not addressed by standard or engineering of the system	x										x			x		x		x	x	x		x	x		x	x	x
9 System design require more skill to operate than local support offer				x	x				x		x		x	x	x	x			x	x	x				x		x
10 Support assumed to be in place by standard, but not available at site				x											x	x											x
11 Complicated system, installation or procedures									x		x			x	x	x	x	x	x	x		x				x	x
12 Fault in system engineering design			x	x	x				x		x				x			x				x				x	x
13 Fault in system installation	x		x	x	x			x	x	x	x			x			x				x						
14 Fault in professional maintenance									x				x			x	x			x							
15 Fault in manufactured part		x		x		x	x			x	x			x				x			x		x			x	
16 Human error (not system design)	x			x	x			x	x	x	x			x	x	x	x	x	x	x	x				x		
17 Physical contact																											
18 Freezing			x		x			x	x	x			x				x					x				x	
19 Ageing																											
20 Tamper																								x			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27

Table 1: Failure modes (factors) involved in the recorded incidents.

		A What specific remedy will prevent this incident from reoccurring?	B What general design approach will prevent this incident from reoccuring?
1	Røldal	New test procedure	Maintenance procedures
2	Høre	High quality non-return valve	Designs without the failed part
3	Høre	Installation quality check	Better freeze protection design
4	Urnes	Improve local instructions	Better freeze protection design
5	Høre	Better freeze design protection	Better freeze protection design
6	Høre	High qualilty non-return valve	Designs without the failed part
7	Høre	High qualilty non-return valve	Designs without the failed part
8	Kaupanger	Installation quality check. Improved local instructions.	Better detection system design Better freeze protection design
9	Flesberg	Reliable logic valve actuator	Better freeze protection design
10	Nore	Installation quality check	Better detection system design Better freeze protection design
11	Hopperstad	Reliable fire detection system	Better detection system design Better freeze protection design
12	Lomen	Keep badgers away	None
13	Hegge	Improve local instructions	Better freeze protection design
14	Torpo	Reliable fire detection system	Better detection system design
15	Borgund	Reliable fire detection system. Installation quality check.	Better detection system design
16	Hedalen	Care in maintenance procedures	Better detection system design
17	Hedalen	Improved service repair skills	Fault tolerant, robust designs
18	Eidsborg	Reliable logic valve actuator	Avoid tailored system accessories
19	Heddal	Care in maintenance procedures. Improved local instructions.	Better detection system design
20	Lom	Care in maintenance procedures.	Better detection system design
21	Rein	Improved service repair skills	Fault tolerant, robust designs
22	Finneloftet	Apply heat, not smoke detectors	Better detection system design Better freeze protection design
23	Rollag	Reliable fire detection system	Better detection system design
24	Kong Carl	None (tamper difficult to avoid)	Preaction system
25	Bibsys	Improved local instructions.	Better detection system design
26	Gol	Double knock detector logic	Better detection system design Better freeze protection design
27	Tanum	Detection algorithm verification tests	Better detection system design

Table 2: Preventive measures to prevent reoccurrence of respective incidents.

5 Conclusions

27 incidents of unintended activations of water based extinguishing systems in heritage applications have been analysed. All known contributing factors have been listed. The following conclusions are made:

The ten dominating factors causing failures, by decreasing order:

1. Human error (consistent with fault statistics of sprinklers in the US[4])
2. Indispensable part added (not addressed by standard) to serve need related to heritage
3. System design require more skill to operate than offered by local maintenance staff
4. Condition required by the heritage application (not addressed by installation standard)
5. Complicated system, installation or procedures.
6. Fault in manufactured part
7. Fault in system installation
8. Fault in system engineering design
9. Freezing
10. Unexpected condition, unforeseen and unlikely to reoccur at such a building

Keep in mind that the incidents are caused by multiple factors, not single ones.

By professional insight and simple logic it is deducted from the tables that:

1. Special accessories to sprinkler or mist systems, notably detection systems, required by heritage concerns, are very often the main cause of failure.

2. Systems are too complicated to design, install and maintain. The designs do not fit the harsh climate conditions well. The installations are uncommon to local service and maintenance personnel. Some of these factors relate to the objects being at remote locations far from cities; still, most of the incidents would have occurred at any location.

Two main factors of failure are dealt with separately: complexity and freezing. A recommended design to avoid leakage incidents due to freezing is presented.

The evaluation introduced a new, provoking set of failure modes to search the possibility that heritage specific conditions, or specific system parts to cater for these, were factors in causing water leakage. Results proved that most causes of incidents were well-known in extinguishing systems in general, except for the detection and actuating systems tailored to suit special façade deluge systems.

6 References

1 Jensen, Geir; Reitan, Arvid: "*Unintentional Activations of Sprinkler and Water Mist Systems in Heritage – Norwegian Record*". 12. June 2005. COWI AS on behalf of RNDCH"

2 NFPA 13 *Standard for the installation of sprinkler systems*. Quincy (MA): National Fire Protection Association.

3 NFPA 25 *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems.* Quincy (MA): National Fire Protection Association.

4 Rohr, Hall: *US experience with sprinklers and other fire extinguishing equipment.* August 2005. NFPA.

5 Sprinkler Reliability. SFPE Fire Protection Engineering. Winter 2001.

6 St Paul Fire Department: *Sprinkler System Operation Information*. An informal memo obtained from Chris Cahill at St Paul Fire Department, as he referenced it on the "SprinklerForum" e-mail list 02.01.2003.

Appendix A: Memo "Unintentional Activations of Sprinkler and Water Mist Systems in Heritage – Norwegian Record" of 12. June 2005. COWI AS on behalf of RNDCH - updated 10.02.2006.

This record includes two recent incidents at Rein Church and Finneloftet, but is otherwise identical to the memo of 12th June 2005.

This is a list of registered incidents of water damage from unintended activations of sprinkler and water mist installations in Norway from 1985 to present. The list is based on known incidents from routine inspections of 148 sprinkler indoor and outdoor systems of wet, dry, special and water mist categories in wooden churches, plus a few that has been reported by newspapers or other. All installations are in heritage buildings. In excess of 90 % of these cover areas that are wholly or partially exposed to sub-zero (freezing) temperatures.

Sprinkler Systems

INCIDENT (Unintentional activation)		LOCA-TION	YEAR	CAUSE	DAMAGE
1	Outdoor water spray penetrating eaves	Røldal	1986	On-site test de luge sprinkler	Water on painting. Minor damage.
2	Sprinkler activated at bell tower building	Høre	1988	Faulty non-return valve	None reported
3	Leaking sprinkler pipe	Høre	1991	Condensed water freezing at weak joint.	None reported.
4	Leaking dry sprinkler pipe, valve activated.	Urnes	1991	Faulty routine. Leaking valve.	Minor (report by H Skaug)
5	Leaking sprinkler pipe	Høre	1993	Condensed water freezing	Not clear. Valve shut after 60 mins.
6	Sprinkler activated at bell tower building	Høre	1994	Faulty non-return valve	Minor or none
7	Sprinkler activated at bell tower building	Høre	1995	Faulty back-flow preventer	Minor or none
8	Façade deluge system activated	Kaup-anger	1996	Pipe joint slide	None reported
9	Façade deluge system activated	Fles-berg	1998	Wrong valve settings	Minor, façade wetting only
10	Sprinkler room pipe rupture	Nore	1998	Pipe joint broke	Room flooded. Dry valve activated and filled pipes in church.

11	Façade deluge system activated	Hopp-erstad	1999	Air leakage in pneumatic line detector. Failed manual response and maintenance.	Water penetrated gap, ran into church nave and froze. No long term damage.
12	Façade deluge system activated	Lomen	1999	Badger cut off double knock pneumatic line detectors	None or minor damage
13	Pipe joint leakage at sprinkler nozzle	Hegge	1999	Condensed water was not drained as per maint. routine.	Water froze, ruptured joint and caused air leakage. Sound alerted personnel who closed valve. No damage.
14	Façade deluge system activated	Torpo	1999	Air leakage in pneumatic line detector. Compressor failure. Delayed manual response.	No damage.
15	Indoor preaction system activated. Pipe end opened.	Borg-und	2001	Double knock optical smoke alarms were improperly acted upon, as a hospital emergency arised	As dry system filled, a pipe end broke open, and a missing nozzle open joint sprayed considerable amounts of water in church nave. Moderate irrevocable damage.
16	Façade deluge system activated	He-dalen	2001	Double knock line heat detectors set in state of alarm when tested.	No reported damage.
17	Façade deluge system activated	He-dalen	2001	Wrongly installed valve could not be fully drained. Water froze.	No reported damage. The incident was result of faulty repair of previous incident above.
18	Outdoor irrigation monitors protecting church activated	Eids-borg	2002	Air leakage at control valve of pneumatic line detection. Valve not 100 % split for double knock. Soiled water.	Minor damage.Breeze-ways heavily wetted. Incident revealed that the type of monitors is unsuitable for this application. Detection valve was reworked.

19	Façade deluge system activated	Heddal	2003	Electric line heat detector triggered by maintenance. Improper manual response.	No reported damage.
20	Façade deluge system activated	Lom	2004	Double knock electric line heat detectors activated at maintenance.	No reported damage.
21	Leakage from broken pipe indoor	Rein	2005	Antifreeze wet sprinkler. Pipe fitting broken by the threads.	Minor damage.
22	Façade deluge system activated	Finne loftet	2006	White frost triggers 3 out of double knock point smoke detectors.	Water ingress at several openings. Extensive drying operation saved items from permanent damage.

Water Mist Systems

23	Water mist deluge in church attic activated	Rollag	1998	Air leakage in pneumatic line detector	Limited water reservoir emptied (designed to avoid damage*). None or minor damage
24	Water mist nozzle activated in hotel room	Kong Carl	1999	Guests broke nozzle bulb.	Dried quickly, no interior or other damage.
25	Water mist smoke scrubbing system activated in computer room. Emptied reservoir.	Bibsys	2000	Welding smoke triggered smoke detectors.	Computers ran throughout - no damage. Borderline of real demand vs unintentional.
26	High pressure deluge water mist activation indoor.	Gol	2002	Single knock pneumatic line detection pipe broke. Below zero temp.(Double knock design 2003 on)	Water mist produced snow. Church nave was cleaned by shovelling and brushing snow. No damage reported.
27	High pressure water mist deluge zone activated.	Tanum	2002	Suspected fault in detection algorithm.	Substantial water damage in church. (System not yet commissioned-delayed valve shut off)

** Limited water reservoir volume deliberately designed to equal the absorption capability of the attic floor insulation, in order to avoid run off to impact water soluble wall and ceiling decorations in church nave. The incident proved the design was successful.*

Extract from: "Water Mist for Protection of Heritage", Interconsult (COWI)
(these incidents are included in above listing)

UNINTENTIONAL SYSTEM ACTIVATION: 4 INCIDENTS

1 + **Bibsys** Smoke scrubbing & extinguishing water mist system in **computer room**. Activated by welding. Computers were running, no damage. System considered for **museum vaults**.

2 + **Kong Carl** Historic **hotel**. Medium pressure water mist. Broken bulb activated nozzle in guest room. *"Never seen a room so perfectly wet; still, no water running or dripping. Dried quickly, no damage to interior*", manager said. " *Nice fitted and unobtrusive*".

3 + **Rollag** **Attic**. Mist system designed to flashover suppression. Limited volume of water designed to be absorbed by insulation of attic floor - to avoid damage to decorated room below. Activated by lightning strike. Worked as designed - no decor damage.

4 - **Tanum** **Church**. Faulty activation of deluge zone of high pressure water mist system. System was not yet commissioned by fire brigade. Therefore, 30 min to find shut off valve. Substantial water damage. High grade system, but detection algoritm questioned.

Registered Full Scale On-Site Tests of Sprinkler and Water Mist Systems in Stave Churches

1	Borgund	Indoor dry and outdoor deluge façade, sprinkler systems
2	Torpo	Indoor dry high pressure water mist, and outdoor deluge sprinkler
3	Reinli	Indoor dry low pressure water mist, and outdoor deluge sprinkler
4	Haltdalen	Indoor and outdoor dry low pressure water mist, zoned deluge.
5	Uvdal	Outdoor façade sprinkler systems, zoned deluge
6	Nore	Outdoor façade sprinkler systems, zoned deluge
7	Rollag	Outdoor façade sprinkler systems, zoned deluge
8	Flesberg	Outdoor façade sprinkler systems, zoned deluge
9	Lomen	Outdoor façade sprinkler systems, zoned deluge
10	Eidsborg	Outdoor 'irrigation' monitors to protect roof, façade, breezeways

Tests are logged for maintenance records only. A few are reported on (Norwegian). Tests were evaluated on-site by key personnel for refining designs.