Estimates of the Operational Reliability of Fire Protection Systems

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INTRODUCTION

Background

Fire protection strategies are designed and installed to perform specific functions. For example, a fire sprinkler system is expected to control or extinguish fires: To accomplish this, the system sprinklers must open, and the required amount of water to achieve control or extinguishment must be delivered to the fire location. **A** fire detection system is intended to provide sufficient early warning of a fire to permit occupant notification and escape, fire service notification, and in some cases activation of other fire protection features (e.g., special extinguishing systems, smoke management systems). Both system activation (detection) and notification (alarm) must occur to achieve early warning. Construction compartmentation is generally designed to limit the extent of fire spread as well as to maintain the building's structural integrity as well as tenability along escape routes for some specified period of time. In order to accomplish this, the construction features must be fire "rated" (based on standard tests) and the integrity of the features maintained.

The reliability of individual fire protection strategies such as detection, automatic suppression, and construction compartmentation is important input to detailed engineering analyses associated with performance based design. In the context of safety systems, there are several elements of reliability, including both operational and *performance* reliability. Operational reliability provides a measure of the probability that a fire protection system will operate as intended when needed. Performance reliability is a measure of the adequacy of the feature to successfully perform its intended function under specific fire exposure conditions. The former is a measure of component or system operability while the latter is a measure of the adequacy of the system design.

The scope of this study was limited to evaluation of operational reliability due primarily to the form of the reported data in the literature. In addition to this distinction between operational and performance reliability, the scope focused on unconditional estimates of reliability and failure estimates in terms of *fail-dangerous* outcomes. **A** discussion of these terms is provided later in the paper.

Scop

This paper provides a review of reported operational reliability and performance estimates for (1) fire detection, (2) automatic suppression, and to a limited extent **(3)** construction compartmentation. In general, the reported estimates for fire detection are largely for smoke detection/fire alarm systems; automatic sprinklers comprise most of the data for automatic suppression, and compartmentation includes compartment fire resistance and enclosure integrity. It should be noted that in some cases the literature did not delineate beyond the general categories of "fire detection" or "automatic suppression," requiring assumptions regarding the specific type of fire protection system.

Several studies reported estimates of reliability for both fire detection and automatic sprinkler system strategies. However, very little information was found detailing reliability estimates for passive fire protection strategies such as compartmentation. **A** limited statistical based analysis was performed to provide generalized information on the ranges of such estimates and related uncertainties. This latter effort was limited to evaluation of reported data on detection and suppression. Insufficient data were identified on compartmentation reliability to be included.

This paper addresses elements of reliability as they relate to fire safety systems. The literature search that was performed for this analysis is reviewed and important findings and data summarized. The data found in the literature that were applicable to sprinkler and smoke detection systems reliability were analyzed, with descriptive estimates of the mean values and 95 percent confidence intervals for the operational reliability of these in situ systems reported.

ELEMENTS OF RELIABILITY ANALYSIS

There is considerable variation in reliability data and associated analyses reported in the literature. Basically, reliability is an estimate of the probability that a system or component will operate as designed over some time period. During the useful or expected life of a component, this time period is "reset" each time a component is tested and found to be in working order. Therefore, the more often systems and components are tested and maintained, the more reliable they are. This form of reliability is referred to as unconditional.

Unconditional reliability is an estimate of the probability that a system will operate "on demand." **A** conditional reliability is an estimate that two events of concern, i.e., a fire and successful operation of a fire safety system occur at the same time. Reliability estimates that do not consider a fire event probability are unconditional estimates.

Two other important concepts applied to operational reliability are *failed-safe* and *failed*-dangerous. When a fire safety system fails safe, it operates when no fire event has occurred. **A** common example is the false alarming of a smoke detector. **A** fire safety system fails dangerous when it does not function during a fire event. In this study, the *failed-dangerous* event defines the Operational probability of failure (1- reliability estimate). **A** sprinkler system not operating during a fire event or an operating system that does not control or extinguish a fire are examples of this type of failure.

The overall reliability of a system depends on the reliability of individual components and their corresponding failure rates, the interdependencies of the individual components that compose the system, and the maintenance and testing of components and systems once installed to verify operability. All of these factors are of concern in estimating ***operational*** reliability.

Fire safety system performance is also of concern when dealing with the overall concept of reliability. System performance is defined as the ability of a particular system to accomplish the task for which it was designed and installed. For example, the performance of a fire rated separation is based on the construction component's ability to remain intact and provide fire separation during a fire. The degree to which these components prevent fire spread across their intended boundaries defines system performance.

Performance reliability estimates require data on how well systems accomplish their design task under actual fire events or full scale tests. Information on performance reliability could not be discerned directly from many of the data sources reviewed as part of this effort due to the form of the presented data, and therefore, it is not addressed as a separate effect.

The cause of failure for any type of system is typically classified into several general categories: installation errors, design mistakes, manufacturing/equipment defects, lack of maintenance, exceeding design limits, and environmental factors. There are several approaches that can be utilized to minimize the probability of failure. Such methods include (1) design redundancy, (2) active monitoring for faults, **(3)** providing the simplest system (i.e., the least number of components) to address the hazard, and **(4)** a well designed inspection, testing, and maintenance program.

These reliability engineering concepts are important when evaluating reliability estimates reported in the literature. Depending on the data used in a given analysis, the reliability estimate may relate to one or more of the concepts presented above. The literature review conducted under the scope of this effort addresses these concepts where appropriate. Most of the information that was obtained from the literature in support of this paper were reported in terms of ***unconditional*** *operational* reliability, i.e., in terms of the probability that a fire protection strategy will not ***fail dangerous.***

LITERATURE REVIEW

A literature search was conducted to gather reliability data of all types for fire safety systems relevant to the protection strategies considered: automatic suppression, automatic detection, and compartmentation. The objective of the literature search was to obtain system-specific reliability estimates for the performance of each type of fire safety system as a function of generic occupancy type (e.g., residential, commercial, and institutional).

Sources of information included national fire incident database reports, US Department of Defense safety records, industry and occupancy specific studies, insurance industry historical records and inspection reports documented in the open literature, and experimental data. Reports on experimental work and fire testing results were utilized only when fire detection, automatic suppression, or compartmentation strategies were explicitly evaluated. Tests of systems used for qualification, approval, or listing were also reviewed for information on failure modes. Published data from the United Kingdom, Japan, Australia, and New Zealand were included.

General Studies

Several broad based studies were identified that reported reliability estimates for fire detection and fire suppression systems as well as construction compartmentation. These included (1) the Warrington Fire Research study [1996] in the United Kingdom, (2) the Australian Fire Engineering Guidelines [Fire Code Reform Center, 1996], (3) a compilation of fire statistics for Tokyo, Japan [Tokyo Fire Department, 19971, and (4) results from a study of in situ performance of fire protection systems in Japan [Watanabe, 19791.

The Warrington Fire Research study addressed the reliability of fire safety systems and the interaction of their components. A Delphi methodology was used to develop discrete estimates of the reliability of detection and alarm systems, fire suppression systems, automatic smoke control systems, and passive fire protection (e.g., compartmentation).

The Australian Fire Engineering Guidelines were developed as the engineering code of practice supporting the new performance-based Building Code of Australia. Following the methods in this guide, building fire safety performance is evaluated for smouldering, flaming non-flashover, and flaming flashover fires. The performance (i.e., probability of detecting, extinguishing or controlling a fire event) of fire safety systems is predicted, accounting explicitly for the operational reliability of the particular system. Reliability estimates from an expert panel rather than from actual data are provided in the Guideline for this purpose.

Finally, operational reliability data were reported in two separate studies in Japan. One study involved evaluation of fire incident reports from the city of Tokyo during the period from 1990 to 1997 [Tokyo Fire Department 19971. The other study involved review of fire incident reports throughout Japan during an earlier time period ending in 1978 [Watanabe 19791.

Table 1 provides a summary of the reliability estimates provided in these studies. Significant differences exist in the individual reliability estimates depending on the parameters used to develop these estimates. Depending on the required accuracy in predicting future operational performance of fire protection systems, dependence on the range of estimates from these studies could significantly alter the results. In addition, the uncertainty associated with a single estimate of reliability or the existence of potentially important biases in the methods used to derive these estimates may limit their direct usefulness in addressing either operational or performance reliability of fire protection systems.

Table 1. Published Estimates for Fire Protection Systems Operational Reliability (Probability of Success (%))

Protection System	Warrington Delphi UK (Delphi Group)		Fire Eng Guidelines Australia (Expert Survey)		Japanese Studies (Incident Data)	
	Smoldering	Flaming	Smoldering	Flaming/ Flash Over	Tokyo FD	Watanabe
heat detector	0	89	0	90 / 95	94	89
home smoke alarm	76	79	65	75 / 74	NA	NA
system smoke detector	86	90	70	80 / 85	94	89
beam smoke detectors	86	88	70	80 / 85	94	89
aspirated smoke det.	86	NA	90	95 / 95	NA	NA
sprinklers operate	95		50	95 / 99	97	NA
sprinklers control but do not extinguish	64		NA		NA	NA
sprinklers extinguish	48		NA		96	NA
masonry construction	81 29% probability an opening will be fixed open		95 if no opening 90 if opening with auto closer		NA	NA
gypsum partitions	69 29% probability an opening will be fixed open		95 if no opening 90 if opening with auto closer		NA	NA

NA= Not Addressed

Review of Available Reliability Data

Due to the limited applicability of the reliability estimates published in the general literature, the literature review was extended in an effort to (1) develop an improved understanding of the elements of each of the three strategies under consideration that influence reliability, and (2) identify and evaluate quantitative data regarding individual system operability and failure rates.

Automatic Suppression Systems (i.e., sprinkler systems)

Table 2 provides a summary of reported operational reliability estimates from several studies that evaluated actual fire incidents in which automatic sprinklers were present. As a group, these studies vary significantly in terms of the reporting time periods, the types of occupancies, and the level of detail regarding the types of fires and the sprinkler system design.

The estimates presented in Table 2 generally indicate relatively high operational reliability for automatic sprinkler systems. While some of the references include fire "control" or "extinguishment" as part of the reliability assessment, the reported data were not consistent. Therefore, operational reliability was assumed to be limited to sprinkler operation. The estimates also indicate **a** range of values, suggesting that it would be inappropriate to assign a single value for sprinkler system reliability without attention to biases in the data sources and general uncertainty associated with combining data from different databases.

Occupancy	Reference	Reliability Value
Commercial	Milne [1959]	96.6/97.6/89.2
	Automatic Sprinkler [1970]	90.8-98.2
	Miller [1974]	86
	DOE [1982]	98.9
	Maybee [1988]	99.5
	Kook [1990]	87.6
	Taylor [1990]	81.3
	Sprinkler Focus [1993]	98.4-95.8
	Linder [1993]	96
General	Building Research Est. [1973]	92.1
	Miller [1974]	95.8
	Miller [1974]	94.8
	Powers [1979]	96.2
	Richardson [1985]	96
	Finucane et al. [1987]	96.9-97.9
	Marryat [1988]	99.5
Residential	Milne [1959]	96.6
Institutional	Milne [1959]	96.6

The "raw" estimates in Table 2 range from a reliability estimate of 81.13 percent [Taylor] to 99.5 percent [Maybee, Manyat]. The relatively low value of 81 percent associated with Taylor's study as well as the somewhat higher estimate reported by Kook (87.6%) appear to reflect significant biases in the databases used in these studies. In both studies, the number of fire incidents was relatively small, and the database did not differentiate between automatic sprinklers and other types of fire suppression systems. The high end estimates of 99.5 percent reported by Maybee and Marryat reflect sprinkler system performance in occupancies where inspection, testing, and maintenance activities were rigorous and well documented.

Another important limitation in the available sprinkler reliability data is that most of the sprinkler systems involved in the documented incidents included standard spray sprinklers. Limited incident data existed in these references regarding quick response or residential sprinkler technology. Of particular concern in attempting to estimate the reliability of residential sprinkler systems are several factors, including (1) permitted coverage limits, (2) lower water supplies, and (3) the potential for no remote alarm or notification in the event of a fire. These, as well as other factors associated with this technology (e.g., level of maintenance) could directly affect the operational reliability of these types of sprinkler systems. Additional field data are necessary for any attempt to address these issues, but based on this latter observation that residential systems in general are less likely to be maintained properly, some decrease in expected operational reliability for residential sprinkler systems may be warranted.

Fire Detection/Alarm Systems

Table 3 shows a summary of operational reliability estimates for selected occupancy groups. The estimates, including the mean reliability and 95 percent confidence limits, were calculated based on data provided by Hall [1995]. The mean reliability estimates range from approximately 68 to 88 percent. These values correspond roughly with the reliability figures presented in the Warrington Delphi study. However, the general range associated with the 95 percent confidence limits is ***66*** to 90 percent.

Table 3. Reliability Estimates for Smoke Detectors [Hall, 19951

Occupancy	Property Use	Mean Reliability (%) n = 10	95% Upper Confidence Interval	95% Lower Confidence Interval
Residential	Apartments	69.3	69.9	68.7
	Hotels/Motels	77.8	79.3	76.4
	Dormitories	86.3	88.4	84.3
Commercial	Public Assembly	67.9	69.8	65.9
	Stores & Offices	71.7	73.5	69.9
	Storage	68.2	70.0	66.3
	Industry & Manufacturing	80.2	81.3	79.1
Institutional	Care of Aged	84.9	86.6	83.3
	Care of Young	84.0	86.3	81.6
	Educational	76.9	79.6	74.1
	Hospitals & Clinics	83.3	85.4	81.2
	Prisons & Jails	84.2	85.9	82.5
	Care of Mentally Handicapped	87.5	90.3	84.8

Compartmentation relies on the functioning of various types of devices such as doors (including hold open devices), walls, floor/ceilings, penetration seals, glazings, fire dampers, smoke dampers, and construction units. While compartmentation is considered a key fire protection strategy, very little data were found in the literature regarding the performance of the individual elements that influence compartmentation. Discrete estimates for construction and partition operational reliability were provided in the Warrington study and the Australian guidelines, but these estimates were based solely on expert judgement. Therefore, no further analysis is provided.

STATISTICAL INDICATIONS AND UNCERTAINTY ESTIMATES

The literature search summarized in the previous section provided general information and data representing estimates for both automatic sprinkler system and smoke detector reliability. The automatic sprinkler system reliability data came from several sources. The smoke detector reliability estimates came from a single reference, Hall [19941, which contained reliability estimates for a ten-year period (1983-1992) and presented the most comprehensive reliability study found in the literature. One of the initial goals of this paper was to provide an overview of operational reliability estimates for the systems studied. For automatic sprinklers and smoke detectors, this was done by performing a statistical analysis on the available data.

Automatic Sprinkler System Analysis

The reliability estimates presented in Table 2 for automatic sprinkler systems were analyzed for each occupancy type. It should be noted that only one source [Milne, 1959] provided reliability estimates for institutional and residential occupancies, and this early data provided no information regarding the reliability of modem day residential sprinkler technology. Histograms illustrating the distributions for each occupancy's reliability estimates are presented in Figure 1. The mean values and the 95 percent confidence limits were calculated for the general (a category reported in some studies that did not distinguish among commercial, residential, and institutional occupancies) and commercial occupancies, and for the combination (commercial, institutional, residential and general occupancies) of reliability estimates. These results are presented in Table 4.

Residential	Institutional	Commercial	General	Combined
n = 1	n = 1	n = 9	n = 7	n = 18
96.6	96.6	88.1 < 93.1 < 98.1	93.9 < 96.0 < 98.1	92.2 < 94.6 <97.1

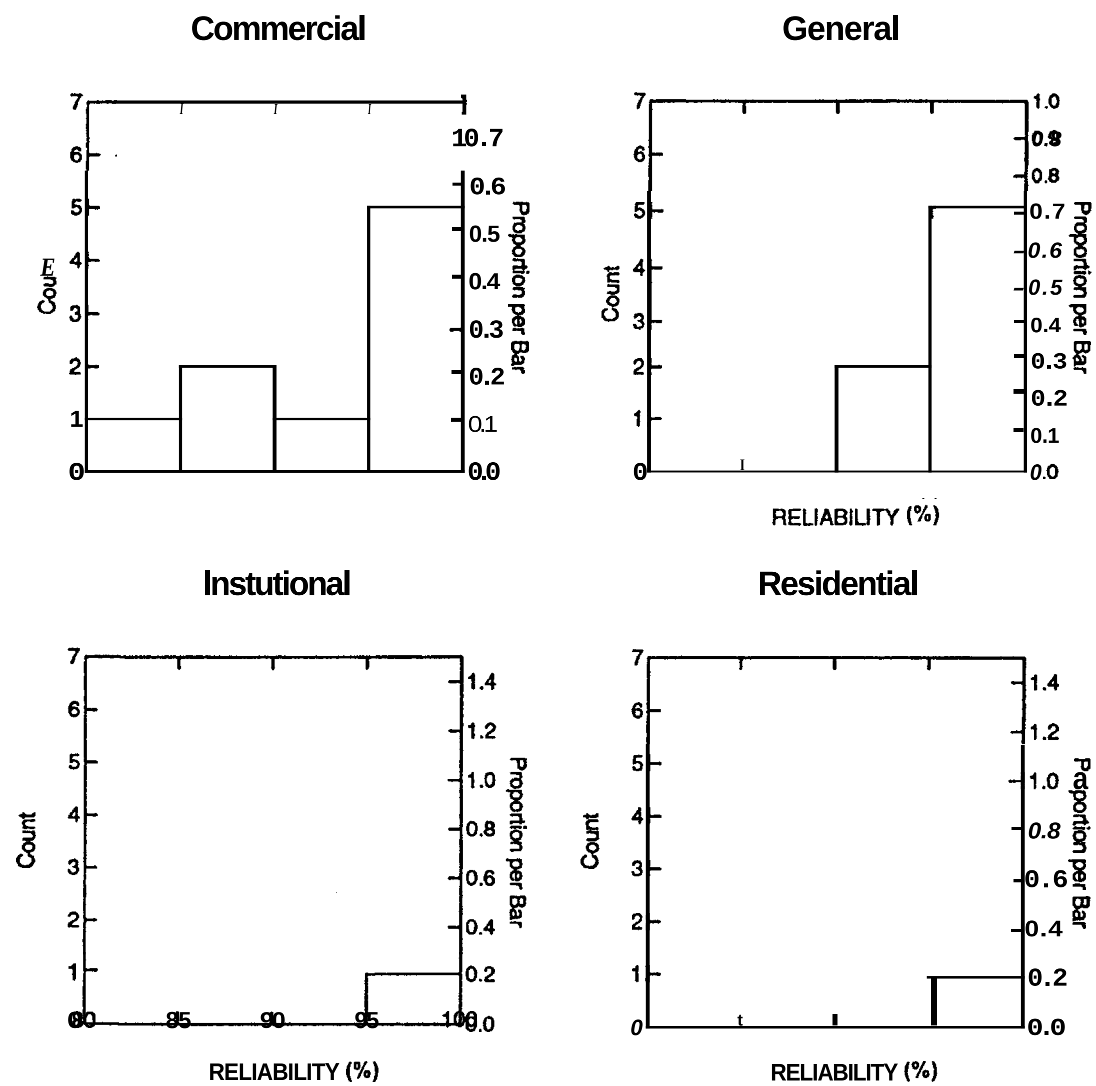

Figure 1. Automatic Sprinkler Reliability Estimates by Occupancy

The mean operational reliability estimates for commercial and institutional occupancies are contained within the 95 percent confidence intervals of the other reported occupancies. The single point estimates for residential and institutional occupancies added somewhat to the usefulness of the combined operational reliability estimates by increasing the size of the overall database, using **18** estimates for the four individual categories. However, the individual point values for residential and institutional occupancies should not be used alone to draw any conclusions.

The reliability estimates for commercial, general, and the combined occupancies provide some useful information. Based on the data available for this analysis sprinkler systems were estimated to have an operational reliability above **–88** percent, and if commercial occupancies are not being considered, sprinkler system reliability can be assumed to be above –92 percent. However, it is important to determine if the particular sprinkler system being compared to these estimates is similar to the referenced systems. The range for "commercial" buildings was estimated at 88 to 98 percent, and for "general," the range was 94 to 98 percent.

Smoke Detector Analysis

The data located for smoke detector reliability estimates was comprehensive. The data set spanned ten years and reported reliability estimates (as reflected in Table **3)** for each year. This was done for several property uses. The analysis presented here examined the property use descriptions and divided them into occupancy classifications. The data from each property use were then used to calculate reliability estimates for each occupancy type. Figure 2 illustrates the distribution for all of the smoke detector reliability estimates across all occupancies.

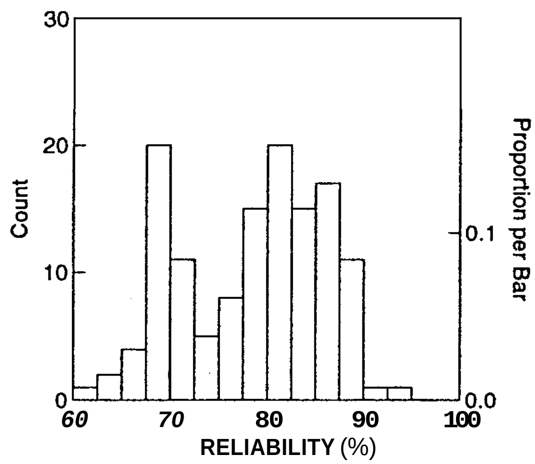

Figure 2. Smoke Detector Reliability Estimate Distribution ıor All Occupancies

As shown in the histogram, the data have a bi-modal distribution. Therefore, to further investigate the possibility of two distinct mean values in this data set, an analysis of variance (ANOVA) was performed. The ANOVA examined the mean reliability estimate and the influence on that estimate by a given occupancy's contribution. A graphical representation of the ANOVA in the form of a least squares means plot is presented in Figure **3.**

The ANOVA results concluded, as Figure **3** illustrates, that the three occupancy classifications each have different mean reliability estimates for smoke detectors. Figure **4** contains histograms describing the reliability estimate distributions for each occupancy classification.

Least Squares Means

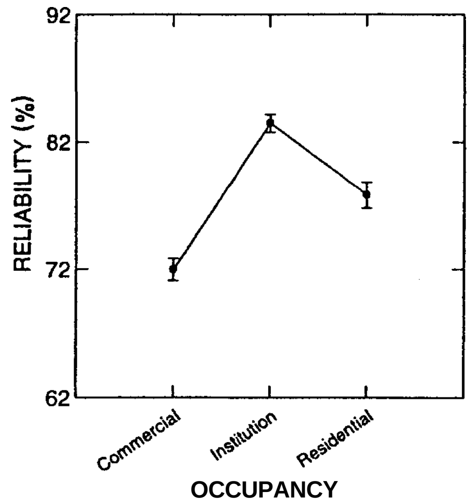

Figure 3. ANOVA Results for Smoke Detector Reliability Estimates by Occupancy

These individual occupancy distributions were analyzed separately for mean reliability estimates and 95 percent confidence intervals. The results are presented in Table 5. The results for each occupancy were significantly different. The confidence intervals between occupancy classification did not overlap as with the automatic sprinkler system reliability estimates. This could be due to the more extensive data set used in the smoke detector analysis. The estimates presented in Table 5 indicate a distinct difference in reliability for smoke detectors depending on the occupancy classifications. Determining the non-data related reasons for the difference is beyond the scope of this analysis.

Residential	Institutional	Commercial
n = 30 75.1 < 77.8 < 80.6	n = 60 82.3 < 83.5 < 84.6	n = 41 70.2 < 72.0 < 73.7

The data used in this analysis were viewed as representative of the systems described in the studies and, currently, the best data available in the open literature on sprinkler system and smoke detector reliability. The representativeness of the data is an important consideration in determining the type of information that can be attained from a statistical analysis of this type. The results of the analysis should be used for making inferences only after examining the referenced studies and determining their applicability to the particular safety strategy employing the analyzed systems. However, the approach as outlined represents a significant advancement in addressing the reliability of different fire protection strategies, including attention to uncertainty and bias in reported data.

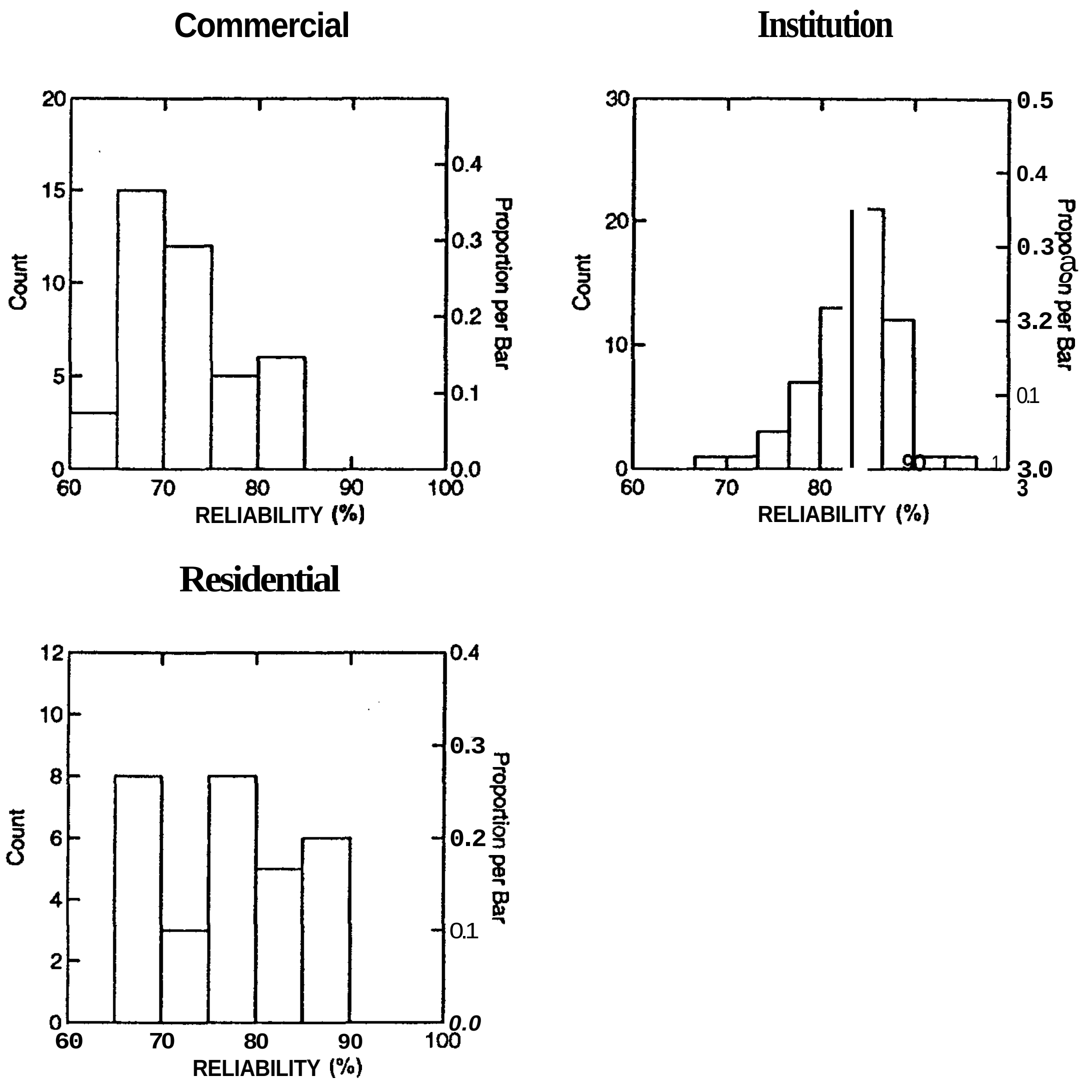

Figure 4. Reliability Estimate Distributions for Smoke Detectors by Occupancy

SUMMARY AND CONCLUSIONS

A detailed literature review and analysis of available operational reliability data were conducted to provide insight regarding the operational reliability of several fire protection strategies, including fire detection, automatic sprinklers, and compartmentation. For this study, operational reliability was defined as the estimate of the probability that a fire safety system will operate on demand. Several recent studies provide such reliability estimates, based primarily on expert judgement. These published values do not directly account for uncertainty or biases in the estimates. For compartmentation, the reliability estimates summarized in Table 1 were the only information found.

In an attempt to address uncertainty in the estimates, several relevant detailed studies of fire incidents and operational performance of smoke detectors and automatic sprinklers were reviewed, and the reported data were extracted for a more structured evaluation. Relevant data for compartmentation were not found. This evaluation included the use of conventional statistical methods to evaluate the available reliability data and provide estimates of mean operational reliability as well as the range of operational reliability values associated with 95 percent confidence limits. Tables **4** and ***5*** summarize the results of this analysis.

The results indicate that the use of a single value for estimating operational reliability of a fire protection strategy is not appropriate. For example, in Table **4,** the operational reliability estimates for sprinkler systems in commercial occupancies range from 88 to 98 percent, with **a** mean estimate of 93 percent. The populations were too small (single values) to calculate mean values and confidence limits for residential or institutional occupancies, but the combined occupancy group had a calculated mean reliability estimate of 95 percent, with 95 percent confidence limits of 92 to 97 percent. The use of the mean value for reliability, based on the knowledge that the value represents the mean of a range with 95 percent confidence limits, is significantly more justified than the use of an arbitrarily derived value. In addition, the use of the entire confidence interval and not just the most probable mean value when comparing systems is significantly more informative since all similar system reliability estimates are included in the comparison. This is a generally accepted statistical approach when comparing one system to many others.

The values for smoke detector operational reliability in Table *5* have a much tighter range associated with 95 percent confidence limits. This may be the direct result of the size and quality of the database as well as the consistency in the initial interpretation of the results by Hall [1995]. Based on the results presented in Table 5, the mean value for operational reliability of smoke detectors was **72.0** percent (lower bound 70.**2%,** upper bound **73.7%)** for commercial, **77.8** percent (lower bound 75.1%, upper bound 80.6%) for residential, and 83.5 percent (lower bound **82.3%,** upper bound **84.6%)** for institutional occupancies.

The **ANOVA** results for smoke detector reliability further indicate that the reliability estimates are occupancy type dependent (see Figure **3)** for the data analyzed. The highest reliability for smoke detector systems was associated with institutional occupancies. This effect may be the direct result of more demanding maintenance and routine system certification requirements for many of the institutional type occupancies.

The methods presented in this analysis can be readily applied to evaluation of the operational reliability of other fire protection strategies. However, it should be noted that the quality of the data in the literature is an important consideration. Considerable variation in the form and detail of the data was observed in the reports and studies reviewed as part of this effort. This study provides a very broad, preliminary attempt to describe fire safety systems operational reliability. Broad data gathering protocols are needed to improve the databases. Such an effort with a focus on obtaining more specific input data for a broader population of systems could provide the basis for significant improvements in estimates of operational reliability for fire protection strategies of interest to design engineers and authorities. This technical information is also necessary for engineering based analyses associated with rapidly progressing performance based design concepts.

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