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INTRODUCTION

When automatic fire sprinkler systems, or any fire protection safety features, are included in a fire protection design package, it is assumed that, if needed, they will perform as expected. One measure of expected performance is a system’s reliability. Reliability is generally reported as probabilistic, i.e., the percent success rate for a given number of systems over a fixed time period. Put more simply, the reliability (i.e., probability of success) is expressed as

\[ P(\text{success}) = \frac{\text{number of successes}}{\text{total number of incidents}} \]  

Several published studies provide reliability estimates for automatic sprinkler systems. These estimates indicate that, historically, sprinkler systems have been highly reliable. However, there are biases and limitations in the data and the analyses that restrict their usefulness. Most of the published studies do not attempt to address these limitations or any other elements of uncertainty in the estimates. Also, most of the studies are more than ten years old and, therefore, do not include more current sprinkler technologies in the databases.

Simple statistical methods are available to more accurately estimate automatic sprinkler system reliability and the uncertainty associated with such estimates. Some of these methods can handle “sparse” databases, i.e., small data sets from a few systems or from a single system over a relatively short period of time. These methods and the resulting predictions are of value to manufacturers (in developing new sprinkler technologies and identifying possible failure modes), the user (in optimizing Inspection, Testing, and Maintenance (ITM) costs and insuring a high level of operational reliability), and the designer (in performing probabilistic-based risk analyses for new design projects). Accurate estimates of reliability are necessary inputs to risk-based analyses where failure rates and redundancy considerations must be evaluated.

This article provides a brief summary of published sprinkler reliability studies. An attempt is made to address uncertainties in the reported failure rates in a systematic manner. Rather than report the results as a single estimate of sprinkler reliability, statistical methods are used to average the individual estimates within specified confidence limits. The value of this simple analysis lies in the estimate. While calculating the “average” value among several available data sources does not in itself improve the quality of the estimate, the simple calculation of the range of possible estimates at least allows the user to perform limited sensitivity analyses. Such analyses provide input to risk-based assessments for existing or proposed fire safety designs.

An illustration of the use of selected statistical methods to evaluate reliability for small or “sparse” data sets is also provided. As an example, limited ITM data for several existing sprinkler systems are analyzed. The results demonstrate the potential usefulness of small or limited data sets in estimating the reliability of a specific automatic sprinkler system as well as the effects of changing ITM frequency on those estimates. These methods can be helpful in evaluating the reliability of newer sprinkler technologies with relatively short field experience.

RELIABILITY CONCEPTS

A detailed discussion of reliability engineering is outside the scope of this article. Modarres provides a more complete review of the subject. Brief descriptions of selected elements of reliability are listed below to orient the reader to the value and limitations associated with published data on automatic sprinkler system reliability.

Reliability is normally defined as an estimate of the probability that a system or component will function as intended when called upon. It is directly affected by the types and frequency of testing and maintenance performed on the system. Operational reliability is a measure of the probability that a system or component will operate as intended when called upon. It is directly affected by the types and frequency of testing and maintenance performed on the system. Performance reliability (i.e., capability) is a measure of the adequacy of the system, once it has operated, to successfully perform its intended function. For a sprinkler system, operational reliability accounts for the “readiness” of the system components, while performance reliability addresses the “capability” of the system to perform satisfactorily under specific conditions.
fire exposures. The capability of the system is related to the scope and adequacy of the engineering design standards (e.g., NFPA 13) and the level of compliance of the system and its components with the standards.

Two other important concepts are failed-safe and failed-dangerous. When a sprinkler system fails safe, it operates when no fire event has occurred. An accidental discharge of a sprinkler is an example of a failed-safe condition. A failed-dangerous condition occurs when a system does not function when needed, e.g., a sprinkler fails to open, or the water supply is unavailable.

Studies that rely on fire incident data to estimate automatic sprinkler system reliability mix both operational and performance reliability elements. They also typically do not include failed-safe incidents in the analysis. On the other hand, studies that rely on testing and maintenance data are, for the most part, providing estimates of operational reliability.

PUBLISHED STUDIES

Several studies have been published that report estimates of automatic sprinkler system “reliability.” For the most part, these studies provide estimates based on review of actual fire incidents where automatic sprinklers were present. As a group, they vary significantly in terms of reporting periods, the types of occupancies, and the level of detail regarding the types of fire incidents and sprinkler system design. Nevertheless, such studies are routinely referenced and provide some basis for estimating sprinkler system reliability.

Table 1 provides a summary of the reported reliability estimates. The three occupancy categories reflect occupancy type variations in the reported estimates. Several studies provided reliability estimates for “commercial” occupancies. These are grouped accordingly in the table. The estimates grouped under the “general” occupancy category were from studies that grouped commercial, residential, and institutional occupancies into a single database.

The estimates indicate relatively high reliability for automatic fire sprinkler systems. However, significant variation exists among the various studies. The reported reliability estimates range from 81.3 percent to 99.5 percent. These differences may be attributable to any number of variations in the protocols or the databases used by each study. For example, the relatively low value of 81.3 percent as well as the somewhat higher value of 87.6 percent reported by Kook appear to reflect biases in the databases. In both studies, the number of incidents was relatively small. And, while most of the suppression systems in the databases were sprinkler systems, apparently other types of suppression systems were also included. In addition, the high-end estimates of 99.5 percent reported by Maybee and Marlayt reflect sprinkler system performance in occupancies where inspection, testing, and maintenance were rigorous and exceeded customary requirements for ITM activities. If these studies were excluded from the group, the range of reliability estimates for the remaining studies is from 86 percent to 97.9 percent, which still represents a significant range.

An additional limitation in the reported sprinkler reliability estimates is that most of the sprinkler systems were more than 15 years old. Therefore, while the reliability estimates provide reasonable information for conventional spray sprinkler technology, it may not be appropriate to rely on these estimates to evaluate the reliability of newer technologies such as quick response, residential, and ESFR sprinklers without addressing additional factors.

LIMITED UNCERTAINTY ANALYSIS

Estimates of reliability are required input to fire risk assessments. The applicability and accuracy of such estimates are perpetuated through the risk analysis and directly reflected in the performance outcomes. The estimates compiled in Table 1 demonstrate variability in sprinkler system reliability among different studies. Unless the parameters of a particular study match those of interest, reliance on the estimate of reliability from a single study can incorrectly alter the results of a risk assessment.

Relatively simple statistical methods are employed here to provide both “estimates” of sprinkler system reliability and measures of “uncertainty” associated with the reported estimates. Uncertainty is reported as confidence intervals, i.e., the upper and lower bounds associated with the reliability estimate.

The estimates of reliability are simple calculations of the “mean” of the values reported in Table 1. The confidence intervals are calculated based

### Table 1. Selected Automatic Sprinkler Reliability Studies (percent)

<table>
<thead>
<tr>
<th>Occupancy</th>
<th>Reference</th>
<th>Reliability Value (of success)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial</td>
<td>Mline⁶</td>
<td>96.6/97.6/89.2</td>
</tr>
<tr>
<td></td>
<td>NFPA¹</td>
<td>90.8-98.2</td>
</tr>
<tr>
<td></td>
<td>Miller⁷</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td>Maybee⁴</td>
<td>99.5</td>
</tr>
<tr>
<td></td>
<td>Kook²</td>
<td>87.6</td>
</tr>
<tr>
<td></td>
<td>Taylor²</td>
<td>81.3</td>
</tr>
<tr>
<td></td>
<td>Linder⁸</td>
<td>96</td>
</tr>
<tr>
<td>General</td>
<td>Miller⁴</td>
<td>95.8</td>
</tr>
<tr>
<td></td>
<td>Miller⁵</td>
<td>94.8</td>
</tr>
<tr>
<td></td>
<td>Powers¹⁰</td>
<td>96.2</td>
</tr>
<tr>
<td></td>
<td>Richardson¹¹</td>
<td>96</td>
</tr>
<tr>
<td></td>
<td>Finucane et al.²²</td>
<td>96.9-97.9</td>
</tr>
<tr>
<td></td>
<td>Marlayt³</td>
<td>99.5</td>
</tr>
</tbody>
</table>
on the degree of certainty required. There are many factors that are involved in selecting a degree of certainty. In its simplest form, it is a measure of the likelihood that the actual mean value falls within the confidence intervals. Assuming normal distribution, the higher the accuracy desired, the wider the confidence intervals (and the higher the required certainty).

Mean reliability estimates and 95 percent confidence limits were calculated for each of the occupancy categories represented in the data sources. Similar estimates were calculated for a category referred to as "combined," which is simply combined estimates for both the commercial and general categories. The 95 percent confidence limits were selected as representative of confidence limits typically used for quality assurance estimates for manufactured machine parts. Other confidence limits are routinely used, depending on the required certainty associated with a particular product or system. Table 2 provides a summary of the results of this analysis.

This relatively simple effort at estimating variance in reported data improves the statistical certainty of the reported reliability estimates. For example, for the three occupancy categories presented in Table 2, the "mean" reliability estimates range from 93.1 to 96.0 percent, a relatively small range, and much smaller than the range associated with the raw reliability estimates in Table 1. Greater confidence in the estimates is also provided by reporting a range of estimates using upper and lower confidence limits. This information reduces the uncertainty in estimating the impact of sprinkler system reliability in risk-based design evaluations.

### Analysis of Small Data Sets

Field performance data for new sprinkler technologies are limited. Therefore, in order to estimate the reliability of these systems or components, methods must be used that can handle small data sets. The results from a pilot study of several existing automatic sprinkler systems are used to demonstrate the usefulness of such analyses.

### Selection of the Pilot Study System(s)

An important step in the pilot study was the selection of the sprinkler systems and collection of the data to be studied. This was accomplished by reviewing existing sprinkler system ITM data, in addition to available system drawings and documentation. Detailed ITM records were obtained for a 6-month period for several sprinkler systems in the same complex of buildings.

### Development of System and Component ITM Database

The second element of the study was the development of a database. The raw ITM data collected for the sprinkler systems were reviewed and an appropriate database scheme developed. The data obtained from the ITM reports were placed in a spreadsheet database in the statistical package. This statistical package offers the ability to serve as a database and a statistical tool for analysis.

![Figure 1. Simplified Automatic Sprinkler Fault Tree](image)
The database spreadsheet set up each inspection form as an individual case. The ITM results were entered for each component in each system identified by the test record. The results for all component tests were either “pass” or “fail.”

**Development of System Fault Trees**

Once component failure rates were developed, system schematics were used to develop fault trees for individual systems. Figure 1 provides a summarized version of the fault tree design. The fault tree structures were programmed into spreadsheets. The spreadsheet programs allowed failure probability and reliability information to be propagated through the systems using the fault tree models, resulting in an overall system reliability estimate.

Once the baseline system reliability information was obtained, further analysis was performed to examine testing and inspection intervals and how altering these intervals affected the system’s reliability. The use of fault trees provided information that offers insight into testing and inspection frequencies and established a means to track system performance.

Fault trees were constructed for each sprinkler system. For the fault tree models, the system’s boundaries were defined as the base of the system riser to the sprinkler grid. Defining the system with boundaries at the riser and sprinkler grid assumed that the water supply was 100 percent reliable.

**Component Failure Rates**

The model used to develop component failure rates was the Exponential Model for Life Testing (EMLT). The EMLT model defines the estimate of the mean life (µ) of a component as

\[ \mu = \frac{T_r}{r} \]  

(2)

where \( T_r \) = accumulated time on test, and \( r \) = number of component fires.

The confidence interval about the mean is given by

\[ \frac{2T_r}{X_{\alpha/2}^2} < \mu < \frac{2T_r}{X_{1-\alpha/2}^2} \]  

(3)

where \( X_{\alpha/2}^2 \) is dependent on the degrees of freedom (DF) and found in statistical tables, and  
DF = 2(r).

The 95 percent confidence interval about the estimated mean was calculated for each component failure rate. The individual system components’ failure rates are provided in Table 3 along with the industry reported failure rates for similar components.

**Reliability Estimates**

Table 4 provides the reliability estimates and associated uncertainty of the system fault tree model calculations. The analysis was performed using the existing ITM frequencies, checking manual valve positions, and sprinkler and pipe inspections conducted each month. The existing frequency tests all other system components quarterly. The system fault tree models were then used to estimate the reliability of the sprinkler system if the monthly inspections were extended to quarterly frequencies. In addition to the actual component failure data, industry component failure data for similar components were used in the fault trees. The reported confidence intervals were also propagated to allow for comparison.

The uncertainty intervals reported for the system reliability estimates reflect the propagation of the 95 percent confidence interval about the mean component failure rates through the fault tree models. This was accomplished by quantifying the component failure rate distributions as fuzzy sets and using interval arithmetic in the fault tree model. Singer presents the theory and methodology for this quantification and propagation.

The mean reliability estimates illustrate the reduction in system reliability that occurs when ITM frequencies are

<table>
<thead>
<tr>
<th>Component</th>
<th>Number of Components in Database</th>
<th>Total Hours in System</th>
<th>Pilot Systems ITM Data</th>
<th>Industry Failure Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>PIV</td>
<td>10</td>
<td>480,480</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>ACV</td>
<td>10</td>
<td>480,480</td>
<td>0</td>
<td>4.0 x 10^-4</td>
</tr>
<tr>
<td>OSY</td>
<td>172</td>
<td>8,264,256</td>
<td>7.5x10^-4 &lt; 3.6x10^-7 &lt; 8.7x10^-7</td>
<td>4.0 x 10^-4</td>
</tr>
<tr>
<td>Main Drain</td>
<td>10</td>
<td>480,480</td>
<td>0</td>
<td>4.0 x 10^-4</td>
</tr>
<tr>
<td>Inspector’s Test</td>
<td>10</td>
<td>480,480</td>
<td>2.3x10^-4 &lt; 8.3x10^-7 &lt; 1.8x10^-5</td>
<td>4.0 x 10^-4</td>
</tr>
<tr>
<td>Row Alarm</td>
<td>10</td>
<td>480,480</td>
<td>5.8x10^-4 &lt; 1.5x10^-5 &lt; 2.7x10^-5</td>
<td>4.6 x 10^-4</td>
</tr>
<tr>
<td>Motor Gong</td>
<td>10</td>
<td>480,480</td>
<td>4.1x10^-4 &lt; 2.5x10^-5 &lt; 1.3x10^-5</td>
<td>2.0 x 10^-4</td>
</tr>
<tr>
<td>Fire Department Connection</td>
<td>10</td>
<td>480,480</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>Piping (gasket failure)</td>
<td>10</td>
<td>480,480</td>
<td>5.0x10^-7 &lt; 4.0x10^-6 &lt; 1.2x10^-5</td>
<td>1.0 x 10^-4</td>
</tr>
</tbody>
</table>

Note: 1 from Finucane and Pickney
2 from WASH-140015
ACKNOWLEDGMENTS

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REFERENCES

6 Milne, W.D. “Automatic Sprinkler Protection Record,” Factors in Special Fire Risk Analysis, Chapter 9, pp. 73-89.
14 SYSTAT, SYSTAT 6.0 for WINDOWS™, SPSS, Inc.

For an online version of this article, go to www.sfpe.org.

Note: Monthly tests of manual valves, sprinklers, and piping; quarterly frequency for other components.