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# PROBABILISTIC ANALYSIS OF FIRES IN NUCLEAR PLANTS

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## ABSTRACT

The aim of this paper is to describe a multi-level (i.e., staged) probabilistic analysis of fire risks in nuclear plants (as part of a general PRA) which maximizes the benefits of the FRA (fire risk assessment) in a cost effective way. The approach uses several stages of screening, physical modeling of clearly dominant risk contributors, searches for direct (e.g., equipment dependences) and secondary (e.g., fire induced internal flooding) interactions, and relies on lessons learned and available data from surrogate FRAs. The general methodology is outlined.

## 1. INTRODUCTION

Fires are potentially high risk contributors, particularly in older plants. Apart from the potential associated public hazards, there are also potential connected costs due to

- modifications to reduce fire risks implemented to satisfy perceived NRC and insurance underwriter requirements, and

(iii) cheap, oversimplified FRAs have proved useless, while maximally detailed FRAs are unreasonably expensive.

More specifically, a review of a number of recent FRAs (carried out as part of nuclear plant PRAs) show the following features:

1. lack of clear cut systematic modeling to assure completeness in the screening phase (e.g., no consideration of fires plus random failures, screening using engineering judgement alone, etc.);
2. use of scanty fire initiation and incidence data;
3. use of questionable and varying approximations in the fire propagation analysis, resulting in non-uniform bias in the results.

These deficiencies do not, of course, apply across the board. However, in those cases where the analyses are ostensibly more systematic and comprehensive, the results do not differ markedly from the other cases, suggesting that at the very least, a more formal and disciplined approach should be presented.

The approach outlined below deals with these problems by

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## 1. INTRODUCTION

Fires are potentially high risk contributors, particularly in older plants. Apart from the potential associated public hazards, there are also potential connected costs due to

- modifications to reduce fire risks implemented to satisfy perceived NRC and insurance underwriter requirements, and
- economic losses caused by the possible reduction of utility power availability.

The most important lessons learned from FRAs so far conducted are the following:

(i) for specific plants and/or specific areas, fires can be a major source of vulnerability involving public risk and/or economic risk (cf. Brown's Ferry, TVA);

(ii) due to the complexity of fires and fire damage phenomena and the consequent use of oversimplified plant (locational) and physical models, unverified data and stochastic combustion models, many FRAs suffer from credibility problems;

while maximally detailed FRAs are unreasonably expensive.

More specifically, a review of a number of recent FRAs (carried out as part of nuclear plant PRAs) show the following features:

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These deficiencies do not, of course, apply across the board. However, in those cases where the analyses are ostensibly more systematic and comprehensive, the results do not differ markedly from the other cases, suggesting that at the very least, a more formal and disciplined approach should be presented.

The approach outlined below deals with these problems by

- using several layers (stages) of screening to refine locations (and connections) of interest,
- showing how to model such locations and connections,
- paying due regard to the physical and probabilistic aspects of the fire, fire damage, and fire suppression processes,
- the utilization of a more extended data base for fire initiation and incidence frequencies by reference to appropriate non-nuclear fire accident data available through the underwriting industry.

## 2. KEY ELEMENTS

The key elements in the approach described here are the following:

### 2.1 Limited Detail Risk Model

This model expresses meaningful measures of risk for the plant in terms of comprehensive sets or sequences of events, occurrences, unavailabilities, failures, etc which do not necessarily descend to the component level.

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*Work done under the auspices of the U.S. Nuclear Regulatory Commission.
Views in this paper do not necessarily represent those of the U.S. Nuclear Regulatory Commission.

The measures of risk include

- public risk, such as CDF, containment failure, large releases, etc, and
- economic risk, such as extended outage time, clean-up, regulatory requirements, occupational hazard costs, etc.

The events involved include most major relevant initiating events which can lead to public or economic risk such as

- accident initiators,
- safety equipment failures,
- failure of BOP to provide safety functions,
- operator failures, etc.

The level of detail varies depending on the data and models available and on plant specific peculiarities and may involve

- systems and subsystems,
- macrocomponents (i.e., sets of components which react, and may be treated as a unit for the purposes of this modeling), and
- component and operator behavior.

This model is available in automated (i.e., computerized) form, and thus rests heavily on plant specific models and data derived from the (internal) systems PRA. It may need to be augmented by (plant specific) fire induced initiators and other perturbations, if called for. (See Sections 2.2 and 2.3 below)

## 2.2 Relational Data Base

This is an organizational data structure which stores a variety of information about plant elements and functions, their locations, and their connectivities. It enables the comprehensive evaluation of the effect of events in one location on equipment and functions in that location and in other places in the plant that may be coupled to it by fire related or fire induced phenomena. It embraces locational coupling, direct interactions (e.g., equipment dependences) and secondary interactions (e.g., non-fire perturbations induced by fire).

Particular emphasis is placed on:

- (general) risk significant equipment,
- support and interactive equipment,
- locational characteristics,
- barriers and their levels of effectiveness, and
- combustible loads, whether they are directly connected with plant operations (e.g. cable insulation, transformer oil, etc) or ancillary (stored oil, rags, procedural documents, etc).

Sources for constructing such a data base include

## 2.3 Fire Phenomenology and Data

The third important element in this approach is the proper consideration of fire initiation, propagation, damage and suppression. It is clearly neither feasible nor appropriate to deal with these topics extensively in the present context. Instead it is proper here to list in tabular form the major considerations and characteristics which must be addressed, accompanied by some qualitative discussion.

There are four major categories of information involved here. These are

- experimental fire data,
- fire initiation characteristics
- fire propagation considerations, and
- target damage modes and criteria.

### 2.3.1 Experimental fire data.

This category includes plant specific and industry-wide fire initiating experience, underwriting data, and review of reportable events at nuclear plants, together with the examination of non-nuclear plant incidence data as an adjunct.

It also involves the frequencies, locations, and magnitudes of fires in the specific plant, and if such information is lacking or scanty, relevant generic data of this type. Finally such data should embrace a comprehensive list of variables and parameters needed to characterize the fires, particularly the initiator: these may include combustible classes, loading, location, ignition susceptibility and activity levels under appropriate conditions.

### 2.3.2 Fire initiation characteristics.

This class of information includes the details of potential initiating fires such as the types, amounts, and geometry of the combustibles, in particular the physical, chemical and pyrolytic properties. It also describes the location of this material in relation to the room geometry, barriers, other combustibles, targets and potentially damaging connective paths.

### 2.3.3 Fire propagation considerations.

In the first instance the major fire propagation considerations are the following:

- the fire scenario and configuration (i.e., the enclosure, initiating fire and target[s]),
- the fire dynamics models (including the fire growth and target damageability models), and
- the physical and combustion data for the burning material.

Some of these have already been dealt with in 2.3.1

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This is an organizational data structure which stores a variety of information about plant elements and functions, their locations, and their connectivities. It enables the comprehensive evaluation of the effect of events in one location on equipment and functions in that location and in other places in the plant that may be coupled to it by fire related or fire induced phenomena. It embraces locational coupling, direct interactions (e.g., equipment dependences) and secondary interactions (e.g., non-fire perturbations induced by fire).

Particular emphasis is placed on:

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- support and interactive equipment,
- locational characteristics,
- barriers and their levels of effectiveness, and
- combustible loads, whether they are directly connected with plant operations (e.g. cable insulation, transformer oil, etc) or ancillary (stored oil, rags, procedural documents, etc).

Sources for constructing such a data base include the following:

- FSAR and plant P&IDs,
- Plant layout drawings,
- Plant system descriptions,
- 10CFR50, Appendix R assessment,
- Security assessment,
- Quality list (Q list), and
- Master equipment lists (MELs).

Special attention should be directed to a plant "walk-down" by a group comprising experts on fire, plant systems and operations, and, if possible, analysts familiar with other extraneous plant perturbations (e.g., flooding).

The data so gathered is also to be available in automated form, and the two elements 2.1 and 2.2 described above should be computationally compatible, and integrated in a manner which allows direct input of the relational data into the limited risk model.

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- the fire dynamics models (including the fire growth and target damageability models), and
- the physical and combustion data for the burning material.

Some of these have already been dealt with in 2.3.1 and 2.3.2 above.

More particularly, detailed consideration must be given here to the target/enclosure geometry, including such factors as the dimensions, openings, ventilation, wall surface characteristics and others.

In the fire dynamics analysis proper, the crucial parameters involve the combusting plume (including the flame height and diffusion, and the ceiling and radiative heat transfer) as well as the hot layer (including its thickness, heat content, radiative and convective heat transfer, and transient combustion.

As part of this analysis, the question of fire detection and suppression must be addressed. This includes the definition of detection and suppression measures, passive, active and procedural and their interaction with the combustible and fire characteristics cited earlier. While the fire dynamics itself is generally modeled in a deterministic (or at least phenomenological way), often via codes such as COMPBRN, the suppression analysis is usually treated in a quasistatistical manner (in terms of a Poisson type model). This also allows the (qualitative) introduction of operator intervention; such HR estimates should however be reviewed in the light of either a more detailed procedural model or as part of a stochastic analyses.

2.3.4 Target damage modes and criteria. The last, though very interdependent, facets of the fire phenomenology concern the target damage modes and criteria. These, of course, also play a major role in the screening and overall risk analysis.

Direct damage modes include the following:

(i) damage to safety equipment due to
- structural failure,
- conductive, convective and radioactive effects due to the fire and its products,
- conductive, convective, corrosive, optical, toxic and psychological effects due to smoke and aerosols,
- direct fire suppression effects.

(ii) damage to control or power cabling from the same sources

Indirect damage includes:

(i) equipment exposed to pressures and temperatures beyond the design basis due to fire caused equipment faults,
(ii) shorting of cables in locations far from the fire caused damage,
(iii) equipment unavailability due to circuit breaker actuation resulting from fire induced shorts, open circuits or other damage,
(iv) human induced equipment unavailability, damage or misfunction caused by spurious instrumentation signals and incorrect information in the control room (particularly due to cable damage and smoke),
(v) secondary fire suppression effects such as flooding.

The target damageability criteria comprise radiative and convective heat fluxes and chemical degradation for safety related equipment, and critical heat flux and accumulated energy for cables. The associated failure modes involve insulation/jacket degradation, piloted and auto-ignition, and electric integrity failure.

## 3. STAGING

### 3.1 Introductory Remarks

The first level of analysis is a screening technique which identifies locations where potentially

scenarios on plant risk measures is estimated using a risk significance model which incorporates major risk producing sequences of events in a format which can be easily updated. In this manner, the increase in risk due to each such fire risk scenario (and the corresponding relative contribution) can be evaluated.

If the combined impact of fires on the plant risk profile is quantifiably small (for example, less than 1% addition to the core damage frequency for point estimate calculation), then no further evaluation is required. In the event that a preliminary estimate of the incremental risk due to fire related scenarios is significant, an additional stage of evaluation is advised. This involves the use of more realistic fire initiators, propagation, and interaction on the major fire related scenarios, combined with a substantial amount of sensitivity and uncertainty evaluations to technically support and qualify conclusions concerning incremental risk. Methodology and requirements for each stage of the FRA are detailed below. (See Table 3.1 and Figure 3.1.)

### 3.2 Initial Screening

The initial screening involves the examination of fire susceptible locations to establish.

(i) whether the failure of all equipment in that location leads to core damage,
(ii) whether the failure of all equipment in that location together with some other random failure leads to a substantial increase in core damage frequency (say, greater than 10%); and
(iii) whether the failure of all equipment in that location together with a similar failure in a connected location (in so far as fire is concerned) leads to core damage. Locations which satisfy any of these criteria are candidates for the further screening described below.

### 3.3 Final Screening

Figure 3.2 illustrates the conceptual features of the limited detail risk model based on the results of the internal events PRA and insights gained from the plant familiarization and walkdown procedures. This model allows:

(i) the evaluation of risk as a function of basic event probabilities and frequencies (subsystem unavailabilities, initiator frequencies, etc.), and
(ii) determination of the relative impact (i.e., increase in risk) of the different locations and location dependent sequences in case of fire.

(ii) shorting of cables in locations far from the fire caused damage,

(iii) equipment unavailability due to circuit breaker actuation resulting from fire induced shorts, open circuits or other damage,

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## 3. STAGING

### 3.1 Introductory Remarks

The first level of analysis is a screening technique which identifies locations where potentially risk significant fire induced interactions can occur. The two initial steps are:

1. the identification of fire susceptible locations, and
2. the determination of the presence in these locations of safety related equipment and/or of the probable incidence of other initiating events.

If a fire at such a location is likely to damage equipment whose failure produces a risk impact such a location is called a critical fire area and the scenarios stemming from such fires are called critical fire scenarios.

The second level of analysis provides preliminary and bounding estimates for the risk potential as a result of such plant fires. For the locational dependent scenarios identified in Stage 1, preliminary estimates are made of the frequency of severe fires at the location of concern. Given that a severe fire has occurred, the equipment in the fire zone which has been identified as critical is assumed to have failed. The impact of such fire induced failure location leads to core damage;

(ii) whether the failure of all equipment in that location together with some other random failure leads to a substantial increase in core damage frequency (say, greater than 10%); and

(iii) whether the failure of all equipment in that location together with a similar failure in a connected location (in so far as fire is concerned) leads to core damage. Locations which satisfy any of these criteria are candidates for the further screening described below.

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(ii) determination of the relative impact (i.e., increase in risk) of the different locations and location dependent sequences in case of fire.

The screening can be computerized to take advantage of algorithms and software which may utilize techniques such as safety significance and locational transfer algorithms to efficiently evaluate and rank a large number of location dependent interactions.

Computer assisted screening techniques include the capacity to:

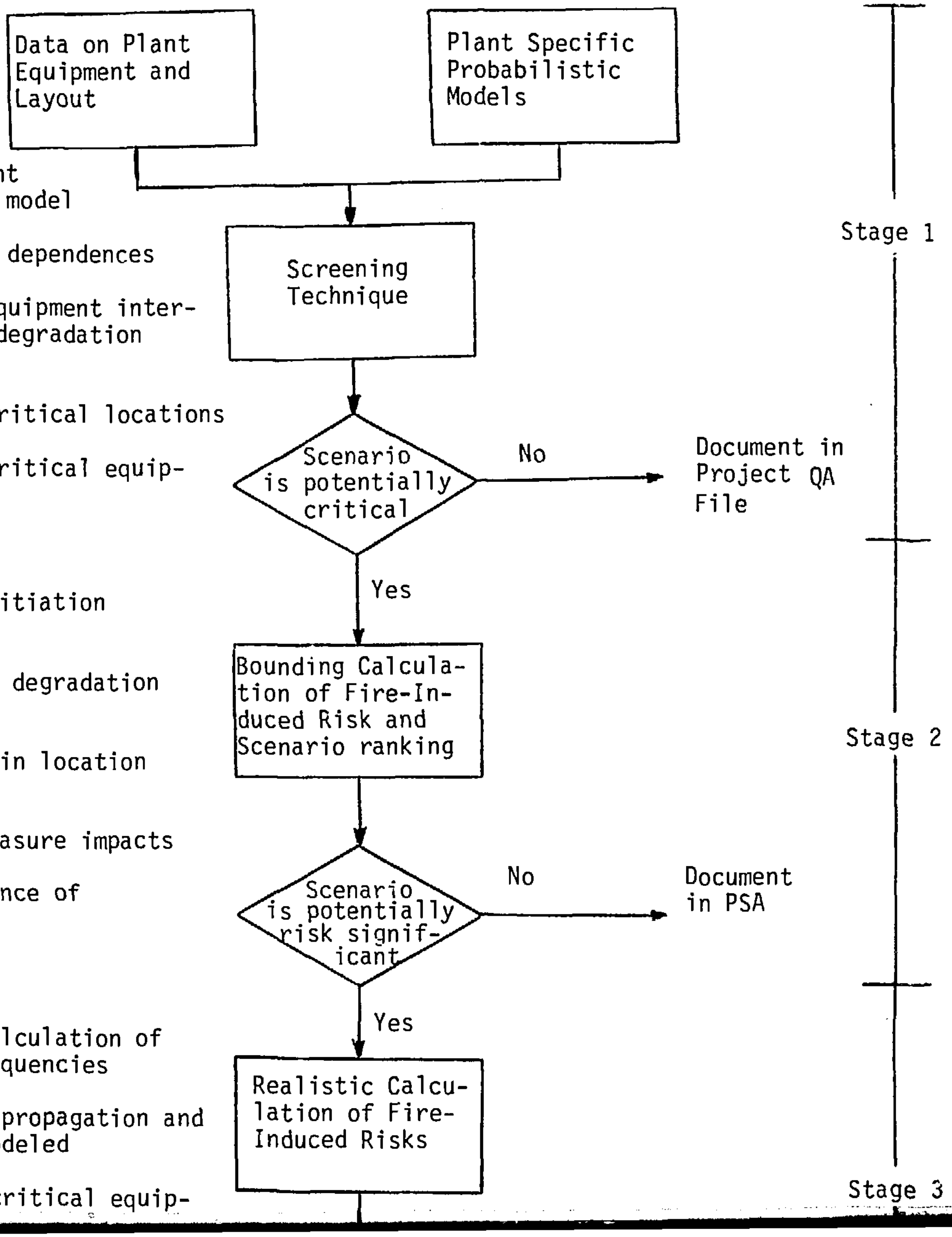
1. Determine the importance of fire at given locations as potentially severe common cause failure sources which can affect multiple safety systems and safety trains by solving for single and multiple locations from which an unsafe core state can be produced.
2. Determine the importance of system and subsystem fire effects by identifying the importance of equipment and procedures as impacts on risk and ranking fire impacts by the relative importance of the equipment affected.

The screening process consists of mapping event sequences which contribute to risk, to the space of plant fire locations, and solving the transformed

- Construction of plant safety significance model
- Mapping of location dependences
- Identification of equipment interaction and barrier degradation scenarios
- Identification of critical locations
- Identification of critical equipment in location

- Preliminary fire initiation frequencies
- Preliminary barrier degradation frequencies
- Critical equipment in location assumed failed
- Preliminary risk measure impacts
- Preliminary importance of fire scenarios

- Physically based calculation of fire initiation frequencies
- Realistic geometry, propagation and growth phenomena modeled
- Fire fragility of critical equip-



- Preliminary fire initiation frequencies
- Preliminary barrier degradation frequencies
- Critical equipment in location assumed failed
- Preliminary risk measure impacts
- Preliminary importance of fire scenarios

- Physically based calculation of fire initiation frequencies
- Realistic geometry, propagation and growth phenomena modeled
- Fire fragility of critical equipment considered
- Sensitivity and uncertainty calculations

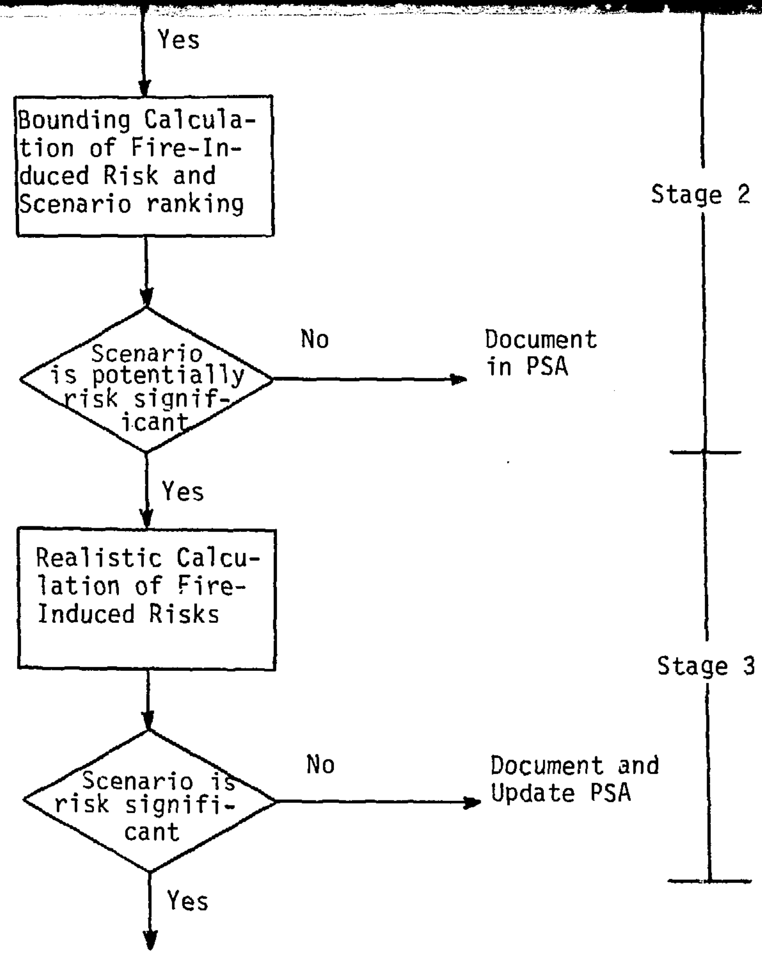
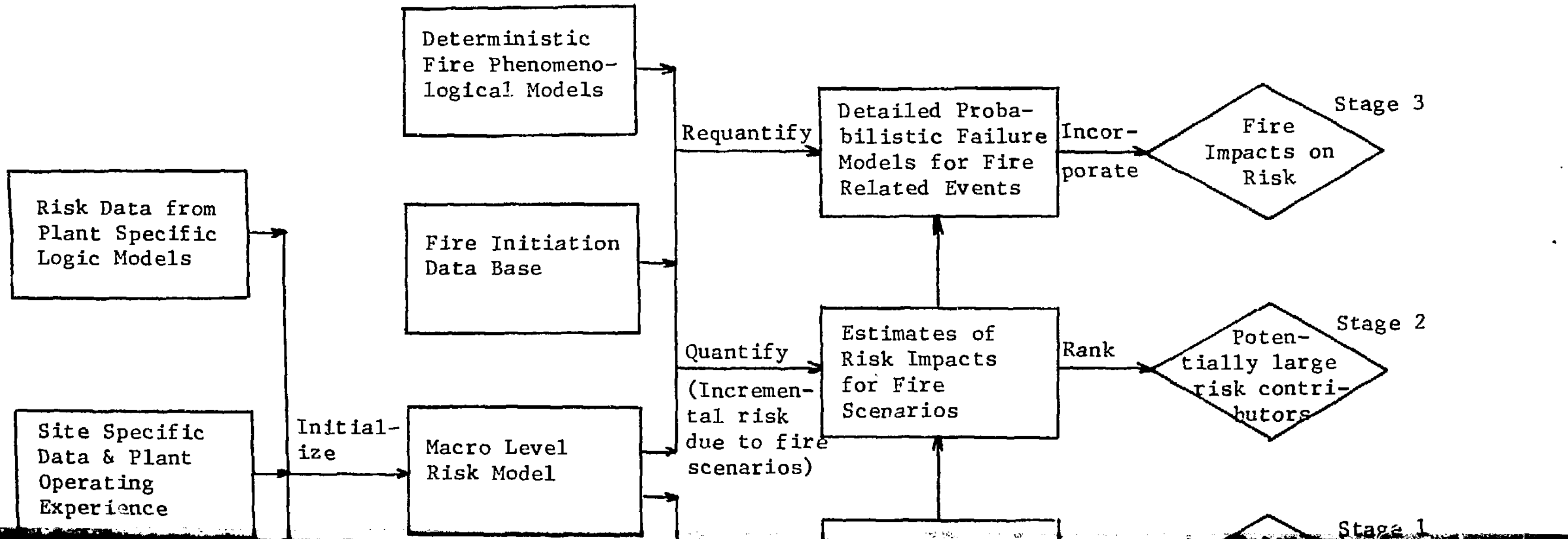


Figure 3.1 Elements of a recommended FRA approach.

Table 3.1 Requirements for Quantification of Incremental Risk Due to Fire at a Specific Location

| Probabilistic Parameter | Affecting Variables |
|---|---|
| • Frequency of fire at location | • Industry experience for general plant building<br>• Geometric location of equipment and "damage" radius<br>• Combustibles loading in area<br>• Access to area |
| • Incremental frequency of core damage (serious release) | • Equipment in location (including cabling<br>• Relationship of equipment at location to risk model inputs<br>• Importance of risk model inputs to risk measures |
| • Probability of fire damage to equipment | • Rate of fire growth as function of fire dynamics and combustibles loading<br>• Rate of fire suppression as function of detection and suppression activity<br>• Flashover and "large" dynamic effects<br>• Geometric effects<br>• Barrier effectiveness<br>• Availability of ventilation<br>• Aerosol formation |



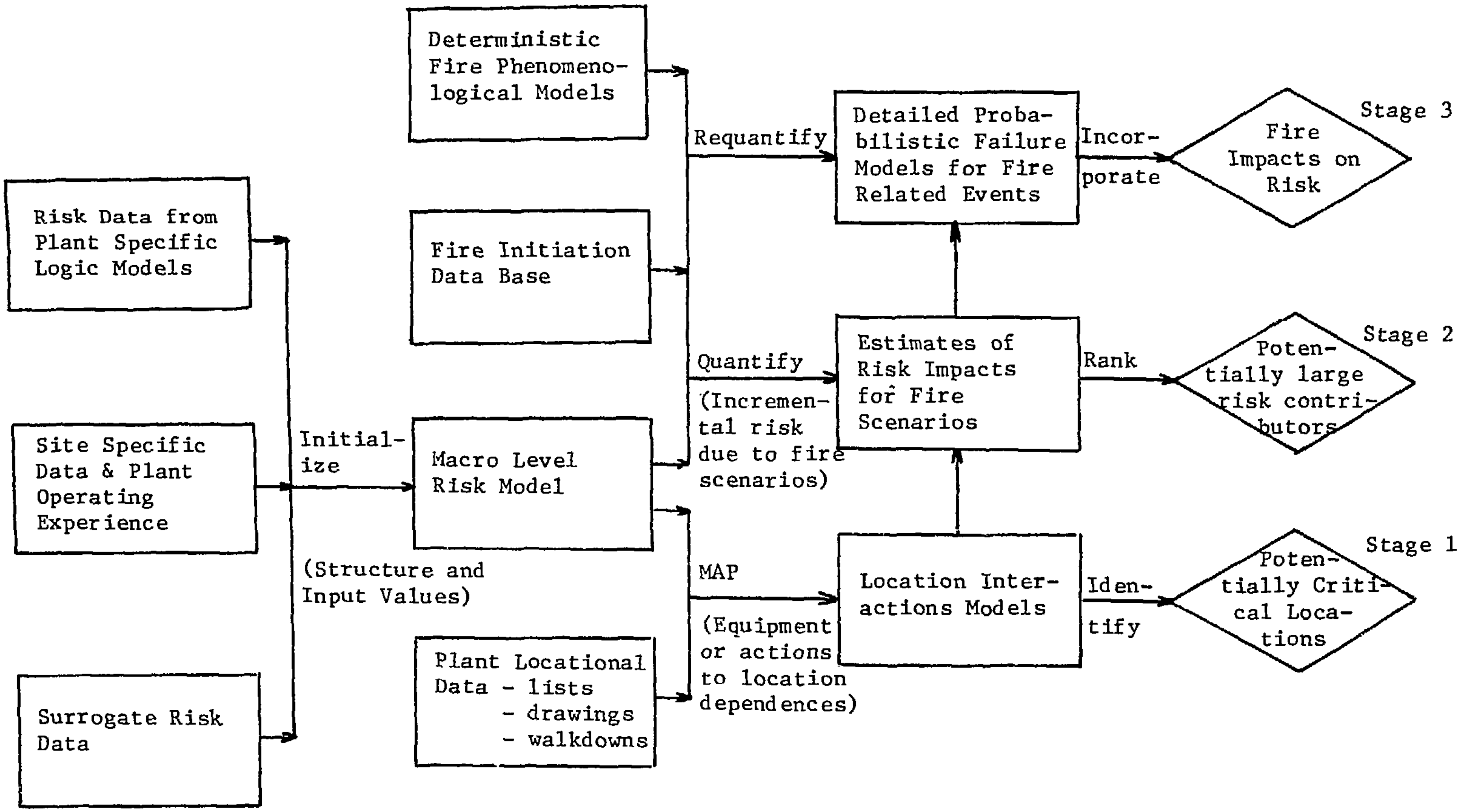


Figure 3.2 Use of limited detail risk model in FRA.

logic for single and multiple locations from which events may occur due to fire related damage which could cause a plant to reach an unsafe condition (vulnerable to core damage). A location cutset consisting of a single zone (singleton) means that sufficient fire damage could occur in that zone to cause the core to reach an unsafe state (initiation of an accident and failure to mitigate its effects). For a double location set (doubleton), the implication is that given damage to a single fire location, some combination of initiating events and/or loss of safety system capability can occur. The loss of a single such zone may be important, depending on the remaining safety margin or resilience of the plant to core threatening events.

## 3.4 Detailed Analysis

The objectives of further detailed probabilistic evaluation of fire risk scenarios are the following:

(i) to determine on as realistic a basis as possible the most critical fire scenarios and their effects,

(ii) to establish the most-important parameters and phenomena which must be included in the physical modeling and the probabilistic and numerical calculations,

(iii) to estimate the sensitivity of the fire risks to these parameters, and

(iv) to estimate the modeling and parametric uncertainties in the fire risk increments calculated using the results of the screening calculations.

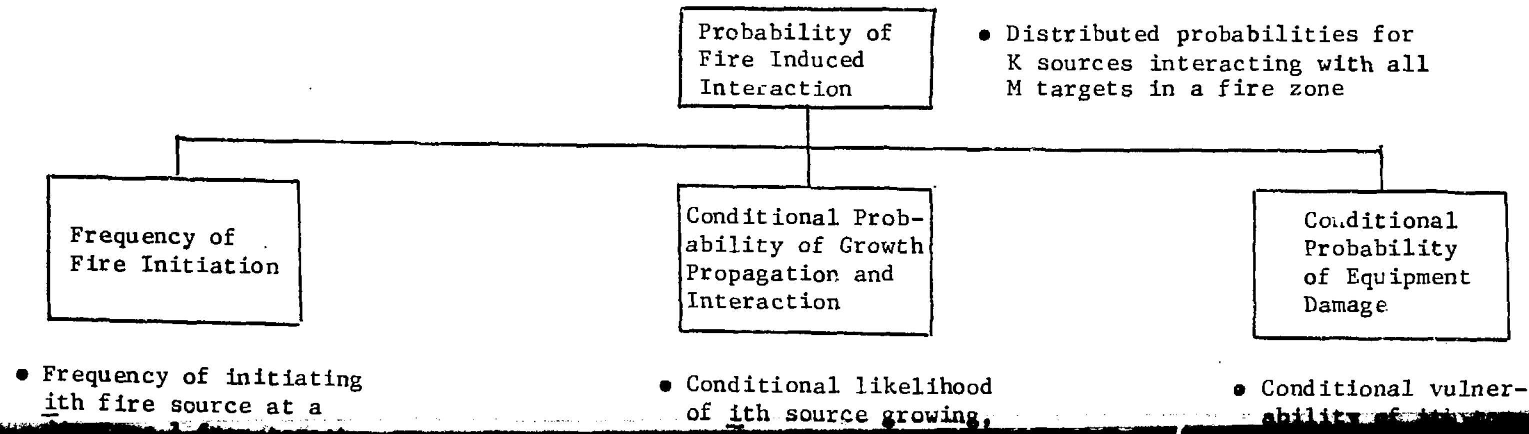
A reasonable approach for calculating the frequency of a fire induced interaction is to consider for each target/source combination:

1. The frequency of source fire initiation,
2. The conditional likelihood that the source grows, propagates, and interacts with the target, and
3. The conditional likelihood that the target is damaged.

The structure of the ensuing calculation and the major variables and parameters which enter, and affect the frequencies and the conditional probabilites of fire propagation and equipment, are shown in Figure 3.3. It is, in fact, possible to express the resulting process in formal mathematical form as:

$$f\left(\begin{array}{l}\text{fire scenario which}\\ \text{causes critical loss of}\\ \text{of equipment at a location}\end{array}\right) = \prod_{i=j}^{K}\sum_{j=i}^{M} f(S_{ij}) \cdot P(P_{ij}(t)/S_{ij})\cdot P(d_{ij}(t)/P_{ij}(t)dt)$$

but in the present state of development, this formula is only useful as a mnemonic. The various quantities are defined in Figure 3.3. The set of parametric effects is not necessarily exhaustive. Nor are the calculations necessarily sensitive to all of the parameters. Each one should be reviewed as a possible impact, however, and arguments concerning the robustness of damage frequencies to specific parameters should be justified in the course of the analysis.



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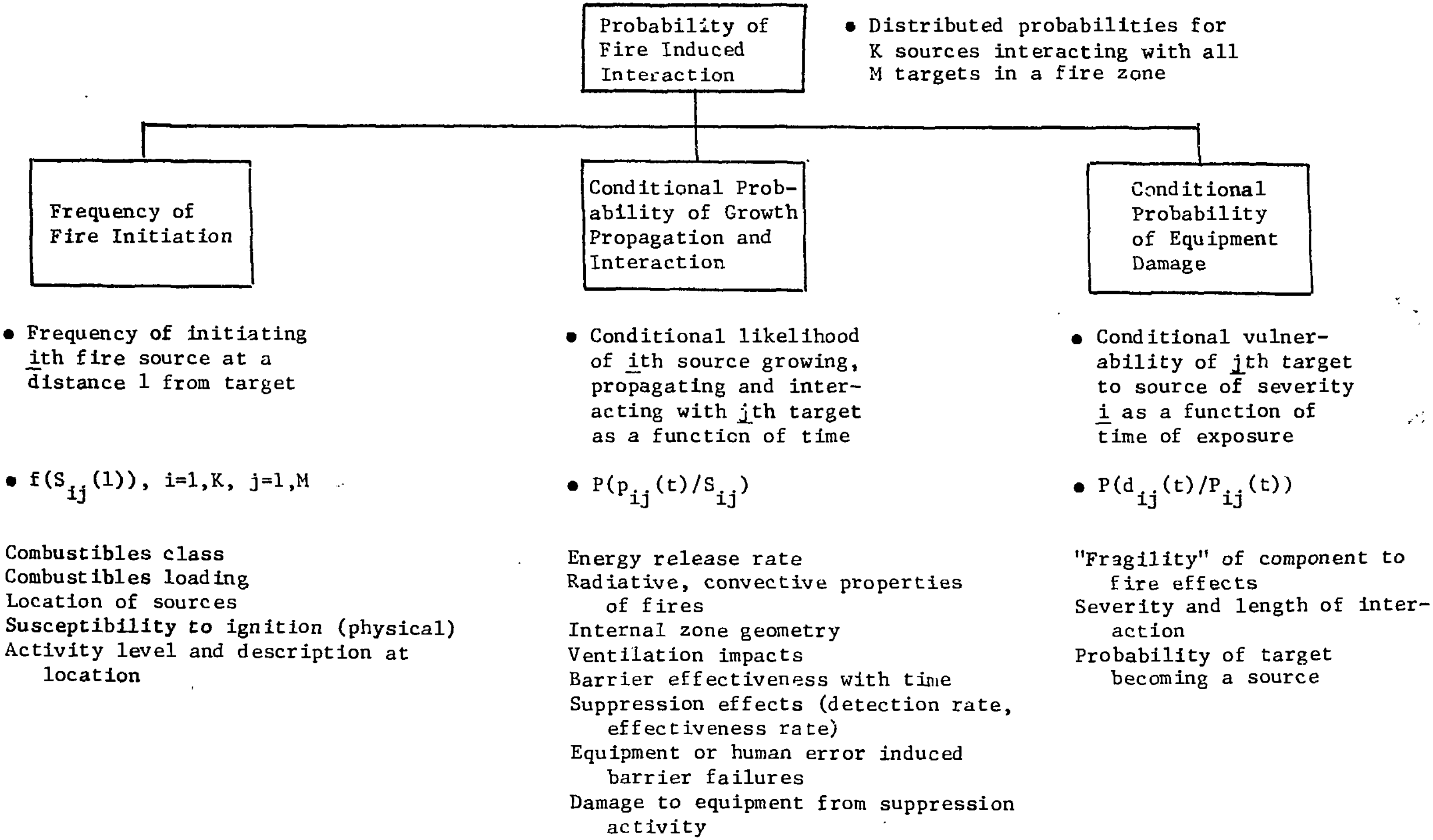

- Distributed probabilities for K sources interacting with all M targets in a fire zone

- Frequency of initiating ith fire source at a distance 1 from target
- $f(S_{ij}(1)), i=1,K, j=1,M$

Combustibles class
Combustibles loading
Location of sources
Susceptibility to ignition (physical)
Activity level and description at location

- Conditional likelihood of ith source growing, propagating and interacting with jth target as a function of time
- $P(p_{ij}(t)/S_{ij})$

Energy release rate
Radiative, convective properties of fires
Internal zone geometry
Ventilation impacts
Barrier effectiveness with time
Suppression effects (detection rate, effectiveness rate)
Equipment or human error induced barrier failures
Damage to equipment from suppression activity

- Conditional vulnerability of jth target to source of severity i as a function of time of exposure
- $P(d_{ij}(t)/P_{ij}(t))$

"Fragility" of component to fire effects
Severity and length of interaction
Probability of target becoming a source

Figure 3.3 Conceptual realistic probabilistic evaluation of fire induced interactions and underlying factors.

For the likelihood of fire at a location, experimental data on nuclear industry experience should be used whenever possible, adapted to the specific situation, and augmented as appropriate by relevant non-nuclear industrial data.

For quantification of conditional fire damage of equipment, considerations include:

1. Geometric location of critical equipment and minimum area fire involvement requirements,
2. Vulnerability of the equipment to fire damage as a function of fire severity, fire fighting activities, and time,
3. Detectability of the fire as a function of time, and
4. Suppression as a function of time.

Quantitative estimates of conditional equipment unavailability ("fire fragility") should be made using the following sources of information in descending order of desirability:

1. Experimental data (direct or extrapolated using expert judgment),
2. Results of phenomenological models,
3. Data bases from previous PRAs, modified by expert judgment as appropriate and documented.

At the present state of knowledge only the use of ranges of the conditional probabilities can be justified. Nor can the lack of statistical data be taken as evidence for invulnerability.

Fire growth, and time dependent equipment damage models should include sufficient sensitivity calculations to identify driving assumptions and heavy reliance on relatively poorly quantified variables. The role of sensitivity calculations in these assessments is to identify variable parameter relationships where uncertainty in the values could have a marked impact on the credibility of modeling results.

Conservative estimates of fire effectiveness and equipment unavailability can be used where the net effect or risk is still small. For related scenarios identified as critical to plant risk, the propagated uncertainties must be reviewed and the basis for range estimates established.

## 4. AN EXAMPLE SCREENING CALCULATION

A sample analysis has been performed using a very simple plant geometry and systems configuration, in order to illustrate the multiple level screening approach. The example problem illustrates some of the strengths and inherent vulnerabilities in the methodology, as well as the need for computerized tools in a

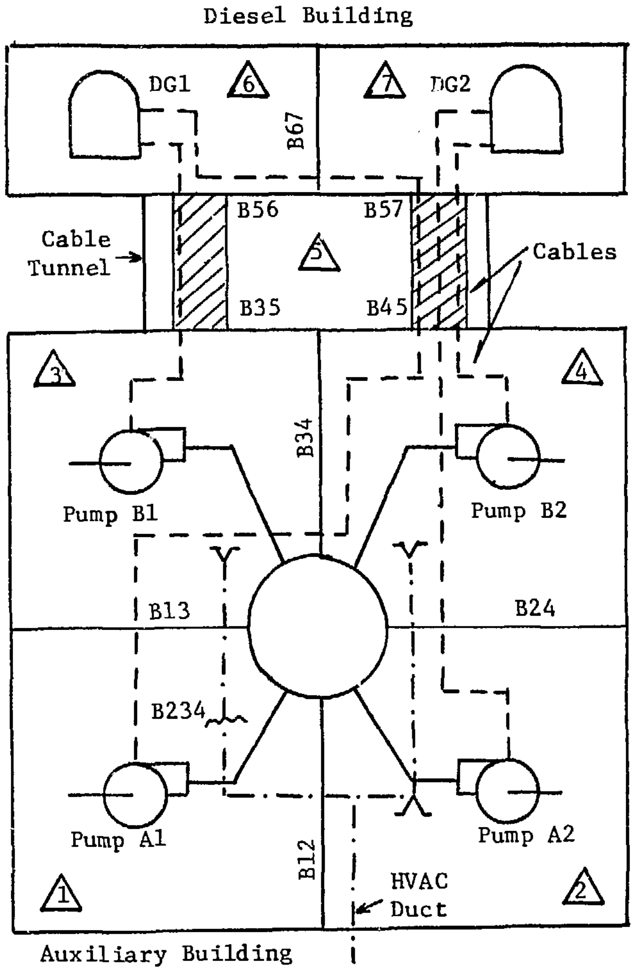

Figure 4.1 Layout of safety equipment.

| T | S1 | S2 | Sequence | Status |
|---|---|---|---|---|
|  |  |  |  |  |

OK

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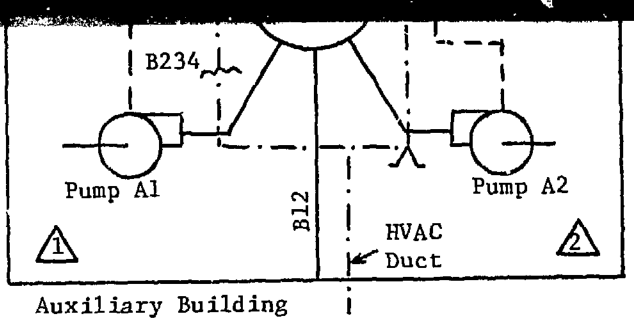
A sample analysis has been performed using a very simple plant geometry and systems configuration, in order to illustrate the multiple level screening approach. The example problem illustrates some of the strengths and inherent vulnerabilities in the methodology, as well as the need for computerized tools in a real plant analysis.

The simplified geometry is shown in Figure 4.1. Notably, the plant as configured would violate current 10CFR50 Appendix R requirements. Probabilistic models illustrating the relationship between a plant risk measure (core damage frequency) component level failures are given in Figures 4.2a and 4.2b. An evaluation of the independent probability of core damage as a result of a transient occurrence followed by the loss of coolant makeup from both systems (S1 and S2) is shown in Table 4.1. Failures of both diesel generators dominate the core damage frequencies with less than a 1% contribution from any other set of failures.

Postulating that a fire can occur in any of the fire zones identified in Figure 4.1, and that the fire could affect some or all of the components at that location, locational dependencies which could directly or indirectly cause equipment failures are shown in Table 4.2. In a plant analysis, layout data would be obtained from plant layout drawings supplemented by walkdowns.



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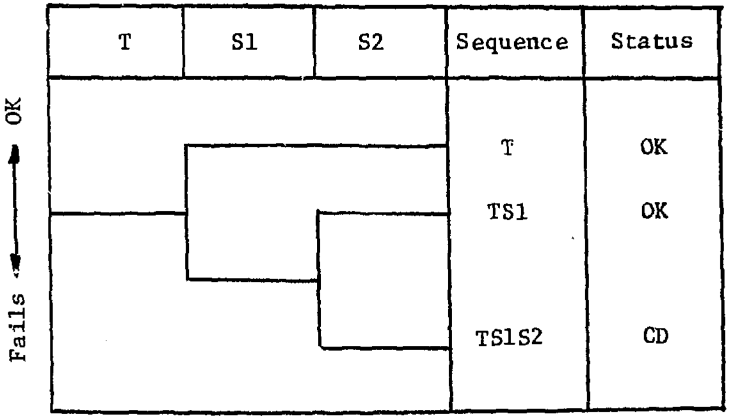

T: Shutdown initiated
S1: System 1 fails
S2: System 2 fails
CD: Core damage

Figure 4.2a Event sequence diagram.

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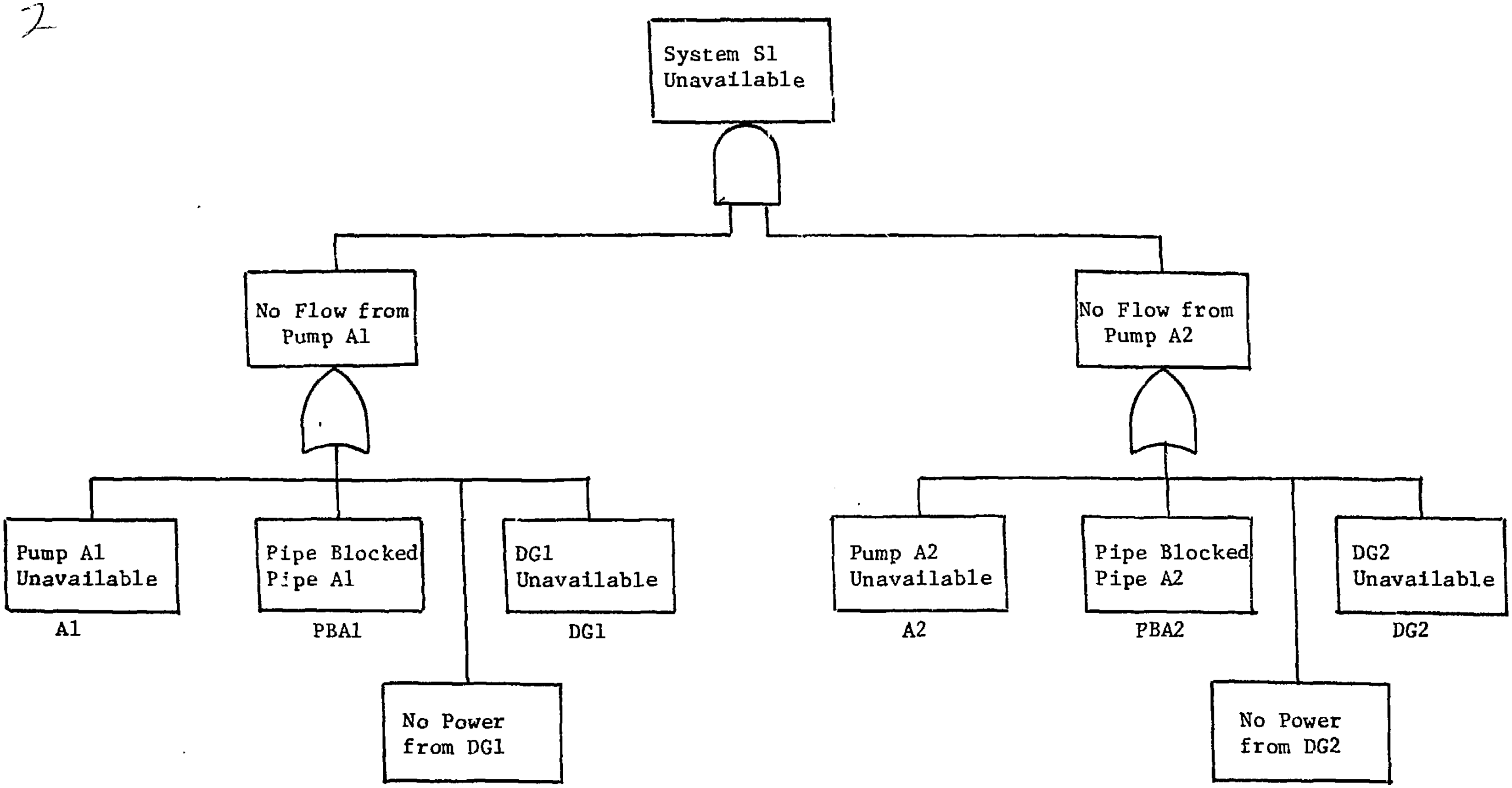

Figure 4.2b Fault logic for failure of system S1 (an analogous diagram applies for the failure of system S2).

### Table 4.1 Independent Failure Evaluation

- Boolean Expression for Core Damage

$$
\begin{aligned}
CD &= T \cdot S1 \cdot S2 \\
&= T \cdot (A1+PBA1+DG1+DG1/A1) \\
&\quad \cdot (A2+PBA2+DG2+DG2/A2) \\
&\quad \cdot (B1+PBB1+DG1+DG1/B1) \\
&\quad \cdot (B2+PBB2+DG2+DG2/B2)
\end{aligned}
$$

- Independent Failure Frequencies and Unavailabilities

$F(T) = 1.0/R\text{-}yr$

$P(DG1) = P(DG2) = 3.0E-2/D$

$P(A1) = P(A2) = 5.0E-2/D$

### Table 4.2 Potential Locational Dependences due to Fire

| Component Failed | Location of Fire | Failure Mode |
|---|---|---|
| A1 | 1 | Fire damage to pump |
| PBA1 | – | None indicated |
| DG1 | 6 | Fire damage to DG |
| DG1/A1 | 6 | Fire damage to power cable |
| | 7 | Fire damage to power cable |
| | 5 | Fire damage to power cable |
| | 4 | Fire damage to power cable |
| | 3 | Fire damage to power cable |
| | 1 | Fire damage to power cable |
| A2 | 2 | Fire damage to pump |

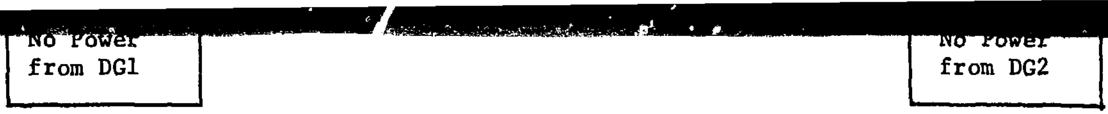

Figure 4.2b Fault logic for failure of system S1 (an analogous diagram applies for the failure of system S2).

### Table 4.1 Independent Failure Evaluation

- Boolean Expression for Core Damage

$$\begin{aligned} CD &= T \cdot S1 \cdot S2 \\ &= T \cdot (A1+PBA1+DG1+DG1/A1) \\ &\quad \cdot (A2+PBA2+DG2+DG2/A2) \\ &\quad \cdot (B1+PBB1+DG1+DG1/B1) \\ &\quad \cdot (B2+PBB2+DG2+DG2/B2) \end{aligned}$$

- Independent Failure Frequencies and Unavailabilities

$F(T) = 1.0/R\text{-yr}$

$P(DG1) = P(DG2) = 3.0E{-}2/D$

$P(A1) = P(A2) = 5.0E{-}2/D$

$P(B1) = P(B2) = 5.0E{-}3/D$

$P(PBA1) = P(PBA2) = P(PBB1) = P(PBB2) = 1.0E{-}4/D$

$P(DG1/A1) = P(DG2/A2) = P(DG1/B1) = P(DG/B2) = 1.0E{-}5/D$

- Dominant Independent Failure Contributors

| Sequence | Frequency[1] (Events/yr) |
|---|---|
| DG1·DG2 | 9.0E-4 |
| DG1·A2·B2 | 7.5E-6 (.0083) |
| DG2·A1·B1 | 7.5E-6 (.0083) |
| DG1·A2·PBB2 | 1.5E-7 (.0002) |
| DG2·A1·PBB1 | 1.5E-7 (.0002) |
| A1·A2·B1·B2 (.0001) | 6.3E-8 |
| | 9.2E-4 |

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[1] Of core damage due to cutset in 1/R-yr. The numbers in parentheses give the incremental fraction of CD frequency as a result of adding new core damage sequence.

### Table 4.2 Potential Locational Dependences due to Fire

| Component Failed | Location of Fire | Failure Mode |
|---|---|---|
| A1 | 1 | Fire damage to pump |
| PBA1 | - | None indicated |
| DG1 | 6 | Fire damage to DG |
| DG1/A1 | 6 | Fire damage to power cable |
| | 7 | Fire damage to power cable |
| | 5 | Fire damage to power cable |
| | 4 | Fire damage to power cable |
| | 3 | Fire damage to power cable |
| | 1 | Fire damage to power cable |
| A2 | 2 | Fire damage to pump |
| PBA2 | - | None identified |
| DG2 | 7 | Fire damage to DG |
| DG2/A2 | 7 | Fire damage to power cable |
| | 5 | Fire damage to power cable |
| | 4 | Fire damage to power cable |
| | 2 | Fire damage to power cable |
| B1 | 3 | Fire damage to pump |
| PBB2 | - | None identified |
| DG1/B1 | 6 | Fire damage to power cable |
| | 5 | Fire damage to power cable |
| | 3 | Fire damage to power cable |
| B2 | 4 | Fire damage to pump |
| PBB2 | - | None identified |

In the first stage of screening it is assumed that a fire in one zone corresponds to failure of components in that zone. The result of mapping input events of the risk model into locations and solving an "equivalent" location model yields the combinations of room failures shown in Table 4.3a. In one case damage at a single location (FL5 - the cable tunnel analogous to a cable spreading room which is a known fire vulnerability in most plants) can result in core damage. Several double locations were identified, including two adjacent locations (FL6 & FL7). A common failure scenario which links fire damage in three rooms as a result of HVAC ducting isolation failures and adjacency is included.

The conditional likelihood of core damage given that fire has resulted in damage to all targets of one fire zone is shown in Table 4.3b. Notably, the result of catastrophic fire in FL4 or FL7 is reliance on the output of a single pump (B1) to maintain core inventory.

Using the above results, a first stage screening assessment is performed in Table 4.4 to identify locations for which the frequency of fire damage to critical components should be estimated as a risk impact. Criteria for the location receiving a preliminary risk evaluation include 1) the location is a point of a single failure, 2) failures at the location plus independent failures can possibly add significantly to plant risk, and 3) fire at the location could propagate to other locales and combined result is a core damage scenario.

Preliminary estimates of fire initiation frequency using the kind of data which is obtained from nuclear experience and existing FRAs conditioned by parameters representing the fire potential at a given location are shown in Table 4.5a. Some (hopefully) typical barrier degradation probabilities are given in Table 4.5b along with evaluation of core damage sequences which could result.

Based on the rough initiation frequencies forecast above and the still very conservative assumption that all equipment in a room is classified damaged, given a fire, an evaluation of single room fires plus independent equipment failures is shown in Table 4.6.

A summary of the results of the second stage screening assessment is shown in Table 4.7, which combines the results of the independent hardware analysis, the barrier degradation analysis and the analysis of the likelihood and impact of fire in a single location. One area clearly requires some additional consideration (FL5), while one area (FL7) could be evalu-

Table 4.3a Stage I Screening Room Fires as Potential Contributors to Core Damage with BarrierDegradation

| Locations | Comments |
|---|---|
| FL5 | Damage at single location can lead to core damage |
| FL4·FL6 | Damage at two locations can lead to core damage, but locations are not adjacent |
| FL6·FL7 | Damage at two locations can lead to core damage and locations are adjacent (B67) |
| FL3·FL7 | Damage at two locations can lead to core damage but locations are not adjacent |
| FL3·FL2·FL4 | Damage at three locations can lead to core damage. Both FL3 and FL2 are adjacent to FL4, (B24, B34); also HVAC ducting links FL2 through FL4 (B234 controls flow in duct) |

Table 4.3b Stage I Screening Room Fires as Partial Contributors to Core Damage for Screening Purposes

| Fire at Location | Independent Failure[1] | Conditional Probability of CD[2] |
|---|---|---|
| FL5 | - | 1 |
| FL4,FL7 | B1 | 5E-3 |
| | PBB1 | 1E-4 |
| | DG1/B1 | 1E-5 |
| FL3,FL6 | A2·B2 | [illegible] |

point of a single failure, 2) failures at the location plus independent failures can possibly add significantly to plant risk, and 3) fire at the location could propagate to other locales and combined result is a core damage scenario.

Preliminary estimates of fire initiation frequency using the kind of data which is obtained from nuclear experience and existing FRAs conditioned by parameters representing the fire potential at a given location are shown in Table 4.5a. Some (hopefully) typical barrier degradation probabilities are given in Table 4.5b along with evaluation of core damage sequences which could result.

Based on the rough initiation frequencies forecast above and the still very conservative assumption that all equipment in a room is classified damaged, given a fire, an evaluation of single room fires plus independent equipment failures is shown in Table 4.6.

A summary of the results of the second stage screening assessment is shown in Table 4.7, which combines the results of the independent hardware analysis, the barrier degradation analysis and the analysis of the likelihood and impact of fire in a single location. One area clearly requires some additional consideration (FL5), while one area (FL7) could be evaluated if there were other locational dependences identified or if a more reasonable basis for estimating contribution to risk were needed. None of the other locations are considered to require further evaluation. While it was expected that the cable tunnel would be identified as a potential source of risk due to fires, several other locations with considerable amounts of equipment were excluded from further review. Also, the appearance of FL7 is potentially counter-intuitive since an essentially identical room is excluded from further evaluation. These results support the adoption of the complete screening approach advocated here. Similar results would have been achieved if importance measures such as Vesely-Fussell or degradability instead of incremental risk were used as the basis for identifying requirements for further analysis. The use of importance measures is more convenient for complex models since incremental core damage frequencies need not be calculated for each locational dependence identified.

core damage. Both FL
and FL2 are adjacent to
FL4, (B24, B34); also
HVAC ducting links FL2
through FL4 (B234 controls flow in duct)

Table 4.3b Stage 1 Screening Room Fires as Partial Contributors to Core Damage for Screening Purposes

| Fire at Location | Independent Failure[1] | Conditional Probability of CD[2] |
|---|---|---|
| FL5 | - | 1 |
| FL4,FL7 | B1 | 5E-3 |
| | PBB1 | 1E-4 |
| | DG1/B1 | 1E-5 |
| F13,F16 | A2·B2 | 2.5E-4 |
| | A2·PBB2 | 5E-6 |
| | A2·DG2/B2 | 5E-7 |
| | PBA2·B2 | 5E-7 |
| | DG2/A2·B2 | 5E-8 |
| | PBA2·PBB2 | 1E-8 |
| FL1,FL2 | A1·B1·B2 | 1.3E-5 |
| | A1·B1·PBB2 | 2.5E-8 |
| | A1·PBB1·B2 | 2.5E-8 |

---

[1] Fire plus independent failure leads to core damage

[2] Given fire in location - which damages all equipment at the location

## Table 4.4 Results of Stage 1 Screening

- A possible fire location is included in a preliminary risk evaluation if:

  1) sufficient equipment can be damaged at that location to result in core damage

  2) damage at that location plus damage at adjacent location(s) can result in core damage if barrier effectiveness is degraded[1]

  3) damage at that location plus independent failures can potentially contribute significantly to core damage frequency

- Locations which are included in a preliminary risk evaluation are:

| Fire Location | Basis for Including |
|---|---|
| FL5 | Damage at single location results in CD |
| FL3, FL6, FL4, FL7 | Damage at location plus independent failures could contribute significantly to CD frequency[1] |
| FL2 | Damage at location plus damage at other locations due to degradation of barrier (B234) can contribute to CD frequency |

---

[1] Probability of fire assumed to be 1. If CD frequency increases by >10%, fire location is <u>potentially</u> significant.

## Table 4.5a Preliminary Estimates of Fire Initiation Frequency by Location (from the Literature)

<u>Experience</u>

- DG Building fires have been recorded at frequency of 1E-2/R-yr
- Auxiliary Building fires have been recorded at frequency of 5E-4/R-yr
- Tunnel or CSR fires have been recorded at frequency of 2E-3/R-yr

## Table 4.5b Preliminary Probabilistic Evaluation of Room Fires plus Barrier Degradation as a Source of Risk

- Fire barriers between rooms with safety grade equipment assumed to consist of solid wall (3 hour) barrier plus equivalently secure doorways or hatches. On this basis, contributions of failures due to structural flaws and failures due to doorways left open or improperly sealed is no greater than 1E-4/fire event. No common modes for barrier failure are assumed identified.

$$P(B24) = P(B34) = P(B67) = 1E-4$$

- Failure of ducting to act as fire/smoke barrier is assumed to require equivalent of double valving failure. No common failure modes are assumed. Therefore, for the preliminary evaluation

$$P(B234) \leq 1E-6$$

- Resulting contributions to core damage frequency come from barrier degradation is therefore assumed to be

| CD Sequence | Contribution to CDF |
|---|---|
| FL6·B67 | 4.8E-7 |
| FL7·B67 | 4.8E-7 |
| FL4·B34·B24 | 6.3E-13 |
| FL2·B234 | 6.3E-11 |
| FL3·B234 | 6.3E-11 |
| FL4·B234 | 6.3E-11 |

## Table 4.6 Preliminary Probabilistic Evaluation of Room Fires Plus Independent Failures as a Source of Risk

| CD Sequence | Contribution to CDF |
|---|---|
| FL5 | 1E-4 |
| FL4·B1 | 3.2E-7 |
| FL4·PBB1 | 6.3E-9 |
| FL4·DG1/B1 | 6.3E-10 |

| | |
|---|---|
| | pendent failures could contribute significantly to CD frequency[1] |
| FL2 | Damage at location plus damage at other locations due to degradation of barrier (B234) can contribute to CD frequency |

Table 4.5a Preliminary Estimates of Fire Initiation Frequency by Location (from the Literature)

Experience

- DG Building fires have been recorded at frequency of 1E-2/R-yr
- Auxiliary Building fires have been recorded at frequency of 5E-4/R-yr
- Tunnel or CSR fires have been recorded at frequency of 2E-3/R-yr

Fractional Weight of Combustibles

| | |
|---|---|
| DG Building equally apportioned between rooms | .5 |
| Auxiliary Building equally apportioned between rooms | .25 |
| Tunnel or CSR, no ignitables, all | .10 |

Surface of Area of Ignitability Factor

| | |
|---|---|
| High percentage of ignitables DG room | .95 |
| Auxiliary building, some ignitables, mostly cables | .5 |
| Tunnel or CSR, no ignitables, all cable | .05 |

Preliminary Frequency of Severe Fires

f(FL6) = f(FL7) = 4.8E-3/R-yr

f(FL1) = f(FL2) = f(FL3) = f(FL4) = 6.3E-5/R-yr

f(FL5) = 1E-4/R-yr

cy come from barrier degradation is therefore assumed to be

| CD Sequence | Contribution to CDF |
|---|---|
| FL6·B67 | 4.8E-7 |
| FL7·B67 | 4.8E-7 |
| FL4·B34·B24 | 6.3E-13 |
| FL2·B234 | 6.3E-11 |
| FL3·B234 | 6.3E-11 |
| FL4·B234 | 6.3E-11 |

Table 4.6 Preliminary Probabilistic Evaluation of Room Fires Plus Independent Failures as a Source of Risk

| CD Sequence | Contribution to CDF |
|---|---|
| FL5 | 1E-4 |
| FL4·B1 | 3.2E-7 |
| FL4·PBB1 | 6.3E-9 |
| FL4·DG1/B1 | 6.3E-10 |
| FL7·B1 | 2.4E-5 |
| FL7·PBB1 | 4.8E-7 |
| FL7·DG1/B1 | 4.8E-8 |
| FL3·A2·B2 | 1.6E-8 |
| FL3·A2·PBB2 | 3.2E-10 |
| FL3·A2·A2·DG2/B2 | 3.2E-11 |
| FL3·PBA2·B2 | 3.2E-11 |
| FL3·DG2/A2·B2 | 3.2E-12 |
| FL3·PBA·PBB2 | 6.3E-13 |
| FL6·A2·B2 | 1.2E-6 |
| FL6·A2·PBB2 | 2.4E-8 |
| FL6·A2·DG2/B2 | 2.4E-9 |
| FL6·PBA2·B2 | 2.4E-9 |
| FL6·DG2/A2·B2 | 2.4E-10 |
| FL6·PBA2·PBB2 | 4.8E-11 |

---

[1] Probability of fire assumed to be 1. If CD frequency increases by >10%, fire location is potentially significant.

Table 4.7 Summary of 2nd Stage Screening Evaluation

- Point Estimate and Ranking of CD Sequences

| CD Sequence | Contribution to CDF |
|---|---|
| DG1·DG2 | 9E-4 |
| FL5 | 1.E-4 (.1111) |
| FL7·B1 | 2.4E-5 (.0240) |
| DG1·A2·B1 | 7.5E-6 (.0073) |
| DG2·A1·B1 | 7.5E-6 (.0073) |
| FL6·A2·B2 | 1.2E-6 (.0012) |
| FL7·PBB1 | 4.8E-7 (.0005) |
| FL7·B67 | 4.8E-7 (.0005) |
| FL6·B67 | 4.8E-7 (.0005) |
| F14·B1 | 3.4E-7 (.0003) |
| DG1·A2·PBB2 | 1.5E-7 (.0001) |
| DG2·A1·PBB1 | 1.5E-7 (.0001) |
| A1·A2·B1·B2 | 6.3E-8 (.0001) |

- Recommendations for Detailed Evaluation

| Fire at Location(s) | Can Contribute ( )% to CDF | Recommended Action |
|---|---|---|
| 5 | >10 | Detailed evaluation |
| 7 | >1 | Possible further evaluation |
| 6 | >.1 | No further evaluation |
| 4 | >.01 | No further evaluation |
| 2, 3 | <.01 | No further evaluation |

## 5. CONCLUSIONS

Substantial improvements in the methodology for estimating the risk of fires at nuclear power plants have been made since the completion of initial power plant risk estimates. These improvements include:

1. automation of risk models as structured data bases such that sensitivities and the importance of identified dependencies can be done quickly and thoroughly,
2. development of large numbers of relational data bases to allow efficient reviewing of large amounts of locational dependences such that poten-

The methodology makes heavy use of current developments in microcomputer based plant risk models and relational data bases. Thus the results of a fire risk analysis can be modified as need be to accommodate newly identified vulnerabilities or conversely to assess the safety significance of planned modification. Thus the resulting analysis stands as a "living" analysis capability which can provide substantial downstream benefits in terms of cost saving and scheduling of fire safety related plant modifications.

Finally it is well recognized that plant fires represent a substantial financial risk to the utility and stockholder. The methodology developed here can be modified slightly to accommodate estimations of other measures of risk such as the economic risk of extended plant downtimes. Used as an economic risk tool a financially optimal plant configuration from the standpoint of fire safety can be defined. Also the relative insurability of plants and their insurance requirements can be estimated and technically supported. The authors hope that the methods presented here will one day lead to a more flexible and pragmatic approach to fire safety in the nuclear industry perhaps even finding broad usefulness in other industries where the systems involved are complex and the consequences of fire damage potentially catastrophic.

## ACKNOWLEDGEMENT

We are indebted to Dr. J. Boccio, Dr. C. Ruger, and Dr. R. Youngblood for helpful suggestions and comments.

| | | |
|---|---|---|
| | | evaluation |
| 7 | >1 | Possible further evaluation |
| 6 | >.1 | No further evaluation |
| 4 | >.01 | No further evaluation |
| 2, 3 | <.01 | No further evaluation |

## 5. CONCLUSIONS

Substantial improvements in the methodology for estimating the risk of fires at nuclear power plants have been made since the completion of initial power plant risk estimates. These improvements include:

1. automation of risk models as structured data bases such that sensitivities and the importance of identified dependencies can be done quickly and thoroughly,
2. development of large numbers of relational data bases to allow efficient reviewing of large amounts of locational dependences such that potentially critical dependences can be identified in a thorough and comprehensive manner,
3. collection of models and experimental data which allow reasonably accurate prediction of conditional equipment damage probabilities based on propagation detection and suppression models,
4. the beginnings of a synthesis of nuclear industry fire experience with experience in other industries. (This should eventually result in a reasonably accurate basis for predicting fire initiator frequencies by location.)

Using the currently available fire risk assessments as a basis for comparison a methodology can now be developed which is systematically complete in its evaluation of existing fire hazards and yet is cost effective to implement since detailed (and resource intensive) calculations for the probabilities of fire propagation and equipment damages are minimized.

catastrophic.

## ACKNOWLEDGEMENT

We are indebted to Dr. J. Boccio, Dr. C. Ruger, and Dr. R. Youngblood for helpful suggestions and comments.