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Application Of Fault Tree Analysis To Ignition Of Fire

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APPLICATION OF FAULT TREE ANALYSIS TO IGNITION OF FIRE

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ABSTRACT

The potential impact of fire can be characterized by (I) the probability of ignition, (II) the probability distribution of fire growth as a function of time and (III) the conditional probability distribution of losses given that a fire has broken out. The original ignition of unwanted fires has four principal causes of ignition: loss of control of wanted fire, arson, spontaneous combustion and malfuntion of equipment. Loss of control refers to ignitions which start with a planned or wanted ignition, but which, due to human error causing a sufficient heat transfer to the target fuel, results in unwanted spread. Malfunction refers to equipment failures such as overloaded electrical circuits or exploding heaters. A fault tree example based on the results of the National Household Fire Survey is constructed for the common situation of fire starting in a kitchen. The minimum cut sets of the fault tree are a listing of the possible fire scenarios to which probability of occurance can be quantitatively assigned by using fire statistics from the field.

INTRODUCTION

According to data reported by the National Fire Protection Association,[1] approximately 9,950 civilians died as a result of the estimated 3.5 million fires in the United States during 1977. Direct property loss in the same period was estimated to be $6.06 billion. Though many of these fires did not progress beyond the original ignition area, they all share the initial event of fire ignition. In some cases, the fire initially represented a useful activity, such as the fire required in cooking and the unwanted fire only occurred when there was a loss of control. In other cases, there was a malfunction of an electrical or gas appliance. This paper addresses the original ignition of fire and Fault Tree Analysis (FTA) is introduced as a means to examine the causes of ignition of fires, and to calculate the probability of ignition.

PRELIMINARY FAULT TREE ANALYSIS[2]

A Fault Tree is a model that represents graphically and logically the various combination of possible events, both fault and normal, occurring in a system and leading to the top event which in the system, is an undesirable event. Fault tree analysis consists of two main parts: construction of the fault tree and evaluation of the fault tree.

Construction of a fault tree:

The first task in the construction of a fault tree is to carefully determine the "top event" which is the undesirable event in the system being analyzed. Applying deductive reasoning, the fault tree is developed by using the following event symbols and logic gates.

Three types of event symbols used in fault tree construction are shown in Figure 1. The rectangle defines intermediate or top events that are the outputs of logic gates. The circle defines a primary failure of a system element and the diamond represents a failure, other than a primary failure that is purposely not being developed any further.

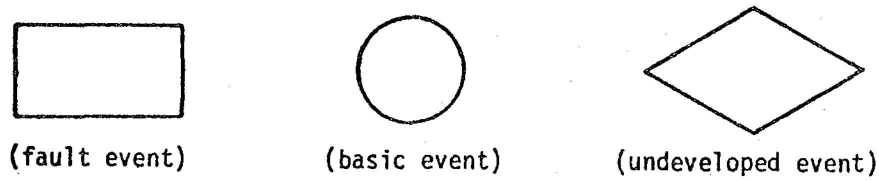

Fig. 1 Event Symbols

These symbols are connected logically by two fundamental logic gates: the OR and the AND gates. The fault event directly above an OR gate will happen if at least one of the input events to the OR gate occurs. The fault event directly above the AND gate, however, will occur only if all the input events to an AND gate have happened. The symbols for the logic gates are shown in Figure 2.

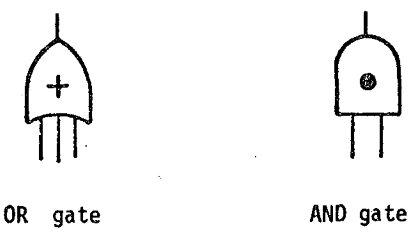

Fig. 2 Logic gates

In the example shown in Figure 3, the event G1 will happen if any one of events E1, E2 or E3 occur; while in Figure 4, the event G2 will happen only if both event E4 and E5 occur. In fault tree analysis the top event

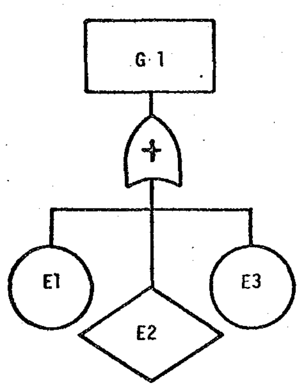

Fig. 3 Example of an OR gate

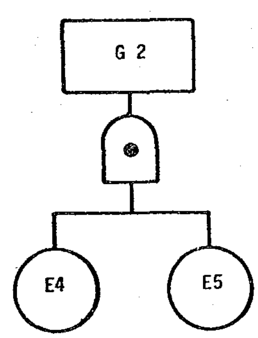

Fig. 4 Example of an AND gate

describes a failure. From the point of view of reliability, one may be interested in the nonoccurrence of the top event. A tree describing the nonoccurrence of the top event is called a dual fault tree. To obtain a dual fault tree from the original tree, every OR gate has to be replaced by an AND gate and vice versa. Also every basic event has to be replaced by the non-occurrence of the original basic event. An example is shown in Figure 5.

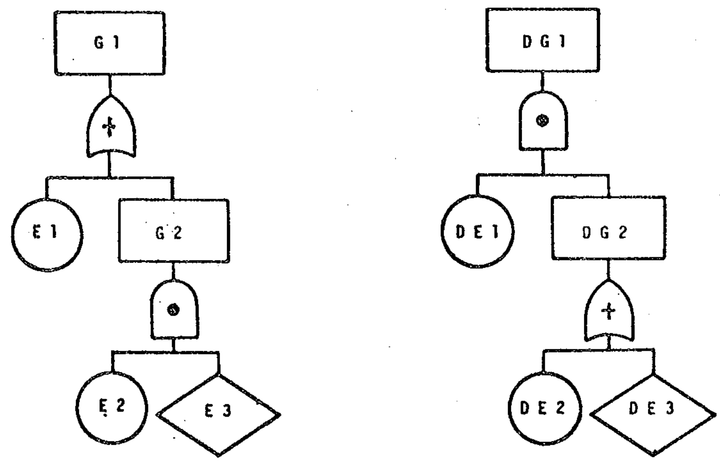

Fig. 5 An illustration of construction of dual fault tree from original fault tree. Dual events are nonoccurrence of corresponding events.

Evaluation of fault tree:

Upon completion of the fault tree, the evaluation can be done qualitatively to find out which element is structurally more important, or quantitatively to find out the probability of the top event occurring.

Qualitative evaluation--minimum cut set algorithm:

A cut set is a set of basic events whose occurrence causes the top event to take place. It is a sequence of events that lead to the failure of the top event. When a cut set cannot be further reduced and still cause the top event to happen, it is called a minimum cut set, or a min cut set for short. The listing of all the min cut sets is useful for both the qualitative and quantitative evaluation of a fault tree. But when a fault tree is large and complicated, it is neither easy nor possible to pick out all the min cut sets just by inspection. A min cut set algorithm was introduced by J. Fussell and W. Vesely.[3] The algorithm is based on the fact that an OR gate always increases the number of min cut sets while an AND gate always increases the size of the min cut set. The algorithm is stated by putting all the events below the OR gate in separate rows and those below the AND gate in separate columns. Continue until all fault events are replaced by basic or undeveloped events. Taking the fault tree in Figure 6, this algorithm is illustrated by the following example:

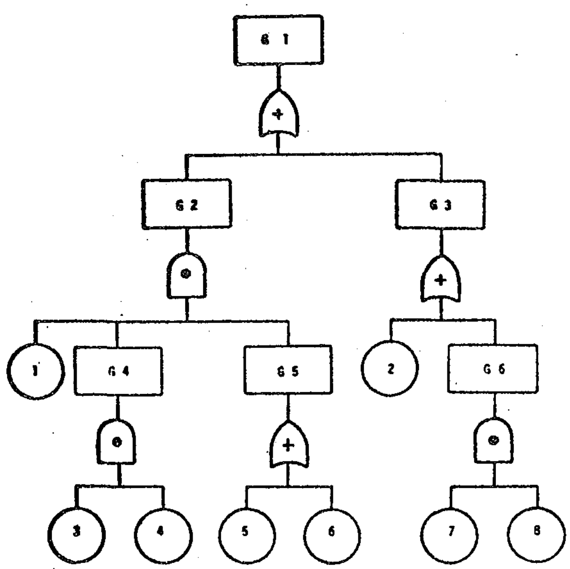

Fig. 6 An example of fault tree to illustrate min cut set algorithm.

Step 1: $\begin{bmatrix} G2 \\ G3 \end{bmatrix}$

Step 2: $\begin{bmatrix} 1 - G4 - G5 \\ G3 \end{bmatrix}$

Step 3: $\begin{bmatrix} 1 - 3 - 4 < {5 \atop 6} \\ G3 \end{bmatrix}$

Step 4: $\begin{bmatrix} 1 - 3 - 4 < {5 \atop 6} \\ 2 \\ G6 \end{bmatrix}$

Step 5: $\begin{bmatrix} 1 - 3 - 4 < {5 \atop 6} \\ 2 \\ 7 - 8 \end{bmatrix}$

The list of all the min cut sets are (1,3,4,5), (1,3,4,6), (2), and (7,8).

ON IGNITION OF FIRE

Ignition of fire refers to the self-sustained burning of one or more items induced by a potential ignition energy. There are four principal causes for ignition of fire: loss of control of a wanted fire, malfunction of equipment, arson and spontaneous combustion.

In the case of ignition due to loss of control of a wanted fire, the potential ignition energy is provided by a wanted or planned ignition, for instance, the stove is lit while cooking. The target fuel is present in the vicinity of the potential ignition energy. The heat source and material property of the target fuel are usually constant. The transfer of energy from the potential ignition source to the target fuel is primarily due to human error. For example, a cook accidentally overturns a pan of oil onto a hot stove; an absent-minded ironer leaves the hot iron on a piece of cloth for too long. These examples depict a special situation where the one who caused the ignition is usually very close by; hence either providing early detection and extinction of the fire or becoming its victim in the case involving flamable fabrics or a large fuel source.

In the case of ignition due to malfunction of equipment, a potential ignition source is created by a failure of the equipment. Equipment is generally designed so that it does not act as an ignition source; however, if combustible material is in the vicinity of the heat energy of a malfunctioning piece of equipment, a fire is likely to start.

Based on this preliminary discussion, a simple fault tree can be constructed as shown in Figure 7. The second level of the fault tree has been patterned on the NFPA decision tree for "Prevent Fire Ignition." The top three levels of the NFPA decision tree are shown in Figure 8 where it can be seen that there are three approaches to preventing ignition.

Quantitative Evaluation of the Fault Tree--Probability evaluation:

Let

$$Y_i = \begin{cases} 1 \text{ if basic events i occurs} \\ 0 \text{ otherwise} \end{cases} \quad \text{and } P\ (Y_i = 1) = q_i$$

Let $(k_1, K_2, \ldots, K_k)$ be the set of min cuts sets and $(P_1, P_2, \ldots, P_p)$ be the set of all min path sets.* If there is no event replication among min cut sets and basic events are statistically independent then

$$P\ (\text{Top event occurs}) = \coprod_{1 \leq s \leq k} \prod_{i \in K_s} q_i \ **$$

If the basic events are independent then

$$\prod_{1 \leq r \leq p} \coprod_{i \in P_r} q_i \leq P\ (\text{Top event occurs}) \leq \coprod_{1 \leq s \leq k} \prod_{i \in K_s} q_i$$

If the basic events are not statistically independent, but rather are "associated", then

$$\max_{1 \leq s \leq k} \prod_{i \in K_s} q_i \leq P\ (\text{Top event occurs}) \leq \min_{1 \leq r \leq p} \coprod_{i \in P_r} q_i$$

If the probability distribution with respect to time of each of the basic events are known, then the probability distribution of the time to occurrence of the top event can be shown as

$$\max_{1 \leq s \leq k} \prod_{i \in K_s} F_i(t) \leq P\ (\text{Tob event occurs by time t}) \leq \min_{1 \leq r \leq p} \coprod_{i \in P_r} F_i(t)$$

* A path set is a set of basic events whose nonoccurrence insure the non-occurrence of the top event. A path set is minimum if it cannot be reduced and still remains a path. Minimal path sets of the original fault tree can be obtained by finding all the cut sets of the dual fault tree using the min cut set algorithm.

** The symbol $\coprod$ is defined as $\coprod_i x_i = 1 - \prod_i (1 - x_i)$

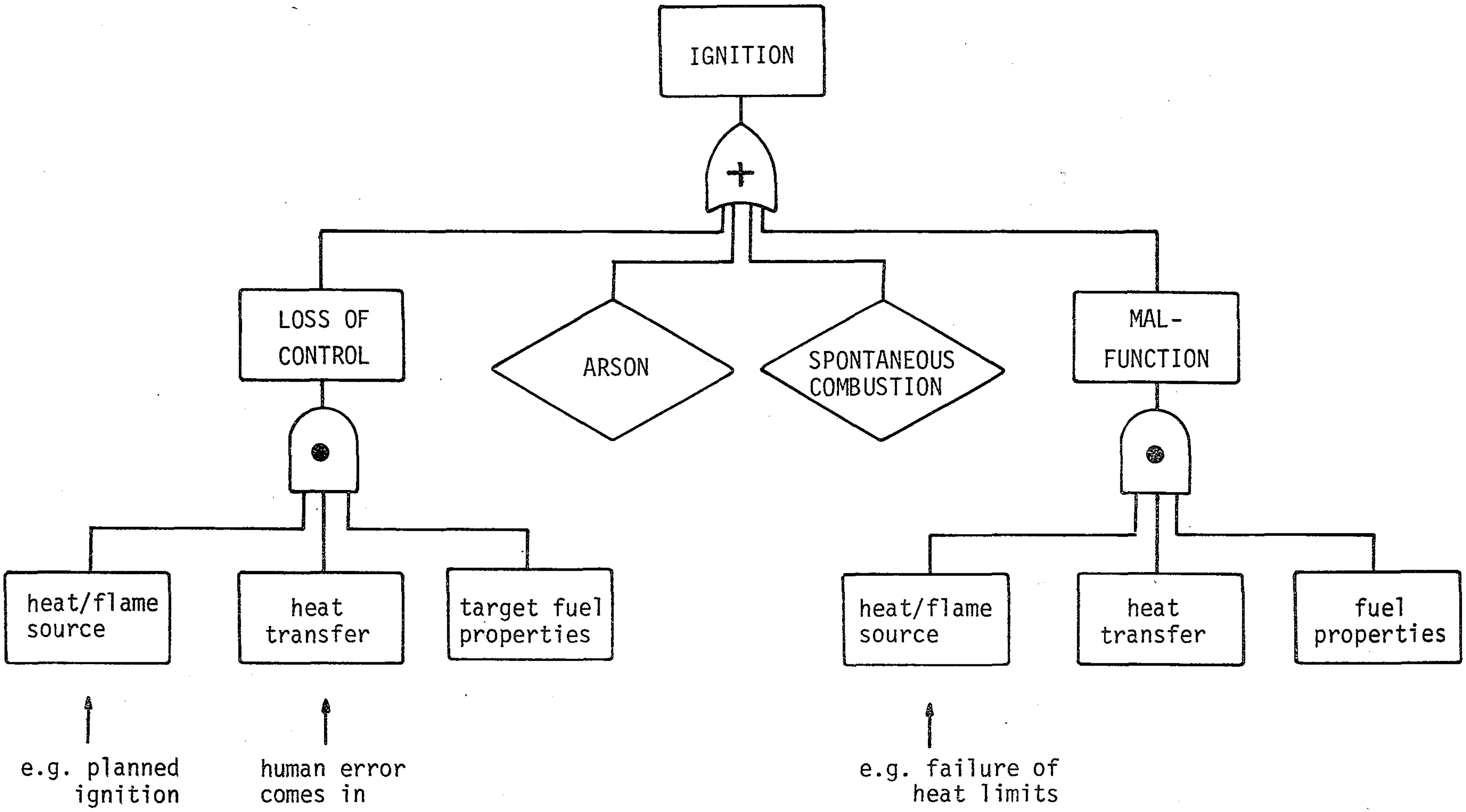

Fig. 7 A simple form of the fault tree for the original ignition process.

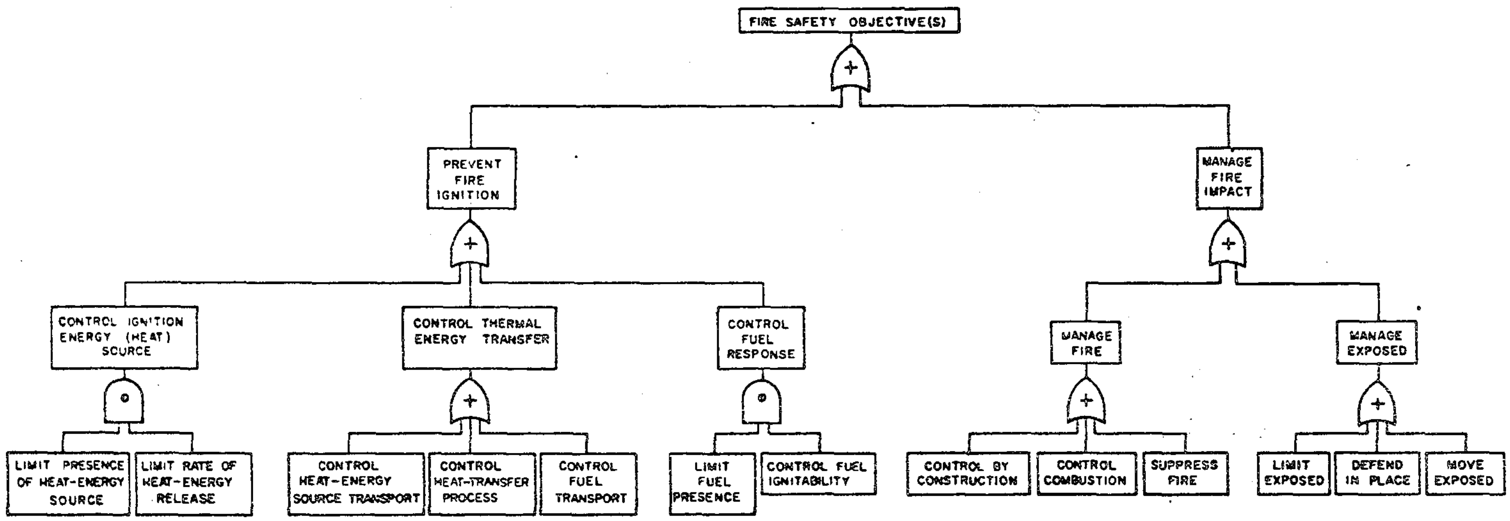

Fig. 8 NFPA Decision Tree for successful control of fire.

It should be pointed out that the NFPA decision tree is a "success tree" which is a dual of the corresponding fault tree. The technique for preventing "ignition" is to either control the ignition energy or control the heat transfer between ignition source and fuel, or control the fuel characteristic. In principle, it is necessary to control only one of these events to prevent ignition; thus the 'OR' gate is placed below the "Prevent Fire Ignition" event in Figure 8. In the fault tree for ignition, there must be an 'AND' gate below either loss of control or malfunction of equipment since ignition requires all these subevents.

To further develop the fault tree in Figure 7, one needs to explore more specific examples. It is also important to incorporate data on actual fire experiences. The following section contains information generated by surveys.

ILLUSTRATION: Kitchen Fire

The most important information about accidents can be gained from a critical-incident survey. A critical-incident survey distributes questionnaire forms in a target population, for instance in a new housing development, calling for brief reports on any recent domestic incidents which could have (but in most cases did not) resulted in a major fire. Crossman[4] presented the techniques and results of a fire survey in the city of Berkeley using the critical-incident survey method. The survey showed that 3 out of 5 fires in the survey started in the kitchen, and that 80% of all the fires were not reported to the fire department. Following informal reports of Crossman's results from the earliest Berkeley survey, NBS Fire Technology Division sought Census Bureau assistance in launching a nationwide sample survey, preliminary results from which have been reported as the National Household Fire Survey (NHFS). The survey, administered on April 15, 1974, asked 33,856

U. S. households to report all fire incidents between April 1, 1973, and April 15, 1974. The incident was to be reported as a fire event if smoke, sparks or flames were detected by the household member. 2, 466 fires were reported and Table 1 contains the estimated number of fire incidents that would have occurred over the entire U. S. population.[5] The estimation of standard error are also shown in Table 1. Although the NHFS is considerably more reliable than Crossman's data,[4] the trends are the same in both surveys.

Table 1

Location of Fire Incidents

LOCATION	NUMBER OF FIRE INCIDENTS	ESTIMATED NUMBER OF FIRE INCIDENTS FOR U.S. POPULATION
Residential	2,017	4,547,000 (SE = 116,000)*
Motor Vehicle	228	527,000 (SE = 38,000)
Other	221	499,000 (SE = 37,000)
TOTAL	2,466	5,575,000

* Standard Error

Room of origin of residential fires can be categorized as shown in Figure 9, and kitchen fires alone constitute about 65% of all residential fires.

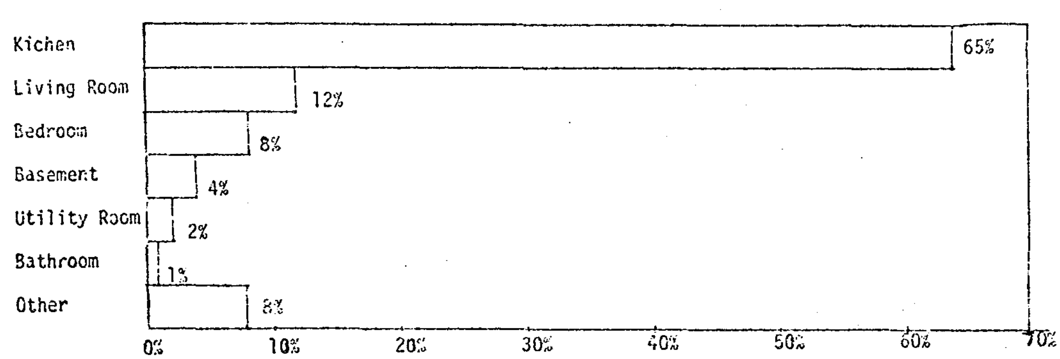

Fig. 9 Room of Origin in Residential Fires

Because of its frequent occurrence, ignition occurring in kitchens is chosen as the example to illustrate the application of the Fault Tree methods to the ignition of fire.

In the NHFS, the respondents were asked to describe the item initially starting the fire -- that is the item from which flames, smoke or sparks originated, and the first item to catch fire. The distribution of what item starts a kitchen fire is shown in Figure 10. The 'other appliances' category includes blenders, electric frying pans, electric mixers and electric coffee pots. Oven and stove top burners are responsible for starting over 80% of all kitchen fires. The first items to ignite may be looked upon as the target fuel. When oven, stove top burners or appliances are reported as

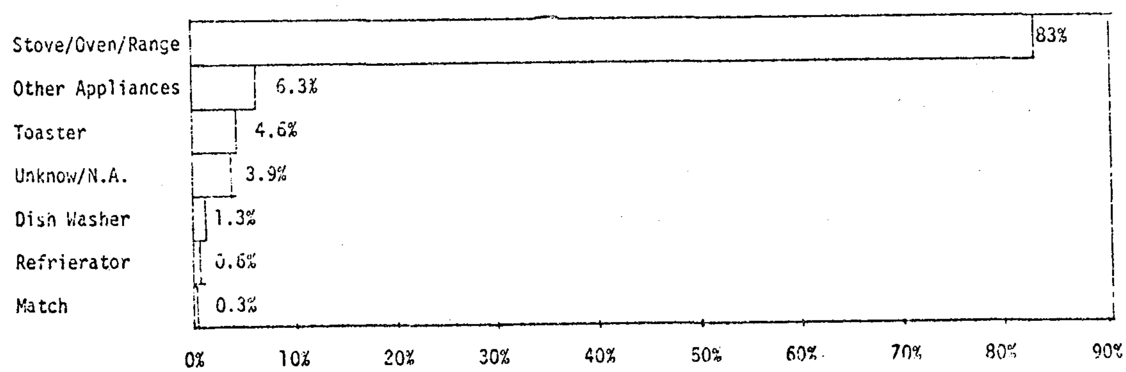

Fig. 10 Ignition Source in a Kitchen (Residential)
'other appliances' category includes blenders, electric frying pans, mixers and coffee pots, etc.

being the first items to catch fire, it is hypothesized that it is actually the grease or food deposit on these appliances that catch fire. Keeping this in mind, the sequences of 'what starts the fire' to 'what caught fire first' are the fire scenarios that lead to the ignition of a kitchen fire. Each scenario can be looked upon as a min cut set in the fault tree. The sequences involved in a kitchen fire are shown in Figure 11. The number attached to each sequence is the probability of that particular sequence occurring.

The probability is estimated as

$$\frac{\text{the number of times a particular sequence has occurred}}{\text{total number of fires}} \cdot \frac{\text{number of reported fires}}{\text{number of sample size}}$$

The first term is the Prob (that a particular sequence occurs | fire occurs).

The second term is the Prob (fire occurs in a household). Note that the

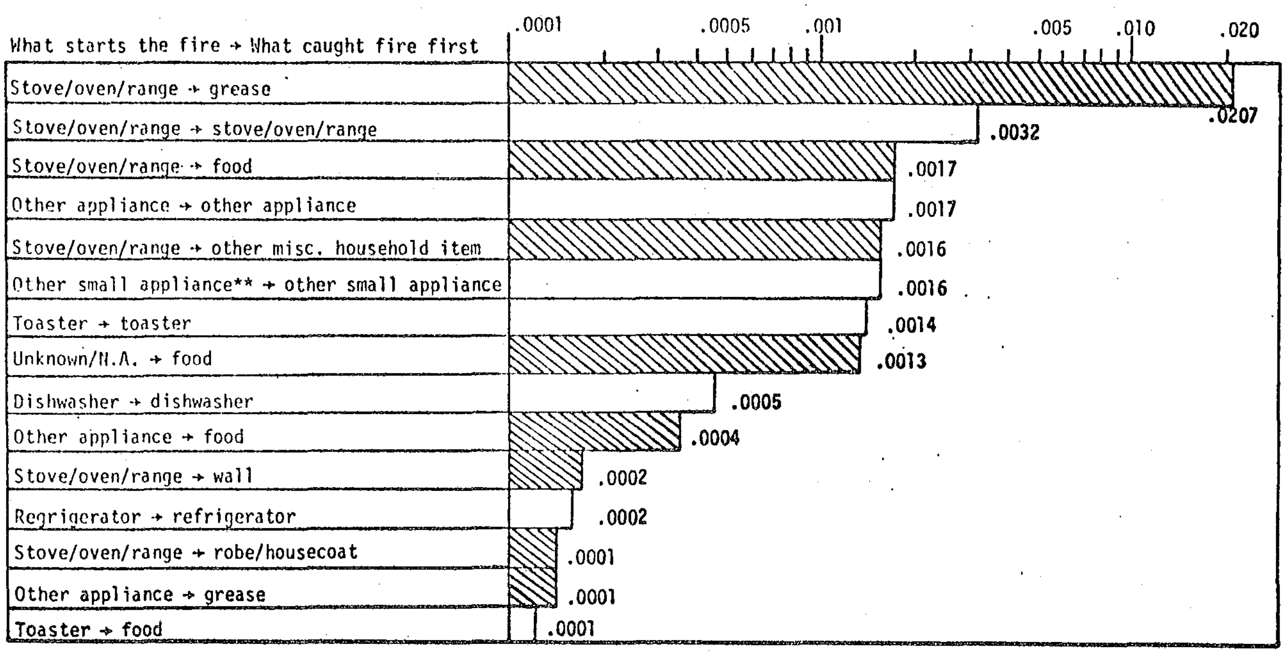

Fig. 11 The Probability of Each Fire Scenario in a Kitchen

 represents those due to loss of control and

 represents those due to malfunction of equipment.

majority of ignitions in a kitchen fire is due to loss of control of a wanted fire. Since a fire in the kitchen is not likely to be as catastrophic as one in a nuclear power plant, the scenarios of a kitchen fire with a probability of less than, say 10^{-3}, can be neglected. Based on the reduced number of scenarios, a fault tree on the ignition of kitchen fire is presented in Figure 12. The dotted portion of the fault tree is caused by a lack of further break down of the data from NHFS. This is espcially true in the area of human error and the type of malfunction. Hence the fault event 'malfunction of equipment' will not be analyzed beyond the level shown. However, the probability of this fault event occurring can be calculated using the results of Figure 11. It gives a probability of 0.009. The probability of the basic events in the subtree under the fault event 'loss of control' is estimated from the data according to the following rules:

$$\text{Prob (event } A_1 \text{ occurs)} = \text{Prob (stove top burner and oven started a fire)}$$
$$= \sum_{\text{all } Y} \text{Prob (the sequence: stove starts a fire and item Y caught fire first)}$$

$$\text{Prob (event } B_j \text{ occurs)} = \text{Prob } (Y_j \text{ caught fire first})$$
$$= \sum_{\text{all } X} \text{Prob (the sequence: item X started a fire and item } Y_j \text{ caught fire first)}$$

for $j = 1,2,3$. The probabilities are shown in Figure 12.

It remains to find Prob (event G_1 occurring), Prob (event G_2 occurring) and Prob (event G_3 occurring), that is, the probabilities of kitchen fires due to arson, spontaneous combustion and sufficient heat transfer in a loss of control case, respectively. In the NHFS data, none of the kitchen fires are due to either arson or spontaneous combustion; hence there is no estimate to their probability of occurring. They will be denoted by P_1 and

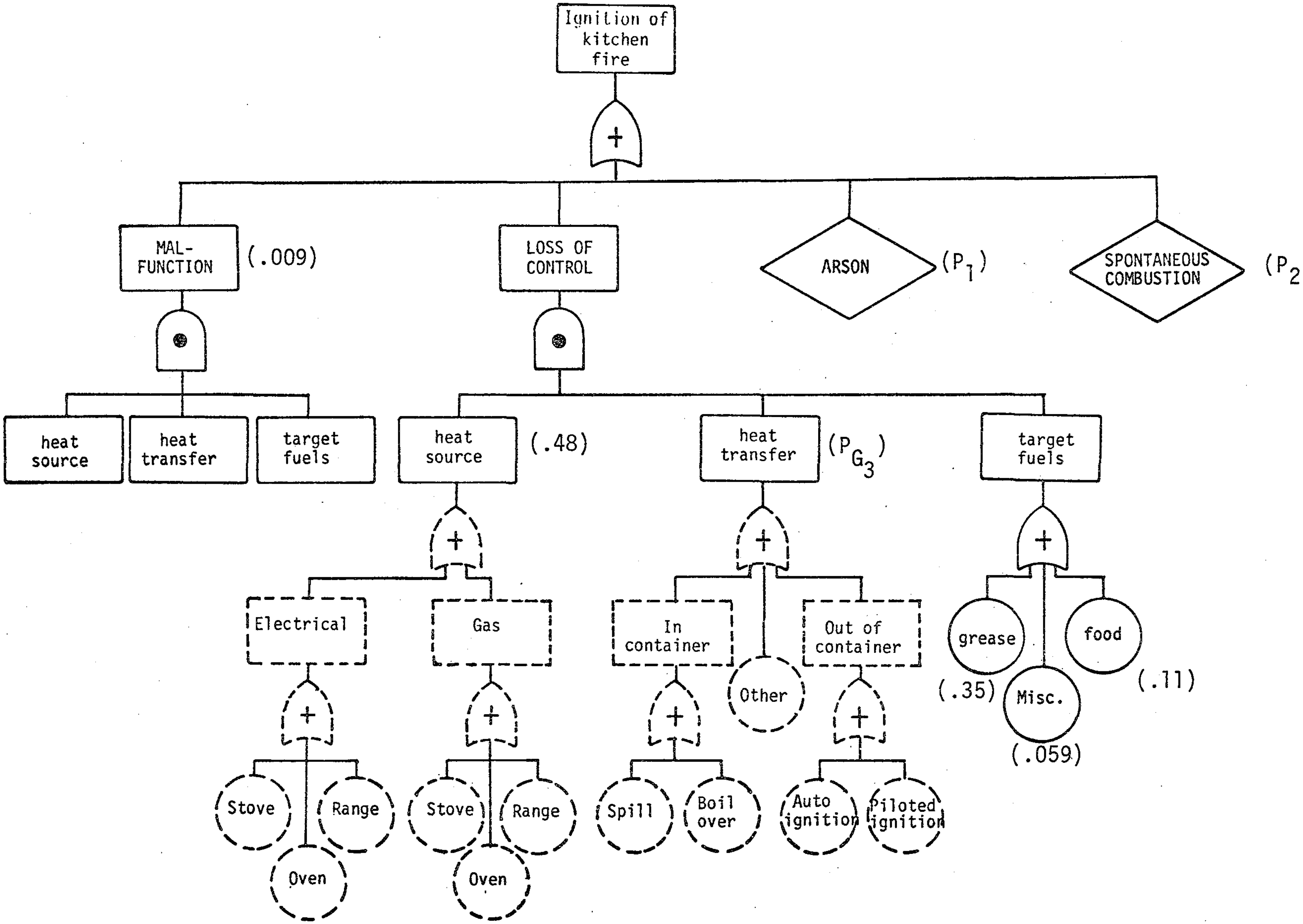

Fig. 12 A Fault Tree on Ignition of Fires in Kitchen. The number associated with each event is the probability of occurrence.

P_2 respectively throughout the rest of this paper. If the probability of ignition of kitchen fire due to loss of control is known and denoted by P_{LC}, then the probability of the top event in the fault tree, i.e.

Prob (ignition of kitchen fire) = $1 - (1-P_{LC}).(1-p_1).(1-p_2).(1-P_M)$ where

P_M = Prob (ignition of kitchen fire due to malfunction of equipment) $\approx .009$.

All the probabilities involved are small, hence the cross product terms drop out and the above equation becomes

Prob (ignition of kitchen fire) $\approx P_{LC} + p_1 + p_2 + 0.009$.

To find P_{LC}, note thtat the fault event "loss of control" is itself a top event for the subtree below it. Hence, P_{LC} can be estimated by

$$P_{LC} \simeq \coprod_{1\le s\le k} \prod_{i\in K_s} q_i \quad \text{where } q_i = \text{Prob [basic event i occurs]}$$

and K_s = the s^{th} min cut set, s = 1,2,..., K.

For the subtree under "loss of control", there are only three min cut sets:

(A_1, G_3, B_1), (A_1, G_3, B_2), and (A_1, G_3, B_3).

Denote Prob [event Z occurring] by P_Z. Then

$$P_{LC} \simeq 1 - \prod_{i=1}^{3} (1-P_{A_1} P_{G_3} P_{B_i})$$

The only unknown here is P_{G_3}. Figure 13 shows the values of P_{LC} versus different values of P_{G_3}. If P_{G_3} = .1 were chosen, P_{LC} would be approximately .0249. Combining all these calculations,

$$\begin{aligned} P \text{ (top event)} &= \text{Prob [ignition of kitchen fire]} \\ &= .0249 + .009 + P_1 + P_2 \\ &= .0339 + P_1 + P_2. \end{aligned}$$

On the other hand, using the NHFS data (out of a sample size of 33,856 households, 2017 fires were reported of which 65% started in the kitchen) directly, the probability of ignition of a kitchen fire equals to

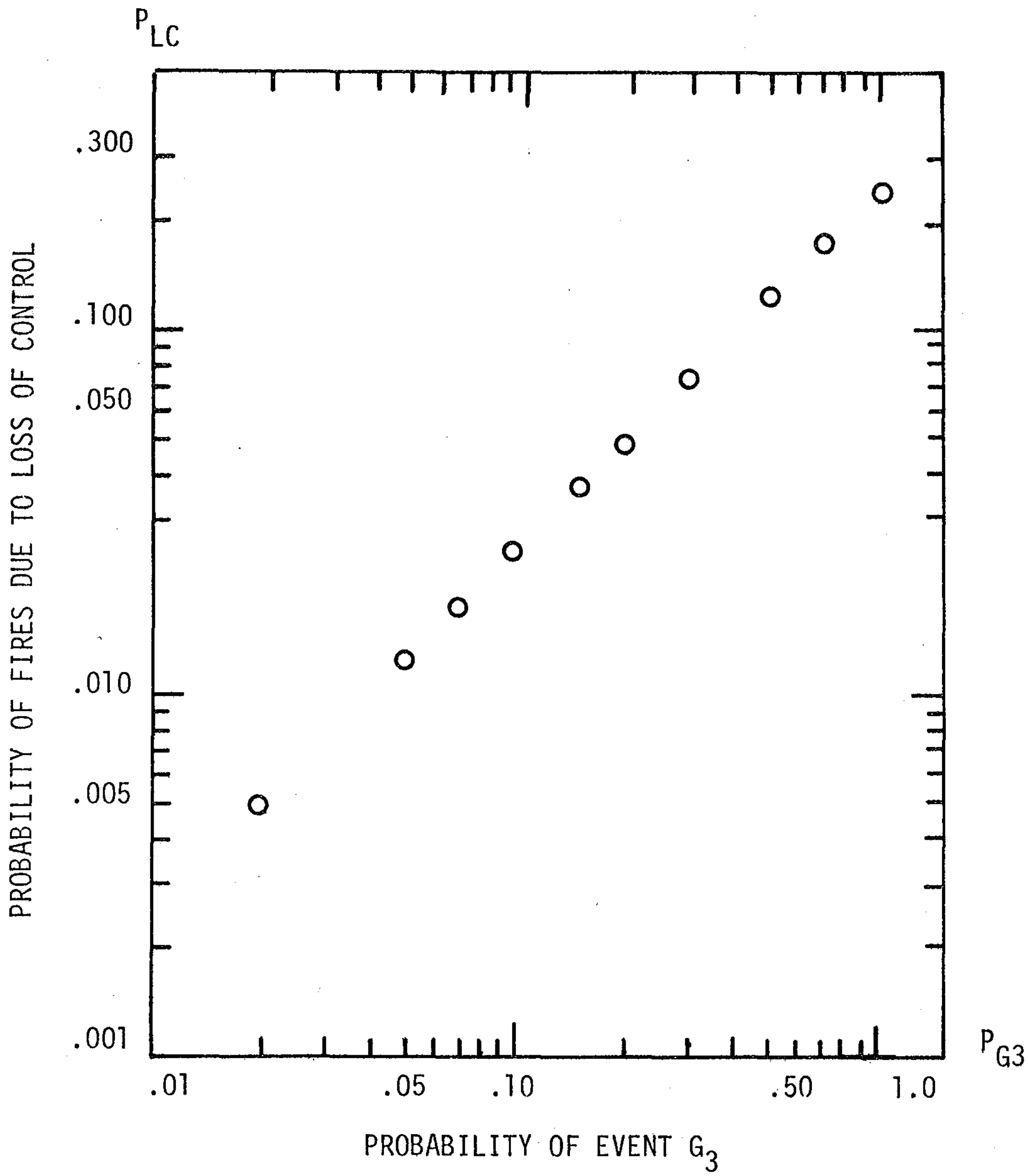

Fig. 13 Probability of Loss of Control of Wanted Fire as a Function of Probability of Sufficient Heat Transfer

$$\frac{2017}{33856}(.65) = .0387$$

The difference between .0387 and .0339 is due basically to the reduction of the number of scenarios (or min cut sets) when the fault tree is constructed. It still is a relatively good approximation. It shows also that the selection of Prob (heat transfer) = 0.1 is an appropriate choice fitting the data, provided that arson and spontaneous combustion are not significant. This would then indicate that in 9 out of 10 incidences the heat source and the fuel were right for a fire, but the heat transfer did not occur to cause fire.

CONCLUSION AND RECOMMENDATIONS

The fault tree on ignition of fire gives not only a graphical representation of the top event, but also a ranking of the scenarios according to their probabilities of occurring. This is important for designing fire tests, especially when new materials are to be compared with traditional materials in similar applications. The Center for Fire Research at the National Bureau of Standards has performed a series of fire tests to evaluate the potential fire hazard resulting from an accidental ignition from cooking on the kitchen range.[6] A 9 inch diameter pan filled to a depth of .5 in (1.27 cm) with cooking oil was ignited by a match after the temperature of the oil reached approximately 380° C. The oil then served as the ignition source, providing a fairly reproducible type of open flame ignition commonly resulting from kitchen activities. Another series of experiments was performed by the American Gas Association laboratories[7] to investigate the surface temperature of kitchen cabinets adjacent to domestic gas ranges. In that study a 9 inch diameter frying pan was placed over the rear burner of a gas range; it contained one pound of vegetable shortening which was used as the ignition source. Both these experiments can be viewed as the application of the scenarios of the fault tree of the ignition of fire in a kitchen. The fault tree analysis supports the choice of ignition sources in these experiments. The application of the ranking of scenarios for choosing an ignition source in fire tests will become more meaningful when the highest probability scenario is not as obvious as the stove/oven/range to grease sequence in a kitchen.

In the process of fault tree construction, a lack of information might be revealed in certain required areas. A critical-incident survey questionnaire must then be designed to fit the need. For example, the dotted portions of Figure 12 could be made 'solid' by designing a questionnaire asking for information on how human error was committed. "Was the pan of grease left unattended too long" or "Was it overturned?" From these answers an analysis could be made to determine the causes of 70% of all fires associated with different appliances and it could also be established if the fire was due to equipment failure or a lack by the designer to take human failings into account. It may then be possible to reduce kitchen fires, hence residential fires, by designing ovens and stoves in such a manner that the probability of the occurrence of the scenarios will be reduced.

The methods presented here have a general applicability, but they require both data and insight into the problem. There are fire situations in occupancies which are relatively new, such as nuclear reactors or wide-bodied airplanes, and which have not yet generated a sufficient number of case histories to identify the many possible fire scenarios. Yet a fire situation in these cases could be disastrous. It would therefore seem important for those cases to take data from other occupancies where the people are performing similar tasks and the same behavior pattern of both people and equipment could be reasonably expected. Thus for instance, the data from restaurants and theaters might be analyzed to see what might be expected in wide-bodied aircraft which has many of the same activities and equipment as restaurants and theaters. Similarly nuclear reactors might be compared with conventional power plants for fires that started with a common activity. These data and subsequent fault tree analyses would help to predict and hopefully prevent potentially dangerous fires.

Acknowledgement

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