J. APPLIED FIRE SCIENCE, Vol. 6(2) 109-126, 1996-97

RISK ANALYSIS OF RESIDENTIAL FIRE DETECTOR PERFORMANCE

LARRY GROSSE, PH.D.
Colorado State University

JAC DEJONG, PH.D.
Texas A&M University

JOHN MURPHY, PH.D.
Colorado State University

ABSTRACT

As the percentage of American homes with smoke detectors increased to an estimated 92 percent in 1994, the fire related death rate in one- and two-family dwellings did not experience a corresponding decrease. To determine the probability of a fatality based on the performance of residential fire detectors, data from various studies were utilized and integrated into a risk analysis. To effectively accomplish this objective, a fault tree model was generated which provided the basis for the development of the risk analysis. Data generated by the National Smoke Detector Project and from real scale experiments conducted by researchers at Texas A&M University was consolidated and utilized in the development of a realistic risk analysis for the performance of fire detectors for various fire scenarios. A review of the risk analysis provides a clear example of the probability of a fatality if there is no consideration as to the risk involved with the use of the various types of fire detectors. Certain types of fire detectors are more responsive for the different types of fires. Therefore, recommendations as to the type and location of the fire detector should include the type of fire ignition that would most likely occur and the most responsive detector that can be installed in that location.

RISK ANALYSIS OF FIRE DETECTOR PERFORMANCE

Background

It has been reported that during a twenty-year period, at least ten independent studies on fire detector performance were conducted producing 206 real-scale experiments in single family houses or apartment buildings utilizing actual household items such as upholstered furniture, mattresses, wiring, and trash baskets as the fire source. As noted, all tests used standard heat and smoke detectors, assumed to be new and available for purchase at the time the tests were conducted. Interestingly, the studies presented conclusions that were essentially identical [1]. Typically, the studies offered a review of the performance profile for the various fire detectors to several different fire scenarios. Conclusions from several of the studies were utilized in the development of the current requirements for residential fire detectors.

Initially, the fire related death rate in residential structures demonstrated a corresponding decline with the increase in the percentage of households with smoke detectors [2]. Annual fire related deaths began this decline from a reported 12,000 deaths in 1975 to approximately 5,000 deaths in 1990, while residential smoke detector coverage increased by 60 percent [3]. The civilian fire related deaths in one- and two-family dwellings reversed the 1980s downward trend in 1992 with an increase of 8.8 percent above the previous year [4]. This upward trend in fire related deaths continued for the next several years, even as the reported percentage of one- and two-family dwellings with a smoke detector increased to a high of 88 percent in 1992 [5] and an estimated 92 percent coverage rate in 1994. This trend has precipitated a number of organizations with an interest in fire safety to develop a review process of the apparent problems being experienced in an effort to determine the cause and a possible solution. An example of this effort was the creation of the National Smoke Detector Project, which was a joint project between the Consumer Product Safety Commission (CPSC), the Congressional Fire Services Institute, the U.S. Fire Administration (USFA), and the National Fire Protection Association (NFPA). This effort resulted in a national survey to determine the numbers and types of smoke detectors installed in households and the proportion of installed detectors that are in working order [5]. Another major study generated by the National Smoke Detector Project was the "Fire Incident Study," developed to identify the reasons why smoke detectors failed to alarm in residential fires [6]. The data collected from both of the previously mentioned studies, while important, was limited in scope since the "Smoke Detector Operability Survey" only utilized non-destructive simulated smoke test to determine if the smoke detector was operable [5]. The "Fire Incident Study" investigated smoke detectors where it was believed the detectors did not alarm when they should have [6]. In order to expand the scope of the study on fire detector inoperability, data from the previous studies were integrated with real-scale experiments conducted by a team of researchers at Texas A&M University with assistance provided by researchers from Iowa State University and Colorado State University. The outcome of this consolidation of data resulted in the development of a realistic risk analysis for the performance of fire detectors for various fire scenarios.

The process of utilizing data from the various studies, integrated into one risk analysis, provides an evaluation tool to determine the probability of success or failure of a fire detector to alarm with normal installation and maintenance in a residential structure. This process permits the incorporation of actual influences such as lack of cleaning, power disconnected because of nuisance alarm, and contact corrosion to be considered with the demonstrated real-scale performance of the fire detectors in controlled experiments. To effectively accomplish this objective, a fault tree model was generated which provided the basis for the development of the risk analysis.

Elements Utilized in Development of Risk Analysis

Smoke Detector Operability Survey

As previously noted, The National Smoke Detector Project generated the "Smoke Detector Operability Survey" to determine the numbers and types of smoke detectors installed in households, the proportion of installed smoke detectors that are working, the ways in which smoke detectors are failing, factors that are leading to non-working detectors, and types of households or housing that are more likely to have non-working smoke detectors (see Figure 1) [5]. As a part of this survey, data were collected for evaluating smoke detectors by including such factors as the types of smoke detectors, the degree of maintenance and the operability of the detector when submitted to the activation of the test button and the application of simulated smoke.

Fire Incident Study

The National Smoke Detector Project also provided for another study and report called the "Fire Incident Study." This study was based on data collected by fire departments from fifteen United States cities. The study stated that its

	Probability of Occurrence	
Conditions Observed	Ionization	Photoelectric
Lack of Cleaning	.029	.008
Power Disconnected Because of Nuisance Alarm	.095	.019
Loose Wires	.0397	.0043
Contact Corrosion	.007	.002
Broken, Not Working-Disconnected Contact Poor	.044	.008

Figure 1. Condition of smoke detectors observed. Source: [5].

investigations of detector operability was based on residential fires where it was believed that the detector did not alarm [6]. The nature of this study limited the data collected, yet it does provide important information on the operability of smoke detectors when exposed to real-scale fires. When factored in with data from the other studies, this study becomes a necessary element in the process to determine why there is a continuing increase in the residential fire related death rate.

Full Scale Testing of Fire Detection Systems

The previous two studies did not address the performance characteristics of smoke detectors when exposed to different real-scale fire scenarios during controlled experiments. For this data, full scale research and testing of fire detection systems were conducted in a residential structure by a team of researchers at Texas A&M University. The tests for this research were conducted during a two and one-half year period beginning in 1991. The residential structure utilized was an existing wood frame, two bedroom, living room, kitchen, bath, and utility room building constructed in 1945 near Taylor, Texas. The interior walls and ceiling of the wood framed structure were covered with one-half inch (1.27 cm) gypsum board with hardwood flooring.

Since various and multiple full scale fire tests were designed to be conducted in the residential structure, a number of modifications were incorporated into the structure to enhance the fire resistance of the areas to be exposed to fire. The modifications were designed to negate the destructive actions of multiple full scale fires limited to the room of fire origin. The modifications were also designed to upgrade the interior conditions to replicate environmental conditions such as a heating/ventilation/air conditioning system (HVAC), and ceiling fans, similar to those found in current residential structures.

Prefabricated fire detector mounting panels were designed for the installation of a new ionization smoke detector, a new photoelectric smoke detector, a new 117°F (47.22°C) fusible link fire detector, and a new 135°F (57.22°C) fusible link residential sprinkler head. Each of the fire detectors were wired to permit continuous monitoring of the detector. The nine volt power supply smoke detectors were wired to create a monitor circuit across the alarm contact points. Alarm activation would cause a voltage flow in the monitor circuit that would be recorded by a computer. Shielded monitor circuits were connected to a mechanical switch on each fusible link detector and across the release spring of each sprinkler head. A remote low voltage power supply served each of these circuits and fuse operation. The point of detector activation caused a resistance change in the monitor circuits, which in turn was recorded on a computer. The prefabricated fire detector mounting panels were installed in the room of fire origin and in the means of egress.

Room of fire origin and means of egress environmental monitoring for tenable conditions included smoke obscuration measurements and thermocouples at the point of fire detector installation, at thirty inches (76.2 cm) and five feet (1.5 m) above the finished floor. Also, to assist in determining the environmental conditions of the room of fire origin and the means of egress at the point of detector activation, probes, utilized to acquire samples from the two rooms under study, penetrated the wall and extended two feet (.61 m) into the test area. The intake end of the probe was protected from direct exposure to heat without restricting the movement of the air sample. The air sample was retrieved from the two spaces to be monitored with a sampling pump connected to equipment capable of providing an analysis of the oxygen, hydrogen sulfide, carbon monoxide, hydrocarbon, and carbon dioxide levels.

The room of fire origin was designed to simulate a typical residential arrangement with fabric and finishes selection based on data from the Fire Incident Reporting System [7]. In order to maintain a constant fire load for each of the fire tests, the fabric and furnishings were identical for all tests.

The fire test scenarios were designed to replicate smoldering ignition and flaming ignition fires. Each of the smoldering ignition fire tests occurred in an upholstered easy chair where the back cushion meets the seat cushion and utilized an electrical heating element rated at 602°F (316.67°C). The flaming ignition fire test originated in a wicker waste basket filled with a weighted amount of news print that was ignited with a wooden kitchen match. There were a total of sixteen different fire test scenarios with the variables being the door between the room of origin and the means of egress in an open/closed position, the HVAC system on/off, and a ceiling fan located in the room of origin on/off. Each of the various fire scenarios were replicated three times with data from the three tests averaged and the result utilized as the data point for evaluation. The only criteria concerning the activation time of fire detectors used in this study required an activation while the room of fire origin was tenable.

Development of an Evaluation Model

Fault tree analysis has become one of the principal methods of systems safety analysis. A fault tree is a model that can both graphically and logically be used as a diagnostic tool. Properly developed, the fault tree is a detailed deductive analysis that can be used to illustrate and predict the most likely cause of system failure. Initially, the fault tree analysis was developed by Bell Laboratories for the U.S. Air Force for the purpose of determining the possibilities and probabilities of an inadvertent launch of a minuteman missile and of an inadvertent arming of a nuclear device [8].

A fault tree model graphically and logically represents the various combinations of possible fault events and normal events that might occur in a system. It is a logic diagram that depicts certain events that must occur in order for other events to occur. The events are called failures if they are basic initiating events and faults if they are initiated by other events. The occurrence of these events will lead to the occurrence of the top event. The different events utilized in the fault tree model are represented by standard event symbols.

The events are connected by fundamental logic gates referred to as the OR and the AND gates. Each gate has an output based on multiple inputs. The gate inputs are the more basic or lower events which relate to the gate output as a higher event. The OR gate describes a situation where the output event will exist if one or more of the input events exist. The AND gate describes the logical operation that requires the coexistence of all input events to produce the output event [9]. The fault tree is composed by using the deductive process by going from the highest or top event to the more basic events, or from output to inputs. The two gates relate the different events by using the Boolean Algebraic operations.

The construction methodology of the fault tree model represents an order of sequences of events that leads to the undesired top event. The sequence of fault events is sequentially related to the undesired top event by OR and AND gates. The input event to each logic gate is also the output of other logic gates at a lower level. These events are developed downward until the sequences of events lead to basic causes called basic events.

The thought process involved in constructing the fault tree follows established rules that determine the types of gate to use and inputs to the gate. The structuring process is used to develop fault flows in a fault tree when a system is examined on a functional basis such as consideration of system element failure. The structuring process identifies three failure mechanisms or causes that contribute to a component being in a fault state.

1. A primary failure is a failure due to the internal characteristics of the system element under consideration.
2. A secondary failure due to excessive environmental or operational stress placed on the system element.
3. A command fault is an inadvertent operation or non operation of a system element due to failure of initiating element to respond as intended to system conditions [10].

Any fault event that can be described in terms of mechanism failure is defined as a state-of-component fault. Events that have a more basic cause that cannot be described in terms of a simple component failure are termed state-of-system fault events.

The evaluation of the fault tree may be qualitative or quantitative, depending on the scope of the analysis. Although it was developed to determine quantitative probabilities, it is more commonly used for its qualitative aspects. The reason for this stems from the sequence of preparing a qualitative analysis first in order to make a quantitative analysis. Often, the objective of fault tree evaluation can be satisfied by preparing the qualitative analysis [8]. If the system design is found inadequate, then the design can be upgraded and the fault tree re-evaluated.

The system of interest in this study is the performance characteristics of various types of fire detectors exposed to two different fire scenarios. One scenario utilized a smoldering fire source and the other scenario utilized a flaming fire source (see Figures 2 and 3). In this study, the undesired top event was stated in terms of a fatality due to no alarm of any or all of the fire detectors, creating an untenable environment from heat, toxic fire gases, or smoke. Injuries are difficult to define, therefore they were not incorporated into this study. The top event was analyzed utilizing statistical information that either exist or can be developed analytically.

Type of Detector	Door Between Room of Origin and Means of Egress Open/Closed	Failure of Activation While Room of Origin is Within Tenable Limit, Probability of Occurrence	Failure of Activation While Means of Egress is Within Tenable Limit, Probability of Occurrence
Ionization	Open	.67	1×10^{-6}
Ionization	Closed	1×10^{-6}	.67
Photoelectric	Open	1×10^{-6}	1×10^{-6}
Photoelectric	Closed	1×10^{-6}	1×10^{-6}
Fusible Link	Open	.999	.999
Fusible Link	Closed	.999	.999

Figure 2. Performance profile of residential fire detectors based on full scale smoldering fire test. Source: [10].

Type of Detector	Door Between Room of Origin and Means of Egress Open/Closed	Failure of Activation While Room of Origin is Within Tenable Limit, Probability of Occurrence	Failure of Activation While Means of Egress is Within Tenable Limit, Probability of Occurrence
Ionization	Open	1×10^{-6}	1×10^{-6}
Ionization	Closed	1×10^{-6}	.67
Photoelectric	Open	1×10^{-6}	1×10^{-6}
Photoelectric	Closed	1×10^{-6}	.50
Fusible Link	Open	1×10^{-6}	.167
Fusible Link	Closed	1×10^{-6}	.50

Figure 3. Performance profile of residential fire detectors based on full scale flaming ignition fire test. Source: [10].

Determination of Minimum Cut Sets

One of the major objectives of a fault tree model is to determine when the occurrence of basic events can cause the occurrence of the top event. This determination can be derived by developing what are called the minimum cut sets. A cut set is a set of basic events whose occurrence will cause the top event to occur. A cut set is minimal if it cannot be replaced and still insure the occurrence of the top event. After the minimal cut sets for a fault tree have been determined, a non redundant fault tree can be developed. A non redundant fault tree consists of basic events that have been eliminated by using certain identities from set theory [9]. The minimal cut sets for system analysis are shown on Figure 4 for smoldering ignition fires and Figure 5 for flaming ignition fires.

Basic Event	Description of Event	Probability Occurrence
X_1	Smoldering Ignition	1.00
X_2	Lack of Cleaning (Ionization Detector)	.029
X_3	Power Disconnected Because of Nuisance Alarm (Ionization Detector)	.095
X_4	Loose Wires (Ionization Detector)	.0397
X_5	Contact Corrosion (Ionization Detector)	.007
X_6	Broken, Not Working-Disconnected, Contact Poor (Ionization Detector)	.044
X_7	Fails, Door Open (Ionization Detector in Room of Fire Origin)	.67
X_8	Fails, Door Closed (Ionization Detector in Room of Fire Origin)	1×10^{-6}
X_9	Fails, Door Open (Ionization Detector Outside of Room of Fire Origin)	1×10^{-6}
X_{10}	Fails, Door Closed (Ionization Detector Outside of Room of Fire Origin)	.67
X_{11}	Lack of Cleaning (Photoelectric Detector)	.008
X_{12}	Power Disconnected Because of Nuisance Alarm (Photoelectric Detector)	.019
X_{13}	Loose Wires (Photoelectric Detector)	.0043
X_{14}	Contact Corrosion (Photoelectric Detector)	.002
X_{15}	Broken, Not Working-Disconnected, Contact Poor (Photoelectric Detector)	.008
X_{16}	Fails, Door Open (Photoelectric Detector in Room of Fire Origin)	1×10^{-6}
X_{17}	Fails, Door Closed (Photoelectric Detector in Room of Fire Origin)	1×10^{-6}
X_{18}	Fails, Door Open (Photoelectric Detector Outside of Room of Fire Origin)	1×10^{-6}
X_{19}	Fails, Door Closed (Photoelectric Detector Outside of Room of Fire Origin)	1×10^{-6}
X_{20}	Mechanical Failure (Fusible Link Detector)	1×10^{-6}
X_{21}	Fails, Door Open (Fusible Link Detector in Room of Fire Origin)	.999
X_{22}	Fails, Door Closed (Fusible Link Detector in Room of Fire Origin)	.999
X_{23}	Fails, Door Open (Fusible Link Detector Outside of Room of Fire Origin)	.999
X_{24}	Fails, Door Closed (Fusible Link Detector Outside of Room of Fire Origin)	.999

Figure 4. Definition of basic event variables, smoldering ignition.

Basic Event	Description of Event	Probability Occurrence
X_1	Flame Ignition	1.00
X_2	Lack of Cleaning (Ionization Detector)	.029
X_3	Power Disconnected Because of Nuisance Alarm (Ionization Detector)	.095
X_4	Loose Wires (Ionization Detector)	.0397
X_5	Contact Corrosion (Ionization Detector)	.007
X_6	Broken, Not Working-Disconnected, Contact Poor (Ionization Detector)	.044
X_7	Fails, Door Open (Ionization Detector in Room of Fire Origin)	1×10^{-6}
X_8	Fails, Door Closed (Ionization Detector in Room of Fire Origin)	1×10^{-6}
X_9	Fails, Door Open (Ionization Detector Outside of Room of Fire Origin)	1×10^{-6}
X_{10}	Fails, Door Closed (Ionization Detector Outside of Room of Fire Origin)	.67
X_{11}	Lack of Cleaning (Photoelectric Detector)	.008
X_{12}	Power Disconnected Because of Nuisance Alarm (Photoelectric Detector)	.019
X_{13}	Loose Wires (Photoelectric Detector)	.0043
X_{14}	Contact Corrosion (Photoelectric Detector)	.002
X_{15}	Broken, Not Working-Disconnected, Contact Poor (Photoelectric Detector)	.008
X_{16}	Fails, Door Open (Photoelectric Detector in Room of Fire Origin)	1×10^{-6}
X_{17}	Fails, Door Closed (Photoelectric Detector in Room of Fire Origin)	1×10^{-6}
X_{18}	Fails, Door Open (Photoelectric Detector Outside of Room of Fire Origin)	1×10^{-6}
X_{19}	Fails, Door Closed (Photoelectric Detector Outside of Room of Fire Origin)	.50
X_{20}	Mechanical Failure (Fusible Link Detector)	1×10^{-6}
X_{21}	Fails, Door Open (Fusible Link Detector in Room of Fire Origin)	1×10^{-6}
X_{22}	Fails, Door Closed (Fusible Link Detector in Room of Fire Origin)	1×10^{-6}
X_{23}	Fails, Door Open (Fusible Link Detector Outside of Room of Fire Origin)	.167
X_{24}	Fails, Door Closed (Fusible Link Detector Outside of Room of Fire Origin)	.50

Figure 5. Definition of basic event variables, flaming ignition.

Probability Assignments for Basic Events

The twenty-four basic events (X_1-X_{24}) for each fire scenario, developed from the fault tree will be used for the model with probabilities for each, given in Figures 4 and 5. Basic event X_1 will be 1.0 for both fire scenarios since the smoldering or flaming fire is ignited in order to conduct the test. Basic events X_2-X_6 were developed from information generated in the Smoke Detector Operability Survey Report on Findings, prepared for the National Smoke Detector Project and adjusted to reflect the performance of the ionization detector [5]. Basic events X_7-X_{10} represents data collected on the performance of ionization detectors in either a smoldering or flaming ignition scenario from the research project titled Full Scale Research and Testing of Fire Detection Systems in a Residential Structure, conducted at Texas A&M University [11]. Basic events

X_{11}-X_{15} were developed from information generated in the Smoke Detector Operability Survey Report on Findings, and adjusted to reflect the performance of the photoelectric detectors [5]. Basic events X_{16}-X_{19} represent data collected on the performance of the photoelectric detectors in either a smoldering or flaming ignition scenario from research conducted at Texas A&M University (see Figures 6 and 7) [11]. Basic events X_{20}-X_{24} represent data collected on the performance of the fusible link fire detector in either a smoldering or flaming ignition scenario from research conducted at Texas A&M University [11].

Fault Tree Model with Fatality as Top Event Due to No Alarm

Utilizing fault tree theory with a non-redundant fault tree, the probability of the top event failure will equal the probability of failure for one or more of the minimal cut sets. In this study, the top event failure is expressed as a fatality due to no alarm while the room of fire origin is within tenable limits. The probability of occurrence of the top event may be obtained by using Boolean Algebra calculus for the different "OR" and "AND" gates.

In general, if the event inputs to an "AND" gate are A_1, A_2, A_3 . . . . . A_n, then the output A_o, in set theoretic terms, is given by:

$$A_0 = A_1 \cap A_2 \cap \ldots\ldots \cap A_n,$$

in which the symbol $\cap$ represents the intersection of the events.

For an "OR" gate with input events B_1, B_2, B_3, . . . , B_n, the output B_o is given by:

$$B_0 = B_1 \cup B_2 \cup \ldots\ldots \cup B_n,$$

in which the symbol $\cup$ represents the union of the events.

In order to obtain the top event probability, the output event of each "AND" and "OR" gate need to be determined by applying the general probability rules to the set theoretic formulas mentioned heretofore.

For two input events to an "AND" gate, the formula becomes:

$$P[A_1 \cap A_2] = P[A_1] \times P[A_2 \mid A_1]$$

in which $P[A_2 \mid A_1]$ stands for the probability of A_2 given the probability of A_1, where $\mid$ means, "given the." If independence exists for the variables of the input events, then:

$$P[A_1 \cap A_2] = P[A_1] \times P[A_2].$$

For multiple variables, this becomes:

$$P[A_1 \cap A_2 \cap \ldots\ldots \cap A_n] = P[A_1] \times P[A_2] \times \ldots\ldots \times P[A_n].$$

which is the multiplication rule.

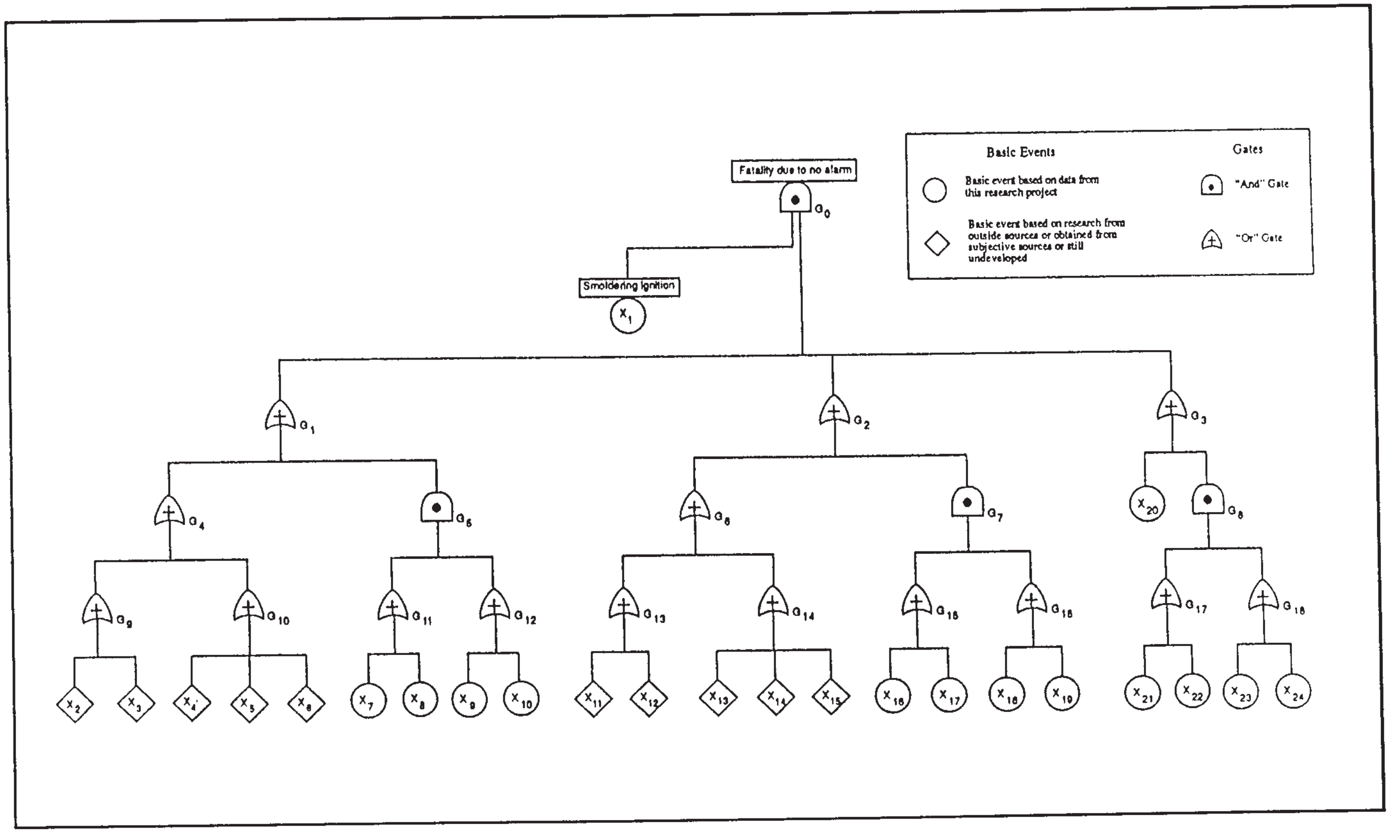

Figure 6. Fault tree development to determine probability of fire detector failure for "smoldering" ignition.

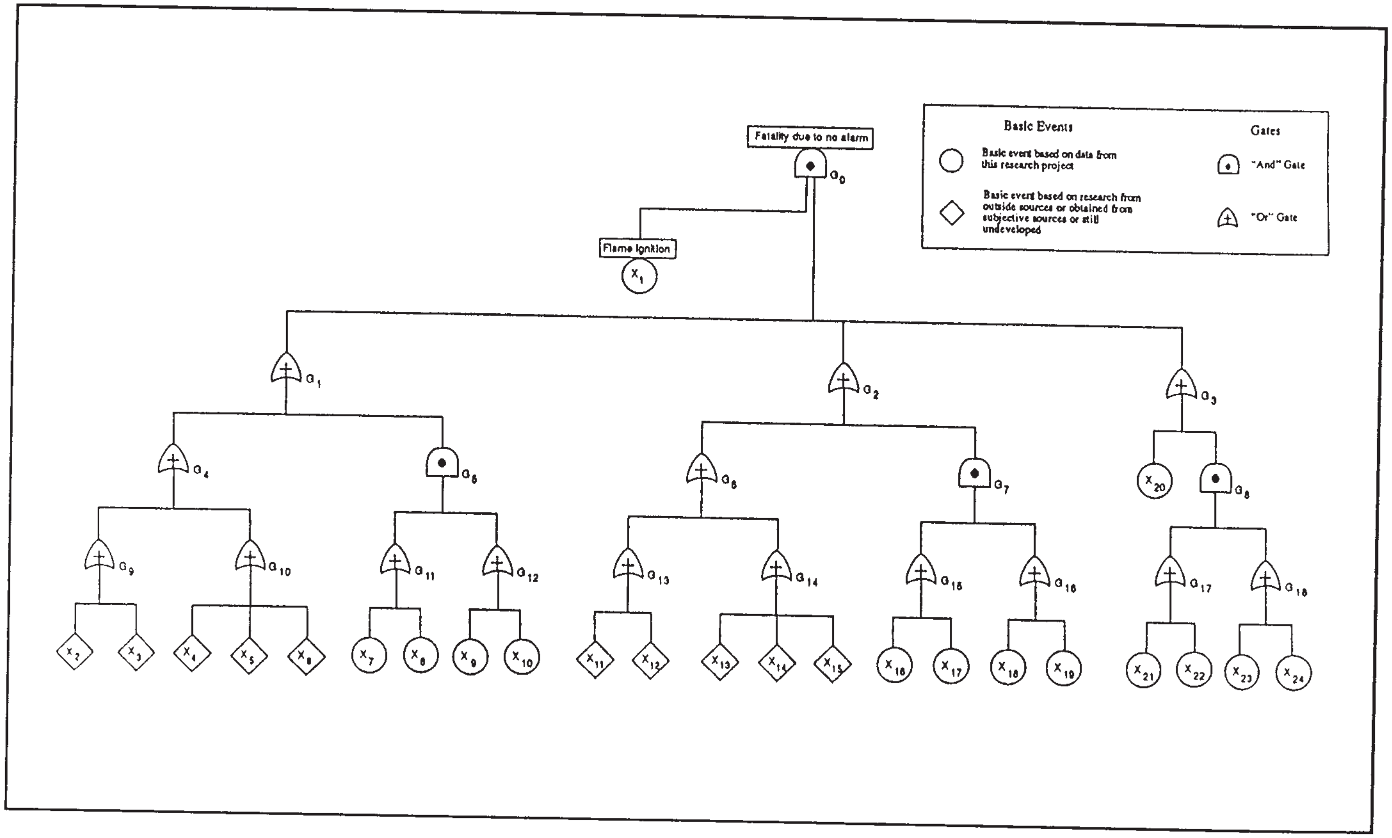

Figure 7. Fault tree development to determine probability of fire detector failure for "flaming" ignition.

Independence here is assumed for these input variables meaning that the probability of A_1, $P[A_1]$, is not affected by the probability of A_2, $P[A_2]$, and vice versa. This independence is assumed to be valid for all event input variables in the actual fault tree model when these variables enter an "AND" gate.

For two input event variables to an "OR" gate, the formula $P[B_1 \cup B_2]$ becomes:

$$P[B_1 \cup B_2] = P[B_1] + P[B_2] - P[B_1] \times P[B_2]$$

for non-mutual exclusive events. In case two input event variables are mutual exclusive, then the formula is:

$$P[B_1 \cup B_2] = P[B_1] + P[B_2]$$

Five input event variables are used in the actual fault tree model. The general formula for five non-mutual exclusive event input variables to an "OR" gate then becomes:

$$\begin{aligned}
&[P(B_1) \cup P(B_2) \cup P(B_3) \cup P(B_4) \cup P(B_5)] = \\
&[P(B_1) + P(B_2) + P(B_3) + P(B_4) + P(B_5)] - \\
&P(B_1) \times [P(B_2) + P(B_3) + P(B_4) + P(B_5)] - \\
&P(B_2) \times [P(B_3) + P(B_4) + P(B_5)] - \\
&P(B_3) \times [P(B_4) + P(B_5)] - [P(B_4) \times P(B_5)] + \\
&[P(B_1) \times P(B_2) \times P(B_3) \times P(B_4) \times P(B_5)]
\end{aligned}$$

Probability of the Top Event Occurring During a Smoldering Ignition Fire

The formula to calculate the probability of the top event (E), based on the performance of the ionization detector is:

$$\begin{aligned}
P(E) = \; &[\, P(X_2) + P(X_3) + P(X_4) + P(X_5) + P(X_6) \,] - \\
&[\, P(X_2) \times P(X_3) \,] - [\, P(X_2 \times P(X_4) \,] - [\, P(X_2) \times P(X_5) \,] - \\
&[\, P(X_2) \times P(X_6) \,] - [\, P(X_3 \times P(X_4) \,] - [\, P(X_3) \times P(X_5) \,] - \\
&[\, P(X_3) \times P(X_6) \,] - [\, P(X_4) \times P(X_5) \,] - [\, P(X_4) \times P(X_6) \,] - \\
&[\, P(X_5) \times P(X_6) \,] + [\, P(X_2) \times P(X_3) \times P(X_4) \times P(X_5) \,] \times \\
&[\, P(X_6) \,] + [\, P(X_7) + P(X_8) \,] \times [\, P(X_9) + P(X_{10}) \,]
\end{aligned}$$

X_7 and X_8 as well as X_9 and X_{10} are mutual exclusive events.

Using the above equation and the values of the variables provided from the summary of probability of basic events in Figure 4, the probability of the top event (E) occurring based on the performance of the ionization detector during a smoldering ignition is:

$$P(E) = 55.8\% \text{ (Ionization detector only)}$$

The formula to calculate the probability of the top event (E), based on the performance of the photoelectric detector is:

$$\begin{aligned} P(E) = {} & [\,P(X_{11}) + P(X_{12}) + P(X_{13}) + P(X_{14}) + P(X_{15})\,] - \\ & [\,P(X_{11}) \times P(X_{12})\,] - [\,P(X_{11}) \times P(X_{13})\,] - \\ & [\,P(X_{11}) \times P(X_{14})\,] - [\,P(X_{11}) \times P(X_{15})\,] - \\ & [\,P(X_{12}) \times P(X_{13})\,] - [\,P(X_{12}) \times P(X_{14})\,] - \\ & [\,P(X_{12}) \times P(X_{15})\,] - [\,P(X_{13}) \times P(X_{14})\,] - \\ & [\,P(X_{13}) \times P(X_{15})\,] - [\,P(X_{14}) \times P(X_{15})\,] + \\ & [\,P(X_{11}) \times P(X_{12}) \times P(X_{13}) \times P(X_{14}) \times P(X_{15})\,] + \\ & [\,P(X_{16}) + P(X_{17})\,] \times [\,P(X_{18}) + P(X_{19})\,] \end{aligned}$$

X_{16} and X_{17} as well as X_{18} and X_{19} are mutual exclusive events.

Using the above equation and the values of the variables provided from the summary of probability of basic events in Figure 4, the probability of the top event (E) occurring based on performance of the photoelectric detector during a smoldering ignition is:

$$P(E) = 4.06\% \text{ (Photoelectric detector only)}$$

The formula to calculate the probability of the top event (E), based on the performance of the fusible link detector is:

$$P(E) = P(X_{20}) + [\,P(X_{21}) + P(X_{22})\,] \times [\,P(X_{23}) + P(X_{24})\,]$$

Using the above equation and the values of the variables provided from the summary of probability of basic events in Figure 4, the probability of the top event (E) occurring based on the performance of the fusible link detector during a smoldering ignition is:

$$P(E) = 99.9\% \text{ (Fusible link detector only)}$$

Probability of the Top Event Occurring During a Flaming Ignition Fire

The formula to calculate the probability of the top event (E), based on the performance of the ionization detector is:

$$\begin{aligned} P(E) = {} & [\,P(X_2) + P(X_3) + P(X_4) + P(X_5) + P(X_6)\,] - \\ & [\,P(X_2) \times P(X_3)\,] - [\,P(X_2) \times P(X_4)\,] - \\ & [\,P(X_2) \times P(X_5)\,] - [\,P(X_2) \times P(X_6)\,] - [\,P(X_3) \times P(X_4)\,] - \\ & [\,P(X_3) \times P(X_5)\,] - [\,P(X_3) \times P(X_6)\,] - [\,P(X_4) \times P(X_5)\,] - \\ & [\,P(X_4) \times P(X_6)\,] - [\,P(X_5) \times P(X_6)\,] + \\ & [\,P(X_2) \times P(X_3) \times P(X_4) \times P(X_5) \times P(X_6)\,] + \\ & [\,P(X_7) + P(X_8)\,] \times [\,P(X_9) + P(X_{10})\,] \end{aligned}$$

Using the above equation and the values of the variables provided from the summary of probability of basic events in Figure 5, the probability of the top event (E) occurring based on the performance of the ionization detector during a flaming ignition is:

$$(P)E = 19.8\% \text{ (Ionization detector only)}$$

The formula to calculate the probability of the top event (E), based on the performance of the photoelectric detector is:

$$\begin{aligned} P(E) = {} & [\, P(X_{11}) + P(X_{12}) + P(X_{13}) + P(X_{14}) + P(X_{15}) \,] - \\ & [\, P(X_{11}) \times P(X_{12}) \,] - [\, P(X_{11}) \times P(X_{13}) \,] - \\ & [\, P(X_{11}) \times P(X_{14}) \,] - [\, P(X_{11}) \times P(X_{15}) \,] - \\ & [\, P(X_{12}) \times P(X_{13}) \,] - [\, P(X_{12}) \times P(X_{14}) \,] - \\ & [\, P(X_{12}) \times P(X_{15}) \,] - [\, P(X_{13}) \times P(X_{14}) \,] - \\ & [\, P(X_{13}) \times P(X_{15}) \,] - [\, P(X_{14}) \times P(X_{15}) \,] + \\ & [\, P(X_{11}) \times P(X_{12}) \times P(X_{13}) \times P(X_{14}) \times P(X_{15}) \,] + \\ & [\, P(X_{16}) + P(X_{17}) \,] \times [\, P(X_{18}) + P(X_{19}) \,] \end{aligned}$$

Using the above equation and the values of the variables provided from the summary of probability of basic events in Figure 5, the probability of the top event (E) occurring based on the performance of the photoelectric detector during a flaming ignition is:

$$(P)E = 3.99\% \text{ (Photoelectric smoke detector only)}$$

The formula to calculate the probability of the top event (E), based on the performance of the fusible link detector is:

$$P(E) = P(X_{20}) + [\, P(X_{21}) + P(X_{22}) \,] \times [\, P(X_{23}) + P(X_{24}) \,]$$

Using the above equation and the values of the variables provided from the summary of probability of basic events in Figure 5, the probability of the top event (E) occurring based on the performance of the fusible link detector during a flaming ignition is:

$$P(E) = 1 \times 10^{-6}\% \text{ (Fusible link detector only)}$$

The foregoing may be summarized as follows.

Risk Analysis of Fire Detector Performance

Based on the data collected for the National Smoke Detector Project and research conducted at Texas A&M University, a risk analysis of the various types of fire detectors was generated for two types of fire scenarios, smoldering ignition and flaming ignition. This risk analysis included basic event considerations such as the known performance of fire detectors under normal use conditions; the door between the room of fire origin and hallway in an open or closed position; and the location of the detector either in the room of origin or in the means of egress. The results of the risk analysis offers the probability of occurrence for failure of the fire detector to provide a warning while the room of origin is still tenable, leading to the top event which is defined as a fatality.

Smoldering Ignition

As can be observed from Figure 8, during the smoldering ignition fire, the photoelectric detector offered the most responsive method of detecting the fire while the room of origin was still in a tenable condition. The probability of a fatality due to the failure of the photoelectric detector to detect a smoldering ignition fire is 4.06 percent. The probability of a fatality due to the failure of an ionization detector to detect a smoldering ignition fire is 55.8 percent. This high probability of a fatality due to the failure of the ionization detector can be contributed to a number of factors such as performance under normal use conditions and an inability to consistently detect smoldering smoke particles. The probability of a fatality due to the failure of the fusible link detector to detect a smoldering ignition fire is 99.9 percent. This higher probability of a fatality is due to the fact that the smoldering fire ignition normally produces a room of origin temperature differential of 10°F (2.8°C) +/–, therefore the required heat to fuse the fusible link detector is not present.

Flaming Ignition

As can be observed from Figure 8, during the flaming ignition fire, the fusible link detector offered the most responsive method of detecting the fire while the room of origin was still in a tenable condition. The probability of a fatality due to the failure of the fusible link detector to detect a flaming ignition fire is 1×10^{-6} percent. The probability of a fatality due to the failure of the photoelectric detector to detect a flaming ignition fire is 3.99 percent. The probability of a fatality due to the failure of the ionization detector to detect a flaming ignition fire is 19.8 percent. While the ionization detector responds effectively to a flaming

Type of Detector	Smoldering Ignition Scenario	Flaming Ignition Scenario
Ionization	55.8%	19.8%
Photoelectric	4.06%	3.99%
Fusible Link	99.9%	1×10^{-6}%

Figure 8. Risk analysis for the performance of fire detectors probability of the occurrence of failure for the top event.

ignition, a number of factors such as performance under normal use conditions tends to increase the probability of failure.

Interpretation

The development of the risk analysis offers a partial insight into why there continues to be a high residential fire related death rate in spite of an increase in the residences reported to have smoke detectors installed. The current thought process demonstrated by officials in the position to make recommendations, has been to just install a smoke detector in the home without consideration as to the type of potential fire ignition. A review of the risk analysis provides a clear example of the probability of a fatality if there is no consideration as to the risk involved with the use of the various types of fire detectors. As illustrated, the various types of fire detectors provide different levels of risk which supports the need for a change in the current thought process. Certain types of fire detectors are more responsive for the different types of fires; therefore, recommendations as to the type and location of fire detectors should include the type of fire ignition that would most likely occur and the most responsive detector that can be installed in that location. Only when the risk involved with the use of a certain type of fire detector is considered in any recommendation, can there be an improvement in the residential fire related death rate.

REFERENCES

1. R. Bukowski, Studies Assess Performance of Residential Detectors, *NFPA Journal*, pp. 48-54, January/February 1993.
2. P. G. Le Coque and K. Harris, State by State . . . An Update of Residential Smoke Detector Legislation, *Fire Journal*, pp. 41-47, January/February 1990.
3. M. Baribault and L. Solomon, *The Smoke Detector Industry,* Venture Development Corporation, Wellesley, Massachusetts.
4. M. J. Karter, Fire Loss in the United States in 1992, *NFPA Journal*, pp. 78-87, September/October 1993.
5. C. L. Smith, *Smoke Detector Operability Survey Report on Findings,* Consumer Product Safety Commission, Washington, D.C., October 1994.
6. L. E. Smith, *Fire Incident Study: National Smoke Detector Project,* Consumer Product Safety Commission, Washington, D.C., March 1994.
7. *Fire Incident Reporting System,* Texas Commission on Fire Protection Personnel and Education, Austin, Texas, 1990.
8. R. Barlow, J. Russell, and N. Singpurwalla, *Reliability and Fault Tree Analysis,* Society for Industrial and Applied Mathematics, 1975.
9. N. Stubbs and C. Sikorsky, *Occupant Safety in Vertical Hurricane Shelters,* Technical Report 4968 S-3, National Science Foundation, Washington, D.C., 1985.
10. D. Haasl, *Advanced Concepts in Fault Tree Analysis,* Product System Safety Symposium, Seattle, Washington, 1985.

11. L. Grosse, *Full Scale Research and Testing of Fire Detection Systems in a Residential Structure,* Technical Report, Texas A&M University, 1995.

Direct reprint requests to:

Larry Grosse
Department of Manufacturing Technology and
Construction Management
Colorado State University
Fort Collins, CO 80523