PLG-0356

COMPARATIVE TRANSFORMER FIRE RISK STUDY

Prepared for
MONSANTO COMPANY
St. Louis, Missouri
August 1984

Pickard, Lowe and Garrick, Inc.
Engineers • Applied Scientists • Management Consultants
Newport Beach, CA Washington, DC

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EXECUTIVE SUMMARY

This study evaluates the impact on fire risk of the decision to replace mineral oil with Askarel as the cooling and insulating fluid for electrical equipment. It compares the frequencies of acute injuries and fatalities arising from operating a mineral oil transformer to those from operating an Askarel transformer. The term Askarel refers to a broad class of fire resistant synthetic chlorinated hydrocarbons used as dielectric fluids. For the purposes of this study, Askarel is defined as a mixture containing 50% Aroclor 1254, a polychlorinated biphenyl (PCB), and 50% 1,2,4 trichlorobenzene.

In the evaluation of the fire risk for the two types of transformer fluid, two separate cases are considered. Case 1 describes a 1-hour fire rated transformer room in a general-use area of a public-use building. Case 2 describes a 3-hour fire rated transformer room in the nonpublic-use basement of a building. These two cases describe typical installations of Askarel and mineral oil transformers.

The results show a significant decrease in fire risk when a mineral oil transformer is replaced by an Askarel transformer. In case 1, the mean frequency of transformer fires that spread beyond the room of origin is a factor of 300 smaller for Askarel compared with mineral oil transformers. For case 2, the reduction is even larger--a factor of 1,000. This demonstrates that the risk from mineral oil transformers is much greater than that from Askarel transformers, since a fire that spreads beyond the transformer room is of more concern than one contained within the room. Also, historical data show that there is a greatar chance of multiple fatalities when a fire spreads beyond its room of origin.

An important factor contributing to Askarel transformer fires is the presence of trichlorobenzene. If an Askarel transformer did not contain trichlorobenzene, its fire frequency would be significantly smaller. This is because trichlorobenzene has a flash point of 99°C, whereas PCB (Aroclor 1254) does not have a flash point up to its boiling point (greater than 350°C). In other words, the use of trichlorobenzene as a blending fluid reduces the fire resistance of the resulting Askarel mixture.

This study estimates that about 1 in 1,000 of all fires confined to the transformer room would involve at least one fatality. For fires spreading beyond the transformer room, about 1 in 100 was estimated to result in fatalities. Based on these values and the frequencies of within-room and beyond room fires estimated in the study, the fatality risks from Askarel and mineral oil transformers are compared. For case 1, the mean frequency of fires involving one or more fatalities is found to be a factor of 6 lower for Askarel transformers than for mineral oil. The reduction in case 2 is comparable--a factor of 4. In both cases, room fires were the dominant contributors to the fatality risk from Askarel transformers. Fires that spread beyond the transformer room were the dominant contributors to the risk from mineral oil transformers. In all cases, transformer rupture was the dominant cause of the injury or fatality fires.

In summary, this study shows that there is a significant decrease in fire risk when mineral oil transformers are replaced by Askarel transformers. Conversely, replacing Askarel with mineral oil would involve a significant increase in transformer fire risk. The risk of conversion from Askarel to mineral oil is most significant for nonvault-transformer installations.

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1. INTRODUCTION

In the 1930s, polychlorinated biphenyls (PCB) were introduced by the electrical industry as nonflammable electrical insulating and cooling fluids called Askarels. The primary goal was to replace the mineral oil in liquid-filled transformers in installations where a fire could lead to public injury or excessive property damage. Since Askarel transformers were typically more expensive than mineral oil transformers, they were used mainly for special applications, such as inside office buildings, in underground mines, etc. The trade name Askarel denoted a mixture of chlorobiphenyls, chlorobenzenes, and stabilizers. (Askarel properties and mixtures are discussed in documents such as References 1 and 2.)

The combined flame resistant and excellent dielectric properties of Askarels led to their widespread use in other electrical equipment as well. They were the primary fluid in all capacitors and were used in special-use motors, magnets, switches, circuit breakers, underground cables, and voltage regulators. They were also used in nonelectrical equipment where the risk of fire was significant; e.g., as a flame resistant hydraulic fluid and heat exchanger fluid.

In spite of the diverse and widespread applications of Askarel, its manufacture was banned in May 1979 because of PCB's environmental persistence. As they fail or reach the end of their useful life, equipment items using Askarel are decreasing in number. Also, many Askarel transformers have been systematically emptied of Askarel and refilled with mineral oil. New types of dielectric fluids that may replace Askarels and mineral oil are being tested for their flammability (References 3 and 4), dielectric, cooling, and health and environmental characteristics. Equipment design is also being changed to accommodate other media, such as gases, for cooling and insulating.

In the 1930s, the decision to replace mineral oil with Askarels was based on a qualitative understanding of risk and risk reduction. In this study, we investigate the actual change in fire risk. That is, we evaluate the difference in fire risk between Askarel-filled and mineral oil-filled transformers. The selected damage indices are acute fatalities and acute injuries caused directly by transformer fires. Risk is expressed in terms of the likelihood (frequency) per transformer year of a fire causing at least one fatality or injury. For example, the frequency per year of fires causing at least one fatality from an operating mineral oil-filled transformer for 1 year is compared with the corresponding frequency for operating an Askarel-filled transformer.

Because of the sparsity of the available information, it became clear that the likelihood of injury or fatality cannot be established by statistical analysis alone. Therefore, two site specific case studies were performed. One site has the characteristics of a typical Askarel-filled transformer installation. An Askarel-filled transformer and a mineral oil transformer at that installation are compared. The second case study involves an installation typical of mineral oil-filled transformers. As in case 1, an Askarel-filled transformer and a mineral oil transformer at the same installation are compared.

In this study, the subject of uncertainty and its propagation through to the final results is given special attention. The Bayesian (subjectivist) school of thought is adopted (References 5 and 6). Uncertainties are always expressed by probability distributions (either discrete probability distributions or density functions). To minimize the confusion arising from semantics, we have adopted the definitions suggested in Reference 6. The word "probability" is used as a measure of our state of confidence. For rates of occurrence and fractions, the word "frequency" is used.

2. TECHNICAL SUMMARY

The approach to performing this comparative risk study involves modeling events and the likelihood that they will lead to a given level of risk. Two initiating events resulting in a fire are chosen: (1) transformer fluid leakage, and (2) transformer rupture. (Note that not all leaks and ruptures lead to fires.)

The barriers that limit the effects of these initiating events are the boundaries of the room where the transformer is installed, the fire protection system in the room, etc. These barriers are modeled by an event tree. An event tree is simply a graphic representation of potential sequences of events. For example, one possible sequence is a leak that leads to a fire during which the room boundary stays intact. In that sequence, fire propagation to an adjacent room is impossible because the room boundary is not breached.

To link event sequences with consequences, the sequences are categorized by what we call "damage states." Those sequences not leading to fire propagation into an adjacent room are categorized as "room fires" (i.e., fires confined to the room of origin). Those sequences leading to fire propagation into adjacent rooms are categorized as "beyond room fires," i.e., fires propagated beyond the room of origin. This categorization is convenient because the statistical data on injuries and fatalities can be identically categorized. The conditional frequency of observing one or more injuries or fatalities given a fire in each category can therefore be easily established.

2.1 CASE 1 - A TRANSFORMER WITHOUT A VAULT

The base case for case 1 is an Askarel-filled transformer installed in a medium-sized, public-use building. The installation characteristics for this case are typical of Askarel units, which means that the transformer is not in a vault and is located on a general-use floor. The alternate case is a mineral oil-filled transformer with identical specifications installed in place of the Askarel transformer without any other changes to the installation or the room.

The transformer is assumed to be in a dedicated room on a general-use floor. The combustible loading and the use of the floor are similar to an office building. For example, the corridor outside the transformer room is assumed to be carpeted and may contain combustibles such as paper and plastics. The walls of the transformer room are made of plaster, have no windows, and are rated as 1-hour fire walls. There is only one door (of the same fire rating) that opens into the adjacent corridor. The walls are covered by mineral tiles on the inside to reduce the transmission of transformer noise into the corridor. Ventilation is provided by fans and openings that lead directly to the outside air.

Special precautions are taken to prevent the storage of combustibles near the transformer. To control any transformer fluid leaks, a curb is provided around the transformer with at least a 4-inch lip and 3 feet of clearance on all sides. A wet-type sprinkler system is installed above the transformer. The temperature setting of the heads is of ordinary classification, which ranges from 135°F to 170°F (57°C to 77°C).

Under normal conditions, no one enters this room except for occasional visits by maintenance personnel. Doors are normally locked and only maintenance and security personnel have the keys.

For the base case, the liquid of the transformer is assumed to be Askarel. A typical mixture is 50% (by weight) Aroclor 1254 (a PCB) and 50% 1,2,4 trichlorobenzene. Askarel leaks would generally be noticed by maintenance personnel. Leaked PCB and trichlorobenzene mixture would not ignite because external heat fluxes of several watts per cm^2 are needed to sustain combustion in PCB, and the flash point and auto ignition point of 1,2,4 trichlorobenzene are about 99°C and 571°C, respectively. The flash point of the Askarel mixture is 110°C. Ignition sources, heat sources, and hot surfaces are not present near leaking transformers or inside the curbs containing the leaking fluid. Thus, severe accident sequences initiated from leaks are taken to have a very low frequency and, therefore, make only negligible contributions to risk.

Violent rupture of the transformer casing may occur due to rapid faults (an arc) in the transformer windings that are immersed in the Askarel. The cause is typically deterioration of the insulation between windings coupled with a rapid increase in the line voltage. In all four Askarel transformer ruptures known to the authors, dense smoke has been reported. Therefore, it is assumed that at every rupture incident, some combustion of the flammable Askarel component, trichlorobenzene, and nearby transient combustibles, will take place.

For rupture of an Askarel transformer in an unvaulted room, the frequencies of injuries and fatalities are dominated by room fires. For injuries, 99% of the mean frequency is from room fires. For fatalities, the corresponding figure is 98%. The dominant contributor to room fires in this case is fires that do not fail the room boundaries (rather than fires that do fail the room boundaries but fail to propagate beyond the room). The reason for this is that room boundary failure from Askarel transformer fires is highly unlikely.

Room boundary failure depends on the impact of pressure waves or missiles on the walls and door, or heat impingement on the walls from burning Askarel. Detonation (an explosion where the flame front propagates supersonically and can create a strong pressure wave) is not judged to be possible, because PCB vapor does not burn easily and 1,2,4 trichlorobenzene has a narrow flammability range (2.5% to 6.6%). Deflagration (an explosion where the flame front propagates subsonically and the resulting pressure wave is weaker than that of a detonation) may take place in the 1,2,4 trichlorobenzene vapor if the vapor temperature is well above 99°C and an iginition source is present, but the pressure increase during deflagration is generally small. Thus, only under extreme conditions (such as very high arc energy, the source of transformer rupture) is the combustion of the trichlorobenzene expected to pose a threat to the integrity of the room boundaries.

If deflagration does not occur, the sudden release of pressurized gas from the transformer may lead to a pressure pulse. The room volume is assumed to be 20 x 20 x 8 = 3,200 ft^3, and the air space above the transformer fluid can only range from 0.5 to 10 ft^3 depending on the size of the transformer. Thus, an increase of 1 psig at the walls requires a 320 to 6,250-psig increase in the tank at the time of rupture. Such a pressure rise is very unlikely. Also, the transformer tank would rupture well below that pressure, thereby mitigating the pressure rise.

Ceiling failure from the rupture is deemed to be very unlikely because the ceiling is assumed to be made of reinforced concrete and to be 6 inches thick. The ceiling can therefore withstand pressures well over 2 psig. As discussed above, the likelihood of such pressures is very small. Missiles may also be generated in some transformer ruptures. The most likely missiles are the tank cover thrown in a vertical direction and slugs of the transformer fluid. The ceiling may be damaged by the transformer cover, but the impact is not expected to breach the ceiling.

Finally, the prolonged impingement of combustion heat on the walls and the ceiling may also lead to room boundary failure. However, even if the sprinklers do not work properly, the walls and the ceiling (which are 1-hour and 3-hour rated, respectively) would contain the fire long enough to allow for manual fire extinguishing efforts. Fire propagation to an adjacent room given room boundary failure is not a likely event either. Prolonged impingement of the heat from transformer fire may ignite the combustibles in the adjacent rooms if the fire is not suppressed in about a half-hour. Overall, the small likelihood of room boundary failure and fire propagation due to Askarel transformer ruptures in unvaulted rooms minimizes the likelihood of Askarel fires propagating beyond the transformer room, and therefore also minimizes the likelihood of injuries and fatalities.

The alternate case assumes a mineral oil-filled transformer in place of the Askarel transformer. The main differences are that (1) leakage of mineral oil could lead to severe consequences, and (2) splattered mineral oil could catch fire. For fires involving mineral oil transformers without vaults, the main contributors to the frequencies of injuries and fatalities (89% of the mean frequency of injuries and 91% of the mean frequency of fatalities) are beyond room fires. The dominant contributors to this damage state are fires originating from transformer ruptures, even though ignition of leaks is also possible.

Fire propagation to an adjacent room given transformer rupture is judged to be certain if splattered mineral oil escapes the transformer room and comes to rest on combustibles such as carpeting. The splattered fluid is likely to be on fire because the temperature difference between the bulk of the oil (about 100°C) and the oil fire point (150°C) is rather small, and because the explosion may set some of the splattered fluid on fire. The explosion itself is not deemed to be capable of igniting combustibles in adjacent rooms, and the sprinkler system above the transformer is not expected to be of any benefit because the events take place at a rapid pace. It should be noted that the assumption of a carpeted hall does not necessarily introduce a bias in favor of Askarel transformers, because burning mineral oil would ignite the many of the materials typically found in a general-use area of a building, whereas the temperature of splattered Askarel would be rather low and very few materials would ignite at that temperature.

If mineral oil does not splatter after the transformer ruptures, the primary fire propagation mode is anticipated to be radiation from flames inside the transformer room. Since this process is not rapid, fire suppression equipment such as the sprinkler system could extinguish the fire prior to propagation. However, the likelihood of fire propagation in this case is still judged to be quite high.

The change in risk when an Askarel transformer in an unvaulted room is replaced by a mineral oil transformer is significant. The mean frequency of fire related injuries increases from once every 300,000 transformer years with Askarel to once every 70,000 transformer years with mineral oil (over a factor of 4 difference). Similarly, for fire related fatalities, the mean frequency increases from once every 4,000,000 transformer years for Askarel to once every 700,000 transformer years for mineral oil (almost a factor of 6 difference).

The use of a mineral oil transformer in an unvaulted room is allowed by the National Electrical Code if a sprinkler system is installed in the area. Thus, the results of this analysis carry an important message: under equal conditions, fire risk decreases significantly when a mineral oil transformer is replaced by an Askarel transformer.

2.2 CASE 2 - A TRANSFORMER WITH A VAULT

The base case of case 2 is a minerel oil transformer in a vault in the basement of a large building. The alternate case is an Askarel transformer with identical specifications. The main difference between case 1 and case 2 is that in case 2 the walls and ceiling are built of 6-inch concrete or 8-inch brick. The following assumptions describe the vault and the transformer in detail and are applicable to both the mineral oil and the Askarel transformers.

A single transformer is assumed to be located in a vault approximately 20 feet by 20 feet by 8 feet. The floor of the vault is sloped 1/[illegible]-inch per foot to a sump 3 feet square and 2 feet 6 inches deep. The vault is assumed to have a dedicated ventilation system. Tha air inlet is equipped with a fire damper, and the air outlet is equipped with louvers to prevent the entrance of rain. The penetrations of the room include air ducts, conduits for electrical cables, and a self-closing, 3-hour rated fire door (5 feet by 8 feet), which is normally locked closed. The vault is assumed to be equipped with an automatic sprinkler system. The temperature setting of the heads is taken to be of ordinary classification, which ranges between 57°C and 77°C (135°F and 170°F

For this case, the frequencies of injuries and fatalities are dominated by beyond room fires. However, the contribution of room fires is noticeable. For injuries, room fires contribute 31% of the mean frequency; for fatalities, they contribute 25%. The contribution of transformer rupture is large, contributing 92% of the mean injury frequency and 93% of the mean fatality frequency. The main reasons for this are (1) the greater frequency of ruptures involving fires compared with leaks involving fires, and (2) the much greater likelihood of vault boundary failure given a rupture as contrasted with given a leak-induced fire.

If the mineral oil in the transformer of the base case is assumed to be replaced by Askarel while keeping other conditions unchanged, any fluid leaking out of the tank can no longer be ignited. Therefore, Askarel leaks do not require further evaluation. The mechanisms for vault boundary failure from rupture of an Askarel transformer are the same as those for room boundary failure in case 1. In this case, however, the likelihood of failure is much smaller because of the strength of the vault boundary.

The pressure pulse from a deflagration has to be very strong (above 7 psig at the vault boundary) to fail a wall. Similarly, the release of pressurized gas from the tank would have to involve a very large initial pressure. This has been shown to be almost impossible. Finally, exposure of the walls to heat flux from combustion of transformer fluid has to last much longer to fail the walls in this case than in case 1 because the walls are much thicker. From this comparison, we assess the mean frequency of vault boundary failure after rupture of an Askarel transformer to be only about 1×10^{-2}. Because of the relatively small chance of vault boundary failure, the frequencies of injuries and fatalities for vaulted Askarel transformers are totally dominated by room fires that do not fail the vault boundaries.

Overall, we can confidently claim that the risk from fires would decrease if a mineral oil transformer in a vault were replaced by an Askarel transformer. The mean frequency of fire related injuries would decrease from once every 100,000 years for mineral oil transformers to once every 300,000 years for Askarel--a factor of 3 difference. Similarly, the mean frequency of fire related fatalities would decrease from once every 1,000,000 years (mineral oil) to once every 4,000,000 years (Askarel)--a factor of 4 difference.

3. DISCUSSION

Many assumptions and judgmentally evaluated parameters are used in this study. In this section, the sensitivity of the final results to these assumptions and parameters is investigated.

The frequency of transformer fires was obtained from statistical data for all transformers. The uncertainties about this frequency are rather small because the number of transformers is very large. The conditional likelihood of a rupture given a fire was evaluated judgmentally and was deemed to be greater than the conditional likelihood of a leak given a fire.

Two important assumptions were made at this stage. It was assumed that (1) fires from Askarel transformers are almost solely from ruptures and (2) their total fire frequency is equal to the fire frequency from rupture of mineral oil transformers. A more realistic risk comparison could be made if the fire frequency for Askarel transformers was evaluated separately from relevant statistical evidence; however, the evidence required for this evaluation is not readily available.

Room boundary failure frequencies for Askarel and mineral oil transformers were evaluated primarily using judgment. For an Askarel transformer, an explosion has to occur for room boundary failure to result. An explosion is possible because the trichlorobenzene in the Askarel can be vaporized (boiling point 214°C) and ignited. PCB would not contribute to the explosion because its boiling point is higher (greater than 350°C), and it does not have a flash point before boiling. The likelihood of boundary failure for Askarel transformers represents the likelihood of an explosion severe enough to damage the walls.

An important element of both the fire frequency and the boundary failure frequency evaluation is the presence of trichlorobenzene. If an Askarel that does not contain trichlorobenzene (e.g., pure Aroclor 1254) had been chosen for this case study, room boundary failure would have been very unlikely. In addition, the frequency of transformer fires specific to this fluid would have had to be quantified explicitly because of its highly flame resistant characteristics (high boiling point and flash point). This would have reduced the risk assessed for Askarel transformers.

Room boundary failure in the case of mineral oil transformer rupture was judged to be very likely. This is because mineral oil is a relatively flammable material, and it was judged that an explosion would occur upon transformer rupture. This may be a conservative conclusion though probably not an extreme one. A decrease in the likelihood of an explosion would decrease the estimated risk of mineral oil transformers

In the case of mineral oil transformer rupture, the importance of room fires to the final results increases as the likelihood of vault boundary failures decreases. If the likelihood of vault failure is further reduced, the mineral oil risk results would move closer to the results for Askarel.

The uncertainties in the fire propagation frequencies are not highly sensitive to the underlying assumptions. For example, in the case of propagation to an adjacent room when room boundaries are breached, the important parameters are the heat flux and the ignition temperatures of the materials in the adjacent room. In view of the large uncertainties about the fire propagation frequencies, any reasonable changes in the values of the ignition temperatures and heat flux would not have a major impact on the final results.

The conditional frequencies of injuries and fatalities given a room or beyond room fire were evaluated using statistical evidence. The most important assumption at this stage of the analysis was the compatibility of the collected evidence with the aims of our case study. For beyond room fires caused by unvaulted transformers, the evidence was judged to be highly applicable because once a fire propagates beyond the room of origin it does not matter how it originated. For room fires caused by unvaulted transformers, the applicability of the evidence for injuries was judged to be good because one of the two data sources on injuries was specific to indoor transformers. For fatalities from room fires, the data may not be as good as those of the other damage indices, such as injuries from beyond room fires. This was reflected by conservative estimations and wide uncertainties.

The data on conditional injury and fatality frequencies are less applicable to vaulted transformers, because vaults are not typically found in buildings. Also, the vault was not assumed to be located in a general-use area, so the occupants of the building would not be highly exposed to the transformer fire consequences. This is especially true for transformer fires that are confined to the vault.

Direct comparison of the results of the two case studies is not warranted for two reasons. First, the same conditional frequencies of injuries and fatalities were used in the two cases, even though in case 1 the rooms adjacent to the transformer room are used by the general public, whereas in case 2 only the building maintenance and building management personnel are typically present in the vicinity of the transformer vault. Second, the models used to estimate the conditional frequencies of boundary failure and fire propagation include many conservative assumptions. The two case studies may involve differing degrees of conservatism, so that a direct comparison may be misleading.

Extension of the final results to other situations is also not warranted. For example, the injury and fatality frequencies used here are not applicable to transformers on poles near suburban homes or transformers installed outside buildings. Of the intermediate results, only the initiating event frequencies and conditional injury and fatality frequencies are applicable outside the two case studies.

4. CONCLUSIONS

Having compared the fire risks from mineral oil and Askarel transformers in two case studies, let us now review the major conclusions of this study.

The risk attributes chosen for the study were acute injuries and fatalities. The two case studies both involved sites in public-use buildings. Case 1 compares an Askarel and a mineral oil transformer at an installation specifically designed for Askarel. For case 2, the site (a vault in a basement) is specific to a mineral oil transformer. The major conclusions of the two case studies are as follows:

- For both cases, there is a significant decrease in fire risk when a mineral oil transformer is replaced by an Askarel transformer in the same installation. Conversely, there is a significant increase in fire risk if Askarel were to be replaced by mineral oil.

- The mean frequency of transformer fires that spread beyond the room of origin is much less for Askarel transformers than for mineral oil transformers. The difference is a factor of 300 for the unvaulted transformers of case 1, and a factor of 1,000 for the vaulted transformers of case 2. This demonstrates that the risk from mineral oil transformers is much greater than that from Askarel transformers, since a fire that spreads beyond the transformer room is of more concern than one contained within the room. In particular, historical data show that there is a greater probability of multiple fatalities when a fire spreads beyond its room of origin.

- The risk of fires involving at least one fatality is significantly smaller for Askarel transformers than for mineral oil transformers. The difference is a factor of 6 for case 1, and a factor of 4 for case 2.

- The risk of fires involving at least one injury is als[illegible] gnificantly smaller for Askarel than for mineral oil. The frequency of fire related injuries is a factor of 4 smaller in case 1, and a factor of 3 smaller in case 2.

- Finally, the presence of trichlorobenzene is an important factor contributing to the risk of Askarel transformer fires. The frequenc of fires would be much smaller for Askarel transformers not containing trichlorobenzene than for those that do. This is because trichlorobenzene has a relatively low flash point (only 99°C), whereas PCBs do not have a flash point up to their boiling point. The 50/50 mixture of trichlorobenzene and PCB leads to an Askarel with flash point of 110°C.

5. DETAILS OF THE ANALYSIS

5.1 OBJECTIVE, DEFINITIONS, AND SCOPE

5.1.1 OBJECTIVE

The goal of this study is to evaluate the impact on fire risk of the decision to replace mineral oil by Askarels as the cooling and insulating fluid for electrical equipment.

5.1.2 RISK ATTRIBUTES

In a risk analysis, the damage indices (or risk attributes) can be numerous. In this case, fire can lead to property damage, fatalities, injuries, and loss of production. Of these indices, we evaluate only the fatalities and injuries caused directly by a transformer fire. Latent effects (that is, fatalities or injuries that may take several years after the fire incident to materialize) are not included in this study.

5.1.3 EQUIPMENT TYPE

Only mineral oil and Askarel-filled transformers will be considered because the goal of the study is to evaluate the fire risk implications of the decision to replace mineral oil with Askarel. The term Askarel refers to a generic name for a broad class of fire-resistant synthetic chlorinated hydrocarbons (such as PCBs) used as dielectric fluids. Their properties and mixtures are discussed in documents such as References 1 and 2. Of the different transformer types, we concentrate on distribution transformers because other types are mainly used in power plants, switching stations, or other special industrial uses where there are normally few personnel present. Other equipment such as capacitors, circuit breakers, switches, motors, magnets, and heat exchangers will not be addressed. Except for the transformers and capacitors, all the other Askarel-filled equipment types are used primarily for industrial applications and are not typically installed close to public areas.

5.1.4 ERA OF THE STUDY

Ideally, to achieve the goal of this study one should analyze the transformer fire risk in the social and industrial environments of the 1930s when the decision to use PCBs was made. However, specific information regarding the characteristics of the transformers and their installations is not easily available from that era. Also unavailable are statistical data regarding the number of transformers operating at that time as well as the number of transformer fires, and the injuries and fatalities resulting from those fires. However, good statistical evidence has been available since the mid-1970s. Several reports have been published estimating the number of transformers and the frequency of fires, injuries, and fatalities. Therefore, the most convenient era for our analysis is the past few years. It is judged that the choice of this era is appropriate because of the available data and the fact that transformer design and installation characteristics have not changed drastically in the past few decades. Transformer design improvements have been in efficiency (less heat generation) and in tolerance to overloads and shorts. There have also been improvements in the strength of the tank that holds the insulating fluid.

5.1.5 SITE

From the available statistical data, one cannot reliably distinguish between Askarel and mineral oil transformer fires. The impact of this deficiency can be reduced if the risk comparison is performed for some specific sites. Two sites are chosen for this study. The fire risk comparison is done separately for each site by assuming that at the same site there is an Askarel transformer and a mineral oil transformer with identical design and installation characteristics. The first site, which is referred to as case 1, has the installation characteristics of an Askarel-filled transformer. It is a transformer room in a public-use building, with regular room boundaries of a 1-hour fire rating; the area outside the room is for general use by the building occupants. The second site, which is referred to as case 2, has the installation characteristics of a mineral oil-filled transformer. It is a transformer vault in the basement of a public use building. However, outside the vault, the floor is used for building service equipment and shops.

5.2 APPROACH

The approach to performing this comparative risk study involves the modeling of events and their likelihood, thus leading to a quantitative statement of risk. The central feature of the approach is to display the uncertainties associated with the figures of merit. The figures of merit are the frequencies of occurrence of different levels of damage. In this study, "damage" is deaths and injuries. Probability is employed to express the confidence in those frequencies. This concept is known as the "probability of frequency" format, or the "probability and consequences" approach to risk assessment (Reference 6). This approach is extensively used in the very comprehensive risk assessments performed for the nuclear industry.

For each of the two fluids (Askarel and mineral oil), risk curves can be developed for each of the risk attributes (acute fatalities and acute injuries). Risk curves are actually families of curves, each with its own probability. An example of such a family is shown in Figure 5-1. This "risk diagram" (Reference 6) is in the above-mentioned "probability of frequency" format. It consists of a family of curves, $\Phi_P(x_i)$, with the parameter P being the cumulative probability. To use this diagram, we would, for example, enter with a specific value, x_i, and choose, say, the curve $P = 0.95$. The ordinate of this curve, $\Phi_{.95}(x_i)$, is then the 95th percentile frequency of x_i. That is, we are 95% confident that the frequency with which damage level x_i or greater will occur is not larger than $\Phi_{.95}(x_i)$.

We can now draw a vertical line that cuts the family of curves at a specific damage level, x_i, that may be of special interest. The

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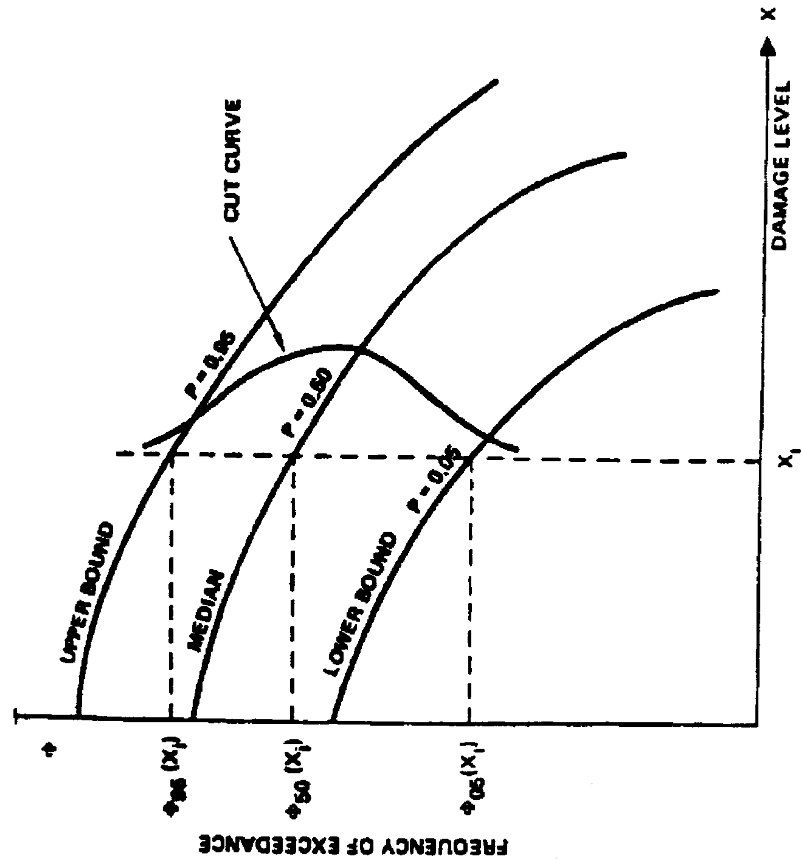

FIGURE 5-1 A FAMILY OF RISK CURVES AND THE CUT CURVE

intersection of this line with the family leads to the curve of P versus $\phi(x_i)$, as shown in Figure 5-1. This curve, which we call a "cut curve," expresses our state of knowledge about the frequency with which events of level x_i or greater occur. These uncertainties are due to uncertainties in the data and the models used.

In this study only, one cut curve is established for each damage index. This cut curve is for one or more fatalities or injuries. To establish complete risk curves, we had statistical data on the exact number of injuries and fatalities per fire incident. Our data sources indicate only single fatality fires and a few multiple injury fires. Therefore, the uncertainties in the multiple injury or fatality parts of the risk curves will be very large and the differences among the different fatality or injury levels will be dominated by the uncertainties. Because of this and because of our fire propagation model (which is described below and considers only two cases--fires that are confined to the room of origin, and fires that propagate beyond the room of origin), the final results would not be very sensitive to the level of damage, that is, the number of fatalities or injuries. Thus, the first-cut curve would yield sufficient information for the risk comparison and the evaluation of any additional cut curves is judged to be of little benefit.

To assess the effect on risk of the decision to change from mineral oil to Askarel means to compare the two curves for each risk index. There are several ways in which such a comparison can be done. The simplest way is to compare the average frequency of one or more fatalities or injuries. A much more detailed way is to compare the cut curves. For the latter, based on the position, shape, and spread of the distributions, we can determine whether there is a significant difference in the frequency of a certain damage level of a certain risk attribute. Both approaches are used in this study.

To establish the cut curves for the two site specific cases, a three-point method graphically displayed by Figure 5-2 is used. In the first part, the "initiating events" (i.e., events that create a disturbance to an otherwise normal system) are identified and their frequencies are quantified. In the second part, "barriers" which tend to limit the effects of the initiating event are identified and analyzed. Finally, the consequences (the extent of damage) of the accident scenarios are assessed.

Two initiating events are chosen: (1) transformer fluid leakage that leads to a fire, and (2) transformer rupture that leads to a fire. The types of disturbances that a transformer may experience are numerous (Reference 7) and are mostly of an electrical nature. A large portion of these disturbances may not lead to a leak or rupture; those that may lead to either a leak or a rupture may also lead to a fire. It should be noted that our definition of the initiating events is very specific because not all leaks or ruptures lead to a fire. The frequencies of the initiating events are evaluated in Appendix A.

The barriers that limit the effects of the transformer disturbances are the transfomer tank itself, the room boundaries where it is installed, the fire protection system in the room, etc. The first barrier (that i

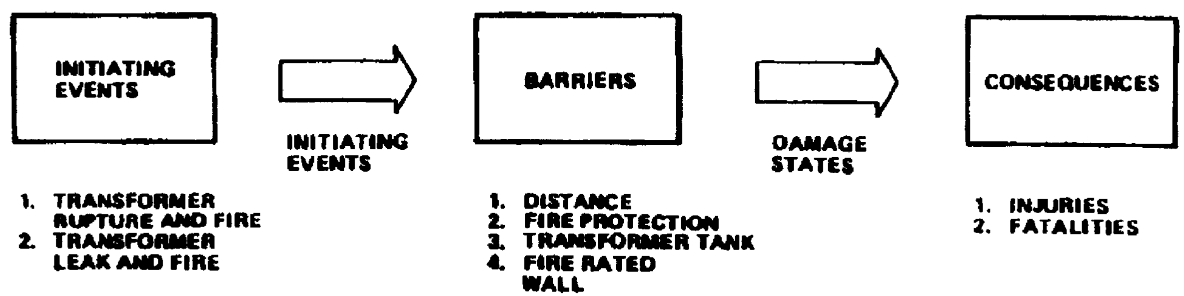

FIGURE 5-2. PICTORIAL REPRESENTATION OF THE RISK QUANTIFICATION STRUCTURE

the tank) is already considered part of the initiating event. The remaining barriers are modeled by an event tree. Figure 5-3 shows an example from one of the cases. An event tree is simply a graphic presentation of potential sequences of events. The events are defined at the top of the tree and there are four of them in Figure 5-3. For example, one sequence of events is sequence 1 of Figure 5-3 where the initiating event is a leak that leads to a fire and the room boundary stays intact. In that sequence, the rupture point and propagation to an adjacent room is immaterial because the initiating event is not a rupture and the room boundary is intact. The second sequence on that tree also starts with a leak and fire but the room boundary is failed. Again, the rupture point is immaterial but propagation to an adjacent room is certain.

To link the event sequences with the consequences, the sequences are categorized by what we call the "damage states." The sequences that do not lead to fire propagation into an adjacent room are categorized as "room fire" (confined to the room of origin). The sequences that lead to fire propagation into the adjacent rooms are categorized as beyond room fire (propagated beyond the room of origin). This categorization is convenient because the statistical data on injuries and fatalities can be categorized identically and the conditional frequency of one or more injuries or fatalities given a fire of certain category can be established.

5.3 <u>CASE 1 - TRANSFORMER IN A REGULAR ROOM</u>

The base case for case 1 is an Askarel-filled transformer installed in a public-use building. The installation characteristics are specific to Askarel type units, which means that the transformer room is not a vault and is on a floor for general use. The alternate case is a mineral oil-filled transformer, with specifications identical to the Askarel unit, installed in place of the Askarel transformer without any other changes to the installation or the room. The risks from these two installation types are evaluated separately. The general assumptions and definitions pertinent to both alternatives are given first.

5.3.1 GENERAL ASSUMPTIONS

The transformer is of distribution type and is liquid-filled using natural convection for dissipating the heat to the room environment. Its power rating is taken to be 167 kVA. Building transformers can range between 100 and 5,000 kVA depending on the size of the building. The range can be deduced from Reference 8 where the number of Askarel transformers (primarily used in populous areas) is tabulated by their power rating. From Reference 8, it can be deduced that 66% of Askarel transformers are in the 100 to 5,000 kVA range. The average number of gallons of dielectric fluid for transformers in the 101 to 500 kVA range is 183 for Askarel transformers and 117 for mineral oil transformers (Reference 8). The power rating of the transformer considered in this study is near the lower end of the above range and, therefore, the volume is expected to be lower than the average; it is taken to be 80 gallons. The transformer is box-shaped, measures 2 feet by 2 feet and is 3 feet tall.

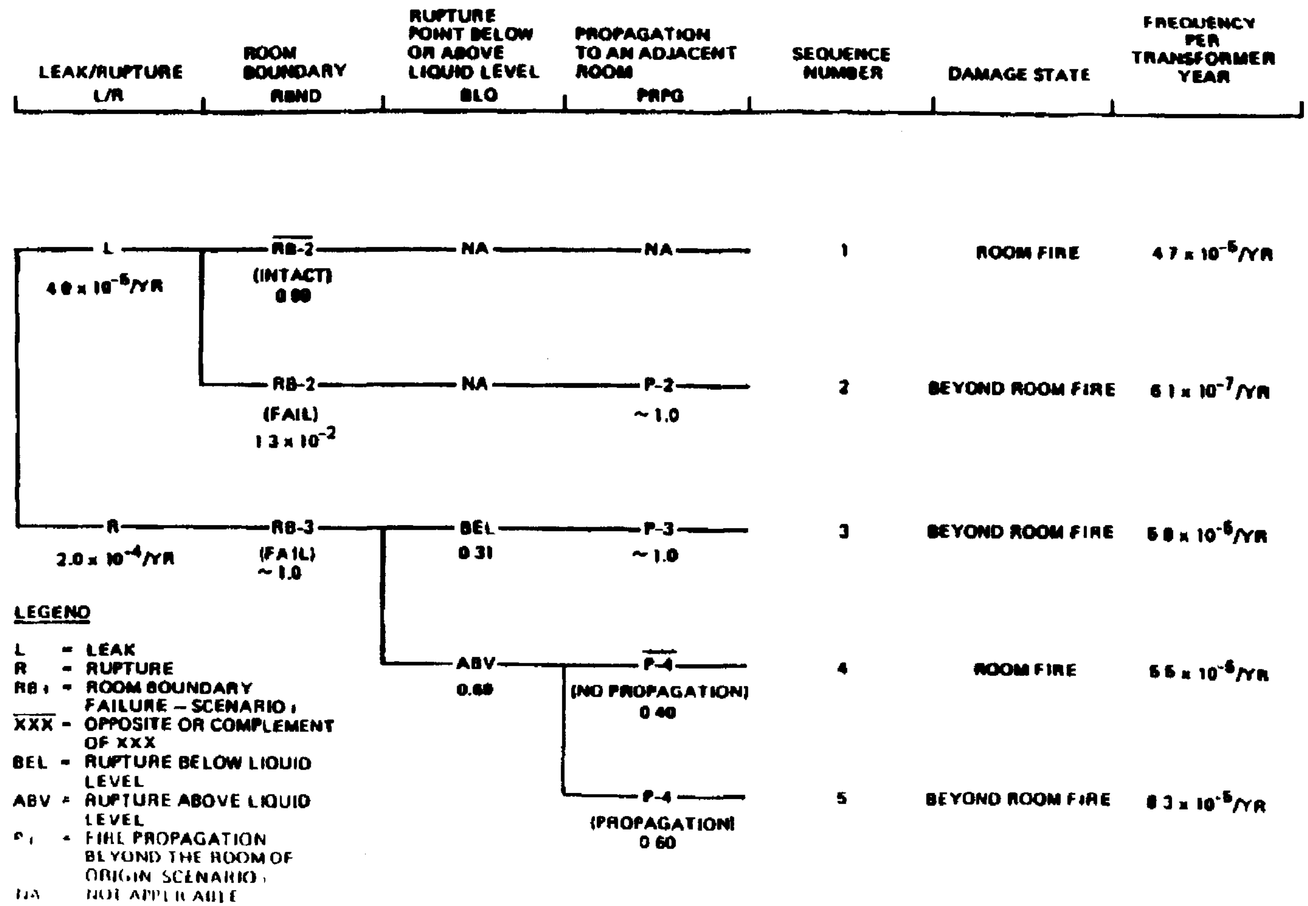

FIGURE 5-3 AN EXAMPLE EVENT TREE

MONS 020625

The building is similar to an office building in terms of the combustible loading and use. Each floor has more than 10,000 square feet of floor area. All the floors are divided into corridors, rooms of different sizes, elevator shafts, ventilation ducts, etc. The transformer room is located in a general-use area. For example, the corridor outside the transformer room is assumed to be carpeted, occupied like any other corridor in the building, and may contain combustibles such as paper and plastics.

The transformer room measures 20 feet by 20 feet and is 8 feet high (see Figure 5-4). The walls are of plaster without windows and are rated as 1-hour fire walls. There is only one door (of the same fire rating) that opens into the adjacent corridor. The walls are covered by mineral tiles on the inside to reduce the transmission of transformer noise into the corridor. The ventilation for this room is provided by fans and openings that directly communicate with the outside air.

Special precautions are taken to prevent storage of combustibles near the transformer. To control any transformer fluid leaks, a curb area is provided under the transformer with at least a 4-inch lip and 3 feet of clearance on all sides. Thus, the curb area dimensions are 8 feet by 8.5 feet.

A wet-type sprinkler system is installed above the transformer and the curbs around it. The temperature setting of the heads is of ordinary classification (see Reference 9 for definition) which ranges from 135°F to 170°F (57°C to 77°C).

The room also contains other electrical equipment such as switches, breakers, and junctions in special electrical cabinets. The electrical cables to and from the transformers or other electrical equipment in the room are generally inside conduits (metal tubes) installed close to the ceiling.

Under normal conditions, no one enters this room except for occasional visits by maintenance personnel. Doors are normally locked and only maintenance and security personnel have the keys. The inspection frequency is judged to range between once a week and twice a day.

In the following sections, it will be seen that the final results are highly sensitive to only a few of these assumptions. Because of a 1-hour rated plaster wall, in the case of mineral oil transformer rupture, fire propagation to an adjacent room is very likely. Because of 6-inch thick reinforced concrete construction, propagation of transformer fire through the ceiling to the floor above is deemed to be very unlikely for all scenarios considered in this case study. The sprinkler system in the room allows for rapid suppression of fires and reduces the likelihood of their propagation to the adjacent rooms. The curb dimensions is important to mineral oil fires from a leaking transformer. It influences the severity of potential fires involving oil collected in the curb.

The details of risk calculations for the two transformer types are given in Sections 5.3.2a and 5.3.2b. To facilitate their comparison, the format of this report is altered and the two sections are presented side by side.

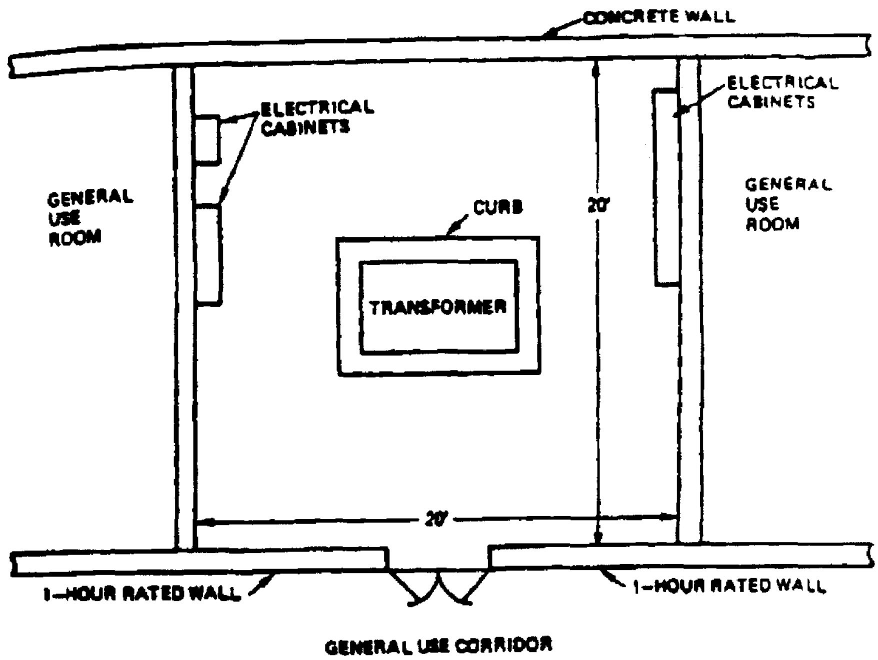

FIGURE 5-4. GENERAL LAYOUT FOR CASE 1 TRANSFORMER ROOM

CASE 1 - ASKAREL TRANSFORMER

5.3.2a CASE 1: BASE CASE - ASKAREL TRANSFORMER

The liquid of the transformer is assumed to contain PCBs. A typical mixture is 50% (by weight) Aroclor 1254 and 50% 1,2,4 trichlorobenzene. For the purposes of this study, the generic term Askarel is used for this mixture. No other assumptions in addition to those above are made for the base case.

Figure 5-5 shows the event tree for the potential event sequences. Each branch point is discussed in detail in the following sections. The initiating events of the tree are leakage and rupture. Both events (i.e., leakage and rupture) may be a result of abnormalities in the electrical characteristics of the transformer, severe surges in the line, degradation of the seals, etc. Reference 7 gives a comprehensive enumeration of these potential failure modes.

The overall structure of the tree is based on the propagation paths given a leak or rupture. In the case of leaks, it is concluded in Section 5.3.2a.1.1 that fires would not occur and no severe consequences are anticipated. For the rupture scenarios, the first obstacle is the room boundaries. They may fail because of air pressure rise or severe heat fluxes. Given the boundary failure, fire may propagate to the adjacent rooms and beyond. The event tree terminates at two damage states: fires confined to the room of origin, and fires propagating beyond the room of origin. Smoke propagation is not modeled explicitly because the impact of the fire on the building's occupants is deduced from the available statistics on injuries and fatalities (which include both smoke and heat effects).

5.3.2a.1 Top Event Quantification

The top events of Figure 5-5 that are represented by symbols such as (L/R), (IGN), etc., are evaluated separately in this section. In the following sections, the damage states and the resulting consequences are quantified.

5.3.2a.1.1 (L/R) Leaks (L)

[illegible] ignition of other combustibles and [illegible] prior to [illegible] and [illegible] central

CASE 1 - MINERAL OIL TRANSFORMER

5.3.2b CASE 1: ALTERNATE CASE - MINERAL OIL TRANSFORMER

This is the alternate case for Case 1 where a mineral oil-filled transformer is assumed in place of the Askarel transformer of the base case. The assumptions as described in Section 5.3.1 are applicable here. This setup is permitted per an exception in part C of Article 450 of the National Electrical Code (Reference 16). The article takes exception to the requirement of 3-hour fire rated boundaries when a fire protection system such as automatic sprinklers is installed in the transformer room and permits 1-hour rated boundaries.

Figure 5-6 shows the event tree for the potential event sequences. It is developed using the same approach as for the base case event tree. The main differences between this tree and that of Figure 5-5 are (1) leakage of mineral oil has the potential for leading to severe consequences, (2) splattered mineral oil may catch fire, and (3) position of rupture point (an additional top event) is important to fire propagation beyond the room of origin. The top event "Ignition" is not included because for both main branches (i.e., leak or rupture) ignition of the transformer fluid is certain.

5.3.2b.1 Top Event Quantification

Each top event of Figure 5-6 is evaluated separately in this section.

5.3.2b.1.1 (L/R) Leaks (L)

In the case of mineral oil, the possibility of a leak is examined in combination with the possibility of its ignition. In Appendix A, the frequency of a leak, λ_I, that also catches fire is established. Its mean value is 4.8×10^{-5} per transformer year

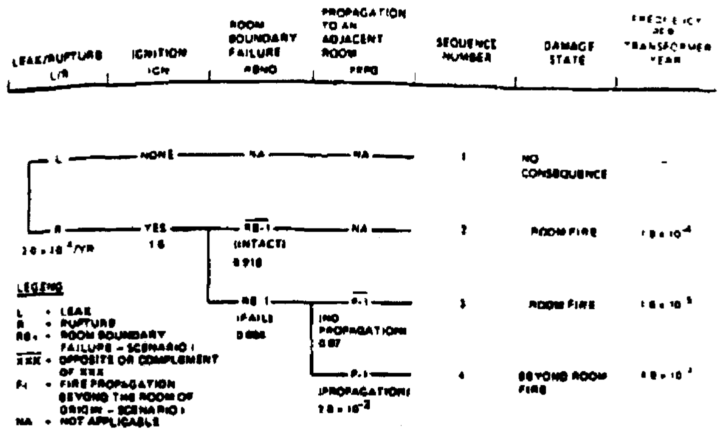

FIGURE 5-5. EVENT TREE FOR THE BASE CASE OF CASE 1, THE ASKAREL TRANSFORMER

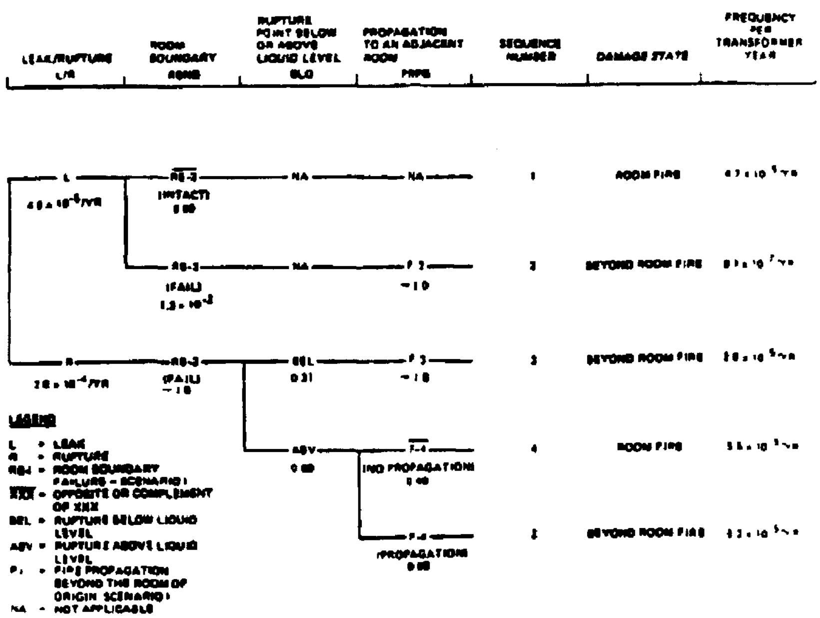

FIGURE 5-6. EVENT TREE FOR THE ALTERNATE CASE, THE MINERAL OIL TRANSFORMER OF CASE 1

CASE 1 - ASKAREL TRANSFORMER

watts per cm^2 are needed to sustain combustion in Askarel, and References 11 and 12 indicate that the flash point and auto ignition point of 1,2,4 trichlorobenzene are 99°C (105°C in Reference 11) and 571°C, respectively. The flash point of the mixture is 110°C (see Appendix I). Ignition sources, heat sources, and hot surfaces are not present near a leaking transformer nor inside the surrounding curbs that would contain the leaking fluid. Thus, fire sequences initiated from a leak are taken to be of very low probability and, therefore, make negligible contributions to risk. These fire sequences are not evaluated further.

5.3.2a.1.2 (RBND) Room Boundary Failure

(Not Applicable)

CASE 1 - MINERAL OIL TRANSFORMER

5.3.2b.1.2 (RBND) Room Boundary Failure (RB-2)

The room boundary failure as a result of a leak is examined here. The possible modes of boundary failure are pressure pulses from an explosion or from severe heat impingement on the walls and the ceiling from a fire within the room. To evaluate the likelihood of the two modes of boundary failure, the possible sources of ignition (for the explosion), the possibility and amount of oil evaporated, and the amount of oil leaking from the transformer need to be established.

For explosion ignition, the only source that can be envisioned is the switchgear cabinets along the walls of the room (see Figure 5-4). The temperature of the transformer casing and its other exposed parts is typically well below 150°C. Under extreme loads, the transformer casing may reach 150°C. It should be noted that the typically hot windings are not exposed during a leak; therefore, they cannot act as an ignition source. Thus, if evaporation occurs, the most likely explosion ignition source would be the switchgear arcs from either the operation of the switches or discharge across high voltage bars because of the change in the dielectric properties of the gas between them.

Since the transformer casing seldom reaches temperatures of 150°C or above, the leaking fluid would not evaporate significantly (the boiling point of mineral oil is 360°C (Reference 11)). Furthermore, the vapor cloud has to fill the whole room to reach the ignition source (the switchgear on the walls) and has to be within the flammability range to explode. Based on these facts, it is judged that the occurrence of an explosion is unlikely with a leaking mineral oil transformer. In Appendix D, it is shown that if these conditions are satisfied and an explosion takes

§ 3.2a.1.3 (PRPG) Propagation to the Adjacent Room

(Not Applicable)

place, it is very likely that the pressure at the walls exceeds their strength. From Reference 14, it is concluded that the type of walls considered for the transformer room may fail at pressures above 1 psig.

For the second mode of barrier failure (that is, severe heat impingement), the amount of burning oil, and the dimensions of the base of the fire and its position relative to the barriers are important. The dimensions and the position of the base of the fire are taken to be that of the curb under the transformer which measures 2.44m by 2.59m (8 feet by 8.5 feet) and is at the center of the room. The amount of oil that is needed to fail the walls is computed in Appendix E. The room boundary is assumed to be 1-hour rated. The wall failure definition is taken from Reference 9 where a vertical fire wall is considered failed when the temperature of the wall surface opposite the fire reaches 140°C. In Appendix E, it is found that wall failure may occur if about 100 gallons of the oil are consumed. This means that there may not be enough oil to cause the failure of the wall. Furthermore, this process would take about 120 minutes if it is not mitigated by the sprinkler system above the transformer. This is a long time window for the fire brigade to arrive and control the fire. The conditional frequency, f_{BB-2}, of failure to suppress the fire before damage to the boundaries is evaluated in Appendix E. Its characteristic values are:

5th Percentile:	9.7×10^{-5}
Median:	5.4×10^{-3}
95th Percentile:	5.5×10^{-2}
Mean:	1.3×10^{-2}

5.3.2b.1.3 (PRPG) Propagation to the Adjacent Rooms (P-2)

Fire propagation to an adjacent room is almost certain given that the primary mode of room boundary failure is severe heat flux on the walls. At this branching point, no credit is given to the available fire suppression measures for stopping the fire growth at the room boundaries. This is because the room boundary failure is from the failure to suppress the fire prior to the damage to the walls.

CASE 1 - ASKAREL TRANSFORMER

5.3.2a.1.4 (L/R) Rupture (R)

Violent rupture of the transformer casing can occur due to rapid faults in the transformer windings which are immersed in the Askarel. The cause of this failure mode is typically deterioration of the insulation between windings coupled with a rapid increase in the line voltage. In this case, an arc would occur through the fluid and would generate a gas bubble. It has been shown experimentally (Reference 13) that the arc energy must be well above 10 kJ for a rupture to occur. Rupture can occur by two mechanisms: (1) a slug of the fluid, pushed by the gas bubble, hammers on the tank boundaries, and (2) the gas bubble rises to the top and pressurizes the gas space above the fluid. The frequency of an Askarel transformer rupture, λ_R, is assessed in Appendix A. Its mean value is 2.0×10^{-4} per transformer year.

5.3.2a.1.5 (IGN) Ignition

The possibility of transformer fluid ignition given a rupture is investigated here. The Askarel is a mixture of a PCB (Aroclor 1254) and 1,2,4 trichlorobenzene. Both substances are difficult to ignite. The flash point of Aroclor 1254 is above its boiling point (greater than 350°C, Reference 1) and the flash point of the 1,2,4 trichlorobenzene is 99°C. The flash point of the mixture is 110°C (see Appendix I). In Appendix I it is found that the mixture flash point strongly depends on the amount of trichlorobenzene. About 3% (by volume) of trichlorobenzene in the mixture leads to a (mixture) flash point of 190°C. It decreases to 110°C for 50% mixture and 99°C for pure trichlorobenzene.

The mechanism that causes the rupture of a transformer is the generation of a high energy arc through the liquid. The amount of vapor created by the arc is about 100 cm^3 per kJ of arc energy (Reference 2). The vapor consists of 97.3% hydrogen chloride, 1.5% inert gases, and a small amount of combustible gases including carbon monoxide, hydrogen, and hydrocarbons. Because of their small amount, combustion of these gases is deemed to be of little significance to the event sequences.

Immediately after the rupture, the remaining fluid that is in contact with the hot surfaces will be vaporized. As [illegible] to leakage, in this case, heat sources may be present. The transformer winding may become very hot because of the arc or abnormalities in the line and act as

CASE 1 - MINERAL OIL TRANSFORMER

5.3.2b.1.4 (L/R) Rupture (R)

The mechanisms leading to the violent rupture of a mineral oil-filled transformer are almost identical with those of an Askarel transformer. The frequency of this event is also 2.0×10^{-4} per transformer year (see Appendix A).

5.3.2b.1.5 (IGN) Ignition

Ignition occurs upon mineral oil transformer rupture.

an ignition source. However, the bulk of the fluid that may still be remaining in the tank would be close to its initial temperature. Thus, if the electricity is removed soon after the rupture, the windings may cool rapidly. (The transformer may be disconnected either by automatic protective devices or by the responsible personnel.) At this time, either the fluid and vapor temperatures have not reached the ignition point or they self-extinguish as soon as the winding temperature drops below a certain level.

The temperature of the bulk of the fluid would rise significantly if the electricity is not removed soon after the rupture. It is possible for the trichlorobenzene to behave somewhat differently. Since its boiling point (about 210°C, Reference 12) is much less than the PCB boiling point (greater than 350°C), the bulk of the generated vapor will be of this substance or its decomposition products. As mentioned earlier, the flash point and auto ignition temperatures of trichlorobenzene are 99°C and 571°C, respectively. If the windings are not totally immersed after the rupture, their surface may reach very high temperatures and act as an ignition source for the trichlorobenzene. Thus, sustained fire is possible from an Askarel transformer rupture.

In summary, ignition may not occur at every transformer rupture incident. However, in all four Askarel transformer ruptures known to the authors (see Appendix A), dense smoke has been reported. Therefore, it is assumed that at every rupture incident some combustion, especially of the trichlorobenzene, will take place.

5.3.2a.1.6 (RBND) Room Boundary Failure (RB-1)

The room boundary failure depends on the impact of pressure waves or missiles on the walls and the door or heat impingement from burning Askarel on the walls. The walls are of plaster and the door swings out (it is normally locked closed). From Reference 14, it is concluded that such walls may fail at pressures above 1 psig. Pressure pulses may be generated from deflagration or detonation of 1,2,4 trichlorobenzene vaporizing from the hot Askarel or from the sudden release of the pressurized gas on top of the fluid. Based upon the calculations presented in Appendix H, it is judged that detonation is not possible. This is because the PCB vapor does not burn easily and the 1,2,4 trichlorobenzene has a small flame velocity and a narrow flammability range (2.5% to 6.6%) per Reference 12, and no explosive range per Reference 11.

5.3.2b.1.6 (RBND) Room Boundary Failure (RB-3)

The room boundary failure modes due to the rupture of a transformer are discussed in Section 5.3.2a.1.6. In the case of a mineral oil-filled transformer, the potential for a detonation or deflagration occurrence is significant. In Appendix O, the possible pressure pulse loads on the walls are investigated. The load levels are derived for the deflagration mode of explosion, and for different levels of arc energy. From Reference 15, it is concluded that at least 100 kJ arc energy is needed to rupture a transformer of the size considered here. For both modes of explosion, that is deflagration and detonation, the pressure load is above 2 psig. From Reference 14, it is concluded that the walls of the room would fail above 1 psig pressure. Thus, it is concluded that upon the rupture of a mineral oil-filled transformer, the room boundaries would certainly fail.

CASE 1 - ASKAREL TRANSFORMER	CASE 1 - MINERAL OIL TRANSFORMER
Deflagration is expected to take place in the Askarel vapor if the vapor temperature is well above 110°C and an ignition source is present. The pressure increase during deflagration is generally small. Thus, only under extreme conditions (such as very high arc energy) is the combustion of the trichlorobenzene expected to pose a threat to the integrity of the room boundaries.	
If deflagration does not occur, the sudden release of the pressurized gas above the fluid may lead to a pressure pulse. Reference 13 shows that this pressure is insignificant. However, the reviewers of that article (their discussions are presented as part of the article) disagree with that conclusion and claim that the pressure rise could be as high as 93 psig. Using static gas volume and pressure relationships, it can be shown that even for 93 psig gas space pressure, the pressure rise in the room is insignificant. Room volume is 20 x 20 x 8 = 3,200 ft^3, and the air space on top of the fluid can range from 0.5 to 10 ft^3 (Reference 13) depending on the size of the transformer. Thus, pressure at the walls would be a 1.6×10^{-4} to 3.1×10^{-3} multiple of the pressure in the transformer at the time of rupture. Thus, an increase of 1 psig at the walls would require 320 to 6,250 psig in the tank at the time of rupture. Reference 13 indicates that such a pressure rise is very unlikely. Also, the transformer tank, which is designed for atmospheric pressure, will rupture at pressures much below that pressure, thereby mitigating the pressure rise.	
Missiles may also be generated in some ruptures. The most likely missiles are the cover of the tank thrown in a vertical direction and slugs of the fluid leaving the tank. Smaller items such as the insulation around the terminal points are not likely to be torn from their mountings. The windings and the iron may be damaged severely but are very unlikely to leave the tank.	
It should be added that ceiling failure from the rupture is deemed to be very unlikely because the ceiling is of reinforced concrete construction and is 6 inches thick. The ceiling can withstand pressures well over 2 psig. As discussed above, the likelihood of such a pressure rise is very small. In the case of the missiles, the ceiling may be damaged from the impact of the transformer top but the impact is not expected to breach the ceiling.	

The prolonged impingement of the combustion heat on the walls and the ceiling may also lead to the boundary failure. The sprinkler system, if available, would arrest the heat generation process and may even completely extinguish the fire. The unavailability of this system ranges from 0.01 to 0.20 (see Appendix B). If the sprinklers do not work properly, the walls and the ceiling, which are 1-hour and 3-hour rated barriers, respectively, would contain the fire for a sufficient length of time to allow for manual extinguishing efforts.

Based on the above discussions, it is judged that the likelihood of barrier failure, f_{BL-1}, given a transformer rupture is rather small and is attributed primarily to deflagration and prolonged burning. This likelihood is evaluated judgmentally and our uncertainties are depicted with a lognormal distribution with 5th and 95th percentiles at 0.005 and 0.3, respectively, and its median and mean values are 0.039 and 0.084, respectively. The likelihood of the barriers remaining intact is the complement of the above likelihood. Its mean value is 0.916.

5.3.2a.1 7 (BLQ) Rupture Point

The position of the rupture point has no significant impact on accident sequences.

5.3.2b.1.7 (BLQ) Rupture Point Below (BEL) or Above (ABV) Liquid Level

Whether the rupture point is above or below the liquid level may determine whether fluids are thrown far from the tank after the rupture. If the rupture is above the fluid level, it is assumed that only a small amount of spillage takes place near the transformer. The conditional frequency f_{BEL} is introduced to represent the fraction of ruptures that occur below the liquid level. The complement of this frequency is the conditional frequency of above-the-liquid-level ruptures, f_{ABV}.

An estimate for f_{BEL} can be found in Reference 17. Quoting from that reference (page 13):

> The experts estimated that 70% of ruptures occur above the fluid level, and the remaining 30% occur below the fluid level.

Reference 13 also indicates that a rupture above the fluid level is the predominant failure mode. In that reference, transformer rupture experiments were performed. It was observed that the behavior of the transient load on the tank is very different in the vapor space than in the liquid space The pressure in the vapor space has only one

5.3.2a.1.8 (PRPG) Fire Propagation to an Adjacent Room (P-1)

At this branch point, the possibility of fire propagation to the adjacent rooms, given that a transformer rupture and the failure of the room boundaries have occurred, is investigated. In Section 5.3.2a.1.6, it is concluded that the most likely cause of boundary failure is the pressure pulse generated by the deflagration of the 1,2,4 trichlorobenzene. This pressure pulse is judged to be attenuated to insignificant levels beyond the transformer room boundaries once they are breached. The events following the pressure pulse would be dense smoke leaving the transformer room through the opening, combustion and splattering of the transformer fluid, and some hot transformer parts glowing from loss of cooling

peak pressure and the overpressure lasts about 10 milliseconds. The pressure in the liquid space has many spikes in the same time frame, and the peak pressure is higher than that observed in the vapor space. As for the peak pressure, the liquid space experiences a higher peak pressure than the vapor space. One explanation for having more ruptures above rather than below the liquid level is that for an impulsive load of the structure, which has a duration much shorter than the period (the reciprocal of the natural frequency), the impulse (i.e., the area under the pressure-time curve) is a better measure of load than the peak pressure. The impulse for the vapor space is higher than that for the liquid space.

Based on the above discussions, the conditional frequencies of rupture above or below the fluid level (f_{BEL} and f_{ABV}, respectively) are estimated. The following discrete distributions express our uncertainties:

Probability	f_{BEL}	f_{ABV}
0.15	0.15	0.85
0.70	0.30	0.70
0.15	0.50	0.50
Mean	0.31	0.69

5.3.2b.1.8 (PRPG) Fire Propagation to an Adjacent Room (P-3)

Fire propagation to an adjacent room given a below-liquid-level rupture of a mineral oil transformer is judged to be a certainty. This is because some of the splattered fluid may escape the transformer room and come to rest on combustibles such as carpeting. The splattered fluid may be on fire because the temperature difference between the bulk of the oil (about 100°C) and the oil fire point (150°C) is rather small and the explosion may set some of the splattered fluid on fire. It should be noted here that (1) the explosion is not deemed to be capable of igni[illegible] combustibles of the adjacent rooms, and (2) the s[illegible]stem above the transformer is not expected to be of any influence on the course of events because the events take place at a rapid pace

CASE 1 - ASKAREL TRANSFORMER

Thus, the propagation of the fire to the adjacent zones can be from. (1) hot gases (carried with the smoke) radiating, (2) direct radiation from the flames or the hot transformer parts to the carpet or other combustibles in the adjacent rooms, or (3) hot fluid splattered on the carpet or other combustibles.

All these processes must heat the target combustibles for a certain period of time before ignition temperatures are achieved. This time period has to be compared with the time for suppressing the fire. There is a sprinkler system on top of the transformer that is very likely to operate (unavailability values range from 0.01 to 0.20 per Appendix B) and suppress the fire much before any ignitions occur in the adjacent room. It can be shown that for the possible levels of heat fluxes from the above-listed sources, the time to ignition is much longer than 10 minutes. Within this time frame, the sprinklers are very likely to become activated. If the sprinklers do not deliver any water, the fire brigade may arrive on time.

Propagation of fire by splattered transformer fluid would be unaffected by the sprinkler system but is of little significance. The minimum temperature for the ignition of fabrics is 400°C (see Appendix B) and the temperature of the splattered fluid would not be above 400°C because the boiling points of PCB and trichlorobenzene are about 350°C and 210°C, respectively. Also, the splattered fluid would not be very hot because tank rupture is due to mechanical forces generated by the expanding vapor around the arc, and when rupture occurs sufficient time has not elapsed for the bulk of the fluid to heat up.

The conditional frequency of propagation, f_{p-1}, given that transformer rupture and room boundary failures have occurred, is evaluated in Appendix B. In summary, the ignition time of the combustibles from an impinging heat flux from flames, hot gases, or hot transformer parts is estimated first. It is then compared with the time for fire suppression, and the conditional frequency f_{p-1} is established.

Its characteristic values are:

5th Percentile.	2.2×10^{-4}
Median	1.3×10^{-2}

CASE 1 - MINERAL OIL TRANSFORMER

The flame temperature of the splattered fluid is greater than 1,500°C (Reference 9) and the ignition temperature of the carpeting can be as low as 400°C (see Appendix B). It should be noted that the assumption of a carpeted hall does not necessarily introduce a bias in favor of Askarel transformers. This is because the burning splattered mineral oil can ignite the majority of materials typically found in a general use area of a building. For example, although the ignition temperature of wood products can be as low as 200°C (Reference 9), the temperature of splattered Askarel is expected to be much lower (lower than 150°C). Thus, the conclusion described in this section (that is, certainty of fire propagation beyond the room of origin given a below-liquid-level rupture of a mineral oil transformer) is not very sensitive to the assumed combustible loading of the adjacent rooms

CASE 1 - ASKAREL TRANSFORMER

95th Percentile: 1.1×10^{-1}

Mean: 2.8×10^{-2}

5.3.2a.1.9 (PRPG) Fire Propagation to an Adjacent Room

(Not Applicable)

5.3.2a.2 Damage State and Consequence Quantification

Having evaluated the frequencies of all the branching points, the event sequences of the event tree of Figure 5-5 can be quantified to yield the frequency of various damage states. These damage state frequencies can then be combined with related health effect likelihood to estimate the frequencies of consequences in terms of injuries and fatalities. In Figure 5-5, the mean frequencies of the sequences and their damage states are indicated.

CASE 1 - MINERAL OIL TRANSFORMER

5.3.2b.1.9 (PRPG) Fire Propagation to an Adjacent Room (P-4)

At this branch point, the possibility of fire propagation is examined for an above-the-liquid-level rupture. As previously noted, it is deemed that the explosion would not be capable of igniting the combustibles in the adjacent room. The primary fire propagation mode is anticipated to be the radiation from the flames inside the transformer room and the hot gas layer that would be generated in the adjacent room from smoke and hot gases escaping through the breach in the wall. The dominant mode of fire propagation is deemed to be radiation from the flames. Since this process is not rapid, the suppression equipment such as the sprinkler system may extinguish the fire prior to propagation. These competing phenomena are described in detail in Appendix F where the conditional frequency of fire propagation given an above-the-liquid-level rupture, f_{P-4}, is evaluated. The cha: -ristic values of f_{P-4} are:

5th Percentile: 0.30

Median: 0.62

95th Percentile: 0.88

Mean: 0.50

5.3.2b.2 Damage State and Consequence Quantification

The frequencies of all the branching points of the event tree of Figure 5-6 have been evaluated in Section 5.3.2b.1. We can now establish the frequencies of the individual sequences, the damage states, and injuries and fatalities. In Figure 5-6, the mean frequencies of the sequences are given.

CASE 1 - ASKAREL TRANSFORMER

5.3.2a.2.1 Damage State Frequencies

The total frequency of the "room fire" damage state can be written as

$$\phi_{ROOM} = \lambda_R[(1-f_{RB-1}) + f_{RB-1}(1-f_{P-1})]$$

$$= \lambda_R(1-f_{RB-1}f_{P-1})$$

and

$$\phi_{ROOM} = \lambda_R$$

The distribution for λ_R is given in Appendix A.

Similarly, the total frequency of "beyond room fire" damage state can be written as

$$\phi_{BYND} = \lambda_R \cdot f_{RB-1} f_{P-1}$$

Using discretized probability distribution arithmetic (see Reference 15 and Appendix G for a summary), we compute the distribution depicting our uncertainties about ϕ_{BYND}. The results are given in Table 5-2.

TABLE 5-2. ANNUAL OCCURRENCE RATE OF ROOM AND BEYOND ROOM FIRES FROM AN ASKAREL TRANSFORMER; BASE CASE OF CASE 1

Percentile	Frequency Per Transformer Year	
	Room Fire	Beyond Room Fire
5th	1.3×10^{-4}	1.1×10^{-9}
20th	1.6×10^{-4}	1.5×10^{-8}
50th	2.0×10^{-4}	1.0×10^{-7}
80th	2.5×10^{-4}	5.0×10^{-7}
95th	2.9×10^{-4}	1.8×10^{-6}
Mean Value	2.0×10^{-4}	4.6×10^{-7}

CASE 1 - MINERAL OIL TRANSFORMER

5.3.2b.2.1 Damage State Frequencies

The total frequencies of each damage state follow. For the "room fire" damage state, the frequency is

$$\phi_{ROOM} = \lambda_L(1-f_{RB-2}) + \lambda_R f_{ABV}(1-f_{P-4})$$

For the "beyond room fire" damage state, the frequency is

$$\phi_{BYND} = \lambda_L f_{RB-2} + \lambda_R(f_{BEL}$$

$$+ f_{ABV} f_{P-4})$$

Using discretized probability distribution arithmetic (see Appendix G), the distributions for ϕ_{ROOM} and ϕ_{BYND} are calculated. Their characteristic values are given in Table 5-1.

TABLE 5-1. ANNUAL OCCURRENCE RATE OF ROOM AND BEYOND ROOM FIRES FROM A MINERAL OIL TRANSFORMER; ALTERNATE CASE OF CASE 1

Percentile	Frequency Per Transformer Year	
	Room Fire	Beyond Room Fire
5th	4.9×10^{-5}	7.4×10^{-5}
20th	7.1×10^{-5}	1.0×10^{-4}
50th	9.8×10^{-5}	1.3×10^{-4}
80th	1.3×10^{-4}	1.8×10^{-4}
95th	1.7×10^{-4}	2.2×10^{-4}
Mean Value	1.0×10^{-4}	1.5×10^{-4}

The contributors to the room fires are the first and fourth sequences of the event tree (see Figure 5-6). Their contributions to the mean frequency of this damage state are almost equal. The first sequence is a fire from a transformer leak that does not lead to boundary failure,

CASE 1 - ASKAREL TRANSFORMER

It should be noted that the "room fire" damage state is dominated (92% of its mean frequency) by the second event sequence of Figure 5-5. In this sequence, the Askarel transformer fire does not cause any boundary failure.

5.3.2a.2.2 Consequences

The conditional frequencies of one or more injuries or fatalities for each damage state are evaluated in Appendix C. The unconditional frequencies are the product of the frequencies of Appendix C and ϕ_{ROOM} or ϕ_{BYND}. For the frequency of injuries, we can write

$$\phi_{I,BC-1} = \phi_{ROOM} f_{I,RM} + \phi_{BYND} f_{I,BD}$$

and for the frequency of fatalities we can write

$$\phi_{F,BC-1} = \phi_{ROOM} f_{F,RM} + \phi_{BYND} f_{F,BD}$$

These are the frequencies of the occurrence of one or more injuries or fatalities from an Askarel transformer installed according to the descriptions given in Section 5.3. The distribution depicting our uncertainty about these frequencies is obtained by propagating the uncertainties in the frequencies on the right-hand side using discretized probability distribution arithmetic. The characteristic values of these distributions are given in Table 5-3.

CASE 1 - MINERAL OIL TRANSFORMER

and the fourth sequence is transformer rupture that fails the boundaries but does not ignite anything outside the room.

Three sequences contribute to "beyond the room" fires. The third and fifth sequences dominate the frequency of this damage state (96% of the mean value). These two sequences originate from a transformer rupture. The third sequence contributes 39% (mean value) of the frequency and it is a below-the-liquid-level rupture incident. The fifth sequence contributes 56% (mean value) of the frequency and it is an above-the-liquid-level rupture that burns until materials outside the room ignite (delay in fire suppression).

5.3.2b.2.2 Consequences

The conditional frequencies of one or more injuries or fatalities for each damage state are evaluated in Appendix C. For the frequency of injuries, we can write

$$\phi_{I,AC-1} = \phi_{ROOM} f_{I,RM} + \phi_{BYND} f_{I,BD}$$

$$= [\lambda_L (1-f_{BB-2}) + \lambda_B f_{ABV} (1-f_{p-4})] f_{I,RM}$$

$$+ [\lambda_L f_{BB-2} + \lambda_B (f_{BEL} + f_{ABV} f_{p-4})] f_{I,BD}$$

For the frequency of fatalities, we can write

$$\phi_{F,AC-1} = \phi_{ROOM} f_{F,RM} + \phi_{BYND} f_{F,BD} =$$

$$= [\lambda_L (1-f_{BB-2}) + \lambda_B f_{ABV} (1-f_{p-4})] f_{F,RM}$$

$$+ [\lambda_L f_{BB-2} + \lambda_B (f_{BEL} + f_{ABV} f_{p-4})] f_{F,BD}$$

The distributions of these frequencies are obtained using discretized distribution arithmetic. The characteri[illegible] of the distributions are given in Table 5-4.

CASE I - ASKAREL TRANSFORMER

TABLE 5-3. ANNUAL OCCURRENCE RATE OF INJURY AND FATALITY FIRES FROM AN ASKAREL TRANSFORMER; BASE CASE OF CASE I

Percentile	Frequency Per Transformer Year	
	Injuries	Fatalities
5th	1.7×10^{-6}	8.6×10^{-10}
20th	2.3×10^{-6}	9.6×10^{-8}
50th	3.1×10^{-6}	2.3×10^{-7}
80th	4.7×10^{-6}	3.9×10^{-7}
95th	5.2×10^{-6}	5.9×10^{-7}
Mean Value	3.2×10^{-6}	2.4×10^{-7}

Both frequencies are dominated by room fires. For injuries, 99% of the mean frequency is from room fires. For fatalities, it is 98%. In view of the dominant contributor to room fires, it is concluded that both injury and fatality frequencies are dominated by fires that do not fail the room boundaries.

CASE I - MINERAL OIL TRANSFORMER

TABLE 5-4. ANNUAL OCCURRENCE RATE OF INJURY AND FATALITY FIRES FROM A MINERAL OIL TRANSFORMER; ALTERNATE CASE OF CASE I

Percentile	Frequency Per Transformer Year	
	Injuries	Fatalities
5th	6.9×10^{-6}	1.7×10^{-7}
20th	9.5×10^{-6}	4.0×10^{-7}
50th	1.3×10^{-5}	1.0×10^{-6}
80th	1.9×10^{-5}	2.2×10^{-6}
95th	2.6×10^{-5}	4.3×10^{-6}
Mean Value	1.4×10^{-5}	1.4×10^{-6}

The main contributor to both of these frequencies is beyond the room fires: 89% of the mean frequency of injuries and 91% of the mean frequency of fatalities. In view of the dominant contributors to this damage state, it is concluded that both injury and fatality frequencies are dominated by fires originating from transformer ruptures.

5.3.3 CASE 1 RISK COMPARISON

The change in risk when an Askarel transformer is replaced by a mineral oil transformer is evident from the frequencies of Tables 5-3 and 5-4. For direct comparison between base case and alternate case results, these frequencies are repeated in Tables 5-5 (for injuries) and 5-6 (for fatalities). More percentiles are given in these tables than in Tables 5-3 and 5-4.

Another way of showing the differences between the risks from the two transformer types is given in Figure 5-7. The mean frequencies of injuries and fatalities can be put together in a 2 by 2 matrix form (item C of Figure 5-7) where the rows represent transformer type and columns represent risk attributes (injuries and fatalities). It can be shown that this matrix can be obtained by multiplying together two 2 by 2 matrices. Matrix multiplication is described below. In the first one, the damage state frequencies are given where rows represent transformer type and columns represent damage states (room and beyond room). In the second matrix, the conditional frequencies of injuries and fatalities are given where the rows represent damage states and columns represent injuries and fatalities.

To explain matrix multiplication, start with item C of Figure 5-7. The four elements of this table (or matrix in this case) are the results of the four equations given in Sections 5.3.2a.2.2 and 5.3.2b.2.2. Matrix multiplication follows the same equations. For example, the mean frequency of injuries from Askarel transformers is obtained from

$$2.0 \times 10^{-4} \times 1.6 \times 10^{-2} + 4.6 \times 10^{-7} \times 8.8 \times 10^{-2} = 3.2 \times 10^{-5}$$

Another example can be fatalities from mineral oil transformers. The mean frequency is obtained from

$$1.0 \times 10^{-4} \times 1.2 \times 10^{-3} + 1.5 \times 10^{-4} \times 8.8 \times 10^{-3} = 1.4 \times 10^{-6}$$

This matrix representation of our risk calculations, as seen below, facilitates the process of identifying the important contributors. Also, these matrices facilitate a sensitivity study of different input parameters.

Table 5-5 shows that for injuries, only a small portion of the two probability distributions overlap and the 5th percentile of the mineral oil distribution is greater than the 95th percentile of the Askarel distribution. Thus, it can be claimed that the frequency of injuries would almost certainly be increased if an Askarel transformer is replaced by a mineral oil-filled one in a setup such as case 1 of this study.

For fatalities, the overlap of the two probability distributions (see Table 5-6) is significant. The 5th percentile and median of the mineral oil distribution are at the two sides of the median and 95th percentile of the Askarel distribution. The two distributions do not intersect. To establish the degree of overlap between the two distributions, the main contributions to the uncertainties and dependencies among them must first be established.

TABLE 5-5. ANNUAL OCCURRENCE RATES OF INJURY FIRES FROM TWO TYPES OF TRANSFORMERS, CASE 1

Percentile	Frequency of Injury Fires Per Transformer Year	
	Askarel	Mineral Oil
5th	1.7×10^{-6}	6.9×10^{-6}
10th	2.0×10^{-6}	7.9×10^{-6}
20th	2.3×10^{-6}	9.5×10^{-6}
30th	2.6×10^{-6}	1.1×10^{-5}
40th	2.8×10^{-6}	1.2×10^{-5}
50th	3.1×10^{-6}	1.3×10^{-5}
60th	3.4×10^{-6}	1.5×10^{-5}
70th	3.7×10^{-6}	1.7×10^{-5}
80th	4.1×10^{-6}	1.9×10^{-5}
90th	4.7×10^{-6}	2.3×10^{-5}
95th	5.2×10^{-6}	2.6×10^{-5}
Mean Value	3.2×10^{-6}	1.4×10^{-5}

TABLE 5-6. ANNUAL OCCURRENCE RATES OF FATALITY FIRES FROM TWO TYPES OF TRANSFORMERS; CASE 1

Percentile	Frequency of Fatality Fires Per Transformer Year	
	Askarel	Mineral Oil
5th	8.6×10^{-10}	1.7×10^{-7}
10th	9.3×10^{-9}	2.5×10^{-7}
20th	9.6×10^{-8}	4.0×10^{-7}
30th	1.2×10^{-7}	5.6×10^{-7}
40th	1.7×10^{-7}	7.5×10^{-7}
50th	2.3×10^{-7}	1.0×10^{-6}
60th	2.7×10^{-7}	1.2×10^{-6}
70th	3.3×10^{-7}	1.7×10^{-6}
80th	3.9×10^{-7}	2.2×10^{-6}
90th	4.8×10^{-7}	3.4×10^{-6}
95th	5.9×10^{-7}	4.3×10^{-6}
Mean Value	2.4×10^{-7}	1.4×10^{-6}

A

MEAN ANNUAL OCCURRENCE RATE OF ROOM OR BEYOND ROOM FIRES		
TRANSFORMER TYPE	MEAN FREQUENCY PER TRANSFORMER YEAR	
	ROOM	BEYOND
ASKAREL	2.0×10^{-4}	4.6×10^{-7}
MINERAL OIL	1.0×10^{-4}	1.5×10^{-4}

×

B

MEAN CONDITIONAL FREQUENCY OF AT LEAST ONE INJURY OR FATALITY GIVEN A ROOM OR BEYOND ROOM FIRE		
EXTENT OF FIRE PROPAGATION	MEAN CONDITIONAL FREQUENCY	
	INJURIES	FATALITIES
ROOM	1.6×10^{-2}	1.2×10^{-3}
BEYOND ROOM	8.6×10^{-2}	8.8×10^{-3}

=

C

MEAN ANNUAL OCCURRENCE RATE OF INJURIES AND FATALITIES		
TRANSFORMER TYPE	MEAN FREQUENCY PER TRANSFORMER YEAR	
	INJURIES	FATALITIES
ASKAREL	3.2×10^{-6}	2.4×10^{-7}
MINERAL OIL	1.4×10^{-5}	1.4×10^{-6}

FIGURE 5-7. SUMMARY OF CASE 1 RESULTS

From Figure 5-7, it is deduced that the frequency of fatalities for Askarel transformers is dominated by room fires and for mineral oil transformers the frequency is dominated by beyond room fires. The conditional frequency of fatalities from a room fire has a wider uncertainty range than the frequency of fatalities from a beyond room fire. This partly explains the wider spread for the Askarel distribution. The dependency between these two conditional frequencies is judged to be weak because the only relationship between the two frequencies that can be identified is that the conditional frequency of fatalities from a room fire is always less than the conditional frequency from beyond room fire ($f_{F,RM} < f_{F,BND}$). This relationship holds for the bulk of the distributions for these two frequencies.

Moving back in the computation process, the uncertainties in the damage state frequencies are investigated. In Section 5.3.2a.2.1, it is found that for Askarel-filled transformers

$$\phi_{ROOM} = \lambda_R$$

and in Section 5.3.2b.2.1, it is found that for mineral oil-filled transformers, 96% of the beyond room fire frequency is from sequences originating by a rupture. Thus, there is a strong dependency between the important parts of the two fatality curves. However, the uncertainties in rupture frequency (λ_R) are much narrower than the uncertainties in the two conditional frequencies of fatalities ($f_{F,RM}$ and $f_{F,BD}$).

In summary, to compare the two fatality distributions, three important points are made: (1) the two cumulative probability distributions do not intersect; (2) there is a weak dependency between the conditional frequencies of fatalities given room and beyond room fires (the two important parameters contributing to the uncertainties of these cumulative curves); and (3) there is a strong dependency among the other parameters (rupture frequency, λ_R) contributing to the uncertainties. From these, we can claim with a high level of confidence that the frequency of fatalities would decrease significantly if an Askarel transformer replaces a transformer in a setup similar to case 1 of this study.

In the discussions above it is observed that the main difference between Askarel and mineral oil transformer fires is in the likelihood of propagation beyond the transformer room. The two frequencies of beyond room fires are compared in Table 5-7 for the two types of transformers. From that table, we conclude that fires from mineral oil transformers are (more than) 100 times more likely than fires from Askarel transformers to have a large impact on the building (beyond the transformer room). In spite of this large difference between the two types of transformers, the injury and fatality frequencies (as can be seen in Figure 5-7) are not as widely apart. The reason for this reduction in the difference lies in the differences between the conditional frequencies of injuries and fatalities for room and beyond room fires (see item 8 of Figure 5-7). Although the transformer rooms in buildings are generally unattended and the general users (except for the maintenance crew and the management of the building) do not have access to these types of rooms, the conditional

TABLE 5-7. ANNUAL OCCURRENCE RATES OF FIRES PROPAGATING BEYOND THE ROOM OF ORIGIN FROM TWO TYPES OF TRANSFORMERS; CASE 1

Percentile	Frequency of Beyond Room Fires Per Transformer Year	
	Askarel	Mineral Oil
5th	1.1×10^{-9}	7.4×10^{-5}
10th	4.2×10^{-9}	9.0×10^{-5}
20th	1.5×10^{-8}	1.0×10^{-4}
30th	3.1×10^{-8}	1.2×10^{-4}
40th	5.9×10^{-8}	1.3×10^{-4}
50th	1.0×10^{-7}	1.3×10^{-4}
60th	1.6×10^{-7}	1.5×10^{-4}
70th	2.7×10^{-7}	1.7×10^{-4}
80th	5.0×10^{-7}	1.8×10^{-4}
90th	9.6×10^{-7}	2.2×10^{-4}
95th	1.8×10^{-6}	2.2×10^{-4}
Mean Value	4.6×10^{-7}	1.5×10^{-4}

frequencies of injuries and fatalities for room fires are significant when compared to the same conditional frequencies for beyond room fires. The applicability of these conditional frequencies to our case studies is discussed in Section 5.3.4.

5.3.4 SENSITIVITY OF THE RESULTS

Many assumptions and judgmentally evaluated parameters are used throughout this case study. In this section, the sensitivity of the final results to these assumptions and parameters is envisioned. For this, it is convenient to follow the sequences of the event trees of Figures 5-5 and 5-6.

The initiating event (i.e., leak leading to fire or rupture leading to fire) frequencies are obtained from (see Appendix A)

$$\lambda_R = \lambda_{fire} f_R$$

$$\lambda_L = \lambda_{fire} (1-f_R)$$

where λ_{fire} is the frequency of transformer fires. It was obtained from statistical data for mineral oil transformers. f_R is the conditional frequency of a rupture causing a fire that is obtained from judgment. The uncertainties in transformer fire frequency (λ_{fire}) are rather small because it is assumed that all transformers behave identically and thus the sampling set is very large (strong statistical evidence leads to a narrow uncertainty range). In evaluating the conditional frequency of a rupture causing a fire (f_R), it is concluded that the likelihood of a rupture given a fire is greater than the likelihood of a leak leading to a fire.

Two important assumptions have been made at this stage. It is assumed that (1) fires from Askarel transformers are almost solely from ruptures, and (2) their fire frequency is equal to the fire frequency from rupture of mineral oil transformers. If these assumptions are true but f_R is overestimated, it can be shown that for smaller f_R the risk from Askarel transformers (that is, injury and fatality frequencies) would decrease and move further away from the mineral oil related frequencies. Essentially, lowering of f_R is the same as reducing λ_{fire} of Askarel transformers. It should be noted that if the Askarel does not contain trichlorobenzene, the second assumption (that is, the frequencies of rupture and fire of two transformer types being equal) would become very conservative, because the PCBs in general (and especially Aroclor 1254) have very high ignition temperature (their flash point is greater than 350°C) when compared to trichlorobenzene. Obviously, a more realistic risk comparison would be made if λ_{fire} for Askarel transformers is evaluated separately from relevant statistical evidence. This evidence is not readily available.

Room boundary failure frequencies for Askarel and mineral oil transformers are evaluated primarily from judgment. For an Askarel transformer, an explosion has to occur first. An explosion is possible because 1,2,4 trichlorobenzene may be vaporized (its boiling point is 214°C) and ignited. The PCB of the Askarel would not contribute to this because its boiling point is higher (greater than 350°C) and does not have a flash point up to boiling. The likelihood of boundary failure was evaluated from judgment with a mean value of 0.084, which represents the likelihood of explosion occurring with sufficient severity to damage the walls.

An important element of the boundary failure evaluation is the presence of trichlorobenzene. If an Askarel that does not contain trichlorobenzene (e.g., Aroclor 1254) was chosen for this case study, room boundary failure would have been very unlikely. However, as f_{RB-1} (conditional frequency of room boundary failure given an Askarel transformer rupture) becomes smaller, it can be shown that the final results would not change much. On the other hand, if the Askarel is assumed to be 100% PCBs (such as Aroclor 1254), the frequency of transformer fires specific to this fluid would have to be quantified explicitly because of its flame resistant characteristics (high boiling point and flash point). As shown earlier, this would have a direct effect on the risk curves and it is anticipated to move them toward lower frequencies.

The likelihood of room boundary failure in the case of mineral oil transformer rupture is judged to be a certainty. This is because mineral oil is a flammable material and it is judged that an explosion may occur upon transformer rupture. This may be a conservative conclusion, but a more realistic likelihood would not be much less than unity. A decrease in this likelihood would increase the frequency of room fire damage state. The overall effect is judged to be a slight decrease in the final risk curves.

The remaining frequencies, reflected on the event trees of Figures 5-5 and 5-6, are from heat propagation analysis (except for the conditional frequencies of below or above-liquid-level rupture). The uncertainties in these frequencies are not highly sensitive to the underlying assumptions. For example, in the case of fire propagation to an adjacent room when room boundaries are breached, the important parameters are the heat flux from the flames and ignition temperature of the materials in the adjacent room. In view of the large uncertainties in the propagation frequencies, any reasonable changes in the values of ignition temperature or heat flux would not have a significant impact on the final results.

An important factor in calculating the fire propagation likelihood is the fire brigade response time (see Appendix B). The evaluation of this reponse time is based primiarily on fire detection time and travel time for the fire brigade. Little consideration is given to special conditions arising from transformer fires. In two of the three Askarel transformer fires involving buildings, the fire brigade delayed their attack by 50 minutes and 3 hours after their arrival. These were the times when the electric power to the transformers were disconnected. A sensitivity study was performed which indicated that large increases in fire brigade response time did not significantly affect the final results; that is, did not increase frequencies of injuries and fatalities

The conditional frequencies of injuries and fatalities, given a damage state, are evaluated using statistical evidence (see Appendix C). The most important assumption at this stage of the analysis is the compatibility of the collected evidence to our case study. For beyond room fires, it is judged that the compatibility is good, because once the fire propagates out of the room of origin, it does not matter how it originated.

For room fires, the compatibility of the evidence is good for injuries because one of the two data sources is specialized to indoor transformers (see Appendix C) and the frequency estimates from individual sources are very close to each other. For fatalities in a room fire, the compatibility may not be as good as the other frequencies. This is reflected by wide uncertainties.

5.4 CASE 2 - TRANSFORMER INSTALLATION WITH MINERAL OIL CHARACTERIZATION

The base case of case 2 is a mineral oil transformer in a vault in the basement of a large building, and the alternate case is an Askarel transformer with identical specifications. Its main differences from case 1 are that the walls and ceiling are required to be built of 6-inch concrete or 8-inch brick, and that the vault is dedicated to the transformer, with no other electrical equipment inside. The following general assumptions describe the vault and the transformer in detail and are applicable to both alternatives of this case.

5.4.1 GENERAL ASSUMPTIONS

A single transformer is located in a vault in the basement of a large building (see Figure 5-8 for a plan view). The transformer converts a 4,800V power source to 120/240V. The rating of the transformer is 167 kVA. It measures 2 feet by 2.5 feet by 3 feet tall and contains 80 gallons of fluid. The vault is approximately 20 feet by 20 feet and 8 feet tall. Its floor is sloped 1/16-inch per foot to a sump 3 feet square and 2 feet 6 inches deep.

The vault has a dedicated ventilation system. The air inlet is equipped with a fire damper. The air outlet is equipped with louvers to prevent the entrance of rain. The capacity of the blower is 2,000 ft^3/minute

The penetrations of the room include air ducts, conduits for electrical cables, and a self-closing, 3-hour rated fire door (5 feet by 8 feet) which is normally locked closed. All walls, the floor, and the ceiling are constructed of 6-inch reinforced concrete or 8-inch brick.

The vault is assumed to be equipped with an automatic sprinkler system. The temperature settings of the heads are taken to be of ordinary classification (see Reference 9 for definition) that range between 57°C and 77°C (135°F and 170°F).

The details of risk calculations for the two transformer types are given in Sections 5.4-2a and 5.4.2b. To facilitate their comparison, the format of this report is altered and the two sections are presented side by side.

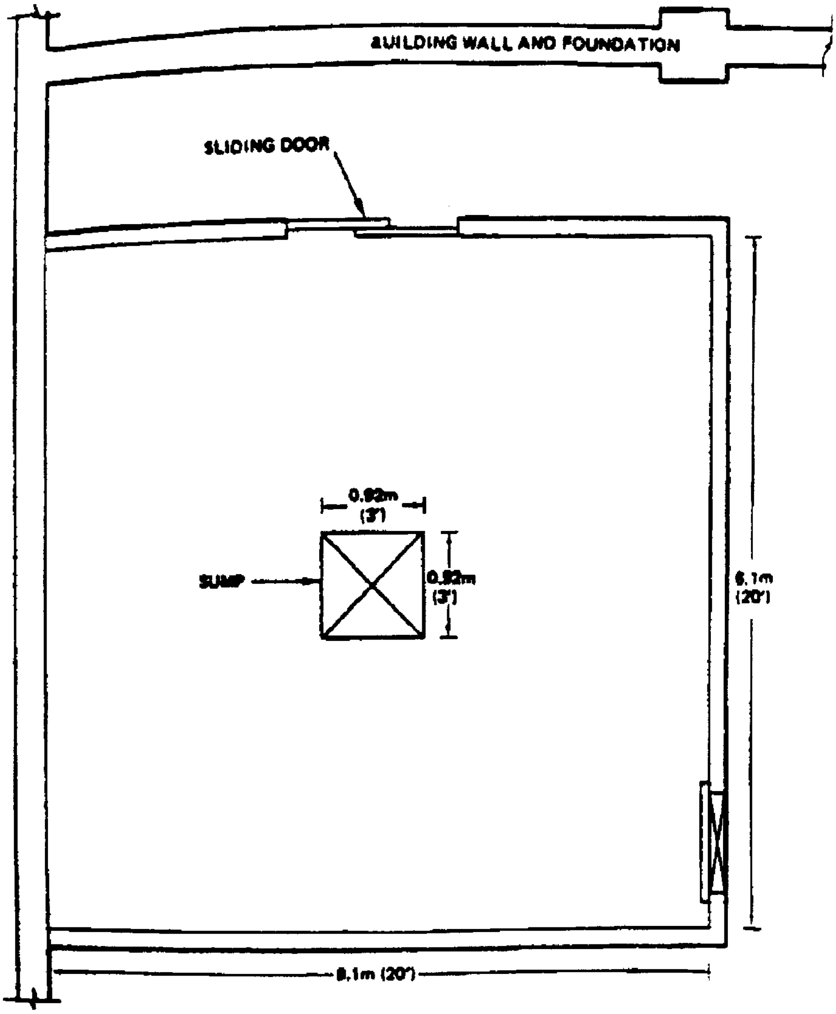

FIGURE 5-8. PLAN VIEW OF THE TRANSFORMER VAULT
FOR CASE 2

CASE 2 - MINERAL OIL TRANSFORMER

5.4.2a CASE 2: BASE CASE - MINERAL OIL TRANSFORMER

The liquid of the transformer is assumed to be mineral oil. Figure 5-9 shows the event tree for the potential event sequences.

Similar to the analysis for case 1, the event tree for case 2 considers two accident precursors, leak and rupture, and two possible end states, a room fire and a fire beyond the room.

5.4.2a.1 <u>Top Event Quantification</u>

Each top event in Figure 5-9 is evaluated in this section.

5.4.2a.1.1 (L/R) Leak (L) or Rupture (R)

In Appendix A, the conditions leading to the leakage of a transformer are discussed and the mean frequency of a transformer fire caused by a leak is assessed to be 4.8×10^{-5} per transformer year. Similarly, the mechanisms causing a transformer rupture are described and the mean frequency of a transformer fire because of a rupture is assessed to be 2.0×10^{-4} per transformer year. In the case of a rupture, it is assumed that the mineral oil is ignited and the fire is spread by the splattering oil.

5.4.2a.1.2 (VBND) Vault Boundary Failure

In order for the fire to propagate outside the vault, its boundaries must be breached. The conditional frequencies of this event, given a leak and a rupture, are assessed separately below.

5.4.2a.1.2.1 <u>(VB-1) Vault Boundary Failure Given a Leak.</u> In the case of a leak leading to a fire, it is assumed that the burning oil is mainly in the sump. The vault boundary may fail if the heat impinging on the wall endures for a sufficiently long time. One factor that may limit the duration of such a fire in the vault is the amount of mineral oil available. The other factor is the operation of the automatic sprinkler system. There are two modes for

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5.4.2b CASE 2. ALTERNATE CASE - ASKAREL TRANSFORMER

The mineral ' in the transformer of the base case is assumed to be ..placed by Askarel while keeping other conditions unchanged. The event tree changes in that the Askarel leaking out of the tank cannot be ignited. The difference between this and the base case of case 1 is that the vault boundary is assumed to be 3-hour rated rather than 1-hour rated and that administrative control is imposed to keep unauthorized personnel and unnecessary material away from the vault.

The same general assumptions as described in Section 5.4.1 are applicable here. The event tree of Figure 5-10 gives the chain of events that may follow an Askarel transformer fire. The events of this tree are quantified below.

5.4.2b.1 <u>Top Event Quantification</u>

Each top event in Figure 5-10 is evaluated in this section.

5.4.2b.1.1 (L/R) ...age (L) or Rupture (R)

In Section 5.3.2a.1.1, it was established that Askarel leaks do not lead to a fire; therefore, leaks do not have adverse consequences and do not require further evaluation. In Section 5.3.2a.1.4, it was established that ruptures of Askarel transformers may lead to fire. The frequency of such fires, λ_R, has been assessed in Appendix A to be 2.0×10^{-4} per transformer year.

5.4.2b.1.2 (VBND) Vault Boundary Failure (VB-3)

In order for the fire to propagate outside the vault, its boundaries must be breached. The conditional frequencies of this event, given a rupture, are assessed separately below.

5.4.2b.1.2.1 <u>Vault Boundary Failure Given a Leak.</u> (Not applicable.)

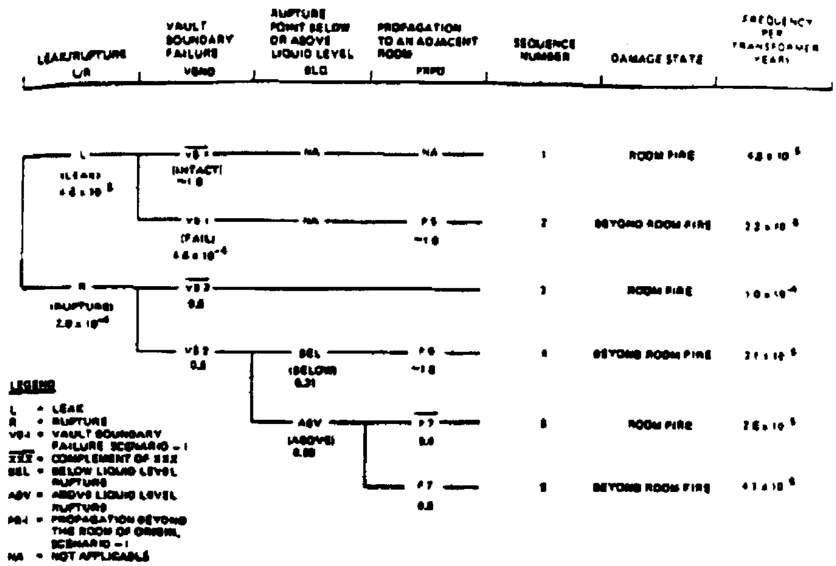

FIGURE 5-9. EVENT TREE FOR THE BASE CASE, THE MINERAL OIL TRANSFORMER OF CASE 2

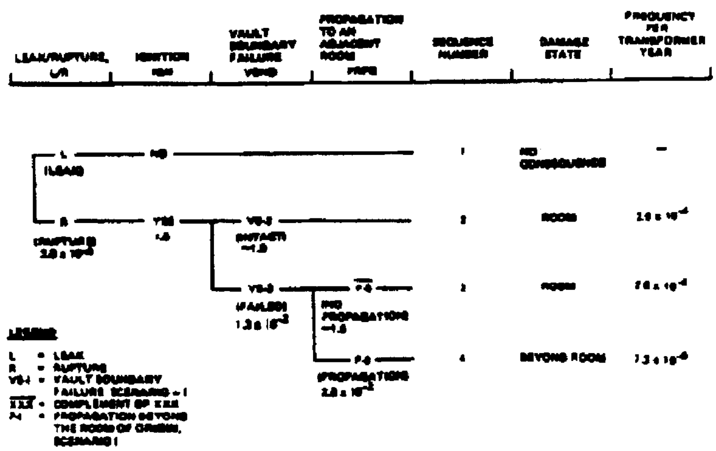

FIGURE 5-10. EVENT TREE FOR THE ALTERNATE CASE OF CASE 2, AN ASKAREL TRANSFORMER IN THE VAULT

CASE 2 - MINERAL OIL TRANSFORMER

failure of the vault boundary. One is that the sprinkler system fails on demand and the amount of fuel is enough to support a fire of long duration, causing vault failure. The other mode is that the sprinkler system starts on demand but the fire suppression time is longer than the time until the vault boundary fails.

The COMPBRN computer code (Reference 18) is used to model such fires and calculate the heat flux on the walls and ceiling. Assuming the area of the fire is equal to the sump area and assuming surface burning rate of 33.2 g/m^2sec (Reference 18), the mass burning rate is 27.8 g/sec, and the heat generation rate is 1.3×10^6 W. The height of the flame calculated using Thomas's correlation (Reference 19) is 2.44 meters, which is only 20 cm below the ceiling. It is conservatively assumed that the heat flux the ceiling receives is equal to the flux inside the flame. The flux inside the flame is equal to the heat generation rate divided by the surface area of a cylinder with base area equal to 0.84 m^2 (9 ft^2) and height equal to the flame height. The heat flux at the ceiling is 133 kW/m^2. Therefore, the ceiling is considered the most likely location of a breach in the vault boundaries. The one-dimensional heat conduction code, THEAT (Reference 20), is used to model the failure of the ceiling. An equivalent flame temperature of 1,238°K is determined by equating the radiative heat flux (σT^4) to the flux at the ceiling calculated using COMPBRN. The radiative boundary conditions can then be used.

It is determined that it takes approximately 119 minutes for the other side of the 6-inch concrete ceiling to experience a temperature rise of 140°C based on the definition of the fire rating of a boundary (Reference 9). The fire rating of 6-inch concrete floor is more than 3.5 hours (Figure 5-8F, Reference 9). The shorter failure time for the ceiling is assumed to be exposed to 1,238°K flame from time zero, while during the standard test the fire temperature is well below 1,238°K during the first 60 minutes (Reference 21). The statistical uncertainty about the time at which the ceiling fails is assumed to be very small compared with the state-of-knowledge uncertainty which is represented by an error factor, E_D. The distribution for the latter type of uncertainty is established using the same approach as used for similar fire propagation times in case 1. A lognormal distribution is assumed for E_D, with 5th and

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95th percentiles at 0.8 and 4.0. The propagation time τ_G is established from

$$\tau_G = 119E_0 \text{ (minutes)}$$

The fire suppression likelihood is taken from Appendix B. The sprinkler system unavailability upon demand, f_{SPR}, is established in Appendix B. Its mean value is .077. Given that the sprinklers are working, the fire suppression time is taken to be exponentially distributed with mean value τ_{SPR}. The state-of-knowledge uncertainty about τ_{SPR} is established in Appendix B. Its mean value is 17.3 minutes. The time for the fire brigade to put out the fire is evaluated in a similar manner. That is, it is taken to be exponentially distributed with mean value τ_{FB}. The mean value of the state-of-knowledge uncertainty is 25.5 minutes. Finally, for the conditional frequency of vault boundary failure given a transformer leak that leads to fire, f_{VB-1}, we can write

$$f_{VB-1} = [f_{SPR} + (1-f_{SPR})\exp(-\tau_G/\tau_{SPR})]\exp(-\tau_G/\tau_{FB})$$

Using the values given above for the parameters of the distributions and using discrete probability distribution (DPD) arithmetic to propagate uncertainty (see Appendix G), the distribution for f_{VB-1} can be calculated. Its characteristic values are:

5th Percentile:	less than 10^{-10}
Median:	3.0×10^{-6}
95th Percentile:	2.3×10^{-3}
Mean:	4.6×10^{-4}

5.4.2a.1.2.2 <u>(VB-2) Vault Boundary Failure Given a Rupture</u>. In the case of a rupture, it is suspected that an explosion (either deflagration or detonation) may take place. (Deflagration is an explosion where the flame front propagates at a subsonic velocity, in detonation, it propagates at a supersonic velocity. Detonation generates a much higher pressure wave than deflagration.) The pressure surge that the vault boundaries may experience is computed in Appendix D. In that appendix, the adiabatic, constant-volume model for the deflagration of mineral oil during a transformer rupture to determine the pressure rise is used. Reference 15 shows that the arc energy needed to

5.4.2b.1.2.2 <u>Vault Boundary Failure Given a Rupture</u>. (Not applicable.)

The mechanisms for vault boundary failure from the rupture of an Askarel transformer are the same as those described in Section 5.3.2a.1.6 for case 1 vault boundary failure. In this case, because of the strength of the vault boundary, the likelihood of failure must be much smaller.

The pressure pulse from a deflagration has to be much stronger (above 7 psig) at the boundaries to fail a wall. Similarly, the release of pressurized gases from the tank has to have very large initial pressure It has been shown

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rupture the tanks of 10 kVA to 100 kVA transformers is in the range of 10 kJ to 80 kJ, and the higher the rating of the transformer, the higher the arc energy needed. With 80 kJ of arc energy, the pressure rise is found to be 2.4 psi. Reference 14 states that an overpressure of 7 to 8 psi will cause an 8-inch-thick brick wall to fail. If we assume that the arc energy that will rupture a transformer tank is proportional to the power rating of the transformer, then the arc energy will be approximately 140 kJ for the 170 kVA transformer considered, and the pressure rise due to deflagration will be 3.9 psi (Table B-2). Therefore, the vault boundary may be able to survive the pressure pulse due to deflagration. The pressure surge from a detonation can be significantly higher than in the case of deflagration, such that the vault boundary will certainly be breached.

During the rupture of a mineral oil transformer, the chance that either a deflagration or a detonation occurs is believed to be very high. However, in one incident of mineral oil transformer rupture, neither explosion nor damage due to pressure pulse was reported (Reference 22). If an explosion occurs, the chance that it is a detonation is probably not as high as the chance of a deflagration, because detonation requires more stringent requirements for it to occur. It must be noted that in the case of an Askarel transformer rupture only deflagration may occur and detonation is deemed to be impossible (see Section 5.3.2a.1.6). In Reference 23, experiments of detonations were conducted. A 10-meter long and 1.6-meter diameter pipe with one end closed and the other end open was filled with mixtures of combustibles and air with concentrations within the detonation limits. The mixtures were ignited at the closed end of the pipe. The pressure wave propagated from the closed end toward the open end. It was found that it took some distance before the wave velocity became supersonic. This distance depends on the type of combustibles, the concentration of the mixtures, and the diameter of the pipe. In all their experiments, it took at least 3 meters before the detonation velocity was reached and this distance increased with pipe diameter. Therefore, it is expected that the likelihood of a detonation in a rupture of mineral oil transformer in a room is low. From this, the following distribution for the

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in Section 5.3.2a.1.6 that this is practically impossible. Prolonged exposure of the walls to the heat flux from combustion of the transformer fluid has to be much longer in this case than in case I because the walls are much thicker. From this comparison with case I, we assess the frequency of a breach of the vault boundary f_{VB-3} from judgment to have a lognormal distribution with 5th and 95th percentiles at 5×10^{-4} and 0.05, respectively, and its median and mean are 5.0×10^{-3}, 1.33×10^{-2}, respectively.

The likelihood of the vault boundary remaining intact is the complement of the above frequency. Its mean value is 0.987.

frequency of vault boundary failure during a mineral oil transformer rupture, f_{VB-2} is established:

Conditional Frequency f_{VB-2}	Probability
0.2	0.3
0.5	0.4
0.8	0.3

Its mean value is 0.5. It represents our state of knowledge about the event.

5.4.2a.1.3 (BLQ) Rupture Point Above (ABV) or Below (BEL) the Liquid Level

This event is the same as the BLQ in case 1. Therefore, the same branch frequencies (that is, the mean of f_{BEL} = 0.31 and the mean of f_{ABV} = 0.69) can be used.

5.4.2a.1.4 (PRPG) Propagation to an Adjacent Zone (f_{P-7})

At this branch point, given that a rupture occurs and the vault boundary is breached, the possibility of fire propagation outside the vault is considered. For the case where the rupture occurs below the liquid level, hot and possibly burning mineral oil is splattered outside the room; therefore, the frequency that the fire is propagated to the outside is assumed to be unity. If the rupture is above the liquid level, most mineral oil will remain in the tank and will be ignited by the arc or the hot coils. The dominant mode of fire propagation is deemed to be radiation from the flames. Since this process is not rapid, fire suppression is possible. Given that the boundary is breached, and the rupture occurs above the liquid level, the scenario is identical to the P-4 event of the alternate case of case 1. Therefore, the suppression model of Appendix F can be used, i.e., mean value of $f_{P-7} = f_{P-4} = 0.60$.

5.4.2a.2 <u>Damage State and Consequence Quantification</u>

Having evaluated the frequencies of all the branching points, the event sequences of the event tree of Figure 5-9 can be quantified to yield the frequency of the two damage states. These damage state frequencies can then be combined with related health effect likelihood to establish

5.4.2b.1.3 (BLQ) Rupture Point

The position of rupture point does not have any significant impact on the accident sequences.

5.4.2b.1.4 (PRPG) Propagation to an Adjacent Room (P-8)

The fire propagation outside the vault given that the rupture breaches the vault boundary is similar to the propagation scenario P-1 (Section 5.3.2a 1.8) that has been modeled in case 1. The same branch point frequency can be used here; i.e.,

$$f_{P-8} = f_{P-1}$$

Its mean value is 2.8×10^{-2}.

5.4.2b.2 <u>Damage State And Consequence Quantification</u>

Having evaluated the frequencies of all the branching points, the event sequences in the event tree of Figure 5-10 can be quantified to yield the frequency of the two damage states. These damage state frequencies can then be combined with related health effect likelihood to

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the frequencies of consequences in terms of injuries and fatalities.

5.4.2a.2.1 Damage State Frequencies

In Figure 5-9, the mean frequencies of the sequences and their associated damage states are indicated. The frequency of the "room fire" damage state is

$$\phi_{ROOM} = \lambda_L (1-f_{VB-1}) + \lambda_R [(1-f_{VB-2}) + f_{VB-2} f_{ABV} (1-f_{P-7})]$$

The total frequency of the beyond room fire damage state is

$$\phi_{BYND} = \lambda_L f_{VB-1} + \lambda_R f_{VB-2} (f_{BEL} + f_{ABV} f_{P-7})$$

Using DPD arithmetic (see Appendix G), the distributions depicting our uncertainties about ϕ_{ROOM} and ϕ_{BYND} can be computed. Their characteristic values are given in Table 5-8.

TABLE 5-8. ANNUAL OCCURRENCE RATE OF ROOM AND BEYOND ROOM FIRES FROM A MINERAL OIL TRANSFORMER; BASE CASE OF CASE 2

Percentile	Frequency Per Transformer Year	
	Room Fire	Beyond Room Fire
5th	8.3×10^{-5}	1.9×10^{-5}
20th	1.2×10^{-4}	3.1×10^{-5}
50th	1.7×10^{-4}	6.4×10^{-5}
80th	2.3×10^{-4}	1.1×10^{-4}
95th	2.9×10^{-4}	1.6×10^{-4}
Mean Value	1.8×10^{-4}	7.3×10^{-5}

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establish the frequencies of the consequences in terms of injuries and fatalities.

5.4.2b.2.1 Damage State Frequencies

In Figure 5-10, the mean frequencies of the sequences and their damage states are indicated. The frequency of the "room fire" damage state is equal to the sum of the frequencies of sequences 2 and 3 in Figure 5-10

$$\phi_{ROOM} = \lambda_R [(1-f_{VB-3}) + f_{VB-3}(1-f_{P-8})]$$

$$= \phi_R (1-f_{VB-3} f_{P-8}) = \lambda_R$$

The frequency of beyond room fire damage state is equal to the frequency of sequence 4 in Figure 5-10

$$\phi_{BYND} = \lambda_R f_{VB-3} f_{P-8}$$

Using DPD arithmetic (see Appendix G), the distributions for ϕ_{ROOM} and ϕ_{BYND} are calculated. Their characteristic values are given in Table 5-9.

TABLE 5-9. ANNUAL OCCURRENCE RATE OF ROOM AND BEYOND ROOM FIRES FROM AN ASKAREL TRANSFORMER; ALTERNATE CASE OF CASE 2

Percentile	Frequency Per Transformer Year	
	Room Fire	Beyond Room Fire
5th	1.4×10^{-4}	1.4×10^{-10}
20th	1.6×10^{-4}	1.6×10^{-9}
50th	1.9×10^{-4}	1.2×10^{-8}
80th	2.4×10^{-4}	6.4×10^{-8}
95th	2.9×10^{-4}	3.1×10^{-7}
Mean Value	2.0×10^{-4}	2.3×10^{-8}

It should be noted that the room fire frequency is dominated by sequences originating from a rupture (73% of the mean value), and almost 100% of the "beyond room fire" frequency is from sequences originating from a rupture.

5.4.2a.2.2 Consequences

The conditional frequencies of one or more injuries and one or more fatalities for each damage state are evaluated in Appendix C. The unconditional frequencies are products of the frequencies of Appendix C and ϕ_{ROOM} or ϕ_{BYND}. For the frequency of injuries, we can write

$$\phi_{I,BC-2} = \phi_{BYND}\, f_{I,BD} + \phi_{ROOM}\, f_{I,RM}$$

and for the frequency of fatalities, we can write

$$\phi_{F,BC-2} = \phi_{ROOM}\, f_{F,RM} + \phi_{BYND}\, f_{F,BD}$$

These are the frequencies of occurrence of one or more injuries and one or more fatalities from a mineral oil transformer installed according to the descriptions given in Section 5.4.1. The distributions depicting our uncertainty about these frequencies are obtained by propagating the uncertainties in the frequencies on the right-hand side of the above equations using discretized probability distribution arithmetic (see Appendix G). The characteristic values of these distributions are given in Table 5-10.

TABLE 5-10. ANNUAL OCCURRENCE RATE OF INJURY AND FATALITY FIRES FROM A MINERAL OIL TRANSFORMER, BASE CASE OF CASE 1

Percentile	Frequency Per Transformer Year	
	Injuries	Fatalities
5th	3.7×10^{-6}	1.3×10^{-7}
20th	5.4×10^{-6}	2.9×10^{-7}
50th	8.3×10^{-6}	6.0×10^{-7}
80th	1.2×10^{-5}	1.3×10^{-6}
95th	1.8×10^{-5}	2.7×10^{-6}
[illegible]	[illegible] $\times 10^{-6}$	8.5×10^{-7}

It should be noted that 99% of the room fire frequency is from the second sequence of Figure 5-10 where the vault boundary stays intact after an Askarel transformer rupture.

5.4.2b.2.2 Consequences

The conditional frequencies of one or more injuries and one or more fatalities for each damage state are evaluated in Appendix C. The unconditional frequencies are products of the frequencies of Appendix C and ϕ_{ROOM} or ϕ_{BYND}. For the frequency of injuries, we can write

$$\phi_{I,AC-2} = \phi_{BYND}\, f_{I,BD} + \phi_{ROOM}\, f_{I,RM}$$

and for the frequency of fatalities, we can write

$$\phi_{F,AC-2} = \phi_{ROOM}\, f_{F,RM} + \phi_{BYND}\, f_{F,BD}$$

These are the frequencies of occurrence of one or more injuries and one or more fatalities from an Askarel transformer installed according to the descriptions given in Section 5.4.1. The distribution depicting our uncertainty about these frequencies are obtained by propagating the uncertainties in the frequencies on the right-hand side using DPD arithmetic (see Appendix G). The characteristic values of these distributions are given in Table 5-11.

TABLE 5-11. ANNUAL OCCURRENCE RATE OF INJURY AND FATALITY FIRES FROM AN ASKAREL TRANSFORMER, ALTERNATE CASE OF CASE 2

Percentile	Frequency Per Transformer Year	
	Injuries	Fatalities
5th	1.7×10^{-6}	2.0×10^{-9}
20th	2.3×10^{-6}	9.3×10^{-8}
50th	3.0×10^{-6}	2.1×10^{-7}
80th	4.0×10^{-6}	3.9×10^{-7}
95th	5.1×10^{-6}	5.9×10^{-7}
Mean Value	3.2×10^{-6}	2.5×10^{-7}

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Both frequencies are dominated by the damage state beyond room fire. However, the contribution of room fire is noticeable. For injuries, the room fire damage state contributes 31% of the mean frequency and for fatalities, it contributes 25%. The contribution of a transformer rupture initiating event is important. It contributes to 92% of mean injury frequency and 93% of mean fatality frequency.

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The main contributor to both frequencies is room fires. Thus, injury and fatality frequencies are mainly from fires that do not fail the vault boundaries.

5.4.3 CASE 2 RISK COMPARISON

The change in risk when a mineral oil transformer is replaced by an Askarel transformer is evident from the frequencies listed in Tables 5-9 and 5-11. For direct comparison between base case and alternate case results these frequencies are repeated in Tables 5-12 (for injuries) and 5-13 (for fatalities). These tables give more percentiles than Tables 5-9 and 5-11. The results are also summarized in the form of matrices (Figure 5-11). The mean frequencies of injury and fatality fires are put together in the form of a 2 by 2 matrix. As shown in Section 5.3.3, this matrix can be obtained by multiplying two 2 by 2 matrices (matrix multiplication is described in Section 5.3.3), the frequencies of room or beyond room fires and the conditional frequencies of injuries or fatalities given a room or beyond room fire.

Based on the following observations, it is judged that with a high level of confidence, the frequencies of injuries and fatalities would decrease if a mineral oil transformer is replaced by an Askarel transformer in a setup similar to case 2 of this study.

Table 5-12 shows that for injuries, the probability distributions overlap to some extent but do not intersect each other. The 5th percentile of the mineral oil distribution is between the median and 95th percentile of the Askarel distribution. The latter (i.e., the Askarel distribution) is mainly from the product of two terms frequency of ruptures (λ_R) and conditional frequency of an injury fire given a room fire ($f_{I,RM}$). This can be easily verified by inspecting Figure 5-11. The mineral oil distribution, however, cannot be expressed as simply; 69% of its mean value is from beyond room fires. This means that an important part of the uncertainties is from the conditional frequency of an injury fire given a beyond room fire ($f_{I,BND}$) and a small portion of it from $f_{I,RM}$. It should be noted that the dependency between $f_{I,BND}$ and $f_{I,RM}$ is judged to be very weak because for almost all probable values

$$f_{I,RM} < f_{I,BND}$$

which is intuitively expected to hold.

Another important part of injury frequencies is the initiating event frequency. For Askarel-filled transformers, 100% of it is from transformer rupture and for mineral oil, 92% of the frequency is from rupture. Thus, there is a strong correlaton between the two injury curves at the initiating event level.

For the fatality distributions the same type of the dependencies among the input parameter exists as for the injury distributions because the same type of contributors are used. Thus, the same conclusions can be reached.

Similar to case 1, from the above discussions we conclude that an important difference between Askarel and mineral oil transformer fires is in the likelihood of propagating beyond the transformer room. The two frequencies of beyond room fires are compared in Table 5-14 for the two

TABLE 5-12. ANNUAL OCCURRENCE RATES OF INJURY FIRES FROM TWO TYPES OF TRANSFORMERS; CASE 2

Percentile	Frequency of Injury Fires Per Transformer Year	
	Askarel	Mineral Oil
5th	1.7×10^{-6}	3.7×10^{-6}
10th	1.8×10^{-6}	4.3×10^{-6}
20th	2.3×10^{-6}	5.4×10^{-6}
30th	2.6×10^{-6}	6.3×10^{-6}
40th	2.8×10^{-6}	7.2×10^{-6}
50th	3.0×10^{-6}	8.3×10^{-6}
60th	3.3×10^{-6}	9.2×10^{-6}
70th	3.6×10^{-6}	1.1×10^{-5}
80th	4.0×10^{-6}	1.2×10^{-5}
90th	4.7×10^{-6}	1.5×10^{-5}
95th	5.1×10^{-6}	1.8×10^{-5}
Mean Value	3.2×10^{-6}	9.2×10^{-6}

TABLE 5-13. ANNUAL OCCURRENCE RATES OF FATALITY FIRES FROM TWO TYPES OF TRANSFORMERS; CASE 2

Percentile	Frequency of Fatality Fires Per Transformer Year	
	Askarel	Mineral Oil
5th	2.0×10^{-9}	1.3×10^{-7}
10th	4.9×10^{-9}	1.9×10^{-7}
20th	9.3×10^{-8}	2.9×10^{-7}
30th	1.3×10^{-7}	3.9×10^{-7}
40th	1.9×10^{-7}	4.9×10^{-7}
50th	2.1×10^{-7}	6.0×10^{-7}
60th	2.6×10^{-7}	7.5×10^{-7}
70th	3.1×10^{-7}	9.4×10^{-7}
80th	3.9×10^{-7}	1.3×10^{-6}
90th	5.2×10^{-7}	1.9×10^{-6}
95th	5.9×10^{-7}	2.7×10^{-6}
Mean Value	2.5×10^{-7}	8.5×10^{-7}

A

MEAN ANNUAL OCCURRENCE RATE OF ROOM OR BEYOND ROOM FIRES		
TRANSFORMER YEAR	MEAN FREQUENCY PER TRANSFORMER YEAR	
	ROOM	BEYOND
ASKAREL	2.0×10^{-4}	7.3×10^{-8}
MINERAL OIL	1.0×10^{-4}	7.3×10^{-5}

×

B

MEAN CONDITIONAL FREQUENCY OF AT LEAST ONE INJURY OR FATALITY GIVEN A ROOM OR BEYOND ROOM FIRE		
EXTENT OF FIRE PROPAGATION	MEAN CONDITIONAL FREQUENCY	
	INJURIES	FATALITIES
ROOM	1.8×10^{-2}	1.2×10^{-3}
BEYOND ROOM	8.8×10^{-2}	8.8×10^{-3}

=

C

MEAN ANNUAL OCCURRENCE RATE OF INJURIES AND FATALITIES		
TRANSFORMER TYPE	MEAN FREQUENCY PER TRANSFORMER YEAR	
	INJURIES	FATALITIES
AREL	3.2×10^{-6}	2.4×10^{-7}
MINERAL OIL	8.2×10^{-8}	0.5×10^{-7}

FIGURE 5-11. SUMMARY OF CASE 2 RESULTS

TABLE 5-14. ANNUAL OCCURRENCE RATES OF FIRES PROPAGATING BEYOND THE ROOM OF ORIGIN FROM TWO TYPES OF TRANSFORMERS, CASE 2

Percentile	Frequency of Beyond Room Fires Per Transformer Year	
	Askarel	Mineral Oil
5th	1.4×10^{-10}	1.9×10^{-5}
10th	4.7×10^{-10}	2.2×10^{-5}
20th	1.6×10^{-9}	3.1×10^{-5}
30th	3.5×10^{-9}	4.3×10^{-5}
40th	7.0×10^{-9}	5.3×10^{-5}
50th	1.2×10^{-8}	6.4×10^{-5}
60th	1.9×10^{-8}	7.7×10^{-5}
70th	3.4×10^{-8}	8.9×10^{-5}
80th	6.4×10^{-8}	1.1×10^{-4}
90th	1.4×10^{-7}	1.4×10^{-4}
95th	3.1×10^{-7}	1.6×10^{-4}
Mean Value	7.3×10^{-8}	7.3×10^{-5}

transformer types. From that table, it is concluded that fires from mineral oil transformers are (more than) 60 times more likely than fires from Askarel transformers to have a large impact on the building.

5.4.4 SENSITIVITY OF THE RESULTS

The discussions on the sensitivity of the results to the underlying assumptions and judgmentally evaluated parameters for case 1 (Section 5.3.4) are almost directly applicable for this case. Similar to case 1, Askarel transformer fire frequency and the likelihood of vault boundary failure are dependent on the presence of trichlorobenzene in the Askarel. Also, similar to case 1, changes in Askarel transformer fire frequency would have a direct effect on the final results. For more realistic results, the frequency of Askarel transformer fire would have to be evaluated from relevant data and is anticipated to be much smaller than the value that has been used.

The likelihood of a vault boundary failure in the case of mineral oil transformer rupture is taken to be small (VB-2 on Figure 5-9). This has increased the importance of room fires to the final results. It can be shown that if this parameter is further reduced (that is, a smaller likelihood for vault failure), the mineral oil risk curves would move closer to Askarel risk curves (given that everything else is kept as is).

Injury and fatality conditional frequencies are less relevant here because (1) those conditional frequencies were based on data from all types of office buildings, and (2) vaults are not typically found in buildings and are not accessible for the general building occupants. Also, outside the vault in this case is not a general use area; thus, the general occupants of the building are less exposed to the transformer fire consequences in this case than in case 1.

5.5 <u>DISCUSSION</u>

Having compared the fire risk from mineral oil and Askarel transformers for two case studies, has the goal of this study been achieved? To answer this question, let us examine some important facets of this study.

The risk attributes chosen are acute injuries and fatalities. In the 1930s, the decision to replace mineral oil with PCBs was made based on a qualitative understanding of risk. It is difficult to assess today whether public health protection or property damage was the main motivation for the decision. Certainly at that time, the environmental persistence of the PCBs was unknown to the experts and the fire resistance characteristic of the PCBs was the focal issue of the decision. Thus, the injuries and fatalities caused by transformer fires were chosen as the two risk attributes for this study. Property damage and loss of production because of transformer fires are not addressed.

The two sites chosen for this study are in public-use buildings. The comparison is made in case 1 between an Askarel transformer at an installation specifically designed for it and a mineral oil transformer replacing the Askarel transformer. Because of the sprinkler system over the transformer, the mineral oil transformer in this setup is allowed per the national electrical code (Reference 16). Thus, the case 1 results carry an important message: under equal conditions, the fire risk decreases significantly when a mineral oil transformer is replaced by an Askarel transformer.

The results of case 2 can be interpreted in a similar way. The setup (a vault in the basement) is specific to a mineral oil transformer. Askarel transformers above 35,000 volts are also put in vaults according to the electrical codes (Reference 16). The risk comparison in this case also represents a realistic situation. The primary side of the transformer considered is 4,800 volts, which is much less than 35,000 volts. However, our analysis is more sensitive to the size of the transformer (dictated by its power level) than the primary voltage. For larger transformers, the amount and surface area of the combustibles (trichlorobenzene in the case of Askarel transformers) are larger than those considered in case 2. Our judgment is that for larger transformers, the injury and fatality frequencies would be farther apart than those obtained in this study, because the mineral oil transformer fire would be more severe.

Comparison between the base cases of the two case studies is not warranted for two reasons. First, the same conditional frequencies of injuries and fatalities are used. These frequencies were obtained from general building fire occurrence data. In both cases, the room of origin is not readily accessible for the general building users (the door is locked closed). In case 1, the rooms adjacent to the transformer room are used by the general building users, whereas in case 2, outside the vault, only the building maintenance or management personnel are typically present. Second, the models used to estimate the conditional frequency of boundary failure and fire propagation include many conservative assumptions so that a direct comparison may be misleading.

The extension of the final results to other situations is also not warranted. For example, the injury and fatality frequencies are not applicable to distribution transformers on poles at the backyard of suburban homes or transformers installed outside the building. However, transformer rooms in large buildings are commonplace and the base cases of our case studies represent real situations. Of the intermediate results, only the initiating events' frequencies and injury and fatality conditional frequencies are applicable outside the two case studies.

In summary, although only two specific cases are examined, the goal of this study was achieved. The comparison of probability distributions for injuries and fatalities for both cases indicate that there is a significant decrease in the fire risk when an mineral oil transformer is replaced by an Askarel transformer.

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APPENDIX A

FREQUENCIES OF TRANSFORMER PROBLEMS

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FREQUENCIES OF TRANSFORMER PROBLEMS

The frequencies of transformer problems are assessed in this appendix using Bayesian methods. In Section 5, it is found that the transformer problems of interest are: (1) ignition of a leaking mineral oil transformer, (2) ignition of a ruptured mineral oil transformer, and (3) rupture of an Askarel transformer. To establish these frequencies, statistical evidence on a sample of transformers and the number of fires (categorized by rupture or leak) that were observed is needed. The data from several sources were reviewed. Individually, none of the sources could provide sufficient information for establishing the number of occurrences and the size of the sampling set. Data used in this appendix are primarily from sources covering all of the United States; however, some important data are obtained from sources specific to the State of California. Also, from the available information, the fire incidence could not be categorized by rupture or leak. Therefore, the combined frequency of fire is first established and then two conditional fractions are introduced. One depicts the conditional frequency of a leak given a fire and the other depicts the conditional frequency of a fire given a rupture.

The frequencies for mineral oil transformers are evaluated in Section A.1. The approach to arrive at these frequencies is also discussed in that section. The results of Section A.1 are extended in Section A.2 to assess the frequencies of problems for an Askarel transformer. Section A.3 discusses all the available information, including information indirectly related to the frequencies of interest. This type of information is used to better establish some of the parameters using judgment.

A.1 FREQUENCY OF FIRE IN MINERAL OIL TRANSFORMERS

A.1.1 GENERAL FRAMEWORK

In Section A.3, it is found that from the available information sources the fire incidence data cannot be categorized by rupture or leak. Therefore, an overall frequency of fire, λ_{fire}, will be established first. This frequency can be written as the sum of two frequencies

$$\lambda_{fire} = \lambda_{rupture\ and\ fire} + \lambda_{leak\ and\ fire} \quad (A.1)$$

where

λ_{fire} = frequency of transformer fire.

$\lambda_{rupture\ and\ fire}$ = frequency of fire caused by transformer rupture.

$\lambda_{leak\ and\ fire}$ = frequency of fire caused by the ignition of the leaking mineral oil.

Further, we define

f_R = fraction of transformer fires that are caused by ruptures.

$f_L = 1 - f_R$ = fraction of transformer fires that are caused by the ignition of the leaking mineral oil.

and we can write

$$\lambda_{\text{rupture and fire}} = \lambda_{\text{fire}} f_R \qquad (A.2)$$

and

$$\lambda_{\text{leak and fire}} = \lambda_{\text{fire}} (1 - f_R) \qquad (A.3)$$

Probability distributions are first assessed for λ_{fire} and f_R, and the frequencies of fire and leak and fire and rupture are obtained from Equations (A.2) and (A.3).

A.1.2 BAYES' THEOREM

The frequency of transformer fires, λ_{fire}, is assessed using Bayes' theorem (References A-1 and A-2). The frequency of transformer fires per transformer year can be considered as the parameter of a binomial distribution. Let N be the number of transformers and K be the number of transformer fires. Given the frequency of transformer fires, λ_{fire} (or λ for short), the likelihood that K transformer fires occur in a population of N transformers is

$$L(N,K|\lambda) = \binom{N}{K} \lambda^K (1-\lambda)^{N-K} \qquad (A.4)$$

The probability distribution $\pi_o(\lambda)$ represents our state-of-knowledge uncertainty about λ prior to collecting the evidence, as the subscript o denotes. Bayes' theorem incorporates the new evidence that K transformer fires occur in a population of N transformers into the prior distribution to obtain the posterior distribution $\pi(\lambda)$; i.e.,

$$\pi(\lambda) = \frac{\binom{N}{K} \lambda^K (1-\lambda)^{N-K} \pi_o(\lambda)}{\int_0 \binom{N}{K} \lambda^K (1-\lambda)^{N-K} \pi_o(\lambda) d\lambda} \qquad (A.5)$$

which represents our new state of knowledge about λ. If we assume that the prior distribution is a beta distribution with density function (Reference A-2)

$$f(\lambda) = \frac{(n-1)!}{(k-1)!(n-k-1)!} \lambda^{k-1} (1-\lambda)^{n-k-1} \quad 0 \leq \lambda \leq 1 \qquad (A.6)$$

where n and k are the parameters of the distribution, the posterior distribution is also a beta distribution whose parameters are n+N and k+K. Since K and N are very large numbers (a few hundred and more than a million, respectively), the precise form of the prior distribution does not matter, as long as it represents the relatively vague state of knowledge that we have prior to receiving the evidence. The noninformative prior with n=k=o is used, which means that the prior distribution has no effect on the parameters of posterior distribution.

Bayes' theorem can be directly applied only if N and K are known exactly. In Section A.3, it can be seen that there are uncertainties about the exact number of transformers and transformer fires; therefore, these uncertainties must also be assessed and propagated.

A.1.3 NUMBER OF FIRES, K

The number of transformer fires in California per Reference A-3 are:

Number of Fires	Year
648	1980
599	1981
500	1982

There is a significant variation in the number of events experienced in different years. This temporal variation is not considered explicitly in our models, because it is judged that the conclusions of a time-dependent analysis would be of little use to the goals of this study. An average value is used and the variations are incorporated; i.e., the assessed state-of-knowledge uncertainty for K is wide enough to accommodate such temporal variation in the uncertainty analysis. A possible explanation for this variation is that state business activity declined in those years and resulted in a decreased load on the transformers and this drop in load has led to a sharp decrease in fire frequency. There may be some underlying phenomenon. For example, some transformers may be operated at loadings slightly above their rated design and consequently experience a higher rate of fire occurrence. A slight drop in the load may thus lead to a substantial decrease in the fire frequency. It should be added that large variations in statistics of this sort are commonplace. For example, airplane crashes, auto accident rates, and drunk driver arrests experience large variations at a state level.

An average number for transformer fires in California is established by

$$\frac{648 + 599 + 500}{3} = 582.3 \text{ incidents per year}$$

This number is assumed to correspond only to mineral oil transformers for several reasons: (1) The national ratio of Askarel transformers to mineral oil units is 1 to 164 (see Section A.3); (2) fire frequency of Askarel transformers is expected to be less than fire frequency of mineral oil transformers; (3) Askarel leaks are not expected to catch fire whereas mineral oil leaks have the potential of doing so, and (4) the cause of transformer rupture is mainly due to the failure of insulation of the windings which does not depend on transformer type.

The standard deviation of the observations is obtained by

$$\left[\frac{(648-582.3)^2 + (599-582.3)^2 + (500-582.3)^2}{3-1}\right]^{1/2} = 75.0$$

The distribution of K is assumed to be a normal distribution with its mean equal to 582.3 and standard deviation equal to 75.0. It is represented by an equivalent discretized probability distribution.

K	Probability, P_K
418	3.99×10^{-2}
498	0.1866
582	0.547
666	0.1866
746	3.99×10^{-2}

A.1.4 NUMBER OF TRANSFORMERS, N

In Section A.3, it can be found that information on the number of transformers is available only at a national level. Our fire incidence data are from California. From Reference A-4, it is concluded that the total number of distribution transformers owned by Pacific Gas and Electric Company and San Diego Gas and Electric Company (two of several large electric utilities in California) is 892,197, while data are not available from other utility companies and other transformer owners in California. Therefore, we estimate it indirectly, using populational ratios. It is assumed that the populational characteristics of transformers in California are almost the same as in the United States and the total number of transformers is proportional to the number of people in the area. The only variations from this that are anticipated are that California has a smaller population of heavy industries (which typically use a lot more energy than the eastern states such as Pennsylvania, Ohio, Michigan, and Illinois) and large California cities have milder climates (which put less demand on area heating or cooling. Thus, we can write

$$\begin{pmatrix}\text{Number of mineral} \\ \text{oil transformers} \\ \text{in California}\end{pmatrix} = \frac{\text{California population}}{\text{U.S. population}} \times \begin{pmatrix}\text{Number of mineral} \\ \text{transformers in}\end{pmatrix}$$

California population = 23.7 million (Reference A-5)

U.S. population = 227.2 million (Reference A-5)

$$\text{Number of mineral oil transformers in California} = \frac{23.7 \times 10^6}{227.2 \times 10^6} \times 23.1 \times 10^6 = 2.4 \times 10^6$$

The statistical data on the population are reasonably accurate. The error rate is probably less than 1%. The number of transformers in the United States estimated by Reference A-4 may have larger uncertainty. Besides the estimate of 23.1×10^6 transformers, Reference A-4 also gives an estimate of 22,870,000 based on the methodology that Reference A-6 had developed. This corresponds to approximately 1% variation. Also, the assumption that the number of transformers is proportional to the population introduces some error. The distribution depicting these uncertainties is derived from judgment.

A 20% variation about the point estimate of 2.4×10^6 is chosen in assessing the following distribution:

Number of Transformers in California, N	Probability, P_N
1.9×10^6	0.3
2.4×10^6	0.4
2.9×10^6	0.3

A.1.5 FREQUENCY OF FIRE

From the two discrete probability distributions for N and K, 15 pairs of (N,K) can be formed with probability $P_{NK} = P_N P_K$. For each pair, a beta posterior distribution $\pi_{NK}(\lambda)$ can be obtained with parameters N and K. The distribution $\pi(\lambda)$ that depicts our state-of-knowledge uncertainty about the frequency of mineral oil transformer fires can be written as

$$\pi(\lambda) = \sum_{N,K} P_N P_K \pi_{NK}(\lambda)$$

Each of the 15 $\pi_{NK}(\lambda)$'s is a narrow distribution and can be approximated by a normal distribution. Table A-1 lists the 15 pairs of parameters, along with their probability and mean values. It can be shown that some of these distributions overlap near the tails of the distributions. Therefore, $\pi(\lambda)$ is a multimodal distribution. Instead of discretizing $\pi(\lambda)$ using the exact expression, the first column and the last column of Table A-1 is chosen as an approximate discretized probability distribution for λ_{fire}. This approximation would be exact if the distributions π_{NK}'s did not overlap. The resulting distribution is collapsed to the discretized probability distribution listed in Table A-2.

TABLE A-1. DISTRIBUTION PARAMETERS FOR $\pi_{NK}(\lambda)$

$P_{NK} = P_K \times P_N$	K	N	Mean
1.2×10^{-2}	418	1.9×10^6	2.2×10^{-4}
5.6×10^{-2}	498	1.9×10^6	2.6×10^{-4}
0.164	582	1.9×10^6	3.1×10^{-4}
5.6×10^{-2}	666	1.9×10^6	3.5×10^{-4}
1.2×10^{-2}	746	1.9×10^6	3.9×10^{-4}
1.6×10^{-2}	418	2.4×10^6	1.7×10^{-4}
7.5×10^{-2}	498	2.4×10^6	2.1×10^{-4}
0.219	582	2.4×10^6	2.4×10^{-4}
7.5×10^{-2}	666	2.4×10^6	2.8×10^{-4}
1.6×10^{-2}	746	2.4×10^6	3.1×10^{-4}
1.2×10^{-2}	418	2.9×10^6	1.4×10^{-4}
5.6×10^{-2}	498	2.9×10^6	1.7×10^{-4}
0.164	582	2.9×10^6	2.0×10^{-4}
5.6×10^{-2}	666	2.9×10^6	2.3×10^{-4}
1.2×10^{-2}	746	2.9×10^6	2.6×10^{-4}

TABLE A-2. DISCRETIZED PROBABILITY DISTRIBUTION OF λ_{fire}

λ_{fire} (per transformer year)	Probability	Cumulative Probability
1.7×10^{-4}	8.4×10^{-2}	8.4×10^{-2}
2.0×10^{-4}	0.251	3.35×10^{-1}
2.4×10^{-4}	0.343	0.678
3.0×10^{-4}	0.255	0.933
3.6×10^{-4}	$6.8\ 10^{-2}$	1.0

NOTE: Mean = 2.48×10^{-4} per transformer year.

A.1.6 FREQUENCY OF MINERAL OIL FIRES CAUSED BY LEAKS AND RUPTURES

The statistical data used in assessing the frequency of fire do not provide information on the relative frequency of fires caused by leaks (f_L) and ruptures (f_R). Other data have to be used to assess the relative frequency. Table A-3 lists some estimates of transformer leakage rate by transformer type.

Reference A-7 estimates that 15 out of 143 failures of indoor transformers resulted in ruptures and fires. Reference A-8 estimates the failure rate for liquid filled transformers to be 4.1×10^{-3} per transformer year. Therefore, a point estimate of $\lambda_{rupture\ and\ fire}$ can be

$$4.1 \times 10^{-3} \times \frac{15}{143} = 4.3 \times 10^{-4} \text{ per transformer year}$$

This estimate is at the extreme high tail of the distribution for λ_{fire} and is judged to be inappropriate for direct application. This discrepancy is not surprising because the exact definitions of the two parameters used in the multiplication are not known to us. This result is interpreted as depicting that the majority of transformer fires result from ruptures.

The frequency of a fire from leakage can be obtained form the estimated leakage rates for the moderate leaks that are listed in Table A-3. They represent the type of leak that can potentially lead to ignition and fire. Reference A-7 estimates the frequency of an ignition of leaked oil as 10^{-3}. Therefore, a point estimate of $\lambda_{leak\ and\ fire}$ can be

$$7.7 \times 10^{-3} \times 10^{-3} = 7.7 \times 10^{-6}\text{/transformer year}$$

This estimate also lies at an extreme tail of the distribution for λ_{fire}, and this is interpreted as indicating that leaks constitute the smaller portion of λ_{fire}.

The above estimates of the frequencies of fires caused by ruptures and leaks indicate that the relative frequency of rupture-caused fires is much higher than that of leak-caused fires. The following distribution is developed judgmentally. It represents our beliefs about the relative frequency of the two phenomena.

Probability	f_R	$f_L = 1-f_R$
0.05	0.5	0.5
0.80	0.80	0.2
0.15	0.95	0.05
Mean	0.81	0.19

TABLE A-3. ESTIMATES OF LEAKAGE FREQUENCY (PER TRANSFORMER YEAR)

Transformer Type		Reference
Mineral Oil	PCBs	
1. Small Leak 8.5 x 10^{-2} Moderate Leak 7.7 x 10^{-3}		A-4
2. Active Leak 6.0 x 10^{-3}	Active Leak 3.2 x 10^{-2}	A-9
3. 1.6 x 10^{-4}	1.6 x 10^{-4}	A-7

The frequency of fires from leaks and ruptures can be obtained from Equations (A.2) and (A.3). Table A-4 gives their characteristic values.

A.2 FREQUENCY OF RUPTURES OF ASKAREL TRANSFORMERS

Transformer ruptures are caused by very large surges in the primary voltage or rapid breakdown of insulation between the windings. They cause arcing between the windings which generates gases and produces pressure spikes. Voltage surges and insulation failures do not depend on the type of fluid used. The gas generated per kJ of arc energy is approximately 100 cc for both mineral oil and Askarel (Reference A-10). Therefore, the conditions leading to ruptures are the same for mineral oil and Askarel, and it is expected that the frequencies of ruptures per transformer year will be the same for both types of transformers. Thus, we will use the frequency of mineral oil transformer rupture that was assessed in Section A.1 for the frequency of Askarel transformer rupture.

To put this estimate in a better perspective, using the mean frequency of rupture of 2.0×10^{-4} per transformer year, the expected number of Askarel transformer ruptures nationwide is calculated

$$2.0 \times 10^{-4} \times 140{,}000 = 28.0 \text{ ruptures per year}$$

This seems to be a large number because Askarel transformer troubles generally draw news media attention. The frequency of citations of Askarel transformer fires is far less than 28 per year.

A.3 SOURCES OF DATA

In this part of the appendix, the sources of data used in Section A.1 are described. Also, some supplemental information are discussed such as sources of statistical data and breakdown of the estimates for the number of transformers, the frequencies of transformer leak, failure, rupture, and fire.

A.3.1 NUMBER OF TRANSFORMERS

In Reference A-4, the utilities throughout the United States were surveyed regarding the numbers of equipment they own that contain mineral oil and polychlorinated biphenyls (PCB) and the amounts of fluid they contain. It is estimated that the number of mineral oil transformers owned by the utility industry is 20,227,428 and the number of Askarel transformers is 39,640. Also given is a breakdown of the number of transformers according to their power rating and the average amount of fluid that the transformers in a range of power ratings contain. It is also estimated that the total number of mineral oil transformers owned by the utilities and other users in the United States is 23,137,493 and the

TABLE A-4. CHARACTERISTIC VALUES OF THE FREQUENCIES OF MINERAL OIL TRANSFORMER FIRES CAUSED BY LEAKS AND RUPTURES

Percentile	λ Leak and Fire (per transformer year)	λ Rupture and Fire (per transformer year)
5th Percentile	1.2×10^{-5}	1.4×10^{-4}
Median	4.8×10^{-5}	2.0×10^{-4}
95th Percentile	7.4×10^{-5}	2.6×10^{-4}
Mean	4.7×10^{-5}	2.0×10^{-4}

total number of Askarel transformers is 140,000. The following list is a breakdown of the mineral oil transformers according to their type:

Distribution Transformers:	
Overhead and Pole-Mounted	19,274,819
Pad Mounted	3,565,842
Small Power Transformers	192,748
Secondary Unit Substation Transformers	52,042
Large Power Transformers	52,042
	23,137,493

The breakdown of the PCB transformers according to users (Reference A-1) is:

Category of User	Number of Units
Utilities	42,000
Industrial and Commercial	97,000
Railroad	1,000
	140,000

In Section A.1, the number of transformers in California is used for frequency evaluation. The only available information is the number of distribution transformers owned by two utility companies in California (Reference A-4):

- Pacific Gas and Electric 779,764
- San Diego Gas & Electric Co. 112,433

Thus, the number of transformers in California must be much greater than 900,000 units since there are several other large utilities such as Southern California Edison and Los Angeles Department of Water and Power.

A.3.2 TRANSFORMER FIRE

At the national level, one primary source of fire data is the National Fire Incident Reporting System (NFIRS) (Reference A-12). In a survey of NFIRS during 1976, 1977, and early 1978 (Reference A-13), one million fires were found to have occurred in eight states and 209 indoor transformer fires were identified. Seven transformer fires were identified in the more recent survey of the 1978 NFIRS data. These transformer fires could be caused by a rupture or the ignition of the leaking oil, and it is not known which type of transformer is involved.

At the state level, the primary source of fire data for California is the California Fire Incident Reporting System (CFIRS) (Reference A-14). A computer search of the data base for fires caused by transformer and associated overcurrent and disconnect equipment shows the following result (Reference A-3):

Year	Number of Fires
1980	648
1981	599
1982	500

Similar to HFIRS, no information is available to determine the types of the transformers involved and the type of abnormality leading to the fire.

Only a few fires involving Askarel transformers are recorded. They are listed in Table A-5. There is insufficient information to determine whether Askarel was burning during these fires, and whether the Askarel transformer was the source of ignition.

A.3.3 TRANSFORMER LEAKS

Three sources have estimated the frequency of transformer leaks. Table A-3 summarizes their results and each source is discussed separately.

A.3.3.1 Electric Utility Owned Transformers

In Reference A-4, data are collected for transformers owned by the electric utilities. Two levels of leak severity are defined. Greasy or oily spots on the transformer body are considered as small leaks and noticeable spills are considered as moderate leaks. Reference A-4 shows that the frequency of a leak is greater for larger transformers and they are less likely to have a moderate leak than a small leak. For mineral oil transformers with power levels below 100 kVA, a point estimate for small leak frequency is 0.0077 per transformer year and for moderate leaks it is less than 0.0077. For mineral oil transformers with power levels between 101 and 500 kVA the small leak frequency is 0.085 and for a moderate leak the frequency is 0.0077 per transformer year.

A.3.3.2 Survey of Chemical Manufacturers

Members of the Chemical Manufacturers Association were surveyed to identify incidents of transformer leaks (Reference A-9). Sixty-eight firms representing about 33% of all U.S. chemical industry sales in Standard Industrial Classification Code 28 were surveyed. Information based on the Environmental Protection Agency (EPA) interim measures regulatory program and firm records indicates 351 leakage incidents per year occurred in a population of 5,231 transformers, including both mineral oil transformers and Askarel transformers. Therefore, the leakage rate is 6.7×10^{-2}/transformer year. If the nondocumented sources such as the judgment or opinion of equipment maintenance or service personnel are included, there are 1,005 leakage incidents in 15,752 transformers. This produces a leakage rate of 6.4×10^{-2} per transformer year. The rates listed in Table A-3 are the estimated rates for "active leaks" which include ruptures and moderate leaks but not minor leaks where there is no evidence for the gathering or dripping of fluid on or about the transformers, using all sources of information collected from the survey.

A.3.3.3 National Bureau of Standards

In Reference A-7, a Westinghouse service engineer is quoted as estimating the leakage rate to be 10^{-5} per transformer year and the frequency that a new transformer experiences a leak to be 1 out of 25 during the first

TABLE A-5. TRANSFORMER FIRES INVOLVING ASKAREL TRANSFORMERS

Date of Occurrence	Place	Location	Transformer Type	Reference
2/5/81	Binghamton, New York	Basement of Office Building	Distribution	A-15
1/19/82	Sequoyah Nuclear Power Plant, Tennessee	Outside, Above Grade, Next to Turbine Building	Power	A-16
5/15/83	San Francisco, California	Transformer Vault in Sub-Basement of Office Building	Distribution	A-17
9/26/93	Chicago, Illinois	Utility Vault Three Stories Below the Street	Distribution	A-15

2 weeks of service. Thus, during the expected life span of 25 years, the average leakage rate is

$$\frac{\frac{1}{25} \times 2 \text{ weeks}}{25 \text{ years}} + 1 \times 10^{-4} = 1.6 \times 10^{-4} \text{ per transformer year}$$

Also given in Reference A-7 is the estimated failure rate of a transformer of 4.1×10^{-3} per year. This is based on the IEEE-sponsored reliability survey of industrial users of transformers (Reference A-19), where failure means loss of power for the transformer. The frequency of a leak being ignited is estimated to be 10^{-3} in Reference A-7.

A.3.4 TRANSFORMER RUPTURES

Reference A-7 states that statistical date gathered by researchers at Factory Mutual indicate that out of 143 failures of indoor mineral oil transformers recorded by Factory Mutual, 18 resulted in rupture of the transformer tank; in 15 out of the 18 ruptures, the mineral oil was ignited. According to Reference A-8, the failures of transformers are caused by flashover or arcing (61%), electrical defect (12%), and mechanical defect (10%). The failure rates for different types of transformers are estimated to be:

Liquid Filled, All Types	4.1×10^{-3}/Transformer Year
601 - 15,000V	3×10^{-3}
Above 15,000V	1.3×10^{-2}
300 - 750 kVA	3.7×10^{-3}

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APPENDIX B

FIRE PROPAGATION FROM AN ASKAREL TRANSFORMER RUPTURE

APPENDIX B

FIRE PROPAGATION FROM AN ASKAREL TRANSFORMER RUPTURE

In this appendix, for the base case of Case I, the potential of fire propagation to an adjacent room given an Askarel transformer rupture leading to room boundary failure is examined. For the purposes of this study, Askarel is defined as a mixture containing 50% (by weight) PCBs (Aroclor 1254) and 50% 1,2,4 trichlorobenzene. In Section 5.3.2a.1.6 of the main report, four modes of fire propagation are identified. Three of the four involve radiative heat transfer to the target combustibles from the flames above the transformer tank, the hot gas and smoke layer under the ceiling, and hot transformer parts. This appendix concentrates on these three modes of fire propagation. The fourth mode involves heat conduction from the splattered fluid and is discussed in Section 5.3.2a.1.6.

The target combustibles for fire propagation are carpets, wallpaper, paper, wood, plastics, and similar materials typically found in an office building environment. Reference B-1 indicates that the ignition temperatures of fabrics range from 400°C (752°F) for cotton to 600°C (1,112°F) for wool. Synthetic fibers have ignition temperatures between these two points. Fire retardant fabrics have ignition temperatures well above 1,000°C (1,832°F). The ignition temperature for wood ranges from 313°C (595°F) to 393°C (740°F), depending on the specific gravity of the wood. For this study, carpeting will be used as representative of the combustibles in the room. Its ignition temperature is chosen to be 600°C (1,112°F).

To calculate the heatup of these materials to their ignition temperature, it is assumed that they are in the form of a semi-infinite slab with an initial uniform temperature T_A. The heat flux $\dot{q}_0''$ (w/m^2) impinges on its surface for t* seconds, the time that the surface temperature reaches the ignition point. From Reference B-2, it can be written

$$t^* = \frac{\pi}{4\alpha}\left(\frac{k(T^* - T_A)}{\dot{q}_0''}\right)^2 \qquad (B.1)$$

where

k = thermal conductivity (w/m °K).

α = thermal diffusivity (m^2/s).

T^* = ignition temperature (°K).

From Reference B-3, it is found that cellulose acetate (a form of synthetic fiber) has the following thermal properties:

k = 0.17 to 0.3 w/m °K

α = 7.6 x 10^{-8} to 2.02 x 10^{-7} m^2/s

For our calculations, we will use 0.25 w/m°K for k and 1.4×10^{-7} m²/s for α. Using T* = 600°C and T_A = 20°C, the following relationship between t* and q_0'' is obtained:

$$t^* = \frac{1.2 \times 10^{11}}{q_0''^2} \text{ (s)} \quad (B.2)$$

We must now establish $\dot{q}_0''$. For this we need the burning characteristics of the Askarel; i.e., the mass burning rate, the heat of combustion, etc. Heat of combustion for trichlorobenzene is 1.5×10^4 kJ/kg (Reference B-4). The other parameters have not been established for Askarel, except that Reference B-5 indicates that a 4-inch diameter pool of Askarel can burn and generate heat at the rate of about 5 kcal per minute only when exposed continuously to a pilot flame or ignition source with greater than 30 kW/m² heat flux. These values compare with 30 kcal per minute or greater heat generation rates for mineral oil-type fluids that, unlike the Askarel, do not require a continuous exposure to the pilot. Also, the heat of combustion 1.5×10^4 kJ/kg is about one-third of that of mineral oil.

In an Askarel transformer rupture, the heat source may be present temporarily. The windings may become red hot from lack of cooling or abnormal currents. This situation is temporary because either the protective or the maintenance personnel devices would isolate the transformer. The isolation time may be as long as 1 hour, depending on how soon the transformer troubles are noticed. It is deemed that the local fire brigade would certainly be called in and that they would request the shutoff of the electric power to the building.

Based on the results of Reference B-5, mentioned above, it is concluded that Askarels have poor burning characteristics. This is interpreted as implying shorter flame heights and smaller mass burning rates than for mineral oil. The latter means less overall heat generation for the same burning surface. Thus, because of shorter flames and less heat generation rate, the heat flux leaving the flames is judged to be much smaller. In Appendix E, the heat generation rate for a pool fire of mineral oil is estimated to be 4.0×10^3 kW, and the heat flux from the fire impinging on the walls is found to be about 34 kW/m². It is conservatively assumed that the heat flux impinging on the walls from an Askarel is one-fourth that of a mineral oil fire; that is, 8.5 kW/m². If this heat is totally absorbed by the carpeting, the ignition time t* is about

$$t^* = \frac{1.2 \times 10^{11}}{(8{,}500)^2} = 1{,}661 \text{ sec} \approx 28 \text{ minutes}$$

Within this time frame, the sprinkler system (if operable) is very likely to suppress the fire. If the sprinklers are not available, the local fire brigade may arrive. The conditional frequency of fire propagation, f_{P-1}, given that a transformer rupture and room boundary failure have occurred, can then be written as

$$f_{P-1} = [f_{SPR} + fr(t^* < t_{SPR})(1 - f_{SPR})]\ fr(t^* < t_{FB}) \qquad (8.3)$$

where

f_{SPR} = the unavailability of the sprinkler system.

$fr(x)$ = frequency of event x.

t_{FB} = time of fire suppression by the fire brigade.

t_{SPR} = time of fire suppression by the sprinkler system.

The terms in the brackets represent the frequency of the sprinkler system failing to suppress the fire before the carpeting ignites. The first term inside the brackets is the unavailability of the sprinkler system and the second term is the frequency of failure to suppress before ignition given that the system is available. The term outside the brackets is the frequency of the fire brigade failing to suppress the fire before ignition. It should be noted that it is judged that the two suppression processes are independent because the fire brigade would be notified upon detection of the fire and they would bring along the appropriate equipment irrespective of the sprinkler system effectiveness.

The unavailability of the sprinkler system can be established by pooling information from several sources. Reference 8-6 lists sprinkler performance records for several types of occupancies. The number of fire incidents in areas with sprinklers is more than 81,000 and the number of unsuccessful operations is about 3,100. The percentage of satisfactory sprinkler operation ranges from 88.2% (for industrial facilities handling beverages and essential oils) to 98.2% (for industrial facilities manufacturing textiles). For office buildings, this percentage is 97.4 (there were 13 unsatisfactory performances recorded in 494 office building fires where there were sprinklers). Thus, based on these records, the unavailability of the system ranges from 0.018 to 0.118. However, the uncertainties about the very sprinkler system of the transformer room under consideration are judged to be greater because the sprinkler system has to operate after surviving the impact of a pressure pulse and the transformer parts or fluid after the transformer rupture. The following distribution is derived from judgment and depicts our uncertainties about the unavailability f_{SPR}:

f_{SPR}	Probability
0.02	0.10
0.05	0.70
0.20	0.20

Its mean value is 0.077.

Since the frequency of ignition time t^* is less than the suppression time by the sprinklers or the fire brigade, it is evaluated using the methods of Reference B-7. The state-of-knowledge uncertainties in t^*, t_{SPR}, and t_{FB} are established first and the statistical distributions of these time periods are convoluted next to establish $fr(t^* < t_{SPR})$ and $fr(t^* < t_{FB})$.

The uncertainties in t^* are primarily from ignoring target heat losses and the augmented heat flux from the flames, the hot gas layer and the hot transformer parts, and using conservative flame surface area, conservative source to target distance, and conservative ignition temperatures. In Reference B-7, an error factor, E_0, is introduced, which is multiplied by the point estimate resulting from the thermal analysis. Also, Reference B-7 interprets the point estimate as representing the mean value of the statistical uncertainty about the ignition time because these uncertainties are overwhelmed by the state-of-knowlege uncertainties. The latter is depicted by the uncertainties in E_0, for which a lognormal distribution is used with 5th and 95th percentiles at 0.8 and 4.0. For this case, it is judged that our uncertainties are wider because we have used judgment in deriving t^*. E_1 is introduced as the error factor with a lognormal distribution and its 5th and 95th percentiles at 0.5 and 4.0. Thus, the mean time to ignition can be expressed as

$$\tau^* = t^* E_1 \tag{B.4}$$

and the distribution for τ^* has the following characteristic values:

5th Percentile:	14.0 Minutes
Median:	39.6 Minutes
95th Percentile:	112.0 Minutes
Mean:	74.5 Minutes

The fire suppression time by the sprinklers, t_{SPR}, can be envisioned as the sum of two time periods: the time of sprinkler head opening and the time of fire suppression given water is pouring from the sprinklers. The statistical uncertainties of suppression time are derived to be significant (Reference B-7) and can be expressed by an exponential distribution. We can write

$$fr(t^* < t_{SPR}) = \exp(-\tau^*/\tau_{SPR}) \tag{B.5}$$

where τ_{SPR} is the mean time of suppression (the parameter of the exponential distribution) and is established from judgment. Reference B-7 has used the following distribution for the mean time to fire suppression for a compartment in a nuclear power plant that contains an automatic CO_2 fire suppression system:

Mean Time to Suppress (minutes)	Probability
5	0.4
15	0.3
30	0.2
60	0.1

It should be noted that this estimate includes the added capability provided by the specialized fire brigade that is typically found in a nuclear power plant. This brigade would attack a fire if the automatic systems fail to control it. Since the suppression system in our transformer room uses water, the distribution for τ_{SPR} is chosen (in spite of the presence of a fire brigade in a nuclear plant) to be skewed further to the longer times than the above distribution. This is supported by Reference 8-8 where the effectiveness of the suppression systems is compared. It shows that a CO_2 system may not properly control the fire for more than 30% of the demands. The distribution for τ_{SPR} is chosen as:

τ_{SPR} (minutes)	Probability
5	0.5
15	0.4
30	0.1

The mean of this distribution is 11.5 minutes.

The suppression time by the fire brigade t_{FB} can be envisioned as the sum of three time periods: detection time, fire brigade arrival time, and fire suppression time. The detection time is judged to be less than 5 minutes because the noise or smoke from a transformer rupture and room boundary failures would be noticed by the occupants of the basement, or the abnormalities in the electric circuits would be noticed by the building maintenance personnel and the general occupants. The fire brigade arrival time is expected to range from 1 to 10 minutes. This is taken from Reference 8-9 where data are collected for fire engine travel times in Manhattan, New York. Finally, the fire suppression time (given the arrival of brigades) is judged to vary from 5 to 30 minutes. This estimate does not take into account any serious delays in taking action for reasons such as delay in disconnecting the electrical equipment in the transformer room from electric power sources.

Similar to the suppression time by the sprinklers, the statistical uncertainties in the suppression time by the fire brigade are taken to be exponential. That is,

$$Fr(t^* < t_{FB}) = \exp(-\tau^*/\tau_{FB}) \quad (8.6)$$

where τ_{FB} is the mean suppression time and is derived from judgment. Based on the above discussions, the following distribution is chosen for τ_{FB}:

τ_{FB} (minutes)	Probability
15.0	0.5
30.0	0.4
45.0	0.1

The mean of this distribution is 24.0 minutes. The expression for f_{P-1} can then be rewritten as

$$f_{P-1} = [f_{SPR} + (1 - f_{SPR})\ \exp(-\tau^*/t_{SPR})]\ \exp\ (-\tau^*/t_{FB}) \qquad (B.7)$$

The distribution for f_{P-1} can be obtained by using discretized probability distribution arithmetic (see Appendix G and Reference B-10). Its characteristics values are:

5th Percentile:	2.2×10^{-4}
Median:	1.3×10^{-2}
95th Percentile:	1.1×10^{-1}
Mean:	2.8×10^{-2}

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APPENDIX C

CONDITIONAL FREQUENCIES OF INJURIES AND FATALITIES

APPENDIX C

CONDITIONAL FREQUENCIES OF INJURIES AND FATALITIES

The conditional frequencies of injuries or fatalities given a fire are evaluated in this appendix for the two damage states (see Section 3 of the main text): (1) "room fire," fires that are confined to the room of origin; and (2) "beyond room fire," fires that propagate beyond the room of their origin. Two sources are found to contain relevant information: (1) Tables 3-18 and 3-19 of Reference C-1, and (2) the 1982 fire incidents as collected by the California Fire Incident Reporting System (CFIRS) (Reference C-2). The applicability of each data source is examined first. Bayesian methods (References C-3 and C-4) are then used to combine the pieces of evidence and evaluate the four conditional frequencies.

C.1 GENERAL FRAMEWORK

As mentioned earlier, the statistical analysis is based on a Bayesian framework. In the next section, we will see that for "room fires," two sources of data are available and for "beyond room fires," only one source is used. For the latter (that is, only one source of data), Bayes' theorem is used in its simplest form. Bayes' theorem is written as

$$\pi(f) = \frac{1}{N} \pi_0(f) \, L(E|f) \quad (C.1)$$

where

$\pi(f)$ = the posterior distribution for f.

$\pi_0(f)$ = the prior distribution for f (prior to obtaining evidence E).

$L(E|f)$ = the likelihood of observing evidence E given f is the true value.

N = a normalization factor to make $\pi(f)$ a probability distribution.

The evidence E can be, for example, r injury fires out of n fires or it can be a set of experts' opinions about the value of f.

For the "beyond the room" damage state, the evidence is in the form of r occurrences out of n observations. Therefore, the likelihood function can be binomial (Reference C-5). That is,

$$L(r, n|f) = \frac{n!}{r!\,(n-r)!} f^r (1 - f)^{n-r} \quad \text{for } 0 \le r \le n \quad (C.2)$$

From Reference C-5, it is also found that the beta distribution conjugates with a binomial likelihood function. That is, if the prior distribution is beta, the posterior also belongs to the beta family of distributions. The density function of the beta distribution is

$$\pi(f) = \frac{(n_o - 1)!}{(r_o - 1)!\,(n_o - r_o - 1)!} f^{r_o - 1} (1 - f)^{n_o - r_o - 1} \tag{C.3}$$

where r_o and n_o are the two parameters of the beta distribution. If this density is used as the prior distribution for an evidence of r events in n observations, the posterior beta distribution would have the parameters

$$r_1 = r_o + r \tag{C.4}$$

$$n_1 = n_o + n \tag{C.5}$$

From these equations, it can be seen that one can reduce the influence of the prior distribution by choosing very small values for r_o and n_o. When $r > o$, one can choose $r_o = n_o = 0$, a noninformative prior distribution.

For "room fire," the two pieces of evidence are also in the form of r events in n observations. However, since they are obtained differently and are from independent sources, they are treated as statements from two independent experts about the value of f (conditional frequency of an injury or a fatality). To combine the two pieces of evidence, a method given in Reference C-6 is employed. For N experts, Reference C-6 writes Bayes' theorem [Equation C.1)] as

$$\pi(f|f_1^*, \ldots, f_N^*) = \frac{1}{N} L(f_1^*, \ldots, f_N^*|f)\, \pi_o(f) \tag{C.6}$$

where f_i^* is the ith experts' estimates for the value of f and L is the likelihood that the experts' estimate will be $(f_1^*, \ldots f_N^*)$ when the true value is f. For independent experts, it can be written

$$L(f_1^*, \ldots, f_N^*|f) = \prod_{i=1}^{N} L_i\,(f_i^*|f) \tag{C.7}$$

where L_i is the likelihood that the ith experts' estimate will be f_i^* when the true value is f. L_i can be interpreted as a measure of credibility, assigned by the analyst, to the ith expert for estimating the true value of f. If the error of an expert is considered as an additive quantity, the likelihood can be represented by a normal distribution.

The posterior distribution can be obtained analytically (similar to the beta and binomial distribution discussed earlier) if the prior distribution (in the case of a normal likelihood) is taken to be normal. The posterior distribution is also normal and for two experts its mean (f) and variance (σ^2) are given by

$$f = w_0 f_0 + w_1 f_1 + w_2 f_2 \qquad (C.8)$$

$$\frac{1}{\sigma^2} = \frac{1}{\sigma_0^2} + \frac{1}{\sigma_1^2} + \frac{1}{\sigma_2^2} \qquad (C.9)$$

where f_0 and σ_0^2 are the mean and variance of the prior distribution and f_i and σ_i^2 (for i = 1 or 2) are the mean and variance of the likelihood function of the ith expert. The weights w_0, w_1, and w_2 are obtained from

$$w_0 = \frac{\sigma^2}{\sigma_0^2} \qquad (C.10)$$

$$w_1 = \frac{\sigma^2}{\sigma_1^2} \qquad (C.11)$$

$$w_2 = \frac{\sigma^2}{\sigma_2^2} \qquad (C.12)$$

Note that the influence of the prior distribution can be reduced by choosing a very large σ_0^2. A noninformative normal distribution can thus be one with σ_0^2 approaching infinity.

For the type of evidence that we have collected, the mean and variance of the likelihood are taken to be the mean and variance estimates of each evidence; that is, r/n and r/n^2, respectively, where r is the number of injury or fatality fires and n is the total number of fires. By using these estimates, the assumption is made that the two pieces of evidence presented by the sources are equally good and the difference in our confidence levels in the two sources is solely dependent on the number of observations that they have made.

C.2 SOURCES OF DATA

C.2.1 DATA FROM REFERENCE C-1

The statistics given in Reference C-1 are extracted from the National Fire Incident Reporting System (NFIRS) (Reference C-7) for 1977 and 1978, based on the National Fire Protection Association (NFPA) Standard No. 901, "Uniform Coding for Fire Protection" (see Reference C-8). NFIRS is a voluntary system. In 1977, 19 states were providing data to NFIRS (Reference C-9) and in 1978, 3 more states were added. Within those 22 states, the extent of reporting varied widely, from nearly complete reporting (most of the fire departments in a given state providing data on most or all of their incidents) to minimal reporting (only a few jurisdictions in a given state reporting partial data).

The data base queried to obtain transformer fire losses for Reference C-1 covered the entire year of 1977 plus one or two quarters from 1978. The data base contained 530,040 records (fire incidents), of which 209 fire incidents involved indoor transformers. The records extracted were those that were coded, per Reference C-6, "Equipment Involved in Ignition Code 42 - Transformer and Associated Overcurrent or Disconnect Equipment."

Of these 209 fires, 200 were coded as confined to the room of origin or material of origin. Table 3-18 of Reference C-1 gives four incidents leading to one injury out of 200 transformer fires that were confined to the room of origin, and Table 3-19 gives zero fatalities for the same 200 fires.

For fires extending beyond the room of origin, the data given in Reference C-1 are deemed to be significantly less relevant to the two case studies of this report (that is, a transformer installed in an office-type building) than the data from CFIRS which is discussed below. This is because the data for fires propagating beyond the room of origin were extracted from the fires in manufacturing properties which typically have fire hazard and occupancy characteristics much different from office buildings.

C.2.2 DATA FROM CFIRS

The CFIRS data are collected in a manner similar to NFIRS. The CFIRS data are actually transferred to the NFIRS to be combined with the records from other states. This may raise a question of dependency between the two sources. Since the data from these sources are collected from different years, they are judged to be independent. There are 165,470 records (fire incidents) in the CFIRS for the year 1982.

Out of the 165,470 fires, 500 involved "transformers and associated overcurrent and disconnect equipment" as the source of heat causing ignition (Reference C-10). These 500 incidents included all types of locations including exterior and interior fires. No injuries or fatalities were reported for any of these fires. The investigation of transformer fire incidents was not pursued any further because it was judged that better evidence could be collected for the conditions specific to the case studies

Since our two case studies involve transformer rooms in an office building environment, the 1982 CFIRS records were searched for similar conditions. Computer searches were conducted for the following "fixed property use classification" (Reference C-2) codes:

Code	Description
441	Hotels, Inns, and Lodges Used Year-Round
591	General Business Office

and for "fire damage" codes:

Code	Description
1	Confined to Material of Origin
2	Confined to Area of Origin
3	Confined to Floor of Origin
4	Building of Origin
5	Spread Beyond Area

Fire damage codes 1 and 2 are interpreted as fires confined to the room of origin; damage codes 3, 4, and 5 are interpreted as fires spreading beyond the room of origin; and the numbers of injury and fatality fires are tabulated.

Table C-1 summarizes the findings from CFIRs and NFIRs. It should be noted that all fatality fires involved only one death and almost all injury fires involved only one injury.

C.3 STATISTICAL ANALYSIS

The approaches for statistical analysis are described in Section C.1. For the case of fires confined to the room of origin, the two pieces of evidence are combined using the approach delineated in Reference C-6. For the fires spreading beyond the room of origin, Bayes' theorem is used in its general form.

C.3.1 INJURIES FROM FIRES CONFINED TO THE ROOM OF ORIGIN

The conditional frequency of an injury, given a fire that is confined to its room of origin, $f_{I,RM}$, is evaluated using the method given in Reference C-6 as described in Section C.1. The two pieces of evidence are 4 injury fires in 200 incidents (NFIRS data) and 16 injuries in 1,048 incidents (CFIRS data). The two sources of data are treated as two experts estimating $f_{I,RM}$ with their point estimates being

$$f_{1,I,RM} = \frac{4}{200} = 0.02$$

$$f_{2,I,RM} = \frac{16}{1,048} = 0.0153$$

The likelihood function of each expert is taken to be normal with means equal to these point estimates. The variances of their likelihood are taken to be equal to an estimate of the variance based on the collected

TABLE C-1. STATISTICS ON INJURY AND FATALITY FIRES

Parameter	Fire Spread Limits		
	Fire Confined to Room of Origin		Fire Spread Beyond Room of Origin (from CFIRS)
	From Reference C-1	From CFIRS	
Number of Injury Fires	4	16	10
Number of Fatality Fires	0	1	1
Total Number of Fires	200	1,048	114

data. An estimate for the variance can be r/n^2 where "r" is the number of injury fires and "n" is the total number of fires. It should be noted that Reference C-11 shows that for strong evidence, the posterior distribution of the Bayesian updating is approximately normal with mean r/n and variance r/n^2. Thus, the two variances are

$$\sigma_1^2 = \text{Var}\left(f_{1,I,RM}\right) = \frac{4}{200^2} = 1.00 \times 10^{-4}$$

$$\sigma_2^2 = \text{Var}\left(f_{2,I,RM}\right) = \frac{16}{1,048^2} = 1.46 \times 10^{-5}$$

For the prior distribution, a noninformative normal distribution can be used to eliminate its influence on the posterior distribution. The variance of a noninformative prior can be viewed as very large compared to σ_1^2 and σ_2^2 such that $\sigma_0^2 \to \infty$.

The variance of the posterior normal distribution can be computed as

$$\sigma^2 = \left(\frac{1}{\sigma_1^2} + \frac{1}{\sigma_2^2}\right)^{-1} = 1.27 \times 10^{-5} \qquad (C.13)$$

The relative weights of the two pieces of evidence w_1 and w_2 are needed to estimate the mean of the posterior distribution

$$w_1 = \frac{\sigma^2}{\sigma_1^2} = 0.127 \qquad (C.14)$$

$$w_2 = \frac{\sigma^2}{\sigma_2^2} = 0.873 \qquad (C.15)$$

The mean of the posterior distribution can be written as

$$f_{I,RM,50} = w_1\, f_{1,I,RM} + w_2\, f_{2,I,RM} = 0.0159 \qquad (C.16)$$

With this mean and variance, all the other parameters of the normal distribution can be found. The characteristic values of $f_{I,RM}$ are:

5th Percentile: 0.0100

Median: 0.0159

95th Percentile: 0.0217

Mean: 0.0159

C.3.2 FATALITIES FROM FIRES CONFINED TO THE ROOM OF ORIGIN

The conditional frequency of a fatality, given a fire confined to its room of origin, $f_{F,RM}$, is evaluated using the same method as for $f_{I,RM}$. The evidence from NFIRS is no fatality events in 200 fires and from CFIRS is 1 fatality fire in 1,048 fires. If r/n and r/n^2 are used for estimating the mean and variance for NFIRS data, zeros will be obtained, which is contrary to our expectation. Therefore, Equations (C.8) through (C.12) cannot be used directly. However, we can try different assumptions about the NFIRS data such as 1 fatality fire in 200 fires or 1 fatality fire in 1,000 fires and see how sensitive the final results are to these assumptions. A reasonable distribution for $f_{F,RM}$ based on these results can be chosen.

Let us begin by assuming that a fatality fire could have been observed in NFIRS if one more observation took place. That is, we modify the evidence to be 1 fatality fire in 200 incidents from the first source and 1 fatality fire in 1,048 incidents from the CFIRS. For this evidence, the mean and variance of the first source are

$$f_{1,F,RM} = \frac{1}{200} = 0.005$$

$$\sigma_1^2 = \frac{1}{200^2} = 2.5 \times 10^{-5}$$

and of the second source are

$$f_{2,F,RM} = \frac{1}{1,048} = 9.5 \times 10^{-4}$$

$$\sigma_2^2 = \frac{1}{1,048^2} = 9.1 \times 10^{-7}$$

The mean and variance of the posterior distribution using Equations (C.8) through (C.12) are obtained as 1.1×10^{-3} and 8.8×10^{-2}, respectively.

Let us now assume that the fatality fires in NFIRS occur at a frequency much less than 1 in 1,000 fires. This means that the likelihood of observing more than 1,000 fires without any fatalities is significant. Let us assume that the mean of the first likelihood is

$$f_{1,F,RM} = 1.0 \times 10^{-3}$$

We keep the variance the same; that is,

$$\sigma_1^2 = 2.5 \times 10^{-5}$$

because it represents our confidence in the first source of data and it is the best 200 observations can provide. Using the same CFIRS data, the mean and variance of the posterior becomes 9.6×10^{-3} and 8.8×10^{-7}. Similarly, if we assume $f_{I,F,RM} = 5.0 \times 10^{-4}$ and the same variance, the mean and variance of the posterior becomes 9.4×10^{-4} and 8.8×10^{-7}.

Two notes are in order here. First, it can be shown that the influence of a prior distribution with wide uncertainties is very small and can be ignored in the computations. Second, the normal distributions given above cover negative numbers as well as numbers above the unity. The probability of a number being negative is 0.15 or less for the above distributions and the probability of being greater than unity is insignificant. To circumvent these problems, the final distribution will be truncated and renormalized between zero and one. This is judged to be of little significance to the final results because the bulk of the uncertainties is not sensitive to these approximations.

The above three exercises show that the final distributions are rather insensitive to the choice of $f_{I,F,RM}$ and are dictated primarily by the evidence from CFIRS. Thus, a normal distribution is chosen with a mean and variance of 1.0×10^{-3} and 8.8×10^{-7}, respectively. To truncate and renormalize this distribution, it is first discretized. Table C-2 gives this distribution and shows that the probability of negative values is 0.1055 and the largest value is less than 1. To truncate, the first four values are deleted, and to renormalize, each remaining probability is divided by 1.0 - 0.1055 = 0.8945. The resulting distribution is given by Table C-3. The mean value of this distribution is 1.2×10^{-3}.

C.3.3 INJURIES FROM FIRES PROPAGATING BEYOND THE ROOM OF ORIGIN

The conditional frequency of an injury given a fire that has propagated beyond the room of origin, $f_{I,BO}$, is evaluated using Bayes' theorem (Equation C.1). The evidence is (r=)10 injury fires in (n=)114 fires that propagated beyond the room of origin. Since the number of injury fires is greater than zero, the influence of the prior distribution on the posterior distribution can be minimized by choosing a noninformative prior; i.e., $r_0 = n_0 = 0$. Thus, from Equations (C.4) and (C.5), it is found that the parameters of the posterior distribution for $f_{I,BO}$ becomes r = 10 and n = 114. Table C-4 gives a discretization of the beta distribution with these parameters. Its characteristics values are:

5th Percentile:	4.9×10^{-2}
Median:	8.5×10^{-2}
95th Percentile:	1.3×10^{-1}
Median:	8.8×10^{-2}

TABLE C-2. DISCRETIZED NORMAL DISTRIBUTION WITH MEAN = 1.0×10^{-3} AND VARIANCE = 8.8×10^{-7}

Value	Probability	Cumulative Probability
-2.0-3	0.0030	0.0030
-1.5-3	0.0091	0.0121
-9.9-4	0.0278	0.0399
-5.0-4	0.0656	0.1055
3.0-6	0.1210	0.2265
5.0-4	0.1750	0.4015
1.0-3	0.1970	0.5985
1.5-3	0.1750	0.7735
2.0-3	0.1210	0.8945
2.5-3	0.0656	0.9601
3.0-3	0.0278	0.9879
3.5-3	0.0091	0.9970
4.0-3	0.0030	1.0000

NOTE: Exponential notation is indicated in abbreviated form; i.e., -2.0-3 = -2.0×10^{-3}.

TABLE C-3. PROBABILITY DISTRIBUTION FOR $f_{F,RM}$

$f_{F,RM}$	Probability	Cumulative Probability
3.0-6	0.135	0.135
5.0-4	0.195	0.331
1.0-3	0.220	0.551
1.5-3	0.196	0.747
2.0-3	0.135	0.882
2.5-3	0.073	0.955
3.0-3	0.031	0.986
3.5-3	0.010	0.996
4.0-3	0.004	1.000

NOTES:

1. Mean = 1.2×10^{-3}.
2. Exponential notation is indicated in abbreviated form; i.e., 3.0-6 = 3.0×10^{-6}.

TABLE C-4. A DISCRETIZED DISTRIBUTION FOR $f_{I,80}$

$f_{I,80}$	Probability	Cumulative Probability
3.3-2	1.04-2	0.010
4.44-2	3.96-2	0.050
5.29-2	5.21-2	0.102
5.87-2	4.79-2	0.150
6.33-2	5.24-2	0.202
6.72-2	4.80-2	0.250
7.08-2	5.16-2	0.302
7.42-2	4.81-2	0.350
7.74-2	4.93-2	0.399
8.22-2	9.89-2	0.498
8.88-2	1.00-1	0.598
9.40-2	4.93-2	0.648
9.78-2	5.08-2	0.698
1.02-1	5.05-2	0.749
1.07-1	5.21-2	0.801
1.12-1	4.99-2	0.851
1.19-1	4.87-2	0.900
1.28-1	4.99-2	0.950
1.44-1	4.03-2	0.990
1.71-1	1.0-2	1.000

NOTE: Exponential notation is indicated in abbreviated form; i.e., 3.3-2 = 3.3×10^{-2}.

C.3.4 FATALITIES FROM FIRES PROPAGATING BEYOND THE ROOM OF ORIGIN

The unconditional frequency of a fatality given a fire that has propagated beyond the room of origin, $f_{F,BO}$, is evaluated in this section using the same method as described in Section C.3.3. The evidence is 1 fatality fire in 114 fires that propagated beyond the room of origin. The parameters of the posterior beta distribution are then r = 1 and n = 114. A discretization of this distribution is given in Table C-5. Its characteristic values are:

5th Percentile:	4.5×10^{-4}
Median:	6.1×10^{-3}
95th Percentile:	2.6×10^{-2}
Mean:	8.8×10^{-3}

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TABLE C-5. A DISCRETIZATION OF THE DISTRIBUTION FOR $f_{F,BD}$

$f_{F,BD}$	Probability	Cumulative Probability
1.00-4	1.12-2	0.011
3.49-4	4.37-2	0.055
7.98-4	5.20-2	0.102
1.25-3	3.95-2	0.146
1.75-3	5.60-2	0.202
2.30-3	4.39-2	0.246
2.90-3	5.75-2	0.304
3.55-3	4.58-2	0.350
4.20-3	4.97-2	0.399
4.93-3	5.22-2	0.452
6.17-3	9.64-2	0.548
8.10-3	1.00-1	0.648
9.93-3	5.20-2	0.700
1.14-2	5.01-2	0.750
1.32-2	4.88-2	0.799
1.54-2	5.18-2	0.851
1.84-2	4.95-2	0.900
2.29-2	4.99-2	0.950
3.14-2	3.99-2	0.990
4.64-2	1.00-2	1.000

NOTE: Exponential notation is indicated in abbreviated form: i.e., 1.00-4 = 1×10^{-4}.

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APPENDIX D

ROOM PRESSURE RISE FROM MINERAL OIL TRANSFORMER RUPTURE

APPENDIX D

ROOM PRESSURE RISE FROM MINERAL OIL TRANSFORMER RUPTURE

In this appendix, room pressure rise as a consequence of mineral oil transformer rupture is calculated. The pressure rise is from the combustion of mineral oil vapors. For a mixture of fuel and air to start burning, a source of ignition must exist and the fuel concentration must be within the flammability limits. That is, the flame cannot propagate if the concentration is too low, and there will not be enough oxygen if the concentration is too high. A table of flammability limits for several types of fuel is given in Reference D-1. The lower limits typically range from 1.2% to 12.5% by volume and the upper limits range from 7.8% to 76%.

Two modes of combustion may take place, depending on the flame velocity detonation (supersonic velocity) and deflagration (subsonic velocity). The detonation limits (in terms of concentration) for a vapor that can detonate are always within the deflagration limits, which are the flammability limits. In this study, because of lack of sufficient information it is assumed that mineral oil vapor can detonate. Thus, in a mineral oil transformer rupture, either mode of combustion may occur. Upon rupture, mineral oil vapor would leave the pool of fluid and would expand in the air. As it expands, it would first reach the upper flammability limit, and if deflagration does not take place, it would expand to the upper detonation limit (if it exists). The process can continue and the air and mineral oil vapor mixture would reach the lower detonation and deflagration limits in the absence of an ignition source.

In this appendix, it is assumed that given a rupture, one of the two modes of combustion takes place. The pressure rise in the room depends on the type of explosion (detonation or deflagration). In this appendix, the relative likelihood of the two modes is not evaluated.

D.1 DEFLAGRATION

In a deflagration, the flame front propagates at subsonic speeds, and the pressure equalizes throughout the enclosure where combustion is taking place. As will be shown below, a small amount of mineral oil vapor is generated in a transformer rupture. Therefore, the uniform mixture of the vapor with air is below the flammability limits. However, deflagration may occur in a smaller volume around the transformer as the vapor cloud is expanding to the limits of the enclosure. Deflagration generates a pressure wave. This wave attenuates as it propagates toward the room boundaries. When it reaches the boundaries, the room is approximately at uniform pressure. Thus, an adiabatic, constant volume model (Reference D-2), as opposed to a dynamic model, can be used for calculating the pressure rise in the room.

Using the adiabatic constant volume model, the amount of mineral oil vapor is computed from an estimate of the energy of the arc, the cause for the rupture. All of the vapor is assumed to burn instantaneously and the heat generated is completely absorbed by the air within the room.

The pressure is then determined using the ideal gas law. The details of the model and the assumptions are given below. The thermal properties and other constants used in the computations and the results are listed in Tables D-1 and D-2, respectively.

D.1.1 THE ARC ENERGY

Reference D-8 presents the results of some experiments in which transformer tanks are ruptured by electrical arcs. Transformers were used in the experiments with ratings in the range of 10 kVA to 100 kVA and applied arc energies ranging from 10 kJ to 80 kJ. The minimum arc energy needed for rupture increases with the transformer rating. The transformer rating considered in their case studies is 225 kVA. A range of arc energies from 10 kJ to 1,000 kJ is used in this study. Based on the experiments described in Reference D-8, it is believed that the minimum energy for rupturing the transformer under consideration is well above 80 kJ.

D.1.2 THE AMOUNT OF VAPOR GENERATED

It is assumed that all of the arc energy is available for heating the mineral oil from its initial temperature to its boiling point and evaporating it. This is a conservative assumption because the energy for rupturing the tank and displacing the rest of the fluid is ignored.

The initial temperature of the bulk oil is assumed to be 100°C. This is somewhat conservative because the normal operating temperature is in the range of 60°C to 75°C (Reference D-9). Under abnormal high load or poor ventilation conditions, this temperature can be above 100°C up to 150°C. The specific heat of the oil (in liquid form) is about 1.5 kJ/kg °K (Reference D-3) and the heat of vaporization is 610 kJ/kg (Reference D-4). The boiling point is 360°C (Reference D-5).

To obtain the mass of the vapor generated, the following heat balance equation is used

$$E = M\,C_p(T_B - T_O) + MH \qquad (D.1)$$

where

- E = arc energy (kJ).
- M = mass of the vapor (kg).
- C_p = specific heat (kJ/kg °K).
- T_B = boiling point (°K).
- T_O = initial temperature (°K).
- H = heat of vaporization (kJ/kg).

TABLE D-1. THERMAL PROPERTIES OF MINERAL OIL AND OTHER CONSTANTS USED IN THE CALCULATION

Parameter	Value	Reference
Specific Heat Liquid (kJ/kg °K)	1.5	D-3
Heat of Vaporization (kJ/kg)	610	D-4
Flash Point (°C)	145	D-5
Heat of Combustion (kJ/kg)	4.7×10^4	D-6
Initial Oil Temperature (°C)	100	See Section D.1.2
Room Dimension (ft x ft x ft)	20 x 20 x 8	Assumed
Specific Heat of Air at Constant Volume (kJ/kmole °K)	21.27	D-2
Ratio of Specific Heats of Air at 1 ATM, γ	1.4	D-7

TABLE D-2. CALCULATION OF PRESSURE RISE USING THE ADIABATIC CONSTANT VOLUME MODEL

Parameters	Arc Energy (kJ)										
	10	42	80	100	140	200	400	600	660	800	1,000
Amount of Vapor (kg)	0.01	0.042	0.08	0.1	0.14	0.2	0.4	0.6	0.66	0.8	1.0
Energy per kmole of Air (kJ/kmole)	127	534	1,015	1,270	1,774	2,541	5,081	7,622	8,384	10,162	12,703
Temperature (°K)	304	323	346	358	378	422	550	666	699	775	881
Pressure Rise (psi)	0.3	1.2	2.4	3.0	3.9	6.1	12.4	18.1	19.8	23.5	28.7

It should be noted that since heat losses into the bulk of the oil are not considered properly, this equation is conservative; that is, it overestimates the vapor mass. Using the above values, we can solve this equation for M, the mass of the vapor. For example, for 200 kJ arc energy, 0.200 kg of vapor is generated. The result of this equation is conservative because the energy expended for superheating the vapor and heating the rest of the pool is ignored.

D.1.3 THE ENERGY GENERATED FROM COMBUSTION

Upon transformer rupture, some of the oil and most of the vapor would be released. It is assumed that all the above computed vapor mass is released into the air. This ignores some condensation that may take place on colder surfaces and while the vapor is still submerged in the liquid. It is also assumed that ignition would occur because the vapor temperature would be above ignition temperatures indicated in Reference D-5 for lubricating mineral oil, and the transformer winding may be red hot and exposed. The energy generated from the vapor combustion is the product of the heat of combustion and the vapor mass. The heat of combustion is taken to be 4.7×10^4 kJ/kg (Reference D-6). This result is also conservative because it assumes that all of the vapor is consumed. For example, combustion of 0.200 kg of vapor can generate 9,400 kJ of energy.

We can now compute the energy generated per kilomole of air. This is simply the total energy generated divided by the total amount of air in the room. The room dimensions are 20 feet by 20 feet and 8 feet from the floor to the ceiling. The volume of the room is, therefore, 3,200 feet^3 (9.06×10^4 liters). Assuming 1 atmosphere pressure and 25°C temperature, the number of moles is

$$\frac{9.06 \times 10^4}{22.4} \times \frac{273}{273 + 25} = 3.71 \times 10^3 \text{ moles}$$

For example, in the case of 200 kJ arc energy, which leads to 9,400 kJ of energy after vapor combustion, the energy per kilo mole is 2,541 kJ/k mole.

In the above calculations, the presence of the combustion products is ignored. It can be shown that their impact is insignificant. In the worst case, that is, 1,000 kJ arc energy, 1 kilogram of vapor is generated. Reference D-10 indicates that burning 1 gram of hydrocarbon leads to about 2 grams of CO_2. Thus, 2 kg or 45.5 moles of CO_2 would be generated in this case. This constitutes 1.2% of the air in the room. Therefore, the presence of CO_2 after the combustion for all arc energy levels under consideration can be ignored.

D.1.4 POST-BURN TEMPERATURE OF THE AIR

To calculate the post-burn air temperature, it is assumed that all the combustion energy is absorbed by the air and the specific heat of air at constant volume is needed. From Reference D-2, it is concluded that the specific heat of the air ranges from 20.9 to 21.5 kJ/kmole °K for the temperature range of 298 to 400°K. Since this variation is small for temperatures below 400°K, a constant specific heat at constant volume of 21.27 kJ/kmole·°K is used. For temperatures above this level, the correlations for the internal energy of oxygen and nitrogen are used (Reference D-2). That is,

$$U(T) = 0.8 \times [31317 + (37.46 - 8.314)T - 4559.3 \ln T] + 0.2 \times [43388 + (42.27 - 8.314)T - 6635.4 \ln T] \text{ (kJ/kmole)} \quad (D.2)$$

where U(T) is the internal energy of air per unit kilomole at temperature T. The expressions within the brackets are the correlations for the internal energy of nitrogen and oxygen, respectively. It is assumed that the air is composed of 80% nitrogen and 20% oxygen. To compute the air temperature above 400°K, the following expression is used:

$$\begin{aligned} u &= U(T) - U(400) + 21.2 \times (400 - 298) \\ &= 0.8 \times [31,317 + (37.46 - 8.314)T - 4,559.3 \ln(T)] \\ &\quad + 0.2 \times [43,388 + (42.27 - 8.314)T - 6,635.4 \ln(T)] \\ &\quad - 0.8 \times [31,317 + (37.46 - 8.314) \times 400 - 4,559.3 \ln (400)] \\ &\quad - 0.2 \times [43,388 + (42.27 - 8.314) \times 400 - 6,635.4 \ln (400)] \\ &\quad + 21.2 \times (400 - 298) \end{aligned} \quad (D.3)$$

Thus

$$u = 30.1T - 4,974.5 \ln(T) + 19,923.8 \quad (D.4)$$

where u is the combustion energy generated per kilomole of air as computed in Section D.1.3. For example, for the case of 200 kJ arc energy, the internal energy is 2,541 kJ/kmole. The temperature rise using the constant specific heat is

$$2,541/21.2 = 119.9°K$$

and the absolute temperature is

$$119.9 + 298 = 417.9^{\circ}K$$

which is above 400°k. Thus, the above equation should be used for establishing the post-burn air temperature

$$2,541 = 30.1T - 4,974.5\, \ln(T) + 19,923.8 \qquad (D.5)$$

Using iterative computational methods, the post-burn temperature of 422°K (149°C) is obtained.

D.1.5 POST-BURN AIR PRESSURE

Knowing the post-burn temperature as well as the amount of air and the volume of the room, the post-burn pressure can be calculated using the ideal gas law

$$P = \frac{nRT}{V} \qquad (D.6)$$

For our case study, n is reasonably approximated by 3.7 kmole, V is 90.6 cubic meters, and R is 8.314 kJ/kmole °K. Thus,

$$P = 0.3395T \times \frac{1}{6.89} \quad \text{(psia)} \qquad (D.7)$$

where T is in degrees K and 6.89 is the conversion factor to express the pressure in terms of pounds per square inch. For example, for the case of 200 kJ arc energy, the temperature is 422°K, which would result in an absolute pressure of 20.8 psia, and the pressure increase is

$$20.8 - 14.7 = 6.1 \text{ psi}$$

D.1.6 PRESSURE VENTING

The pressure rise in a deflagration is sufficiently slow to permit relieving of the pressure through openings in the transformer room. These openings for the two transformer rooms considered in this study are ventilation openings toward the outside air.

The following equation from Reference D-11 can be used to establish whether sufficient vent area is available.

$$A_v = \frac{CL_1L_2}{\sqrt{P}}$$

where

A_v = necessary vent area (ft^2).

C = constant, depends on the burning vapor.

L_1 = smallest dimension of the transformer room (ft).

L_2 = second smallest dimension of the transformer room.

P = maximum pressure that the room boundaries can withstand (psi).

For the type of gases that may be generated from mineral oil vaporization, Reference D-11 suggests C = 2.6 (in English units). Thus, for a 20 ft x 20 ft x 8 ft room, we obtain the relationship

$$A_v = \frac{416}{\sqrt{P}} (ft^2)$$

For case 1, the room boundaries may withstand pressures up to 1 psig. To prevent the burning gases from reaching this level the total vent area must be 416 ft^2. For case 2, the room boundaries may withstand pressures up to 7 psig. For this case, the vent area must be 157 ft^2. For both cases, the required vent area is signficantly larger than reasonably sized ventilation openings. Thus, for arc energy levels that lead to room pressures above 1 and 7 psig, the room boundaries for cases 1 and 2, respectively, are very likely to fail.

D.1.7 RESULTS

Using the method outlined above, the pressure increase in the room is calculated for 11 levels of arc energy. Table D-2 shows the results. As can be seen, above 80 kJ arc energy the differential pressure is above 2 psi. The walls of the room will experience this pressure rise for only a short period because the ventilation openings will rapidly relieve the pressure. The momentary pressure rise is deemed to be uniform throughout the room, because the deflagration process is envisioned as being an expanding pressurized gas volume in the room.

D.2 <u>DETONATION</u>

In a detonation, the flame front moves at supersonic velocity and there is significant pressure drop across the flame front. The maximum pressure that can be reached at the flame front is several times (it can be as much as seven times) the initial pressure (Reference D-12). The impact of the shock wave on the room boundaries is a complex process, much different from the impact of the pressure waves from deflagration. The forces exerted by the shock wave on the walls are dependent on the shock wave characteristics and wall shape and angle. Simple relations, such as PV = constant (P is pressure and V is volume), cannot be used to represent the physical processes.

The impact of detonation on the room boundaries is significantly more violent than the impact of the pressure waves from deflagration. It is judged that (for the amounts of vapor generated above 80 kJ of arc energy) a detonation of the mineral oil vapor would almost surely lead to an equivalent static pressure on the walls greater than 1/2 atmospheric pressure.

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APPENDIX E

ROOM BOUNDARY FAILURE FROM SEVERE HEAT FLUX

APPENDIX E

ROOM BOUNDARY FAILURE FROM SEVERE HEAT FLUX

In this appendix, for the alternate case of case 1, the chance that the room boundary is breached due to a fire caused by the ignition of leaked mineral oil is evaluated. The failure of the wall due to the radiative heat flux impinging on it is the most likely mode of failure. The convective element of heat transfer from the fire to the walls is judged to be less important than radiative heat flux. Convective heat flux is important when ceiling failure is considered. The ceiling in this room has a 3-hour rated concrete construction. Therefore, its failure is less likely than the walls which are 1-hour rated. For the thermal calculations, it is assumed that there is enough mineral oil for the fire to last until boundary failure and that the fire is not affected by the sprinklers or the fire brigade. The approach that was used in Appendix B to model fire propagation from an Askarel transformer rupture is also used here. First, the time to wall failure is established and the expression

$$f_{RB-2} = [f_{SPR} + (1 - f_{SPR}) \exp(-\tau^*/\tau_{SPR})] \exp(-\tau^*/\tau_{FB}) \qquad (E.1)$$

is used to find the conditional frequency of boundary failure given the fire. The distributions for f_{SPR}, τ_{SPR}, and τ_{FB} as assessed in Appendix B are applicable here. τ^* is the mean time at which wall failure occurs. It is determined using a one-dimensional heat conduction code (Reference E-1).

The leaked mineral oil is assumed to be contained by the curb on the floor. The surface area of the mineral oil is the area of the curb minus the area of the transformer; i.e.,

$$8 \text{ ft} \times 8.5 \text{ ft} - 2 \text{ ft} \times 2.5 \text{ ft} = 63.5 \text{ ft}^2 = 5.9 \text{ m}^2$$

The mass burning rate depends on the amount of air available. If it is assumed that there is sufficient air, combustion is controlled by the surface area; that is, the mass burning rate is equal to the surface area times the mass burning rate per unit area, which has been determined experimentally to equal 3.3×10^{-2} kg/m^2 second (Reference E-2). This is the rate at which the mineral oil is consumed due to combustion and the formation of unburned fumes, which occurs because the combustion efficiency is not 100%. Reference E-2 estimates the heat of combustion of mineral oil to be 4.7×10^4 kJ/kg. Assuming 100% combustion efficiency, the heat generation rate for an area of 5.9 m^2 is 9.3×10^3 kJ/second. The mass burning rate is 0.196 kg/second. At this rate, the 80 gallons of mineral oil can last for about 23 minutes.

Reference E-3 estimates that approximately 1 cubic foot of air is needed for every 113 Btu of energy generated in a combustion. To sustain a mass burning rate of 0.196 kg/second for a surface area controlled fire, the air supply needed is

$$\left(\frac{9.3 \times 10^3 \text{ kJ/sec}}{113 \text{ Btu/ft}^3}\right)\left(\frac{60 \text{ sec}}{\text{min}}\right)\left(\frac{\text{Btu}}{1.0551 \text{kJ}}\right) = 4.68 \times 10^3 \text{ ft}^3\text{/min}$$

which is higher than the assumed capacity of 2,000 ft^3/minute for the ventilation system. Therefore, the actual burning is ventilation controlled. It can be calculated using the assumed capacity of the ventilation system; i.e.,

$$\text{Heat Generation Rate} = 113 \text{ Btu/ft}^3 \times 2{,}000 \text{ ft}^3\text{/min} = 3.97 \times 10^3 \text{ kJ/sec}$$

and

$$\text{Mass Burning Rate} = \frac{3.97 \times 10^3 \text{ kJ/sec}}{4.7 \times 10^4 \text{ kJ/kg}} = 8.45 \times 10^{-2} \text{ kg/sec}$$

At this rate, 80 gallons of mineral oil can last for 53.3 minutes.

Wall failure is assumed to occur when the temperature rise at the cool side of the wall reaches 140°C. This is the definition used in the fire rating of structures (Reference E-3). The time to failure t* is determined by using the THEAT computer code (Reference E-1). The wall is assumed to be a 2-inch thick concrete slab (Reference E-3 indicates that 2-inch thick concrete covers are 1-hour rated fire protection for beams, joists, and girders). On one side, a constant heat flux is used as the boundary condition; on the other side, convective cooling is assumed.

The constant heat flux is estimated using a conservative model. Because of the large surface area of the base, the flame is expected to reach the ceiling. It is assumed that the flame is in the shape of an 8-foot high cylinder with its horizontal cross sectional area equal to the area enclosed by the curb. Therefore, its radius is equal to

$$\sqrt{\frac{8 \times 8.5}{\pi}} = 4.65 \text{ ft}$$

The room boundary is assumed to be a concentric cylinder with radius equal to 10 feet and height equal to 8 feet. Assuming that radiative heat flux is emitted from the flame radially, the heat flux decreases linearly with distance. The heat flux at the room boundary is therefore equal to the total radiative power divided by the curved surface area of the outer cylinder; i.e.,

$$\frac{3.97 \times 10^3 \text{ kJ/sec} \times 0.4}{2\pi \times 10 \text{ ft} \times 8 \text{ ft}} \times \left(\frac{\text{ft}^2}{0.0929 \text{m}^2}\right) = 34 \text{ kW/m}^2$$

where 0.4 is the fraction of total energy emitted as radiative heat flux (Reference E-4).

Using this constant heat flux, t* is found to be 31 minutes. It relates to τ^* by $\tau^* = E_0 t^*$ (see Appendix B for a discussion of the parameter E_0), where E_0 is lognormally distributed with 5th and 95th percentiles equal to 0.8 and 4.0, respectively. Therefore, τ^* is lognormally distributed with parameters $\mu = 4.02$ and $\sigma = 0.489$. Its characteristic values are:

5th Percentile:	24.8 Minutes
Median:	55.5 Minutes
95th Percentile:	124.0 Minutes
Mean:	62.5 Minutes

The conditional frequency of breaching the boundary, f_{RB-2}, is found to have the following characteristic values:

5th Percentile:	9.7×10^{-5}
Median:	5.4×10^{-3}
95th Percentile:	5.5×10^{-2}
Mean:	1.3×10^{-2}

E.1 REFERENCES

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E-2. Hemstreet, R. A., "Flammability Tests of Askarel Replacement Fluids," Factory Mutual Research Corporation, RC78-T-42, August 1978.

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APPENDIX F

FIRE PROPAGATION TO AN ADJACENT ROOM FROM AN ABOVE-LIQUID-LEVEL RUPTURE OF THE CASE 1 MINERAL OIL TRANSFORMER

APPENDIX F

FIRE PROPAGATION TO AN ADJACENT ROOM FROM AN ABOVE-LIQUID-LEVEL RUPTURE OF THE CASE 1 MINERAL OIL TRANSFORMER

The possibility of fire propagation to an adjacent room in the case of an above-liquid-level rupture of the Case 1 mineral oil transformer is analyzed in this appendix. Since the rupture point is above the liquid level, little fluid is splattered. If any fluid escapes the tank, it is anticipated to end up within the curb boundaries around the transformer. It is certain that the oil remaining in the tank would be in flames because of the hot windings and contact with the air. Some of the hot gases and smoke generated from this fire would escape to the outside of the building through the openings, and some of it would escape to the adjacent rooms through the walls breached by an explosion following the rupture. The hot gases would also engulf the sprinkler heads above the transformer, which would eventually open and pour water on the fire.

The combustibles in the adjacent room would heat up primarily from the radiation of the hot gas layer and the flames. In Appendix E, it is found that in the case of a burning oil leak, the heat flux on the room walls is expected to be about 30 kW/m^2. This can conservatively be taken as the heat flux impinging on the carpeting or other combustibles in the adjacent rooms. Using the semi-infinite slab model of Appendix B, the time of ignition t* can be calculated (see Appendix B for its derivation) from

$$t^* = \frac{1.2 \times 10^{11}}{\dot{q}_o''} \text{ (s)}$$

where $\dot{q}_o''$ is the impinging heat flux in W/m^2. Thus,

$$t^* = 133 \text{ seconds}$$

To establish the conditional frequency of fire propagation, f_{P-4}, the approach used in Appendix B can be followed. We can write

$$f_{P-4} = \left[f_{SPR} + \exp\left(-\tau^*/\tau_{SPR}\right)\left(1-f_{SPR}\right)\right] \exp\left(-\tau^*/\tau_{FB}\right)$$

Since t* is very short in this case, the likelihood of the fire brigade arriving is small and $\exp(-\tau^*/\tau_{FB})$ is assumed to be unity.

As discussed in Appendix B, the statistical uncertainty about t* is deemed to be overwhelmed by the state-of-knowledge uncertainties. The error factor, E_o, suggested in Reference F-1 can be used here. It is lognormally distributed with 5th and 95th percentiles at 0.8 and 4.0, respectively. Multiplying this error factor by t*, the mean fire propagation time is obtained

$$\tau^* = t^* E_o$$

This quantity is also lognormally distributed and has the following characteristic values:

5th Percentile:	1.8 Minutes
Median:	4.0 Minutes
95th Percentile:	8.9 Minutes
Mean:	4.5 Minutes

Using discretized probability distribution arithmetic (see Appendix G and Reference F-2), the distribution for f_{p-4} can be computed. Its characteristic values are:

5th Percentile:	0.30
Median:	0.62
95th Percentile:	0.88
Mean:	0.60

F.1 REFERENCES

F-1. Siu, N. O., and G. Apostolakis, "Probabilistic Models for Cable Tray Fire," Reliability Engineering, Vol. 3, pp. 213-227, 1982.

F-2. Kaplan, S., "On the Method of Discrete Probability Distributions in Risk and Reliability Calculations - Application to Seismic Risk Assessment," Risk Analysis, Vol. 1, p. 189, 1981.

APPENDIX G

UNCERTAINTY PROPAGATION USING DISCRETE PROBABILITY DISTRIBUTIONS

APPENDIX G

UNCERTAINTY PROPAGATION USING DISCRETE PROBABILITY DISTRIBUTIONS

The contents of this appendix are based on Reference G-1. To propagate uncertainties through a complicated equation such as (see Equation (B.7) in Appendix B)

$$f_{p-1} = \left[f_{SPR} + (1 - f_{SPR}) \exp(-\tau^*/\tau_{SPR})\right] \exp(-\tau^*/\tau_{FB})$$

using analytical methods can often be an impossible task. One method for uncertainty propagation is using discrete probability distribution (DPD) and replacing the multiple integrations by consecutive multiplications and summations.

All probability distributions can be approximated by DPDs. Let us use the notation $\langle p_i, X_i \rangle$ for the ith element of a DPD for variable X, where X_i is the ith value of X and p_i is its probability. Also, the p_i of every DPD must satisfy

$$\sum_{i=1}^{n} p_i = 1$$

Let us use the notation $\{\langle p_i, X_i \rangle\}$ to represent the DPD for variable X.

If X has a continuous probability distribution, $P_X(X)$, its DPD can be obtained by first chosing a set of intervals in the range of all possible X and obtain the X_i and p_i from

$$X_i = \frac{1}{p_i} \int_{\tilde{X}_{i-1}}^{\tilde{X}_i} x \, P_x(X) dx$$

$$p_i = \frac{1}{p_i} \int_{\tilde{X}_{i-1}}^{\tilde{X}_i} P_x(X) dx$$

where $\tilde{X}_{i-1}$ and $\tilde{X}_i$ are the boundaries of the ith interval. It should be noted that several of the frequencies used in this study are assessed in terms of DPD.

As a simple example for uncertainty propagation, suppose the variables X, Y, and Z are related by

$$Z = X + Y$$

and the variables X and Y have DPDs of $\{\langle p_i, X_i \rangle\}$ (total of I elements) and $\{\langle q_j, Y_j \rangle\}$ (total of J elements). The DPD for Z can then be written as

$$\{\langle p_i q_j, X_i + Y_j \rangle\}$$

That is, the DPD of Z has I x J elements with probability $r_{ij} = p_i q_j$ and values $Z_{ij} = X_i + Y_j$.

As a simple numerical example, take the DPDs for X and Y to be

$$X = \{\langle 0.1,-1 \rangle \langle 0.5,1 \rangle \langle 0.4,2 \rangle\}$$

$$Y = \{\langle 0.2,5 \rangle \langle 0.8,10 \rangle\}$$

then

$$Z = \{\langle 0.02,4 \rangle \langle 0.1,6 \rangle \langle 0.08,7 \rangle \langle 0.08,9 \rangle \text{ x } \langle 0.4,11 \rangle \langle 0.32,12 \rangle\}$$

In the general form, when

$$Z = f(X,Y)$$

where X,Y are independent DPDs,

$$X = \{\langle p_i, X_i \rangle\}, \; Y = \{\langle q_j, Y_j \rangle\},$$

Z is the DPD

$$Z = \{\langle r_{ij}, Z_{ij} \rangle\}$$

where

$$r_{ij} = p_i q_j, \; Z_{ij} = f(X_i, Y_j)$$

and

$$\sum_{\substack{\text{all} \\ i \text{ and } j}} r_{ij} = 1.0$$

In the case of a complicated equation, the number of variables of the function f can be increased and the probability of each combination of values becomes the product of the appropriate probabilities. For example, the above equation for f_{p-1} has four variables: f_{SPR}, τ^*, τ_{SPR} and τ_{FB}. All are assessed in terms of three-element DPDs (see Appendix B) except for τ^*, which has a lognormal distribution.

A discretization of that distribution into 20 (elements) yields for its third value $\tau_3^* = 8.75$ with $p_{\tau,3} = 0.012$. The first element of f_{SPR} is <0.10, 0.02>, the second element of τ_{SPR} is <0.4, 15.0> and the second element of τ_{FB} is <0.4, 30.0>. Using these values, one of the elements of the DPD for f_{p-1} becomes

$$\langle P_{1,3,2,2}, f_{p-1_{1,3,2,2}} \rangle = \langle 0.10 \times 0.012 \times 0.4 \times 0.4, [0.02 + (1 - 0.02) \exp(-8.75/15.0)] \exp(-8.75/30.0) \rangle$$

$$= \langle 1.9 \times 10^{-4}, 0.42 \rangle$$

Since these variables have 3, 20, 3, and 3-element DPDs (see Appendix B), the DPD for f_{p-1} would have 540 elements. The number of elements is obviously very large if it has to be used in further uncertainty propagation. The elements of a large DPD can be condensed by taking the mean of subgroups of elements

$$X_i = \frac{1}{p_i} \sum_{\substack{\text{all k of} \\ \text{the subgroup}}} X_k \, p_k$$

and

$$p_i = \sum_{\substack{\text{all k of} \\ \text{the subgroup}}} p_k$$

The above example involved a relatively complicated function of four variables. The terms within the function [such as $\exp(-\tau^*/\tau_{SPR})$ and $\exp(-\tau^*/\tau_{FB})$] share identical variables (in this case τ^*). Because of this dependency, these terms could not be separately evaluated and combined by the appropriate relationship. However, in many cases, uncertainty propagation has to be done for independent terms. For example,

$$Q = X(Y+Z)$$

The uncertainties can be propagated through this equation in two steps. In the first step, the DPD for Y+Z can be obtained by summing the DPDs for Y and Z. In the second step, the DPD for Q can be obtained from multiplying the DPDs for X by Y+Z (obtained in the first step). This process can be repeated for complicated equations but comprised of independent variables.

G.1 REFERENCES

G-1. Kaplan, S., "On the Methods of Discrete Probability Distributions in Risk and Reliability Calculations - Application to Seismic Risk Assessment, "Risk Analysis, Vol. 1, p. 189, 1981.

APPENDIX H

FLAMMABILITY OF CHLORINATED ORGANIC VAPORS

APPENDIX H

FLAMMABILITY OF CHLORINATED ORGANIC VAPORS

Examined in this appendix are the flammability characteristics of chlorinated organic vapors. The two principal components of Askarel, polychlorinated biphenyl (PCB) and trichlorobenzene (TCB), are such organics. Flame velocity in the vapor phase for a chemical is used in this appendix to compare the flammability of chlorinated organics with other flammable chemicals such as benzene and methane. Slower velocities indicate a less flammable material, and slower energy release, by implication, yields a less violent explosion. It should be noted that the rate of energy released by a burning gas is directly related to its flame velocity.

Although the physical properties of TCB are known (References H-1 through H-3), very little is published on their flammability. Currently, data pertaining to the flammability of TCB consist of data on a flash point (99°C) and reports indicating that it is nonflammable or suppresses flammability (References H-1, H-4, and H-5). Since these data are inconsistent, the following analysis is intended to determine the hazard level of TCB by determining its flame velocity and thus determine which data are correct.

An analysis of the flammability properties of specific chemicals is given by Exner (Reference H-6). The analysis in Reference H-6 is based, to a large extent, on data developed by Gupta and Valeiras (Reference H-7) which was published at a date later than Reference H-6. Also, work by other specialists in the field (Reference H-8) gives some insight into how mixtures of nonflammable and flammable gases will behave.

An algorithm for determining the flame velocity of a chlorinated organic vapor is:

1. Establish the weight fraction of chlorine in the vapor phase.

2. Establish the heat of combustion from Figure H-1.

3. Establish the flame velocity from a correlation equation with heat of combustion.

The heat of combustion of all chlorinated organics can be established from Figure H-1. If their molecule is structured like benzene, the curve for aromatics should be used, and if their molecule is structured like methane, the curve for alkanes should be used. TCB is an aromatic compound. The weight fraction of chlorine in TCB is 0.59. From Figure H-1 the heat of combustion of TCB is 3.4 Kcal/gram.

From the heat of combustion, one can establish the flame velocity for an organic vapor. This is concluded from an inspection of the equations for burning velocities given in Reference H-6. Table H-1 summarizes the data

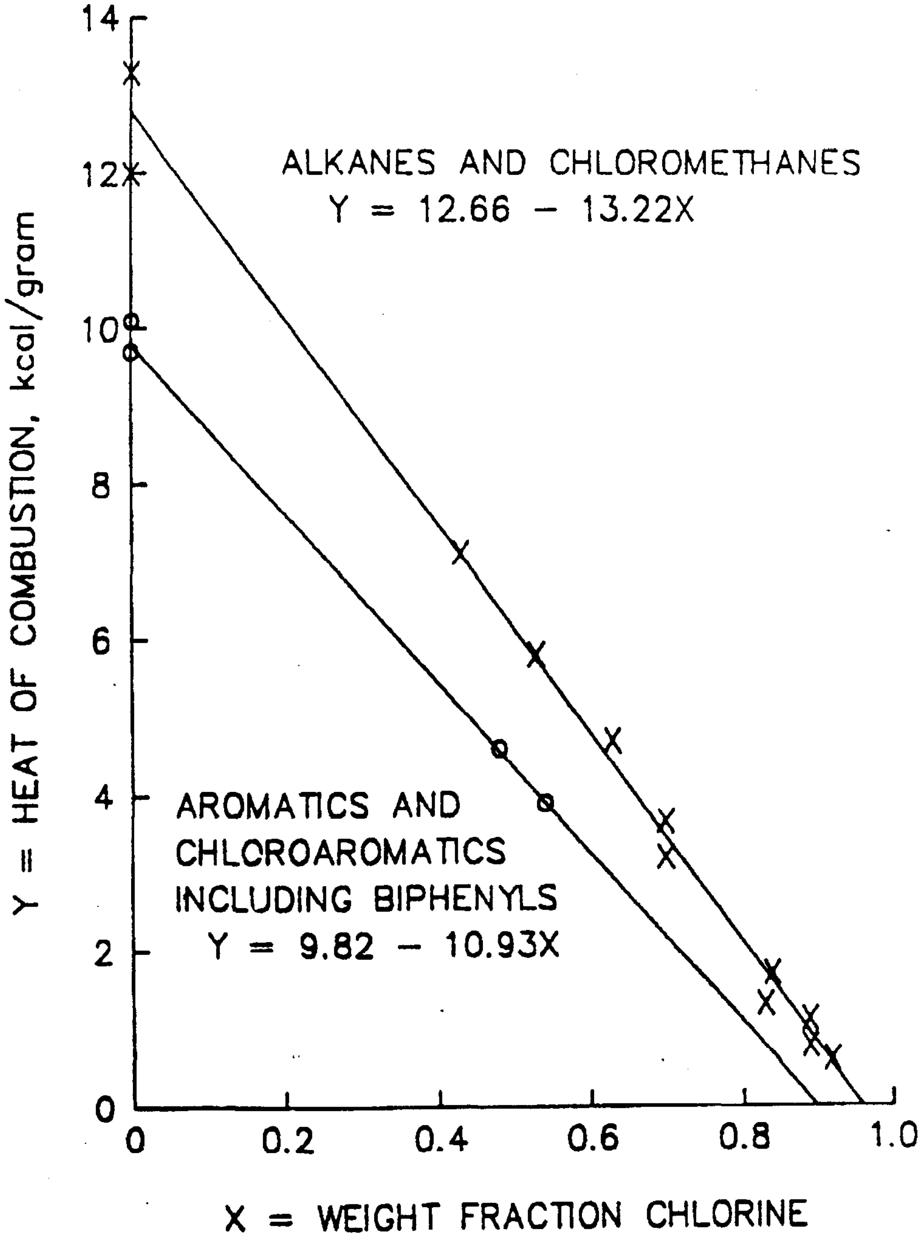

FIGURE H-1. CORRELATION BETWEEN HEAT OF COMBUSTION AND CHLORINE WEIGHT FRACTION OF MOLECULE

TABLE H-1. SUMMARY OF FLAME VELOCITY RELATED INFORMATION REPORTED IN REFERENCE H-6

First Order Combustion Reactions:

$$U_b^2 = \frac{2\lambda C_p A}{\rho_o L^2} \frac{T_o}{T_f} \left[\frac{RT_f^2}{E}\right]^2 \exp\left[\frac{-E}{RT_f}\right]$$

Second Order Combustion Reactions:

$$U_b^2 = \frac{4\lambda C_p^2 A n_o}{\rho_o L^3} \frac{T_o}{T_f} \left[\frac{RT_f^2}{E}\right]^3 \exp\left[\frac{-E}{RT_f}\right]$$

R = .008314 kJ°K gm mole

Chemical		T_f, Flame Temperature °K	E, kJ/Mole	n_o	Flame Velocity U_b cm/sec	Heat of Combustion kJ/Mole
Methane	CH_4	2,164	340	0.0535	70	845.6
Chloromethane	CH_3Cl	2,190	180	0.107	11	726.3
Chloromethane	CH_2Cl_2	2,011	26	0.156	1.7	447.1
Chloromethane	$CHCl_3$	1,995	-10.0	--	0	441.6
Chloromethane	CCl_4	1,840	-164.0	--	0	385.11
Benzene	C_6H_6	2,290	1,257.6*	0.012	40	3,237.2
Chlorobenzene	C_6H_5Cl	2,220	1,094.2*	0.013	27	3,032.6
Mixture of	CH_3Cl/CH_4 K** = 0.48	2,172*	291		30	806.6
Methane and	CH_3Cl/CH_4 K** = 1.0	2,177*	250		25	785.9
Chloromethane	CH_3Cl/CH_4 K** = 2.0	2,181*	253		20	766.0
	CCl_4/CH_4 K** = 1.0	2,002*	88		13	615.3

*Calculated.

**K is the molar ratio of chloromethane and methane.

given in Reference H-6. A linear or regression analysis (curve fitting) of the chloromethane data yields the correlation

$$U_b = 5.34\ (\Delta Hc) - 4.15 \qquad (H.1)$$

where

ΔHc = heat of combustion (Kcal/g).

U_b = flame velocity (cm/sec).

The number of data points is 7 and the correlation coefficient (R^2) is 0.964. Although this linear equation is not consistent with our understanding of the phenomenology, it is an acceptable correlating form.

Table H-2 gives a comparison of calculated velocities (using Equation H.1) and experimentally determined flame velocities for different chemicals. The experimental data are summarized in Table H-3.

The deviations between measured and calculated flame velocities in Table H-2 implies that the relationship is different for each family of organics. This is consistent with the relationship found for the chlorine content and heat of combustion. Therefore, we modify the correlation in Equation H.1 to specialize it to chlorinated benzenes. The ratio of measured and calculated velocities for chlorinated benzenes, per Table H-2, ranges from 0.8 to 0.9. The slope of the curve is thus modified by multiplying 0.9 and 5.34. The correlation equation for chlorinated benzenes becomes

$$U_b = 4.81\ (\Delta Hc) - 4.15 \qquad (H.2)$$

This correlation gives a burning velocity for trichlorobenzene ($C_6H_3Cl_3$) of 12 cm/sec. This is equivalent to the burning velocity of methylchloride. The prediction of a positive burning velocity for trichlorobenzene implies that the reported flash point is a valid number. Based upon this, we conclude that TCB is flammable. However, TCB has poorer flammability characteristics than chemicals such as benzene and methane. This becomes evident when the flame velocities and heats of combustion are compared.

Finally, it should be noted that similar calculations for PCBs (e.g., Aroclor 1254) are not possible because almost no data are available for this homologous series. Reference H-9 reports combustion of an Askarel that was composed of 70% PCB and 30% TCB. Burning was possible only when considerable external heat (3 to 6 watts/cm^2) was applied to a 4-inch diameter pool of Askarel. The flames were weak and the heat release rate from the Askarel was 3 to 6 Kcal/min. It is also reported in Reference H-9 that self-sustained combustion of the Askarel was not possible. The combustion occurred only within the range of external heat fluxes noted above. In the same test, other transformer fluids such as mineral oil and 50-centistoke dimethyl silicone established self-sustained combustion at lower external heat fluxes than 3 watts/cm^2 and generated heat at much greater rates (above 15 Kcal/min).

TABLE H-2. COMPARISON OF FLAME VELOCITIES

Chemical		Flame Velocity (cm/sec)	
		Measured	Calculated
Methane	CH_4	70	67
Chloromethanes	CH_3Cl CH_2Cl_2 $CHCl_3$	11 1.7 0	13 to 15 2.6 -0.14 to 1.3
Mixtures of Methane and Chloromethanes	CH_3Cl/CH_4 K* = 0.48 CH_3Cl/CH_4 K* = 1 CH_3Cl/CH_4 K* = 2 CCl_4/CH_4 K* = 1	30 25 20 13	34 26 21 5.6
Benzene	C_6H_6	40	48 to 50
Chlorobenzene	C_6H_5Cl	27	30

*K is the molar ratio of chloromethane and methane.

TABLE H-3. FLAMMABILITY PROPERTIES OF CHLORINATED ORGANICS SUMMARIZED FROM REFERENCES H-4 AND H-7

Sheet 1 of 2

Chemical	Molecular Weight	Explosive Limits		Flame Velocity cm/sec	Chlorine Weight Fraction	Heat of Combustion	
		LEL Volume %	UEL Volume %			kcal/g	kcal/mole
Methane and Chloromethanes							
CH_4	16	5.35	14.1	70	0	11.95 to 13.30	191.2 212.798
CH_3Cl	50.49	10.7	17.4	11	0.70	3.25 to 3.62	164.2 to 182.8
CH_2Cl_2	84.93	15.6 in O_2		1.7	0.83	1.26	106.8
$CHCl_3$	119.38	Nonflammable		--	0.89	0.75 to 1.02	89.2 to 121.8
CCl_4	153.82	Nonflammable		--	0.92	0.60	92.0
Aromatics and Chlorinated Aromatics							
C_6H_6	78.1	1.3	7.9	40	0	10.1 to 9.7	789.1 to 757.6
C_6H_5Cl	112.56	1.4	9.6	27	0.31	6.43*	723.95
$C_6H_4Cl_2$	147.0	2.2	9.2		0.48	4.57	671.8
$C_6H_3Cl_3$	181.45	2.8			0.59	3.37*	611.72*

*Calculated from correlations:

For Alkanes and Chloromethanes

$y = 12.66 - 13.22X;\ n = 12;\ r^2 = 0.9938$

or

$y = 12.63 - 12.908X - 0.345X^2;\ n = 12;\ r^2 = 0.9938$

For Aromatics and Chlorobenzenes

$y = 9.8z - 10.93X;\ n = 5;\ r^2 = 0.9969$

or

$y = 9.82 - 11.03X + 0.1929X^2;\ n = 5;\ r^2 = 0.99685$

y - Chlorine Weight Fraction

x - Heat of Combustion; kcal/gm

TABLE H-3 (continued)

Sheet 2 of 2

Chemical	Molecular Weight	Explosive Limits		Flame Velocity cm/sec	Chlorine Weight Fraction	Heat of Combustion	
		LEL Volume %	UEL Volume %			kcal/g	kcal/mole
Aromatics and Chlorinated Aromatics							
$C_{12}H_{10}$	154.2	0.7	5.8		0	9.66	1,493.6
$C_{12}H_9Cl$	188.64				0.19	7.74*	1,460.7*
$C_{12}H_5Cl_5$	326.35				0.54	3.92	1,279.05
Mixtures of Chloromethanes and Methane							
CH_3Cl/CH_4 K** = 0.48	27.18			30	0.43	7.09	192.76
CH_3Cl/CH_4 K** = 1.0	33.25			25	0.53	5.65	187.75
CH_3Cl/CH_4 K** = 2.0	38.99			20	0.61	4.69	183.0
CCl_4/CH_4 K** = 1.0	84.91			13	0.84	1.73	147.00

*Calculated from correlations:

For Alkanes and Chloromethanes

$y = 12.66 - 13.22X;\ n = 12;\ r^2 = 0.9938$

or

$y = 12.63 - 12.908X - 0.345X^2;\ n = 12;\ r^2 = 0.9938$

For Aromatics and Chlorobenzenes

$y = 9.8z - 10.93X;\ n = 5;\ r^2 = 0.9969$

or

$y = 9.82 - 11.03X + 0.1929X^2;\ n = 5;\ r^2 = 0.99685$

y = Chlorine Weight Fraction

x = Heat of Combustion; kcal/gm

**K is the molar ratio of chloromethane and methane.

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APPENDIX I

FLASH POINT OF TRICHLOROBENZENE-AROCLOR MIXTURES

APPENDIX I

FLASH POINT OF TRICHLOROBENZENE-AROCLOR MIXTURES

The flash points of different Askarels are determined in this appendix. Askarels are mixtures of Aroclors [polychlorinated biphenyls (PCB) and trichlorobenzene (TCB)]. The flash point is the liquid temperature at which the gas phase in equilibrium with the liquid contains sufficient fuel to burn in air upon exposure to an ignition source. The fuel is provided by vaporization of the liquid. At the flash point, the vapor phase concentration of the fuel may be calculated using vapor-liquid thermodynamics and the flash point temperature. The thermodynamic relation between the gas and liquid phases may be written as (Reference I-1)

$$y_i = \gamma \frac{x_i P_i}{P_t} \tag{I.1}$$

where y_i is the vapor phase mole fraction in equilibrium with the liquid phase. The liquid phase mole fraction, x_i, equals 1 for a pure substance. The activity coefficient, γ, equals 1 for an ideal solution or a pure substance. The total pressure, P_t, equals 760 mm Hg at standard conditions. The vapor pressure, P_i, of the liquid may be calculated using a vapor pressure correlation such as the Antoine equation (Reference I-2) and the flash point temperature.

The lowest reported flash point of pure 1,2,4 trichlorobenzene (TCB) is 99°C (Reference I-3). The vapor pressure of TCB has been correlated by Ohe (Reference I-4) as

$$\log_{10}(P_1) = 7.51512 - 2110.983/(T + 242.429) \tag{I.2}$$

where P_1 is given in mm Hg and T is in °C. The vapor pressure of TCB at 99°C may be estimated from the correlation of Ohe as 21.5 mm Hg. The calculated vapor phase mole fraction of TCB at the flash point is 0.02828 or 2.828 volume percent (mole percent).

Table I-1 presents flash point data on various fluids. From Reference I-5, Aroclor 1254 does not have a flash point. For a mixture of TCB and Aroclor 1254, the flash point will occur when the vapor contains 2.828 volume percent TCB. Because both the TCB and the Aroclor 1254 are chlorinated aromatic compounds, the mixture of the two chemicals should behave in an ideal manner.

The vapor pressure of Aroclor 1254 may be correlated, using an Antoine equation, as

$$\ln(P_2) = 37.999 - 33256/(T + 733.83) \tag{I.3}$$

where P_2 is given in mm Hg and T is in °C. The estimated vapor pressure of Aroclor 1254 is 0.40 mm Hg at 120°C. The vapor pressure of TCB is two orders of magnitude greater than that of the Aroclor 1254. Thus, the contribution of the Aroclor 1254 to the total vapor pressure of the mixture may be neglected.

TABLE I-1. FIRE PROPERTIES OF VARIOUS FLUIDS

Fluid	Flash Point, °C	Reference (with page number)
Aroclor 1254	None	I-5
Aroclor 1260	None	I-5
1, 2, 4 Trichlorobenzene	99 110	I-2 (799) I-6 (1043)
1, 2, 4, 5 Tetrachlorobenzene	155	I-6 (1012)
Mineral Oil	229	I-6 (835)
Transformer Oil	149	I-6 (1038)

The flash point of a mixture of TCB and Aroclor 1254 is calculated by the following algorithm:

1. Set the liquid phase mole fraction of TCB, x_i.

2. Set the vapor phase mole percent of TCB equal to 2.828.

3. Compute the vapor pressure of TCB using the thermodynamic relation between the liquid and gas phases (Equation I.1).

4. Compute the flash point temperature using the vapor pressure correlation for TCB (Equation I.2).

5. Pick a new value of the liquid phase composition and repeat the above calculation.

The results of these calculations are presented in Table I-2 and plotted in Figure I-1. The effect of the Aroclor 1254 is to dilute the TCB and raise the flash point. As the weight percent of TCB is reduced from 70% to 30% (by weight) TCB, the flash point of the mixture changes from 104°C to 120°C. The flash point of a 50 weight percent mixture of Aroclor 1254 and TCB is 110°C.

I.1 REFERENCES

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I-4. Ohe, S., Computer Aided Data Book of Vapor Pressures, Data Book Publishing Company, Tokyo, 1976.

I-5. Monsanto Company, "The Aroclor Polychlorinated Polyphenyls," Technical Bulletin O-FF/1.

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TABLE I-2. CALCULATED FLASH POINTS OF MIXTURES OF TCB AND AROCLOR 1254

Fraction TCB Weight Percent	Flash Point, °C
0.0	None
2.8	190
5.8	165
12.2	143
19.2	131
27.0	123
35.7	116
45.5	111
50.0	110
56.5	108
69.0	104
83.3	101
100	99

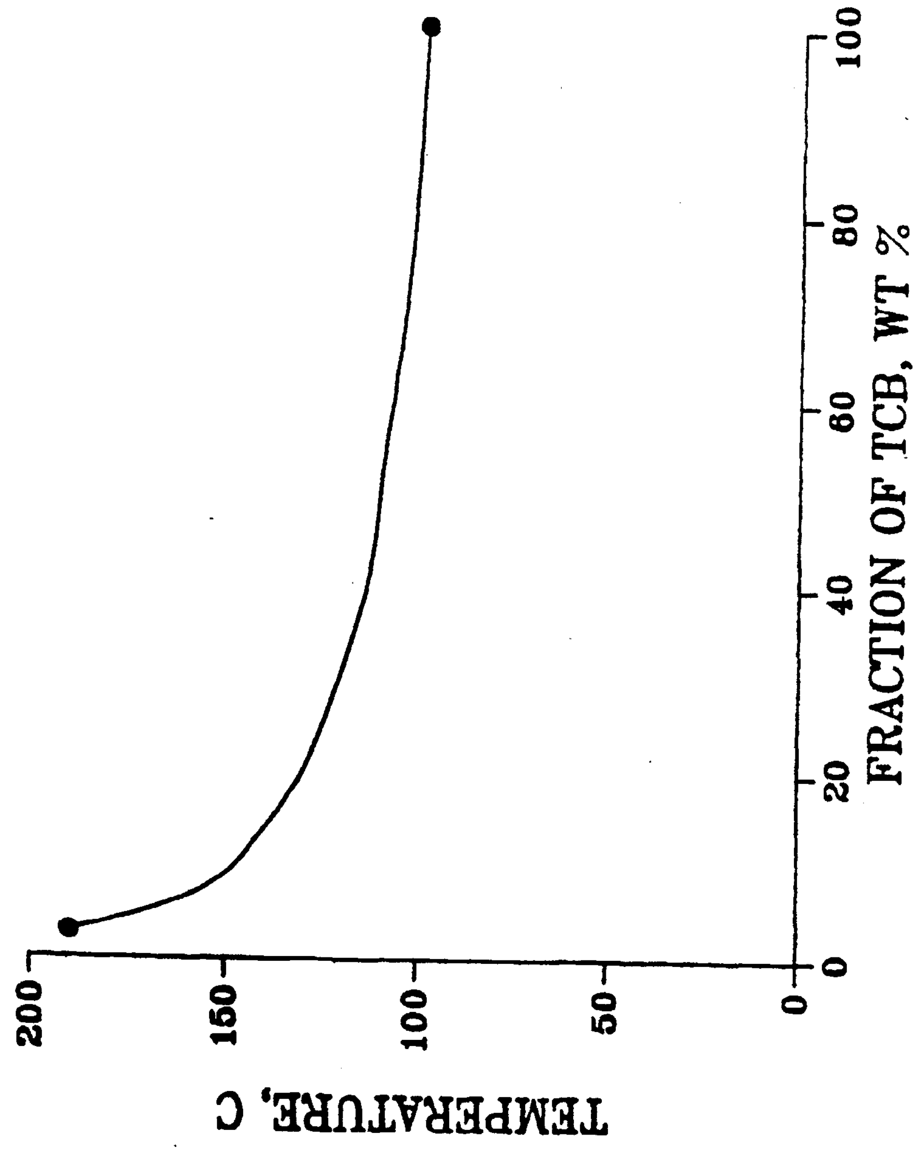

FIGURE I-1. ESTIMATED FLASH POINTS OF MIXTURES OF TCB AND AROCLOR