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**RISK ASSESSMENT OF MAJOR FIRES
IN AN HTGR PLANT**

by
KARL N. FLEMING

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RISK ASSESSMENT OF MAJOR FIRES IN AN HTGR PLANT

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ABSTRACT

The HTGR Risk Assessment Study [1] has been extended to include major fires as initiating events. The major aspects of this study have included the development of methodology, the collection and interpretation of fire experience data and the application of these methods and data to an HTGR plant. Qualitative and quantitative methods were derived to screen a nuclear plant layout and identify important fire locations. A fire propagation model was used in conjunction with experience data and detailed fault tree analyses to estimate common cause failure probabilities associated with a spectrum of potential fires. It was determined that fires make a significant contribution to the HTGR risk assessment only at accident frequency levels below 10^{-7} /reactor-year.

INTRODUCTION

An important event in the U.S. reactor operating experience was the cable-tray fire at Brown's Ferry in 1975. Although the fire resulted in no release of radioactivity or irreparable plant damage, the impact on redundant safety systems was extensive. In the context of risk assessment methodology, the fire underscored the importance of common-cause failures, not only in the estimation of accident probabilities, but also in the delineation of accident sequences. The term "common-cause failure" is used to describe multiple failures of two or more components or systems caused by a single, common event. There are five different event tree/fault tree analysis techniques that have been used in the HTGR Risk Assessment Study to treat common-cause failures and these are summarized in Table 1.

The first step in the risk assessment methodology is the selection of initiating events. Of the entire list of initiating events analyzed in the HTGR Risk Assessment Study, which numbers approximately 40, several including earthquakes and loss of all AC power were selected because of their potential to cause multiple failures. Although fires were not selected initially, the fire at Brown's Ferry showed that these events could not be ruled out as potentially important accident initiators. Hence, a risk assessment study of fires was undertaken. The purpose of this paper is to briefly summarize the results of this study [3].

METHODOLOGY

The development and refinement of the risk assessment methodology has been a continuing effort in the safety studies carried out at General Atomic since 1974. In the case of fires, some new techniques had to be added in consideration of their unique characteristics. One such characteristic is that fires can occur at essentially any location in a nuclear power plant. Since it would be highly inefficient and expensive to perform quantitative event tree/fault tree analyses at all potential fire locations, methods were needed to screen the plant layout and identify the most important ones. Although it was desirable to minimize the number of candidate locations remaining after screening, it was also an important objective to minimize the possibility that an important location might be overlooked.

Two methods were developed to carry out this screening process. The first one, a quantitative bounding procedure, presupposes the existence of some risk information for initiating events other than fires. The risk information is expressed in terms of accident frequency and extent of system impact necessary to result in predefined release categories which span the consequence spectrum. Fires are then postulated to occur in each plant location whose inventory of components and systems has been determined. By comparing the frequency of a fire at this location, hypothesized to contribute significantly to the risk, to bounds on the fire frequency set by the experience base, it is possible to eliminate numerous unimportant fire locations. Application of this technique to an HTGR plant designed in 1975 resulted in the elimination of all but the six locations illustrated in Figure 1.

Further screening of plant locations is accomplished with use of a qualitative technique patterned after "Failure Modes and Effects Analysis." Each of the remaining locations is evaluated by listing the inventory of combustible material, major components including pipes and cables, failure modes and system effects, fire barriers, fire detection and suppression equipment, fire brigade access and other factors relevant to the initiation and progression of fires. After these lists have been completed and compared for all remaining locations, a qualitative assessment is made of the relative potential of each to produce dominant risk accident sequences initiated by fires. In the case of the HTGR plant shown in Figure 1, this technique was successful in narrowing down the list of candidate locations to two: the cable-spreading room and a vertical equipment chase located between the control building and the reactor service building. Event tree/fault tree analysis of cable-spreading room fires is described below.

An integral part of the methodology is the collection and interpretation of fire experience data. In addition to the direct use of these data in the quantification of occurrence rates and probabilities, insights are obtained which are useful in delineation of accident sequences as well as in the identification of important locations. The experience

compilations of Verna [4] were found to be quite useful in estimating the average fire occurrence rate and propagation characteristics listed in Table 2.

A final aspect of the methodology that was refined and specialized for cable-tray fires is the estimation of location-dependent common-cause failure probabilities. Fault trees were developed in sufficient detail to identify specific faults in all the control and instrumentation circuits routed through the cable-spreading room for each system postulated to fail in the event tree. The allocation of circuits to cable trays and the cable tray layout and separation distances were determined. In view of the practice of routing cables from different systems in the same trays intersystem dependencies had to be considered. The method of linking the system fault trees together with an "AND" gate was used. The minimal cut sets of the fault trees consisted of combinations of component failures and sets of specific cable trays damaged by the fire. In this respect, the risk assessment accounted for failures that may occur independent of the fire but compound its consequences. The probability that specific sets of cable trays would be damaged were estimated with use of a simple fire propagation model which utilizes a probability distribution of the distance of fire spread estimated from the data base.

APPLICATION TO HTGR

The event tree presented in Figure 2 was constructed with an emphasis on accidents involving overheating of the reactor core. The occurrence rate for a fire of any size starting at any location in the cable-spreading room was assessed at 1×10^{-3} /reactor-year. The magnitude of accident consequences is in terms of point estimates of the most important doses for these accidents (whole body gamma and thyroid). Details of the assessment of consequences and their uncertainties can be found in Refs. [3] and [5]. When compared with event trees for all other initiating events analyzed for the HTGR [1] it is clear that fires are an important class of common-cause failures, not only in the case of redundant systems but also sets of multiple diverse systems.

The above point is illustrated in Table 3 where the probability quantification of event tree sequence F-D is compared with that for a similar sequence in the event tree for Loss of Condenser Function. The failure probability of the auxiliary cooling system (Event 4) is increased by three orders of magnitude, and that of the containment isolation valves (Event 6) by more than two orders. This results from the possibility that a single fire could result in failure of both systems depending on where it initiates and how far it propagates. The net impact of fires along the entire sequence is an increase in the frequency of accidents involving core heatup and containment failure of two orders of magnitude. This is true despite a relatively small contribution to the frequency of accidents involving core heatup only. This explains the overall impact of fires on the HTGR risk assessment curve presented in Figure 3. Fires are seen to make a small contribution to risk (about 30% increase) at frequencies greater

than 10^{-7} /reactor-year and below this frequency they tend to dominate.

The HTGR design assumed in this study was completed in 1975. Since then, the design has been substantially revised, in part, to comply with changes in separation and fire protection criteria. The most significant change is the use of multiple cable-spreading rooms for redundant divisions of cables. Although the reduction has not been quantified, it is clear that the risk assessment would have been diminished if this design feature had been present.

REFERENCES

1. HTGR Accident Initiation and Progression Analysis Status Report - Phase II Risk Assessment, General Atomic Report for Department of Energy No. GA-A15000, April 1978.
2. K. N. Fleming and P. H. Raabe, "A Comparison of Three Methods for the Quantitative Analysis of Common Cause Failures," Proceedings of the ANS Topical Meeting on Probabilistic Safety, May 8-10, 1978, Los Angeles
3. K. N. Fleming, W. J. Houghton and F. P. Scaletta, "A Methodology for Risk Assessment of Major Fires and Its Application to an HTGR Plant," General Atomic Report for Department of Energy No. GA-A15402, July 1979.
4. B. J. Verna, "Nuclear Power Experience," NPE Inc., Encino, California, Jan. 1972 - April 1978.
5. D. J. Wakefield and A. W. Barsell, "Monte Carlo Method for Uncertainty Analysis of HTGR Accident Consequences," Paper to be presented at this meeting, New Trends in Licensing Session.

TABLE 1
TREATMENT OF COMMON CAUSE FAILURES IN AIPA RISK ASSESSMENT METHODOLOGY

| Phase of Methodology | Methods for Treatment of Common Cause Failures | Examples of Common Cause Failures Treated Using Indicated Method |
|----------------------------|---|---|
| Initiating event selection | 1. Consider causes of multiple failures in fault trees of radioactivity barriers | Fires, earthquakes, loss of electric power |
| Event tree construction | 2. Identify system interdependencies explicitly 3. Treat event probabilities as conditional; link fault trees with "and" gates | System A fails as consequence of failure of system B System A and system B both depend on common support system |
| Event tree quantification | 4. Identify specific causes of multiple failures within systems 5. Treat multiple failures in redundant systems as dependent, quantify coupling factor (β) for each component using experience data (Beta-Factor Method [2]) | Component X fails as direct consequence of failure of component Y Redundant set of components left out of service due to improper test, or share same design error |

TABLE 2
SUMMARY OF FIRE EXPERIENCE DATA

| | |
|-------------------------------------|-------------------|
| Number of reactor units | 65 |
| Reactor-years operating experience* | 372 |
| Number of fires (in operation) | 49 |
| Mean rate of occurrence | 0.13/reactor-year |
| Mean (max) diameter of fire damage | 8.6 ft (67 ft) |
| Mean (max) time to put out fire | 1 hr (24 hr) |

*From first electrical generation through April 1978

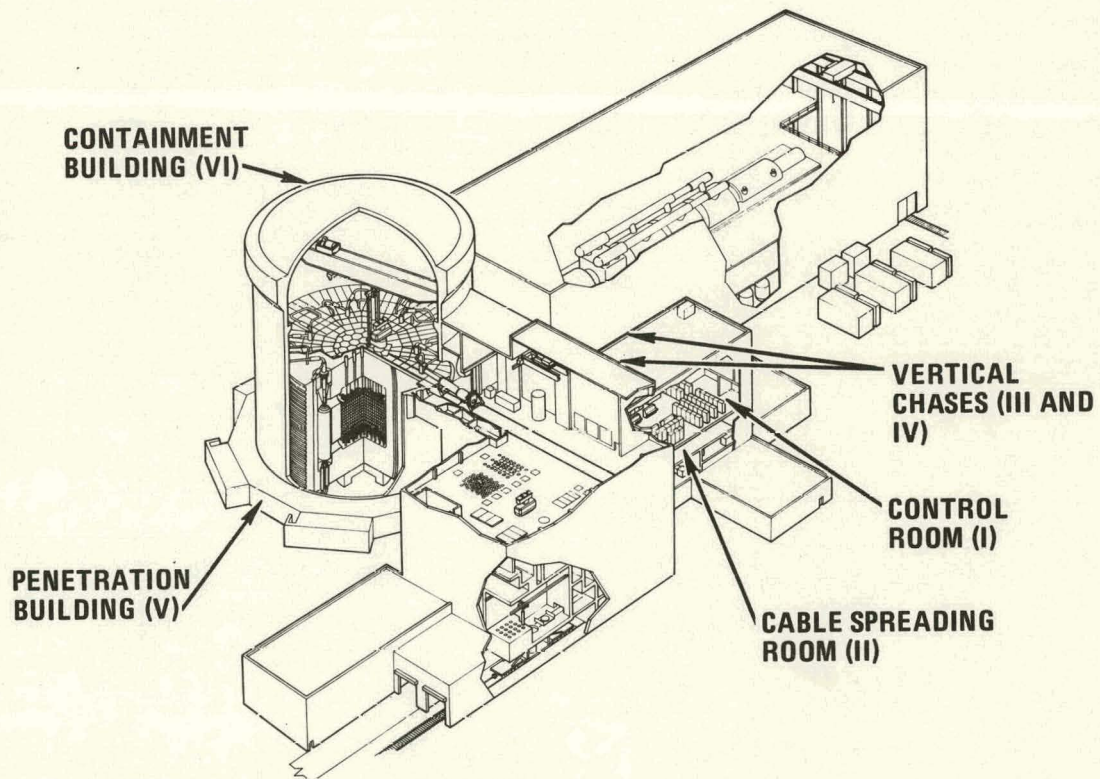
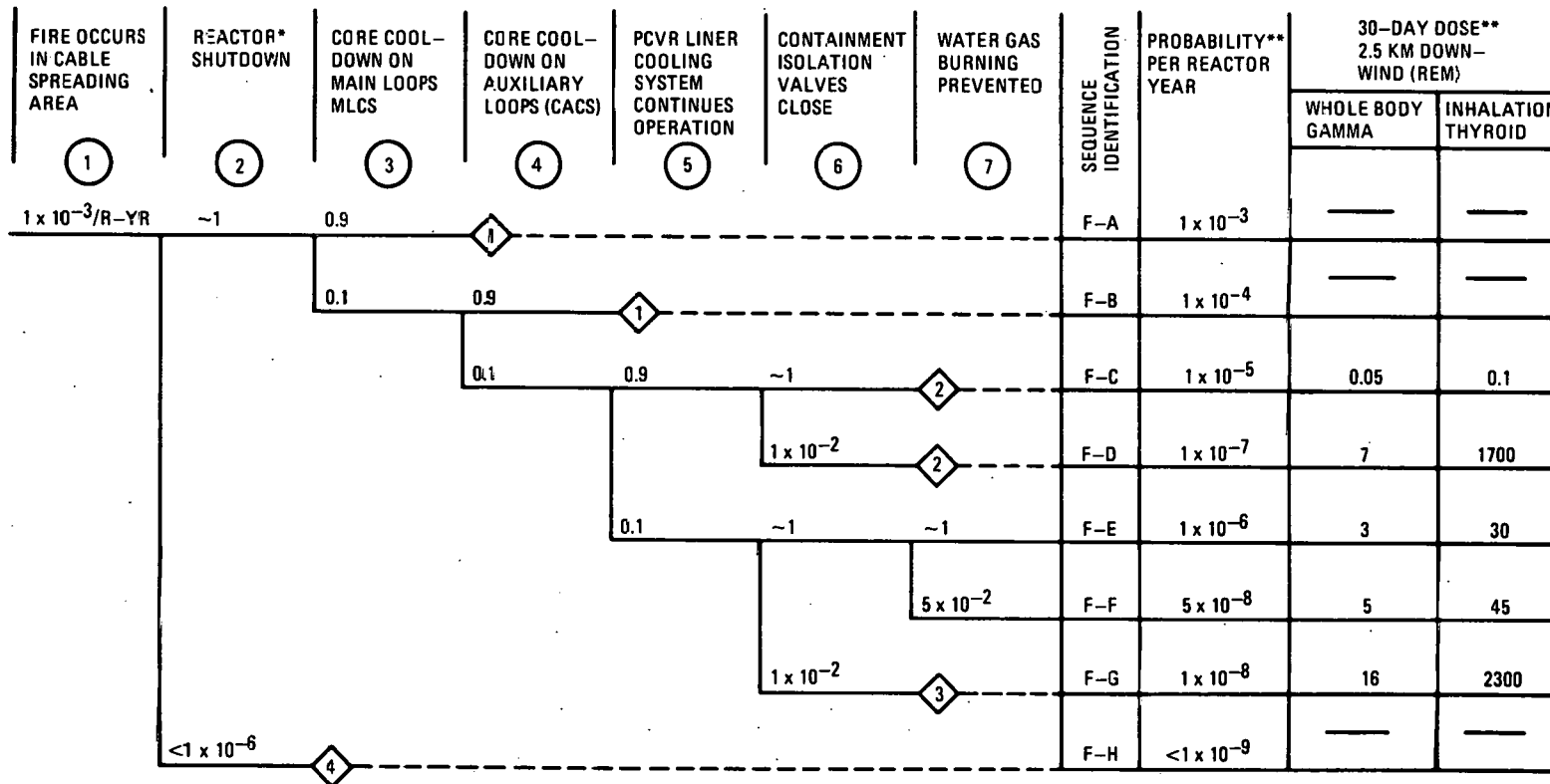


Fig. 1. Important potential fire locations in an HTGR plant



- ◇ INDICATES TERMINATION OF EVENT TREE SEQUENCE
- ① TERMINATION WITH NO RELEASE
- ② PRECLUDED BY PRIOR EVENTS
- ③ INCONSEQUENTIAL DUE TO PRIOR EVENTS
- ④ NOT DEVELOPED DUE TO EXTREMELY LOW PROBABILITY ($< 1 \times 10^{-9}$ /REACTOR-YEAR)

*FAILURE REQUIRES FAILURE OF TWO DIVERSE SYSTEMS

**POINT ESTIMATES

Fig. 2. Event tree for fire in cable spreading area

TABLE 3
 IMPACT OF FIRES ON THE FAILURE PROBABILITY OF MULTIPLE
 REDUNDANT SYSTEMS ALONG ACCIDENT SEQUENCE D

| Events Along Accident Sequence | Event Probability | |
|--|--------------------------------|--------------------------------|
| | Loss of Condenser | Cable Spreading Room Fire |
| 1. Initiating event | $3 \times 10^{-1}/\text{r-yr}$ | $1 \times 10^{-3}/\text{r-yr}$ |
| 2. Reactor shutdown | ~ 1 | ~ 1 |
| 3. Main loop cooling system fails | ~ 1 | 10^{-1} |
| 4. Auxiliary core cooling fails | 10^{-4} | 10^{-1} |
| 5. PCRV liner cooling maintained | ~ 1 | ~ 1 |
| 6. Containment isolation valves fail | 3×10^{-5} | 10^{-2} |
| Frequency of core heatup (events 1-4 only) | $3 \times 10^{-5}/\text{r-yr}$ | $1 \times 10^{-5}/\text{r-yr}$ |
| Frequency of core heatup with containment failure (events 1-6) | $10^{-9}/\text{r-yr}$ | $10^{-7}/\text{r-yr}$ |

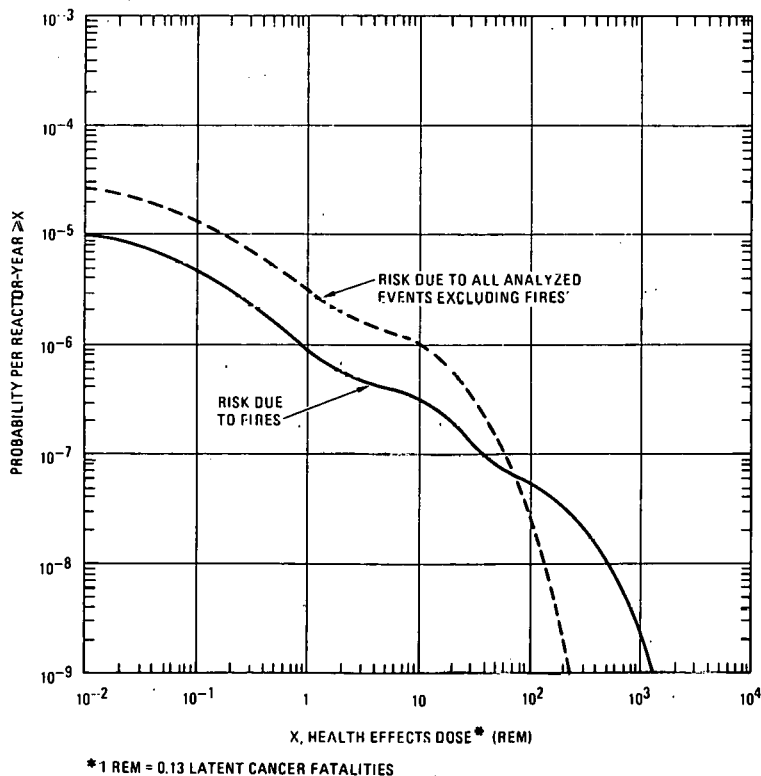


Fig. 3. Comparison of risk of HTGR accidents due to fires with risk due to other analyzed initiating events

SLIDES PRESENTED AT THE MEETING

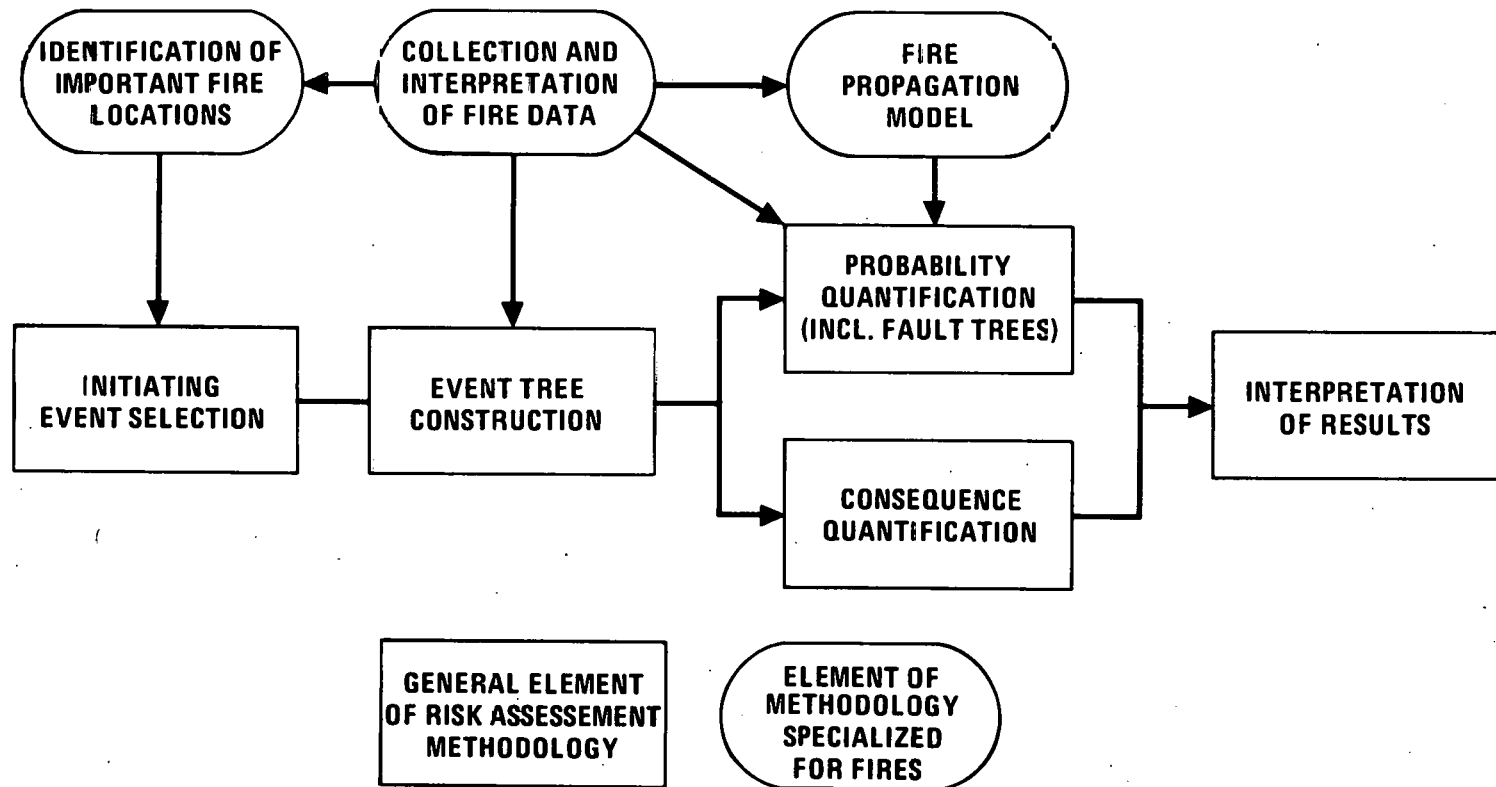
RISK ASSESSMENT OF MAJOR FIRES IN AN HTGR PLANT

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TREATMENT OF COMMON CAUSE FAILURES IN AIPA RISK ASSESSMENT METHODOLOGY

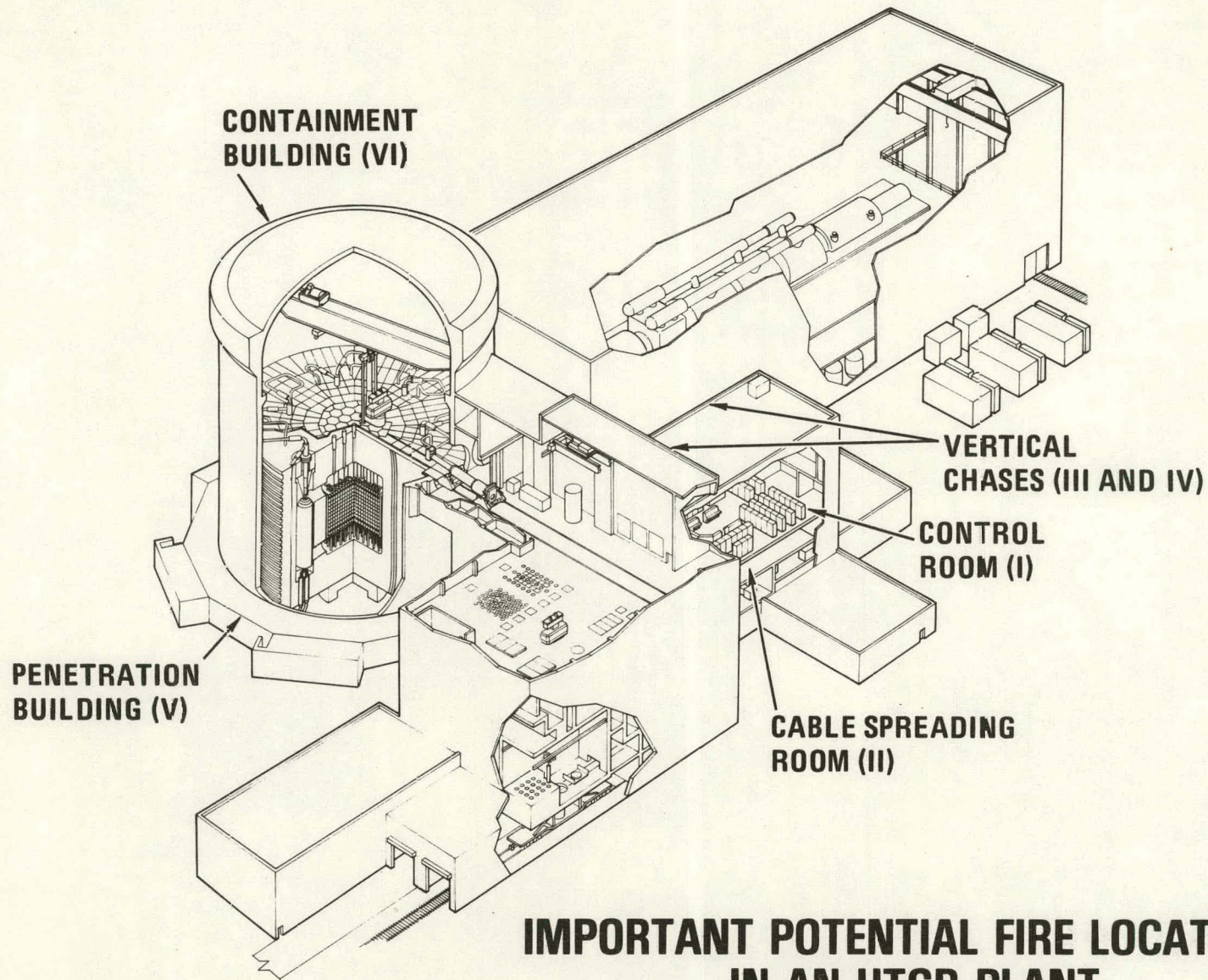
| PHASE OF METHODOLOGY | METHODS FOR TREATMENT OF COMMON CAUSE FAILURES | EXAMPLES OF COMMON CAUSE FAILURES TREATED USING INDICATED METHOD |
|---|--|---|
| INITIATING EVENT SELECTION | 1. CONSIDER CAUSES OF MULTIPLE FAILURES | FIRES, EARTHQUAKES, LOSS OF ELECTRIC POWER |
| EVENT TREE CONSTRUCTION | 2. IDENTIFY SYSTEM INTERDEPENDENCIES EXPLICITLY | SYSTEM A FAILS AS CONSEQUENCE OF FAILURE OF SYSTEM B |
| EVENT TREE QUANTIFICATION/FAULT TREE ANALYSIS | 3. TREAT EVENT PROBABILITIES AS CONDITIONAL; LINK FAULT TREES WITH "AND" GATES | SYSTEM A AND SYSTEM B BOTH DEPEND ON COMMON SUPPORT SYSTEM |
| | 4. IDENTIFY SPECIFIC CAUSES OF MULTIPLE FAILURES WITHIN SYSTEMS | COMPONENT X FAILS AS DIRECT CONSEQUENCE OF FAILURE OF COMPONENT Y |
| | 5. TREAT MULTIPLE FAILURES IN REDUNDANT SYSTEMS AS DEPENDENT: QUANTIFY COUPLING FACTOR (β) FOR EACH COMPONENT USING EXPERIENCE DATA (BETA-FACTOR METHOD) | REDUNDANT SET OF COMPONENTS LEFT OUT OF SERVICE DUE TO IMPROPER TEST, OR SHARE SAME |

SPECIALIZED ELEMENTS OF METHODOLOGY FOR RISK ASSESSMENT OF FIRES



SIGNIFICANT CHARACTERISTICS EVALUATED IN QUALITATIVE LOCATION SCREENING

- **INVENTORY OF COMBUSTIBLE MATERIAL**
- **INVENTORY OF MAJOR COMPONENTS**
- **FAILURE MODES OF EQUIPMENT CAUSED BY FIRE**
- **IMMEDIATE SYSTEMS EFFECTS**
- **FIRE BARRIERS/ADJACENT FIRE CELLS**
- **FIRE DETECTION AND PROTECTION EQUIPMENT**
- **FIREMAN (BRIGADE) ACCESS**
- **VENTILATION/SMOKE EXHAUST PATHWAYS**
- **LIKELIHOOD OF INITIATION AND SIGNIFICANT PROGRESSION (QUALITATIVE ASSESSMENT)**



**IMPORTANT POTENTIAL FIRE LOCATIONS
IN AN HTGR PLANT**

SUMMARY OF FIRE EXPERIENCE DATA

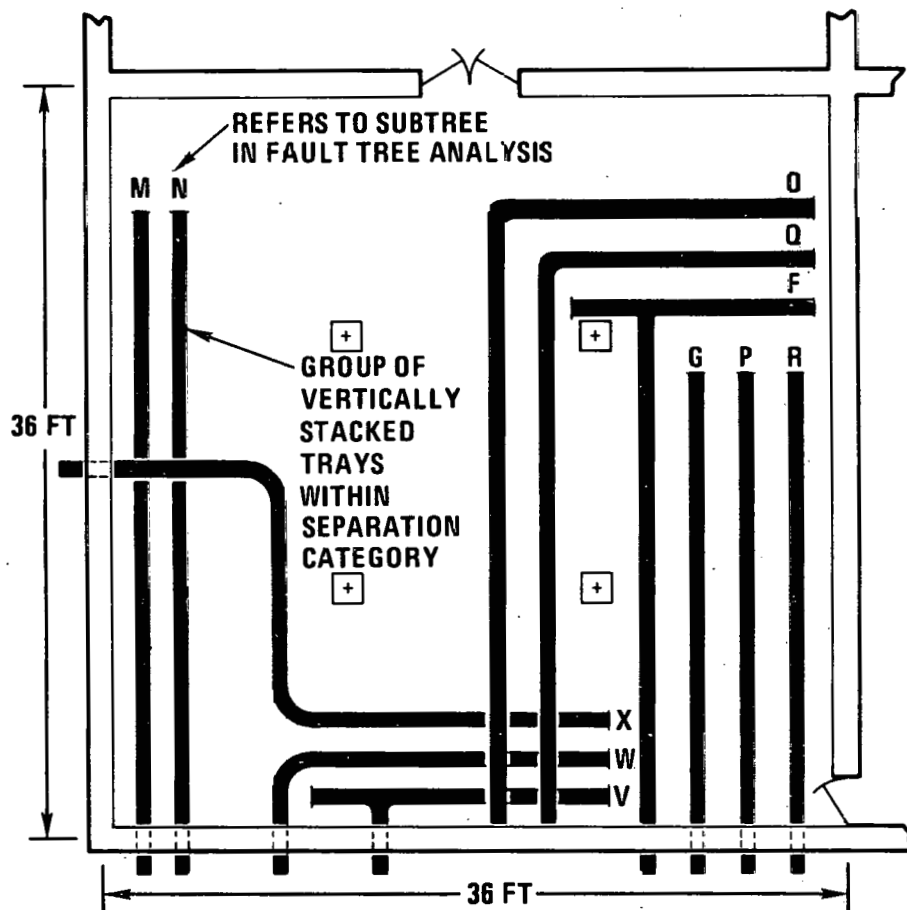
| | |
|---|------|
| NUMBER OF REACTOR UNITS | 65 |
| REACTOR-YEARS OPERATING EXPERIENCE* | 372 |
| NUMBER OF FIRES (IN OPERATION) | 49 |
| AVERAGE RATE OF OCCURRENCE (PER REACTOR-YEAR) | 0.13 |

*FROM FIRST ELECTRICAL GENERATION THROUGH APRIL 1978

FREQUENCY DISTRIBUTION OF DISTANCE AND BURN TIME

| APPROX. MAXIMUM DIAMETER OF FIRE (FT) | TIME TO PUT OUT FIRE (HR) | | | |
|---|---------------------------|-----|------|-------|
| | 0-1 | 1-3 | 3-10 | 10-30 |
| 0-1 | 6 | -- | -- | -- |
| 1-3 | 12 | -- | -- | -- |
| 3-10 | 23 | 3 | -- | -- |
| 10-30 | 7 | 1 | 1 | -- |
| 30-70 | 1 | 2 | 1 | 1 |

LAYOUT OF KEY CABLE TRAYS IN CABLE SPREADING ROOM



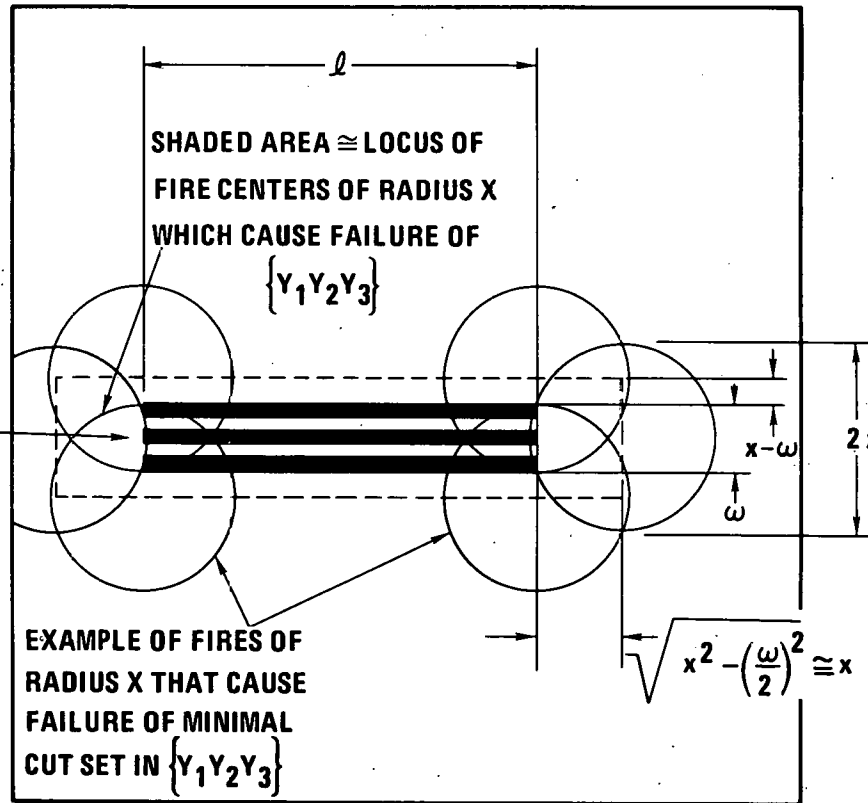
SPREADING ROOM FIRE PROPAGATION MODEL

$\{Y_1, Y_2, Y_3\}$ - SET OF CABLE TRAYS CONTAINING A MINIMAL CUT SET

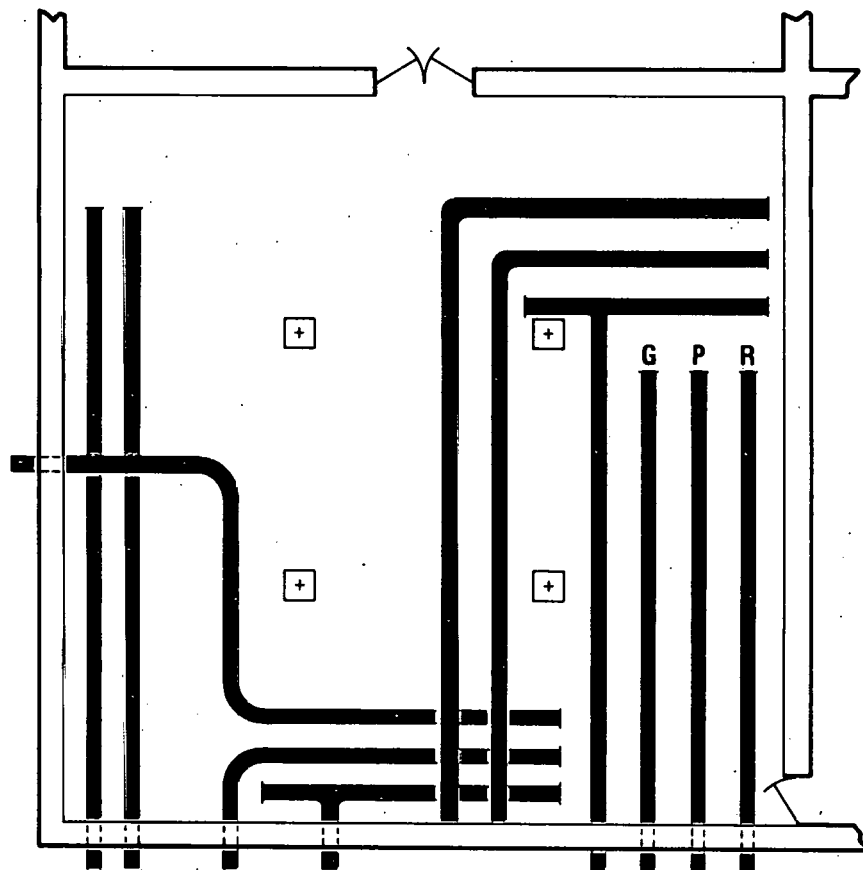
$$\Pr\{Y_1, Y_2, Y_3\} = \int f(x) \Pr\{Y_1, Y_2, Y_3 \mid x\} dx$$

$$\Pr\{Y_1, Y_2, Y_3 \mid x\} \cong \frac{(\ell + 2x)(2x - \omega)}{L^2}$$

$$f(x) = \alpha e^{-\alpha x}$$

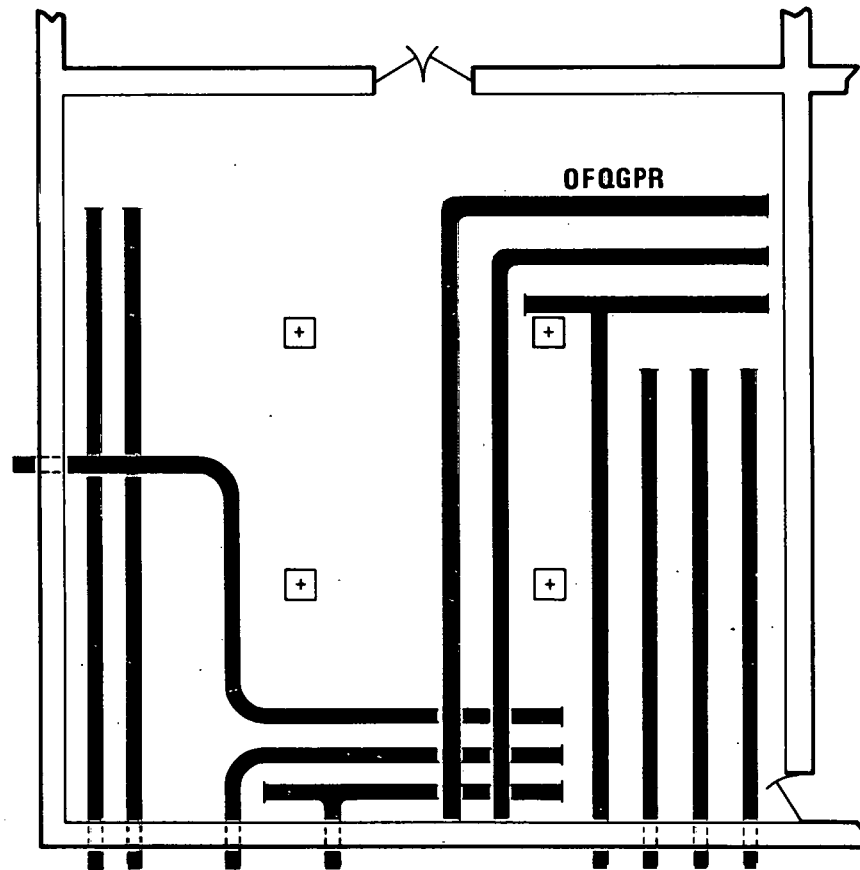


PROPAGATION MODEL RESULT FOR CABLE TRAY SET {G,P,R}



$$\Pr\{G,P,R\} = \begin{cases} 0.2; \alpha^{-1} = 17 \text{ FT} \\ 0.02; \alpha^{-1} = 3 \text{ FT} \end{cases}$$

PROPAGATION MODEL RESULT FOR CABLE TRAY SET {O,F,Q,G,P,R}

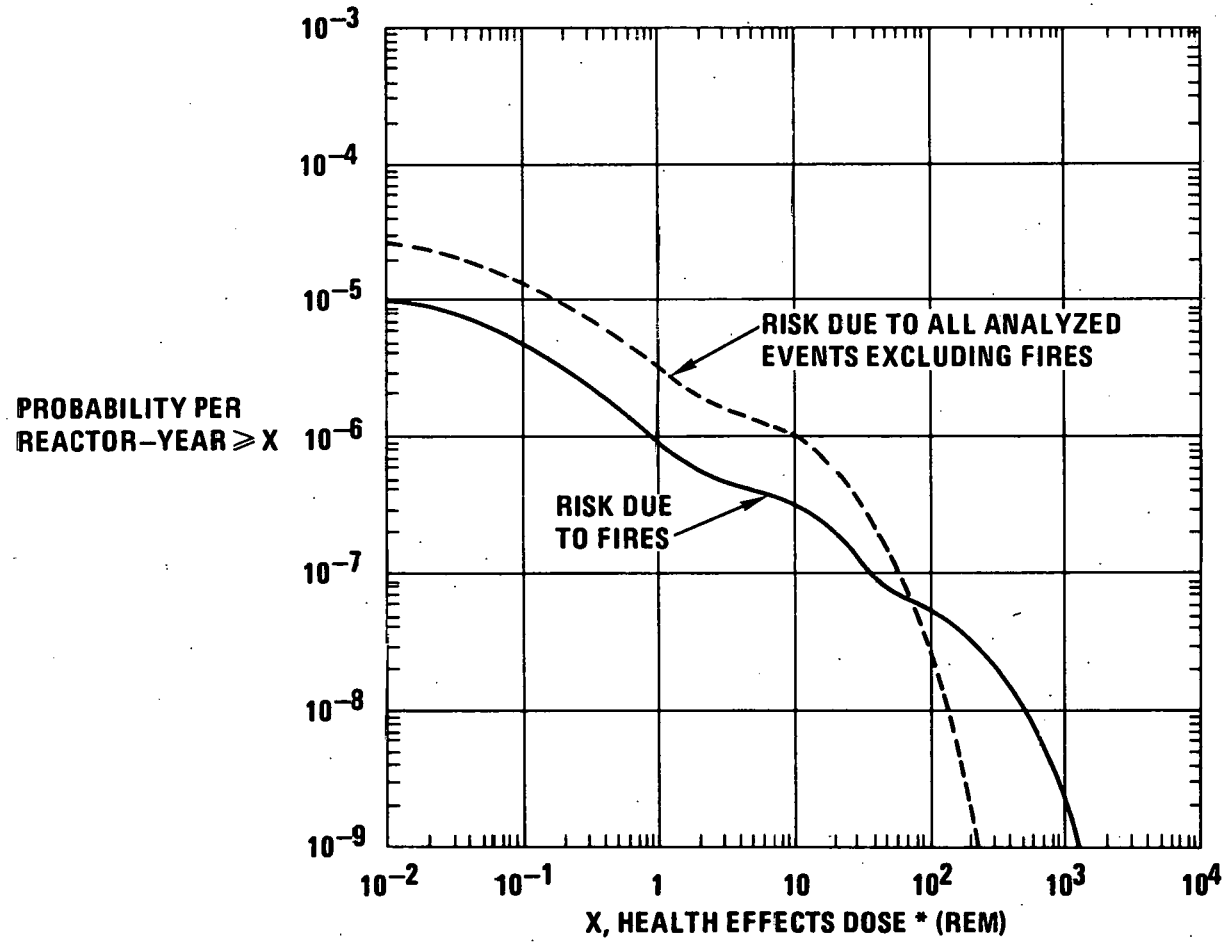


$$\text{Pr}\{O,F,Q,G,P,R\} = \begin{cases} 0.1; \alpha^{-1} = 17 \text{ FT} \\ 0.002; \alpha^{-1} = 3 \text{ FT} \end{cases}$$

INTERSYSTEM DEPENDENCIES CAUSED BY FIRE

| EVENTS ALONG ACCIDENT SEQUENCE | PROBABILITY RESULTS | |
|--|--------------------------|---------------------------|
| | LOSS OF CONDENSER VACUUM | CABLE SPREADING ROOM FIRE |
| 1. INITIATING EVENT | $3 \times 10^{-1}/R-YR$ | $1 \times 10^{-3}/R-YR$ |
| 2. REACTOR SHUTDOWN | ~ 1 | ~ 1 |
| 3. MAIN LOOP COOLING SYSTEM FAILS | ~ 1 | 10^{-1} |
| 4. AUXILIARY CORE COOLING FAILS | 10^{-4} | 10^{-1} |
| 5. PCRV LINER COOLING MAINTAINED | ~ 1 | ~ 1 |
| 6. CONTAINMENT ISOLATION VALVES FAIL | 3×10^{-5} | 10^{-2} |
| FREQUENCY OF CORE HEATUP (EVENTS 1 - 4 ONLY) | $3 \times 10^{-5}/R-YR$ | $1 \times 10^{-5}/R-YR$ |
| FREQUENCY OF CORE HEATUP WITH CONTAINMENT FAILURE (EVENTS 1 - 6) | $10^{-9}/R-YR$ | $10^{-7}/R-YR$ |

RISK CONTRIBUTION OF FIRES



*1 REM = 0.13 LATENT
CANCER FATALITIES

CONCLUSIONS

- RISK ASSESSMENT OF 1975 HTGR DESIGN DOMINATED BY FIRES AT LEVELS OF ACCIDENT FREQUENCY $\leq 10^{-7}$ /REACTOR-YEAR
- IMPORTANCE OF LOCATION-DEPENDENT COMMON CAUSE FAILURES HIGHLY DEPENDENT ON DESIGN DETAILS
- MORE RECENT HTGR DESIGNS OFFER ENHANCED PROTECTION AGAINST FIRES (NOT YET QUANTIFIED)
- DATA BASE SHOULD BE EXTENDED
- PROPAGATION MODELS SHOULD BE IMPROVED



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