NUREG/CR-3852
SAI-84/3026

Insights into PRA Methodologies

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Science Applications, Inc.

Prepared for
U.S. Nuclear Regulatory
Commission

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Manuscript Completed: August 1984
Date Published: August 1984

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NRC FIN B0783

ABSTRACT

Probabilistic Risk Assessments (PRAs) for six nuclear power plants were examined to gain insight into how the choice of analytical methods can affect the results of PRAs. The PRA scope considered was limited to internally initiated accident sequences through core melt. For twenty methodological topic areas, a baseline or "minimal" methodology was specified. The choice of methods for each topic in the six PRAs was characterized in terms of the incremental level of effort above the baseline. A higher level of effort generally reflects a higher level of detail or a higher degree of sophistication in the analytical approach to a particular topic area. The impact on results was measured in terms of how additional effort beyond the baseline level changed the relative importance and ordering of dominant accident sequences compared to what would have been observed had methods corresponding to the baseline level of effort been employed. This measure of impact is a more useful indicator of how methods affect perceptions of plant vulnerabilities than changes in core melt frequency would be. However, the change in core melt frequency was used as a secondary measure of impact for nine topics where availability of information permitted.

The results are presented primarily in the form of effort-impact matrices for each of the twenty topic areas. A suggested effort-impact profile for future PRAs is presented. This study should be most useful in establishing appropriate methods and levels of effort for future PRAs.

ACKNOWLEDGMENTS

Mr. Sanford Israel of the NRC Risk and Reliability Branch was the contract monitor for this study. Through numerous discussions and comments, Mr. Israel provided guidance and helped shape the course of the study. The authors gratefully acknowledge his considerable contributions.

The authors also acknowledge the assistance of their colleagues at SAI, Ms. Mary Drouin and Mr. Phuoc Le.

This work was performed under contract with the Department of Energy, Contract DE-AC05-81OR20837. It was funded by the U.S. Nuclear Regulatory Commission (FIN B-0783) through an Interagency Agreement.

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1.0 INTRODUCTION

This report seeks to provide insight into the relative importance and levels of effort associated with reliability methods used in PRAs. This will have direct application in better defining the level of detail required to assure a reasonable PRA. It can also illuminate areas where additional expenditures of time and effort on probabilistic methods have yielded a more realistic depiction of reactor safety.

In 1975, a new approach to evaluating reactor reliability and risks - Probabilistic Risk Assessment (PRA) - was presented in the Reactor Safety Study (RSS), WASH-1400 (Reference 1). This approach is based upon the concept of defining reactor system functions required for specific challenges (event trees) and estimating the probability of failure of system and functional requirements (fault trees). Since the completion of the RSS, reliability and risk assessment methods have been slowly evolving to the degree that they have become generally accepted for providing a reasonable analysis of the safety of a nuclear power plant. During the mid to late 1970s, the Reactor Safety Study Methodology Applications Program (RSSMAP) developed the concept of dominant accident sequences to simplify the construction of detailed event and fault trees. Following RSSMAP, the Interim Reliability Evaluation Program (IREP) sponsored five reliability assessments to determine plant differences by utilizing a variety of probabilistic assessment methods and implementation techniques. In addition to these NRC-sponsored studies, the nuclear power industry has conducted a number of reliability and risk studies. Examples include the Zion, Indian Point, Oconee, and Limerick PRAs. These studies have also made significant advances to the state-of-the-art in probabilistic analysis.

At the present time about 20 probabilistic safety analyses on specific nuclear power plants have been completed. Table 1.1 lists pertinent information about these studies. All of the studies are primarily based on the methods developed in the Reactor Safety Study. However, most of the studies have attempted to improve upon the original probabilistic concepts. Depending upon specific objectives, they have included analyses which are in greater or lesser detail than those originally used in the RSS and which therefore cannot be immediately compared with one another. Because of the unique features of every power plant, there have remained

Table 1.1. Completed PRAs

Plant	Issuance	Operating License	Rating (MWe)	NSSS/AE[1]	Containment	Sponsor	Report
Surry 1 **	1975	1972	788	W/S&W	Dry-Cylinder	NRC	NUREG-75/014 (WASH-1400)
Peach Bottom 2	1975	1973	1065	GE/Bechtel	Mark I	NRC	NUREG-75/014 (WASH-1400)
Big Rock Point **	1981	1962	71	GE/Bechtel	Dry-Sphere	Utility	USNRC Docket 55-155
Zion 1 & 2 **	1981	1973	1040	W/S&L	Dry-Cylinder	Utility	USNRC Docket 50-295
Indian Pt. 2 & 3	1982	1973	873	W/UE&C	Dry-Cylinder	Utility	USNRC Dockets 50-247 and 50-286
Yankee Rowe	1982	1960	175	W/S&W	Dry-Sphere	Utility	USNRC Docket 50-29
Limerick 1 & 2	1983	(1985)	1055	GE/Bechtel	Mark II	Utility	USNRC Docket 50-352
Shoreham	1983	(1984)	819	GE/S&W	Mark II	Utility	USNRC Dockets 50-322 and 50-353
Millstone 3*	1983	(1986)	1150	W/S&W	Dry-Cylinder	Utility	Controlled document
Susquehanna 1*	1983	1983	1050	GE/Bechtel	Mark II	Utility	Draft
Oconee 3*	1983	1973	860	B&W/Duke	Dry-Cylinder	EPRI/NSAC	Draft

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**PRAs used in this study.

* Completed but not yet publicly available.

[1] NSSS--Nuclear Steam System Supplier; AE--Architect-Engineer.

Table 1.1. Completed PRAs (continued)

Plant	Issuance	Operating License	Rating (MWe)	NSSS/AE[1]	Containment	Sponsor (program)	Report
Oconee 3	1981	1973	860	B&W/Duke	Dry-Cylinder	NRC (RSSMAP)	NUREG/CR-1659
Sequoyah 1	1981	1981	1148	W/TVA	Ice Condenser	NRC (RSSMAP)	NUREG/CR-1659
Grand Gulf 1	1981	1982	1250	GE/Bechtel	Mark III	NRC (RSSMAP)	NUREG/CR-1659
Calvert Cliffs 1	1981	1974	845	CE/Bechtel	Dry-Cylinder	NRC (RSSMAP)	NUREG/CR-1659
Crystal River 3	1982	1976	797	B&W/Gilbert	Dry-Cylinder	NRC (IREP)	NUREG/CR-2515
Browns Ferry 1**	1982	1973	1065	GE/TVA	Mark I	NRC (IREP)	NUREG/CR-2802
Arkansas 1**	1982	1974	836	B&W/Bechtel	Dry-Cylinder	NRC (IREP)	NUREG/CR-2787
Millstone 1**	1983	1970	652	GE/EBASCO	Mark I	NRC (IREP)	NUREG/CR-3085
Calvert Cliffs 2	1983	1974	845	CE/Bechtel	Dry-Cylinder	NRC (IREP)	Draft

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[1] NSSS--Nuclear Steam System Supplier; AE--Architect-Engineer.

**PRAs used in this study.

questions concerning the importance of the techniques used for the analysis as compared to the safety of the power plant itself. Thus, it has been extremely difficult to directly compare the results of the studies or to determine the importance of a modified approach. In addition, there is a cost associated with every change to the methods, data, or assumptions used in the PRA. This cost manifests itself not only in the resources required to develop and implement the change, but also in the review process for assuring that the change is valid and has been implemented appropriately.

This report provides an assessment of the reliability methodologies used in a selected set of existing PRAs. The objective is to characterize the impact of employing methods requiring increasing levels of detail and effort on results of the PRAs. The impact on results is measured in terms of changes in the relative ordering of dominant sequences and in the identification of dominant vs. non-dominant sequences. This is a good way to represent impact on changes in perceptions of plant vulnerabilities. In addition, changes in estimated core melt probabilities were estimated. The methods examined are delineated as twenty topic areas, defined in Table 1.2, all arising from within the general framework of fault tree/event tree analysis. A systematic approach to extracting objective comparisons within the various topic areas is described.

Six completed PRAs were selected to be analyzed for this study: Surry 1, Big Rock Point, Zion 1 and 2, Browns Ferry 1, Arkansas 1, and Millstone 1. They include PWRs and BWRs as well as industry and government sponsored risk assessments. They represent a reasonable set of PRA methodology variations that could readily be analyzed and provide meaningful insight into the impact and level of effort required in a PRA. The identities of the six PRAs are not maintained so the report can focus on the efficacy of differing methods without any implication of judgment on individual studies.

The next chapter of the report (Technical Approach) will provide an overview of the study methodology and its limitations, including the details of the metrics that were used in the comparisons. Results will be presented and discussed in Section 3.0. Finally, Section 4.0 will present the conclusions and recommendations of the study.

Table 1.2 DEFINITION OF TOPIC AREAS

DESIGNATOR	DESCRIPTION	DESIGNATOR	DESCRIPTOR
IIE	Identification of transient and LOCA initiators	CM	Analysis of common mode human error
FIE	Determination of frequency of transient and LOCA initiators	R	Treatment of recovery
ET	Event tree modeling characteristics	AC	Modeling of AC power systems
SDA	System hardwired dependency analysis	L	Modeling of logic systems
SIA	System interaction (other than hardwired) analysis	CC	Common cause analysis
PAHR	Treatment of the post accident heat removal phase	DB	Data base used
HN	Human errors during normal operation	DFP	Use of demand failure probabilities
HA	Human errors during accident progression	MVM	Use of means vs use of medians
		AIE	Aggregation of initiating events
		SSC	Determination of system success criteria
		TM	Modeling of test and maintenance outages
		EQ	Modeling of equipment environmental qualification

2.0 TECHNICAL APPROACH

A Probabilistic Risk Assessment (PRA) is a very complex undertaking involving many disparate methodological topic areas. Any given topic area is amenable to analysis by a variety of approaches. In some cases the alternatives are mutually exclusive; often, however, the spectrum of alternative methods is merely a reflection of the range in the level of detail which an analysis can take. For example, with regard to the topic of the reliability data base (DB), one approach would be to rely entirely on generic data. Another would be to start with the same generic data but modify it, using Bayes' Theorem, on the basis of plant-specific data. These two approaches are not so much fundamentally different (as a labeling of "classical vs Bayesian" would imply) as that the latter differs by the addition of an extra step, namely the plant-specific analysis. In this report, this is considered to be an increased level of detail requiring extra effort relative to the first approach. The issue at hand is whether such extra efforts are essential to achieving credible results in performing a PRA.

It is important that the insights and guidance provided by this study reflect past experience in actual PRAs rather than just the opinions of the analysts; the study is an empirical one. It was therefore necessary to formulate an approach for systematically extracting from the PRAs under investigation lessons and insights on the impact of alternative methods in terms of well-defined concepts, criteria, and characterizations. While this type of analysis obviously does not lend itself to a high degree of precision, the outcome should be reproducible if the study were repeated, with the same objectives and approach, by a different set of analysts.

The basic problem is to decide how much effort should be devoted to each of the essential topic areas that must be addressed in a PRA. (For purposes of this study, "how much effort" is meant to convey the same notion as level of detail, depth of analysis, or degree of sophistication.) The main criterion is that the methods chosen should produce results worthy of a high degree of confidence. Among other things, this requires that the outcome of a PRA not be highly sensitive to variations in the degree of effort devoted to analyzing the various topic areas. This leads naturally to the idea of measuring the impact on PRA results of changes (increments) in level of effort for individual topic areas. With this idea as the foundation, we have built an approach from the following ingredients:

Topic Areas: From a starting list, we developed a comprehensive list of methodological topics covering the PRA reliability analysis process. The list was shown in Table 1.2. Accident progression, containment response, radiological releases, and consequences are outside the scope of our considerations. Also, "external event" analyses covering initiators from seismic events, floods, wind and fire hazards were not addressed in this study.

Baseline PRA: It was necessary to define a benchmark methodology from which to measure changes or increments in levels of effort. The baseline is defined by specifying an approach to each of the topic areas that would constitute a "minimal" PRA. For some topics, the baseline approach would be to do nothing. To our knowledge, a baseline PRA according to our definition has never been performed. That is, all PRAs have employed more than the minimally required effort in some of the topic areas.

Incremental Level of Effort: An absolute scale for characterizing the incremental levels of effort associated with variations in methods and approaches was invented. The scale is labeled: A. None; B. Minimal; C. Moderate; D. Significant; E. Large. Definitions are as follows:

A.	None	Baseline level of effort
B.	Minimal	Small extra effort above baseline level, perhaps 1-2 man-weeks. Work could probably be accommodated without an increase in overall manpower requirements and without lengthening the schedule for completion of the PRA.
C.	Moderate	Moderate amount of additional work above the baseline, up to about 1 man-month. Small but measurable increase in overall manpower requirement but no lengthening of schedule.

D.	Significant	A larger increase in manpower above the baseline level, perhaps 1-2 man-months. Small increase in project duration could be anticipated.
E.	Large	A relatively large increase in effort and manpower, 2-6 man-months, would be required to perform the expanded scope of work represented by this level; a significant increase in project duration could be anticipated.

For individual topics, two to four increasing levels of effort were defined in terms of specific methods and variations. The lowest level is always considered to be the baseline or minimal level and, for some topics, is no effort at all. These are topics which might be omitted from a baseline PRA. System Interaction Analysis (SIA) is an example.

The levels of effort for each topic were defined after all six PRAs had been pre-analyzed for each topic. Thus, the defined levels were for the most part suggested by the options actually chosen in the six PRAs for completing the work defined by each topic area. This helped to assure the approach would be general enough to permit application to all six PRAs under consideration yet specific enough that reliable measures could be obtained and differences between plants could be distinguished for each topic area.

The individual levels of effort within topics were placed on the absolute scale, A-E, defined above, according to the judgments of the analysts (all with extensive PRA experience) as to how much effort would be necessary to carry out the work. This was among the more subjective aspects of the analysis but two independent teams arrived at very nearly the same results; differences never involved more than one level of effort and these were resolved in discussions between the teams. Table 2.1 indicates the relationships between topic areas, alternative methods and levels of effort.

Some judgment was occasionally required when assigning a particular PRA to a particular topic level of effort. Whenever questions arose as to the placement of PRAs in a level of effort, a second team of analysts

Table 2.1 INCREMENTAL LEVELS OF EFFORT FOR EACH TOPIC

TOPIC DESIGNATOR	TOPIC DESCRIPTION	LEVELS OF EFFORT
IIE	Identification of initiating events	A WASH-1400 initiators used
		B WASH-1400 plus EPRI NP-801 used (generic data)
		C Generic data plus plant specific data
FIE	Frequency of initiating events	A Generic (for example from NP-801)
		B Generic plus classical use of plant specific data
		C Two stage bayesian
ET	Event tree modeling characteristics	A Small systemic event trees
		B Large event trees including global human actions
SDA	System hardwired dependency analysis	A Use of engineering judgement
		C Systematized hand analysis
		E Boolean reduction code used
SIA	System interaction analysis	A No analysis performed
		C Engineering insight
		D Plant walkthrough
		E FMEA plus plant walkthrough
PAHR	Treatment of the post accident heat removal phase	A Standard (WASH-1400) accident length used (24 hours)
		B Realistic accident length based on sequence requirements
		D Realistic accident length and component recovery considered

Table 2.1 INCREMENTAL LEVELS OF EFFORT FOR EACH TOPIC (continued)

TOPIC DESIGNATOR	TOPIC DESCRIPTION	LEVELS OF EFFORT
HN	Human errors during normal operation	A Scoping human error analysis C Non-detailed human error analysis E Detailed human error analysis
HA	Human errors during accident progression	A Scoping human error analysis C Non-detailed human error analysis E Detailed human error analysis
CM	Common mode human error analysis	A No analysis performed B Analysis performed on an inconsistent basis D Detailed consistent analysis performed
R	Treatment of Recovery	A No recovery actions considered C Recovery of human errors and actuation faults considered D Recovery of human errors, actuation faults and individual component faults considered
AC	Modeling of AC power systems	A Previous study results used C Simple non-detailed models used E Detailed system models used
L	Modeling of logic systems	A Previous study results used C Simple non-detailed models used E Detailed system models used
CC	Common cause analysis	A No analysis performed B Analysis performed on components determined by engineering judgement C Detailed comprehensive analysis performed

Table 2.1 INCREMENTAL LEVELS OF EFFORT FOR EACH TOPIC (continued)

TOPIC DESIGNATOR	TOPIC DESCRIPTION	LEVELS OF EFFORT
DB	Data base used	A Generic C Generic plus classical plant specific E Plant specific, bayesian
DFP	Use of demand failure probabilities	A Use of generic demand failure probabilities for long test periods C Use of failure rates developed from DFP for long test periods
MVM	Use of means vs use of medians	A Use of mean failure rates A Use of median failure rates
AIE	Aggregation of initiating events	A Complete aggregation C Functional (phenomenological) aggregation E No or little aggregation
SSC	Determination of system success criteria	A FSAR data used C Plant specific (realistic) analysis performed
TM	Modeling of test and maintenance outages	A Generic data used B Generic data plus plant specific repair times used D Plant specific data used
EQ	Modeling equipment environmental qualification	A Do not consider B Use engineering judgment C Estimate environmental conditions at time of accident and use manufacturers' specifications for equipment E Estimate environmental conditions at time of accident and perform engineering analyses of equipment to estimate probability of failure

would perform the analysis. Differences were resolved through discussion between the teams.

Two comments are in order. First, we have tacitly implied that a higher level of effort leads in some sense to a better analysis, e.g., through a higher level of detail or sophistication, more realistic results or results worthy of greater confidence may be produced. This is generally true, the issue being whether the improvement is worth the extra effort. There are exceptions, however. For example, the topic "aggregation of initiating events (AIE)" has as its highest level of effort no or little aggregation at all. This is almost certainly inefficient and is likely to obscure potential insights into plant vulnerabilities. Second, the topics may not be independent in the sense that the appropriate level of effort for one topic may depend on the level chosen for another topic. For example, the appropriate level for analysis of AC power (AC) depends on the level chosen for analysis of hardwired system dependencies (SDA). Except for this readily apparent case, no systematic attempt was made in this study to identify all such interdependencies. However, this is not a serious limitation at the level of precision appropriate to a study of this nature.

Impact on PRA Results

It was decided early in the study that for a given level of effort expended on a topic, a measure of impact that accounted for the identification and ordering of the dominant accident sequences would be more useful than a measure that simply indicated the impact on the core-melt frequency. This is because the identification and ordering of dominant sequences is more pertinent to understanding plant vulnerabilities. The influence of PRA methods on core melt frequency was considered as a secondary measure of impact for nine of the twenty topic areas. Judgments of correctness of the PRA analyses were not to be included in the scope of the study; only impact for the level of effort expended.

The basic approach was to assess the impact, for each of the six PRAs and twenty topic areas, by comparing the ordering and identification of the dominant sequences, or the core melt frequency, actually achieved in the PRA to the situation that would have resulted if the baseline level of effort had been used. The baseline situation was generally determined by re-estimating the probabilities of dominant cutsets of dominant sequences. Also, to the extent permitted by the available documentation, cutsets and sequences that were not found to be significant in the original PRA but appeared to be candidates for dominance in a baseline PRA were identified and their probabilities re-estimated.

For the main thrust of the analysis, wherein impact was measured in terms of ordering of sequences, analysis of each PRA with respect to a given topic area resulted in placement of the PRA into one of five levels of impact which were defined as follows:

Impact Level 1 - Effort above the baseline level resulted in no apparent change in which sequences were dominant or in their order.

Impact Level 2 - Added effort resulted in a slight rearrangement of dominant sequences, but no interchange between dominant and non-dominant sequences occurred. Perceptions of plant vulnerabilities did not change.

Impact Level 3 - Added effort resulted in either a major rearrangement of the dominant accident sequences or a slight rearrangement of the dominant sequences and a minor interchange between dominant and non-dominant sequences. There could be a slight shift in viewpoint concerning plant vulnerabilities.

Impact Level 4 - Extra effort beyond the baseline caused a slight interchange between dominant and non-dominant sequences, possibly with a rearrangement of the dominant sequences. Perceptions of plant vulnerabilities may have changed moderately.

Impact Level 5 - The extra effort leads to a major reordering of dominant versus non-dominant sequences and a major change in perception of plant vulnerabilities.

In all cases, level 1 of the impact measure was automatically assigned to the baseline level of effort, level A. Some judgment was required in assigning levels of impact to the levels of effort for each topic area. For instance, if just one dominant sequence near the bottom of the list of dominant sequences were to change to nondominant status and this did not alter in any way our perception of plant vulnerabilities, a level 3 impact would have been assigned instead of a level 4 impact. Similarly, a major reordering of the dominant sequences with some sequences changing status between dominant and nondominant categories might be assigned a level 5 impact instead of a level 3 if our perception of plant vulnerabilities was substantially altered. Several of the topics were assessed several times by different teams; differences were resolved to make the assignments as objective as possible.

The secondary impact measure, the effect of the levels of effort for each topic on the core melt frequency, was assessed in an analogous way. However, only those topics where enough information was available to permit a clear-cut quantitative result were assessed. There were nine such topics: use of demand failure probabilities (DFP); common cause analysis (CC); common mode human error analysis (CM); human errors during normal operation (HN); human errors during accident progression (HA); treatment of recovery (R); identification of initiating events (IIE); modeling of AC power systems (AC); and treatment of post accident heat removal phase (PAHR).

The results in terms of the primary measure are presented as matrices showing the level of effort versus the measure of impact as illustrated by Figure 2.1. The absolute scale for level of effort is shown down the left side of this matrix, while the impact on the identification and ordering of the sequences is shown across the top. The matrix is drawn for a particular topic area, and the PRAs fall into cells of the matrix. The arrows indicate the high and low payoff portions of the matrix. Thus, for the hypothetical topic area, PRA-X shows no impact above the basecase for a level of effort B. On the other hand, PRA-Z shows a high impact from a level of effort C, which is a relatively small additional effort over the baseline level. PRA-Y shows a modest impact for a relatively high level of effort.

Matrices such as that shown in Figure 2.1 are presented in Section 3.0 for each topic area. Also, matrices are presented for each PRA with the topic areas shown in the matrix cells in Appendix B. Summary matrices are also presented.

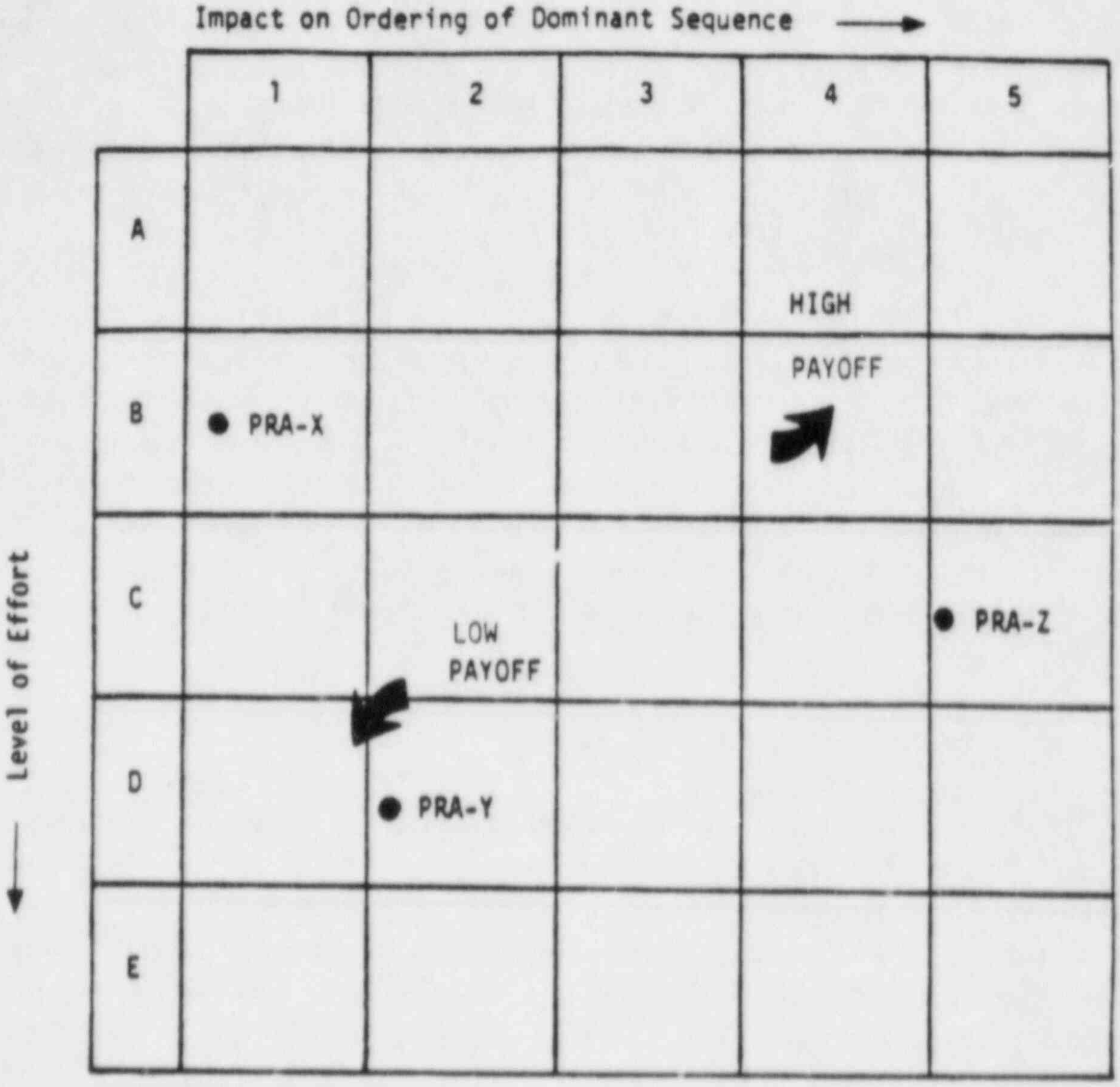

Figure 2.1 CONCEPTUAL ILLUSTRATION OF EFFORT-IMPACT CHART

3.0 RESULTS

In this section we present the results of the analysis in several forms. The results with impact measured in terms of dominant sequence ordering are presented and discussed by topic area. For each topic area the effort and level of impact are categorized for each of the six plants analyzed for this report. The plants and probabilistic risk assessments (PRAs) used for this analysis are not specifically identified; instead, the plants and their corresponding PRAs are referred to as plant 1 through plant 6 and PRA 1 through PRA 6. (The results grouped on a plant by plant basis are presented in Appendix B.)

For each of nine topic areas for which adequate information could be obtained from the available PRA documentation, the effect on the core melt frequency of additional effort beyond the baseline was estimated for each of the six PRAs. The core melt frequency calculated assuming a minimal effort for the topic area was compared to the core melt frequency presented in the PRA. The change in core melt frequency was determined and expressed as a factor relative to the value estimated in the PRA. These results are briefly noted in discussions of individual topics and are presented collectively in Section 3.2.

3.1 RESULTS BY TOPIC AREA

For each of the 20 topic areas, the results of the analysis for the six plants are presented. The results for each topic include an explanation of the topic, a brief description of the possible levels of effort, a description of the level of effort expended by each PRA, and the impact on the results of the PRAs. The PRAs are briefly discussed individually and collectively; a graphical summary of all six PRA efforts and impacts is presented as an effort-impact matrix.

3.1.1 IIE - Identification of Initiating Events

This topic area includes the work performed in the PRA to identify both transient and LOCA initiating events. Three levels of effort were assigned as indicated earlier in Table 2.1. The baseline level of effort, level A, is to use WASH-1400 (Ref. 1) initiating events only. An increase in effort to level B requires that the list of WASH-1400 initiating events be expanded to include EPRI NP-801 (Ref. 2) transient categories. A level C effort involves the use of generic events augmented by an analysis of plant-specific initiating events to complete the initiator list. Levels A, B and C were sufficient to span the range of efforts used in the six PRAs considered. Levels D and E were not defined for this topic.

The impact level was determined by first identifying the accident sequence initiators found through the additional effort, above the baseline, for each PRA. Then the dominant accident sequences that were initiated by these events, or by an aggregated group of initiators that included some plant-specific initiators, were identified. The impact level assigned reflects the differences in the dominant accident sequences that resulted from the inclusion of initiators that would not have been identified if a baseline effort had been performed. This topic is also one of the nine for which impact on core melt frequency was analyzed.

Four of the six PRAs used plant-specific as well as generic initiating events. The impact of this extra effort ranged from no impact to the identification of half of the dominant accident sequences for Plant 3. In three of the PRAs some dominant accident sequences were found because of the additional effort. The results for this topic area are shown in matrix form in Figure 3.1. (In Figures 3.1 through 3.20, Roman rather than Arabic numerals are used to delineate the PRAs.) Comments on individual PRAs follow below.

PRA-1: Effort C; Impact 2

PRA-1 used both WASH-1400 and EPRI NP-801 as the basic data source for the identification of initiating events. These data were modified by using plant-specific Licensee Event Reports to identify potential initiators for this plant. For the LOCA initiators, the number of LOCA types was based on plant-specific mitigation system requirements. For the identification of initiating events this is a level C increase in effort. The increased effort applied to this topic area did not result in the identification of any initiators that by themselves created new dominant accident sequences. However, once the transient initiators were aggregated, the effort expended in identifying plant-specific initiators did result in some additions to the

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	VI				
B				IV	
C	V	I		II	III
D					
E					

Figure 3.1 Effort-Impact Profile
Topic Area: Identification of Initiating Events

contributors in the initiator categories (such as loss of Power Conversion System transients). These changes resulted in a slight rearrangement of the dominant accident sequences, a level 2 impact. The estimated core melt frequency was increased by about 10 percent due to the level C effort.

PRA-2: Effort C; Impact 4

PRA 2 supplemented use of the generic lists of initiating events from WASH-1400 and NP-801 with additional generic data sources. In addition to the generic initiators, the analysts who performed PRA 2 considered the possibility of plant-specific initiators. Their analysis consisted of a Failure Modes and Effects Analysis (FMEA) for the support systems whose failure could possibly result in a reactor trip. The identification of generic and plant-specific initiators in the detail performed in this PRA is a level C increase in effort. This extra effort resulted in the identification of an additional initiator, loss of instrument air, which led to the identification of three of the 16 dominant accident sequences. One of these three sequences is the most dominant of the internally initiated accident sequences, increasing core melt probability by about 30 percent over what would have been estimated by the baseline effort. The identification of a few additional dominant sequences is a level 4 impact.

PRA-3: Effort C; Impact 5

In PRA-3 a very detailed list of plant-specific initiators was developed. Failures were postulated in every plant system which interfaced with a mitigating system to determine if a plant trip and degraded condition could result. As in PRA-2, this PRA used an FMEA to identify support system failures that could be initiators. A number of different failures were examined for each system considered, including many partial system failures. This is a level C increase in effort. During the performance of the FMEA one AC and 2 DC buses whose failure would result in a reactor trip were identified. Eight of the fourteen dominant accident sequences for this plant are initiated by a loss of power at one of these three buses. The addition of these eight sequences approximately doubled the estimated core melt frequency. This was the largest impact on core melt frequency in the six PRAs for this topic. These sequences would not have been identified had the analysts not performed the detailed FMEA and therefore the increased effort resulted in a level 5 impact.

PRA-4: Effort B; Impact 4

PRA-4 utilized the WASH-1400 initiators augmented by other generic initiators identified in the FSAR and EPRI NP-801. No plant-specific evaluation of potential initiators was performed. This is a level B increase in effort. The use of these additional generic initiators resulted in the identification of a dominant sequence caused by one of these initiators (a loss of offsite power induced by a spurious safety injection signal). The impact on the PRA results is level 4. Although the extra effort had a moderate impact with respect to perceptions of plant vulnerabilities, it increased the core melt frequency by only about 10 percent.

PRA-5: Effort C; Impact 1

PRA-5 utilized WASH-1400 initiators plus other generic initiators identified primarily in EPRI report NP-801. Additionally, an evaluation to find plant-specific initiators was performed. This involved a review of support systems to identify potential initiators, particularly those that would have an effect on mitigating systems. This qualifies as a level C increase in effort for this topic area. Although some plant-specific initiators were identified, these did not result in any new dominant sequences nor did they rearrange any existing dominant sequences. This is a level 1 impact. They had negligible effect on the plant core melt frequency.

PRA-6: Effort A; Impact 1

A generic list of initiators based on WASH-1400 was used in PRA-6. This has been defined as a baseline level of effort for this topic, a level A effort. Consequently the impact on the overall results is categorized as Level 1.

3.1.2 FIE - Estimation of the Frequency of Initiating Events

This topic area includes the work performed to estimate the frequencies of the transient and accident-initiating events. Options range from simply using generic initiating event frequencies to using generic and plant-specific data to produce Baysian estimates of initiator frequencies. Three levels were identified. The baseline level of effort A, is to use only generic data for initiator frequencies. A level B increase in effort requires the use of generic data and plant-specific data to estimate some initiating event frequencies (classical estimates). The third level identified, a level C effort, involves estimating initiating event frequencies using a two-stage Baysian process.

The impact of increased levels of effort was determined by replacing the plant-specific initiator frequencies with generic data from WASH-1400 and NP-801. The frequencies of dominant accident sequences and some non-dominant sequences were recalculated. Impact levels were assigned based on the differences between the PRA results and the recalculated results.

Four of the six PRAs used plant-specific data in one form or another, classically or modified using a Bayesian technique, for at least some of the initiators. In two cases the use of plant-specific data resulted in modifications to the list of dominant accident sequences. In the case of PRA-4 the methodology used to modify the frequency of initiating events led to the change in the list of dominant accident sequences rather than the fact that plant-specific data were used. These results are shown in matrix form in Figure 3.2. The PRAs are discussed individually below.

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	III VI				
B	V	I		II	
C				IV	
D					
E					

Figure 3.2 Effort-Impact Profile
Topic Area: Estimation of the Frequency of Initiating Events

<u>PRA-1: Effort B; Impact 2</u>

Plant-specific data were used for all transient initiators in PRA-1. These data were used classically, that is, in place of generic data, not as a basis for modifying the generic data. LOCA initiator frequencies were WASH-1400 frequencies altered to account for the different number of LOCA categories used in this PRA. The modifications to the LOCA frequencies were based on the fraction of all piping that fit into each of the LOCA categories. This is a level B increase in effort. The modifications to initiator frequencies did not result in significant changes from the generic initiator frequencies and resulted in only minor rearrangement of the dominant sequences, a level 2 impact. In particular, the sequences initiated by a loss of offsite power were found to be a factor of 2 or 3 less frequent than generic data would indicate. These are the sequences shifted the most due to the use of plant-specific initiator frequencies.

PRA-2: Effort B; Impact 4

The analysts who performed PRA-2 developed a plant-specific data base for frequencies of the transient initiating events, a level B effort. Generic data were used only in those cases where plant-specific data appeared to be inadequate. In many of these cases, owners group information was used rather than data from NP-801. LOCA frequencies were based in part on a plant-specific analysis of piping size and location. Some shifting in the order of the 16 dominant sequences was noted and two sequences initiated by a spurious opening of the turbine bypass valve appear as dominant sequences due to the larger failure frequency that resulted from the use of plant-specific data. Additionally, a plant-specific value for inadvertent safety/relief valve openings (which was smaller than the generic values by at least a factor of 10) may have resulted in the elimination of one sequence that would have been dominant had generic initiator frequencies been used. This is a level 4 impact.

PRA-3: Effort A; Impact 1

In PRA-3 generic data were used for the frequencies of all the initiating events. Even the plant-specific initiators identified were quantified using generic data for similar occurrences throughout all U.S. nuclear plants. The level of effort is A; thus, the impact on the analysis is level 1.

PRA-4: Effort C; Impact 4

PRA-4 initiating event frequencies were determined by using generic data as prior distributions for a Bayesian analysis. Plant-specific data were used to form the posterior estimates. This is a level C increase in effort. It resulted in two major effects on initiating event frequencies. First, for very infrequent events of high uncertainty, specifically large and medium break LOCAS, the small size of the plant-specific data base as related to the expected frequency of the event results in a much higher posterior frequency than the generic data and thus an overall increase in these LOCA frequencies. The approximately one order of magnitude increase in these frequencies resulted in the identification of one medium LOCA dominant accident sequence which would not have been dominant had generic

LOCA frequencies been used. Second, for generically frequent transients which have not occurred at the plant, the analysis results in a plant-specific posterior frequency estimate which is much lower than the generic and thus in an overall decrease in the transient frequency. The effect on the transient initiators did not have as large an impact on the dominant sequences as the change in LOCA frequencies. Thus, the impact on the analysis is level 4.

PRA-5: Effort B; Impact 1

PRA-5 primarily used generic data for the frequencies of the initiating events. However, for some types of initiators plant-specific data were used instead of generic data. Uniqueness of plant system designs was used as the basis for determining whether to use plant-specific or generic data. That is, if a system whose failure could result in a plant trip was determined to be of a significantly different design than the "generic" system, plant-specific data were used. PRA-5 exerted a level B increase in effort for the determination of the frequency of initiating events. This additional effort did not impact the frequency of event classes once they were aggregated and therefore did not impact the dominant accident sequences. This is a level 1 impact.

PRA-6: Effort A; Impact 1

Generic data were used for the frequencies of all the initiating events in PRA-6. This is the baseline level of effort, level A, and is considered not to have an impact on the overall results. Thus, the impact is categorized as level 1.

3.1.3 ET - Event Tree Modeling Techniques

This topic area covers the options for accident sequence modeling using event trees. Options include both small systemic event trees, one for each class of initiating events (IREP style), and large event trees developed for each plant state (large event tree, small fault tree style). The small systemic event trees were adopted as the baseline level of effort, level A. The large event tree technique was assigned to the level B increase in effort category.

Only one of the six PRAs selected for this study performed anything other than the baseline effort for event tree modeling. To evaluate the impact, a qualitative assessment of changes in the dominant accident sequences was made. The extra effort for this one PRA resulted only in a level 2 impact. The results for this topic area are shown in matrix form in Figure 3.3.

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	*				
B		IV			
C					
D					
E					

* I, II, III, V, VI

Figure 3.3 Effort-Impact Profile
Topic Area: Event Tree Modeling

PRA-1: Effort A; Impact 1

Small systemic event trees were used for PRA-1. No operator actions are modeled on the event trees. This is a level A effort for the event tree model. By definition the impact of this effort is a level 1 impact.

PRA-2: Effort A; Impact 1

Small systemic event trees were used for PRA-2. Only on the event tree for loss of offsite power is a support system, AC power, present. However, unlike some other PRAs which used the small event tree technique, PRA-2 did include some recovery actions, i.e., some operator actions, on the event trees. This still qualifies as a small event tree in part due to the fact that many of the system interactions modeled on large event trees are handled as part of the fault tree analysis in this case. This is a level A effort and has a level 1 impact by definition.

PRA-3: Effort A; Impact 1

Small systemic event trees, which included only front-line mitigating systems, were used in the analysis for PRA-3. This is an A level of effort; thus the impact on the analysis is level 1.

PRA-4: Effort B; Impact 2

A large event tree approach was utilized in PRA-4. The event tree explicitly included functional (or "global") operator actions on the tree. Additionally, support systems were implicitly included on the tree by the use of support states (the support state becomes an event in each sequence). This is a level B increase in effort. Constructing the event tree in this way has very little effect on the results. These event trees can be used in the same way as small event trees. The only effect is that the inclusion of the sequence-dependent operator actions on the trees resulted in a different treatment (or emphasis) of these actions which led to a slight rearrangement of the order of the dominant sequences. Thus, the impact on the analysis is level 2.

PRA-5: Effort A; Impact 1

Small systemic event trees were used for PRA-5. Only front line mitigating systems were included on the event tree (no support systems were included). The only human action included on any of the event trees was included because the human action failure probability dominated the system failure probability. This type of event tree analysis is a level A effort for this topic area. By definition this level of effort has a level 1 impact.

PRA-6: Effort A; Impact 1

Small functional and systemic event trees were used in PRA-6. The headings on the systemic event trees are all front line systems except for the AC power system which is also included on the systemic event trees. This corresponds to the baseline level of effort, level A. Thus, the impact on the overall results is categorized as level 1.

Since only one of the PRAs differed significantly from the others in its approach to event trees, the present analysis is inconclusive from the standpoint of choosing appropriate levels of effort. Event trees are so basic to the PRA concept that analytical technique is of fundamental importance to several methodological topic areas. Perhaps the two most important considerations are the preferences of the PRA sponsor and the prerogatives of the analysts.

3.1.4 AIE - Aggregation of Initiating Events

This topic refers to the philosophy of initiating event aggregation utilized in the PRA. Three levels of effort were identified as options concerning aggregation of initiating events. The baseline level, level A, is defined as complete aggregation, i.e., one initiating event category with a single event tree. The second level, a level C increase in effort, is defined as aggregation of initiators along functional or phenomenological lines, e.g., transients and LOCAs as in IREP. The third level, a level E increase in effort, is defined as little or no aggregation. The requirement for an event tree for each individual initiating event makes this a level E increase in effort.

To evaluate the levels of impact for the PRAs that exerted more than the baseline effort, the identified initiating events were aggregated to the WASH-1400 level (nearly complete aggregation). Obviously, if little or no aggregation of initiating events is performed there are more accident sequences, each contributing a smaller percentage to the total accident frequency. The impact of additional effort was not measured by a change in the number of dominant sequences, but rather, on the basis of whether the aggregation of the initiating events resulted in a change in the perceived importance of some events, or in the addition of some dominant sequences.

The aggregation of initiating events was treated in three different ways by the group of six PRAs. Three PRAs performed functional aggregation, one complete aggregation, and two little or no aggregation. While these differences in techniques do not necessarily change the total results of the PRA they can lead to a changed perception of what the dominant sequences are for a particular plant. Functional aggregation of transient initiators tends to emphasize transients more than LOCAs, while no aggregation tends to increase the perceived importance of LOCAs as dominant sequences. The results for this topic area are presented in matrix form in Figure 3.4.

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	VI				
B					
C		I III V			
D					
E	II		IV		

Figure 3.4 Effort-Impact Profile
Topic Area: Aggregation of Initiating Events

PRA-1, PRA-3, PRA-5: Effort C; Impact 2

Functional aggregation was performed on the initiating events for PRA-1, PRA-3, and PRA-5. That is, all initiators which would have the same overall effects on the plant response and mitigating systems were grouped into a single category for the event tree construction and sequence analysis. This is a level C increase in effort. The effect was a slight reduction in the frequency of one class of transient initiators by removal of some transient initiators to their own category. This reduction was only sufficient to move a few of the dominant sequences down in relation to some of the others, but not enough to change the dominant sequence list. Thus, the impact on the analysis is level 2.

PRA-2: Effort E; Impact 1

The analysts who performed PRA-2 chose to do almost no aggregation of initiating events. Several transient initiators were grouped under the heading of a turbine trip but very few of the remaining transients are grouped in any way. This resulted in the construction of over twenty event trees, each of which was analyzed independently. The analysis of that large a number of event trees results in a level E increase in effort. The lack of aggregation for the initiating events at plant 2 did not impact the identification of dominant accident sequences. There were more sequences, each of which contributed a smaller fraction to the core melt frequency. However, no sequences were eliminated and none were found due to the aggregation. For PRA-2 the impact of this topic area is a level 1 impact.

PRA-4: Effort E; Impact 3

In PRA-4 very little aggregation was performed; basically, event categories identified in the safety analysis section of the FSAR were utilized. Since no plant-specific functional aggregation was performed, not all events which resulted in the same plant response and system effects were aggregated. This constitutes a level E increase in effort; it resulted in diluting the contributions and causing an occasional sequence, which would have been dominant had the initiators been aggregated, to be broken up into a set of sequences, only some of which were dominant. For instance, several initiators that could have been classified as a loss of the power conversion system were each treated as separate initiators. Had some aggregation of the initiating events been performed the transient initiators would have been more dominant, especially relative to the LOCA initiators. Thus, the impact on the analysis is level 3. It should be noted that this particular impact, unlike the others which are noted, is definitely negative, in the sense that greater effort led to a poorer result. This has nothing to do with whether the procedure used is "right" or "wrong" in an absolute sense, but simply that it accomplishes nothing other than the loss of information.

PRA-6: Effort A; Impact 1

For PRA-6, the initiators were aggregated into two broad categories of LOCAs and transients, with separate event trees developed for different LOCA sizes. Although all the transients were aggregated onto one generic event tree, unique transient initiators such as loss of offsite power were treated separately during the analysis. The level of effort in this case is A (baseline) and the impact on the overall results is categorized as level 1.

3.1.5 SDA - Hardwired System Dependency Analysis

This topic covers the work performed in the PRA to identify and quantify the impact of hardwired system dependencies, such as the impact of AC power or component cooling, as well as the impact of shared components among systems.

Three options leading to three levels of effort were identified. The baseline, level of effort A, is to model hardwired system dependencies using engineering judgment to identify and account for dependencies. This level of effort is based on the prior knowledge and insights of the analysis team. Very little effort is used in the actual analysis of the systems being modelled. An increase in effort to level C involves the use of a systematic hand analysis to account for hardwired dependencies. At this level of effort the plant systems are examined, generally through the use of P&IDs and one-line diagrams, and the PRA analysts select the system dependencies to be analyzed. This is the technique used to develop the system states which are the basis for the large event tree style. The approaches taken in the hardwired dependency analysis for levels of effort A and C are very similar. The difference in effort is a result of a more rigorous system analysis for a level C effort. However, a level E effort involves a different approach to this topic area. Rather than the analyst being responsible for identifying all system interactions, especially interactions that involve several systems, a large-scale Boolean reduction code is used. Use of this option requires considerable effort in developing and employing a consistent component naming scheme and in preparing data for the code.

The dominant cut sets for the PRAs that performed a level C or level E effort were examined and the component faults that appeared to have been found through this extra effort were identified. The changes in the dominant accident sequences resulting from the removal of the identified component faults is the basis for the determination of the impact level.

Additional effort in the system hardwired dependency analysis had an impact on only two of the five plants which expended the extra effort. The two plants that did show an impact were the two for which the level E increase in effort was performed. The three plants where only a level C increase in effort was performed did not show any impact due to the increased effort. The results for this topic area are shown in matrix form in Figure 3.5.

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	VI				
B					
C	I II IV				
D					
E			III	V	

Figure 3.5 Effort-Impact Profile
Topic Area: Hardwired System Dependency Analysis

PRA-1: Effort C; Impact 1

Fault trees were constructed for all front line and support systems in PRA-1. Although these fault trees were fairly detailed, the analyses of hardwired system dependencies were evaluated using simplified computer models which relied a great deal on the ability of the analyst to recognize the system interactions that exist. In effect, the hardwired dependency analysis was performed by hand (by the analyst), not by using computer models of the systems. This method may not include dependencies which are not support system interfaces. For example, dependencies which are the result of shared components or are imbedded in cut sets which are only partially identical (not entirely common) between two systems might not be found. This study made no attempt to find these dependencies but rather performed a purely statistical bounding calculation to estimate the potential contribution of "other unidentified dependencies." This is a level C increase in effort for PRA-1. The effect of this method is that subtle and intrusive dependencies, if present, are likely to be missed. Further, the statistical bounding calculations do not allow the identification of any actual dependencies, so no engineering insights would be gained from that technique. At this level of effort, no dependencies are identified as dominant contributors which would not have been identified by the baseline level of effort. Thus, the impact for this topic is level 1.

PRA-2: Effort C; Impact 1

Although detailed fault trees were constructed for all front line and support systems in PRA-2, the hardwired system dependencies were actually evaluated by hand. Each of the system fault trees was evaluated independently of the other system fault trees. This implies that each analyst who performed a system analysis had to identify all the system interactions and assign them an importance. The system fault trees were then modeled assuming different support states for the hardwired system dependencies of importance. This is a level C increase in effort. No hardwired system dependencies were found other than those that would have been found through a baseline effort. Therefore the impact of this additional effort for PRA-2 is a level 1 impact.

PRA-3: Effort E; Impact 3

In PRA-3, hardwired dependencies were handled by detailed modeling on the fault trees and Boolean reduction by computer. The precise nature of each component dependency was explicitly entered on the fault trees as an undeveloped event. This event noted the support system and component from which the dependency was supplied (e.g., electric bus number). The event name matched a gate name on the support system tree, which was then appended onto the undeveloped event. The increase in level of effort is E. This identified some dependencies which may otherwise have been overlooked. The most important of these were room cooling faults that would fail portions of the AC and DC power systems and faults that would fail portions of the emergency feedwater actuation logic. No new dominant sequences were found, just new contributors to sequences already identified as dominant. These new contributors did result in changing the frequencies of a number of the dominant sequences, causing them to be reordered on the dominant sequence list. Thus, the impact on the analysis is level 3.

PRA-4: Effort C; Impact 1

Hardwired dependencies are handled by direct identification and isolation in PRA-4. That is, the analyst was expected to find all the systems interactions and separate them from the main analysis so they could be treated individually, thus creating a series of system models which are totally independent of each other. This method implicitly treats these dependencies as part of the event tree analysis (which is inductive) as opposed to being part of the fault tree analysis (which is deductive). This simplifying method involves a level C increase in effort. This method might easily miss any subtle and intrusive dependencies that are present. At this level of effort, system dependencies had very little impact on the results of this study, thus the impact is level 1.

PRA-5: Effort E; Impact 4

In PRA-5, hardwired system dependencies are handled through detailed fault tree analysis and the use of a Boolean reduction code at the sequence level. This is the most detailed analysis considered for this topic area and would be expected to find the most hardwired system dependencies. This effort qualifies as a level E increase in effort for this topic area. (The methodology used in this PRA is identical to that used in PRA-3.) The effort expended for this topic area resulted in the addition of a few sequences to the list of dominant sequences for this plant and in an increase in the importance of several of the dominant accident sequences. The faults identified in this PRA that may not have been identified had a less detailed analysis been performed were AC power faults. In particular, for the two sequences most affected by the additional effort for this topic, additional AC power faults which propagated through the actuation logic but did not directly affect the mechanical components were identified. These would not have been identified with the baseline effort. This is a level 4 impact.

PRA-6: Effort A; Impact 1

Hardwired dependencies among front line and support systems were essentially handled using engineering judgment in PRA-6. Since each individual system was analyzed separately to find the dominant contributors to the failure of that system, no systematic sequence cut set generation was performed. Thus, some accident sequence cut sets could be missed because of lack of systematic modeling, Boolean reduction and cut set generation. The level of effort in this case is judged to be the baseline, level A, and the impact on the overall result is categorized as level 1.

3.1.6 SIA - System Interaction Analysis

This topic covers the treatment of possible systems interactions other than hardwired systems interactions. Options range from treating no systems interactions other than hardwired interactions to detailed investigations involving plant walk-throughs and Failure Modes and Effects Analysis (FMEA). Four levels of effort were identified for this topic. The baseline level of effort, level A, is to perform no analysis to identify non-hardwired system interactions. Level of effort C is to rely on engineering insights to identify and quantify these interactions. Level of effort D is to perform a plant walk-through to attempt to identify these interactions. Level of effort E is to perform a plant walk-through coupled with a detailed FMEA to identify these interactions.

The impact levels for this topic area were assigned in a manner similar to that for the topic area SDA. The interactions found through the additional effort were identified and the dominant accident sequences reevaluated assuming no interactions were found. The changes to the dominant accident sequences formed the basis for the determination of impact levels.

No PRA considered in this study performed more than a systems interaction analysis based on engineering judgment and insights. No systematic methodology was used to address this topic. In fact, none of the PRAs even referred explicitly to Systems Interactions Analysis as a separate topic. For the three PRAs that did expend more than the minimal effort no additional insights were drawn from the analysis; the highest impact was a level 2. The results for this topic area are presented in matrix form in Figure 3.6.

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	III IV V				
B					
C	I II	VI			
D					
E					

Figure 3.6 Effort-Impact Profile
Topic Area: System Interactions Analysis

PRA-1: Effort C; Impact 1

One system interaction other than hardwired dependencies was considered in PRA-1. This was the effect that the containment functional state could have on the operability of mitigating systems. The selective consideration of one potential systems interaction is an analysis based on engineering insights rather than detailed comprehensive analysis. This is a level C increase in effort for this topic area. The analysis of containment functional state effects had a nearly uniform impact on the dominant accident sequences. Additionally, the changes in sequence frequencies were very small. For these reasons the systems interaction analysis performed in PRA-1 had a level 1 impact.

PRA-2: Effort C; Impact 1

No effort was made in PRA-2 to perform a consistent systems interaction analysis. Rather, only selected items were evaluated for the possibility of a nonhardwired system dependency. This engineering judgment approach to systems interaction analysis is a level C increase in effort. No insights were gained in this systems interaction analysis and therefore it had no impact on the dominant accident sequences.

PRA-3: Effort A; Impact 1

These types of system interactions (spatial, etc.) were not considered in the analysis for PRA-3. No attempt was made to evaluate the potential effects. The level of effort for this topic is therefore A and had an impact of level 1.

PRA-4, PRA-5: Effort A; Impact 1

These types of system interactions were also not considered in the internal events part of PRA-4 nor in PRA-5, which places them in the same effort-impact category as PRA-3.

PRA-6: Effort C; Impact 2

In PRA-6, a potential spatial systems interaction was identified in a sequence involving a large LOCA and failure of the emergency core cooling system. It was assumed that the study searched for this type of interaction although no other cases were identified. Thus, the increase in the level of effort in this case was identified as a level C, an analysis based on engineering insights. This discovery resulted in a small change in placement of one dominant accident sequence. Thus, the impact on the overall results is categorized as level 2.

The results of our examination of this topic are clearly inconclusive as guidance for future PRAs. Part of the problem is that the topic is relatively new (as a separate topic) and not well defined. Moreover, the types of interactions in question can readily be treated within the same analytical framework as hardwired dependencies. This, in fact, is how they have been treated, but only in an ad hoc way, with results highly dependent on the skill, experience, and knowledge of the analysts. At whatever level of effort is deemed appropriate, and whether or not as a separate topic, it seems clear that the subject of system interactions should be addressed in a systematic fashion.

3.1.7 PAHR - Treatment of the Post Accident Heat Removal Phase

This topic covers the treatment the PRA afforded to the post-accident heat removal phase of an accident or transient. In particular, it concerns the duration assumed for the earliest and most dangerous phase of an accident and assumptions regarding recoverability of failed equipment during this phase.

Three levels of effort were identified for treatment of the post accident heat removal phase of a PRA. The baseline, a level A effort, is to use the PAHR accident length of 24 hours as in WASH-1400 and to assume that all mechanical failures that occur in this phase are nonrecoverable. An increase in effort to level B involves use of realistic accident lengths during the PAHR phase but with the assumption, as in WASH-1400, that all mechanical failures during this phase are nonrecoverable. The level D effort involves use of realistic accident lengths but with the possibility of fault recovery during the PAHR phase also considered. This level of analysis might require a code such as the FRANTIC code (Reference 3) to adequately consider fault recovery.

To determine the impact level the dominant accident sequences containing PAHR system failures were examined to determine what type of faults were evaluated. For the PRAs where extra effort was exerted, the dominant sequences were re-evaluated using the baseline assumptions. The impact levels were determined by the changes in the dominant sequences due to the re-evaluation.

Only two of the PRAs evaluated in this study performed more than the baseline effort. In neither of these two PRAs did the additional effort for this topic area result in the identification of dominant accident sequences that would not have been found with the expenditure of the minimal effort. The only impact was in PRA-2 where a rearrangement of the dominant sequences did occur. We consider this to be an inconclusive result for purposes of guiding future PRA efforts. The results for this topic area are presented in matrix form in Figure 3.7.

Impact On Ordering of
Dominant Sequences

Increase In Absolute
Level of Effort

	1	2	3	4	5
A	III IV VI V				
B	I		II		
C					
D					
E					

Figure 3.7 Effort-Impact Profile
Topic Area: Treatment of the Post Accident Heat Removal Phase

PRA-1: Effort B; Impact 1

PRA-1 used a different accident duration (10 hours) than that used in WASH-1400 (24 hours). The difference was based upon a calculation of the time to core melt after an accident where the containment cooling has failed. This plant-specific handling of the length of the post-accident heat removal phase is a level B increase in effort. The change in the post-accident heat removal phase duration did not impact the identification of dominant accident sequences nor did it alter the order of the sequences. This is a level 1 impact.

PRA-2: Effort B; Impact 3

PRA-2 used sequence-dependent accident lengths. This means the length of the demand on the post accident heat removal systems varied from sequence to sequence. The calculated accident durations varied from one month to half a year. The quantification of recovery was treated in the same manner for this phase of the accident as for all other phases of the accident. No special credit was taken to account for possible repair of failed components which would be possible given the long time frame considered and the existence of redundant components. This is a level B effort for this topic area by PRA-2. Some of the dominant sequences found in PRA-2 were more dominant due to the fact that longer accident durations were used. A significant shuffling of dominant sequences did occur. However, no sequences became dominant sequences because of the treatment of the accident duration. This is a level 3 impact.

PRA-3, PRA-4, PRA-5, PRA-6: Effort A; Impact 1

PRA-3, PRA-4, PRA-5 and PRA-6 all used the WASH-1400 time frame for operation of the long term cooling systems. There was no attempt to define realistic accident lengths based on sequence conditions and plant design. No additional analysis was performed to account for the recovery of failed equipment during the long term cooling phase. This is a level A effort with a level 1 impact.

3.1.8 HN - Evaluation of Human Errors During Normal Operation

This topic refers to the quantification of human errors that might occur during normal plant operations (e.g., miscalibration of sensors, or leaving a valve aligned in an unsafe position after test or maintenance). Three levels of effort were identified. These levels of effort do not reflect differences in the number or type of human errors modelled but rather increases in the quantification effort for the errors modelled. The baseline level of effort, level A, is to use conservative scoping values (e.g., 1E-2 per act) throughout the study. An increase in effort to level C involves estimating human errors using a non-detailed human error analysis that relies partly on information contained in a human error analysis manual, such as the Human Error Handbook, NUREG/CR-1278 (Reference 4) and partly on engineering judgment. A level C effort would involve the use of performance shaping factors such as stress levels, time available to perform the task, and the number of operators available to perform the task, but it would not involve task analysis. An increase in effort to a level E effort would utilize a detailed methodology, perhaps based on NUREG/CR-1278, which would include the development of THERP (Technique for Human Error Rate Prediction) trees. This requires the use of performance shaping factors and task analysis. The task analysis would include an evaluation of the action to be performed to determine whether it is a simple or complex and time consuming action; it would also involve an analysis of the procedures available to direct the performance of the task.

To evaluate the impact of increased detail in the modeling of these types of human errors, the calculated values for the human errors were replaced by the baseline value, 1×10^{-2} per act. This was done for errors that appeared in the dominant accident sequences and in some cases for human errors in some non-dominant accident sequences. The impact level was determined by the dominant accident sequence changes resulting from this reanalysis of this type of human errors. Changes in core melt frequency associated with extra effort were also estimated.

Five PRAs performed more than the baseline effort; four of them performed nondetailed analyses on human errors that can occur during normal operation. Most of the nondetailed analyses were relatively simplistic and had a wide range of effects on the results of the PRA. Only one analysis resulted in a change in the dominant accident sequences (PRA-2). The results for this topic area are shown in matrix form in Figure 3.8.

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	IV				
B					
C	I	VI	V	II	
D					
E	III				

Figure 3.8 Effort-Impact Profile
Topic Area: Treatment of Human Errors During Normal Operation

Although PRA-2 was the only one in which the extra effort affected the identification of dominant accident sequences, the largest change in core melt frequency, a decrease by a factor of about 3, occurred in PRA-6. The core melt frequency in PRA-2 was reduced by a factor of about 2.

PRA-1: Effort C; Impact 1

In PRA-1, human errors during normal operation were dealt with using simplified human error analysis. The analysis was based on techniques and probabilities from NUREG/CR-1278; however, the detailed task analysis and THERP trees called for in that document were not performed. This is a level C increase in effort for this topic. The human error rates developed did not significantly differ from screening values. These human errors did not contribute to the dominant sequences, nor would they have if screening values had been used. Thus, the impact of this topic is level 1.

PRA-2: Effort C; Impact 4

Human errors that can occur prior to an accident initiator, during normal operation, were evaluated using nondetailed human error analysis in PRA-2. The basis for the analyses was NUREG/CR-1278; however, the detailed analyses that can be performed using this document's methodology were not performed for this PRA. The nondetailed human error analysis used in PRA-2 is a level C increase in effort. It resulted in the reduction, by an order of magnitude, of the probability associated with some human errors that did contribute to dominant and nondominant sequences, namely, the failure to restore valves in the long term cooling systems to the proper position after test or maintenance. Had the extra effort not been expended two of the non-dominant sequences that contain long-term cooling faults would have been dominant. Therefore, this is a level 4 impact for this topic area for PRA-2.

PRA-3: Effort E; Impact 1

In PRA-3 these human errors were dealt with by performing a detailed human error task analysis of each action. NUREG/CR-1278 was used as the guideline for the development of the human error rates and THERP trees were constructed as specified in that document. The increase in the level of effort for this topic is E. The error rates determined were not significantly different than screening values in most cases, and did not constitute a significant contribution to any sequences. There were no noticeable changes in any of the sequence values; thus the impact of this topic is level 1.

PRA-4: Effort A; Impact 1

In PRA-4, these human errors were dealt with using basic screening probabilities from NUREG/CR-1278. No specific task analysis was performed for any of the actions. The level of effort for this topic is A. This is a baseline level of effort with an impact of level 1.

PRA-5: Effort C; Impact 3

Human errors during normal operation were assigned initial screening values in PRA-5. Any errors that appeared to contribute significantly to the dominant sequences were to be evaluated either in a detailed or nondetailed manner. For this PRA one human error, a failure to restore a high pressure ECCS makeup valve to the proper position after maintenance, contributed significantly to the dominant sequences so a nondetailed human error analysis was performed for this error. This is a level C effort which resulted in some rearrangement of the dominant sequences. Those dominant sequences which contain the system in which the evaluated human error appears have lower estimated frequencies than if screening values had been used for all human errors. Since a class of dominant sequences was moved in the dominant sequence list, but none became non-dominant, the effort in this topic area had a level 3 impact.

PRA-6: Effort C; Impact 2

Nondetailed human error analysis was performed for human errors during normal operation in PRA-6. Attention was paid to each individual action, whether written procedures were available, the number of people involved, and the number of human actions that had to be performed as part of a task. Thus, the increase in the level of effort was judged to be C. The impact of this level of effort on the overall results was a slight rearrangement of dominant accident sequences. Thus, the impact level is 2.

3.1.9 HA - Evaluation of Human Errors During an Accident

This topic refers to the quantification of human errors that could occur during an accident (e.g., failure of the operator to switch to the ECCS recirculation mode). The same three levels of effort described in the previous section were identified for this topic. The baseline level of effort is to use scoping values (e.g., 1×10^{-2} per act) throughout to evaluate the human errors. An increase in effort to a level C effort involves estimating human errors using a nondetailed human error analysis that relies partly on information such as that contained in NUREG/CR-1278 (Reference 4) and partly on engineering judgment. A further increase in effort to level E is to utilize a detailed methodology such as the one employed in NUREG/CR-1278 which includes the development of THERP trees to systematically evaluate all or most human errors.

To evaluate the impact of increased detail in the modeling of these types of human errors, the calculated values for the human errors were replaced by the baseline value of 1×10^{-2} per act. This was done for errors that appeared in dominant, and in some cases non-dominant, accident sequences. The impact level was determined by the dominant accident sequence changes from the reanalysis of this type of human errors. The impact of additional effort on core melt frequency was evaluated in the same manner, i.e., by replacing all calculated human error rates with the screening value 1×10^{-2} per act.

All six PRAs performed more than the minimum effort and the additional effort had some impact. Four sets of dominant accident sequences were changed because of the nondetailed or detailed human error analysis performed. The calculated changes to core melt frequencies did not correlate exactly with the impacts on dominant accident sequences. The PRAs with the largest core melt frequency changes, PRAs 1, 3 and 4, had impacts of level 4, whereas PRA-5 exhibited the largest dominant sequence impact, level 5. The results of the analysis for this topic area are presented in matrix form in Figure 3.9.

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A					
B					
C		VI		II	
D					
E		IV		I III	V

Figure 3.9 Effort-Impact Profile
Topic Area: Treatment of Human Errors During Accident Conditions

PRA-1: Effort E; Impact 4

Human errors in the course of an accident were dealt with, in PRA-1, by performing detailed human error task analysis of each action. NUREG/CR-1278 was used as the guideline for the development of the human error rates and THERP trees were constructed as specified in that document. This is a level E increase in effort for this topic area. This method gave consistently lower error rates than less detailed analyses. In particular the human error rate for failure to perform manual depressurization was lowered significantly. The differences were such that a few sequences related to injection phase cooling failures during transients requiring manual depressurization were eliminated. Without the detailed analysis these sequences would have been dominant. Thus, the impact of this topic on the analysis is level 4.

PRA-2: Effort C; Impact 4

PRA-2 used nondetailed human error analysis for the quantification of human errors that can occur during an accident. Although many of these human errors were evaluated in greater detail than the human errors that can occur during normal operation at plant 2, the level of detail was not sufficient to be considered a detailed analysis. For the treatment of human errors during the accident, this is a level C increase in effort. The human error analysis that had the most impact was the analysis of the operator failure to supply an alternate water supply during certain loss of offsite power conditions. The detailed analysis resulted in the elimination of two loss of offsite power sequences that would have been dominant had screening values been used for all human errors. This is a level 4 impact.

PRA-3: Effort E; Impact 4

In PRA-3, these human errors were dealt with the same way as in PRA-1. PRA-3 therefore falls into the same effort (level E) and impact (level 4) categories as PRA-1. The only significant difference is that the sequences eliminated involved failures related to emergency cooling recirculation rather than emergency cooling injection. (In this PRA a detailed analysis of the operator failing to switch to recirculation cooling was performed.)

PRA-4: Effort E; Impact 2

In PRA-4 human errors during accidents were dealt with by performing detailed human error task analysis of each action. NUREG/CR-1278 was used as the guideline for the development of the human error rates. Stress factors, the presence of multiple operators, and dependency between operators were all taken into consideration. Although no THERP trees were constructed, the narrative descriptions of the event quantifications indicate that the actual trees were the only items missing from the evaluation of the events. Therefore the increased level of effort for this topic is E. This method gave consistently lower error rates than a less detailed analysis and resulted in the reordering of a few of the sequences. However, the differences in this study did not appear significant enough to alter the status of any of the dominant sequences. Thus, the impact of this topic is level 2.

PRA-5: Effort E; Impact 5

PRA-5 treated human errors during an accident in the same manner as it did human errors during normal operation, i.e., screening values were assigned to all identified human errors during the accident. For those errors which contributed to the dominant sequences both detailed and nondetailed analyses were performed. Nondetailed analyses were performed first, while detailed analyses were performed only for a limited number of human errors. This corresponds to a level E increase in effort for PRA-5. The human error evaluated that had the largest impact was the failure to manually supply makeup to an emergency system during a loss of offsite power. The analysis produced an error rate an order of magnitude lower than the screening value and resulted in a class of dominant sequences being eliminated. This is a level 5 impact.

PRA-6: Effort C; Impact 2

Nondetailed human error analysis was performed in PRA-6 for human errors during accidents. The level of effort for this analysis is higher than required for a scoping human error analysis. In performing the nondetailed human error analysis several factors were considered. These include: level of stress, quality of displays and controls, quality of training, quality of written instructions, operator redundancy, and human error coupling. For a few multistep human actions, simplified THERP trees were developed. The increase in the level of effort in this case was judged to be C. Since the extra level of effort beyond the baseline level in this case resulted in a slight rearrangement of dominant accident sequences, the impact on the overall results is categorized as level 2.

3.1.10 CM - Common Mode Analysis

This topic covers the level of effort applied to common mode human error analysis in the PRA.

Three levels of effort were identified for treatment of common mode human errors. The baseline, level A, is to perform no common mode human error analysis. The second level, a level B increase in effort, occurs when common mode human error analysis is performed selectively (and therefore inconsistently) throughout the PRA; that is, when only a few human error situations are analyzed. For a level B effort the events to be analyzed as part of a common mode system are selected based on the prior knowledge and experience of the PRA analyst. An increase in effort to a level D effort includes as part of the analysis a determination of the common mode actions. This results in the consideration of more potential common mode failures and a more consistent evaluation of common mode errors. For this topic area the increase in effort from a level B to a level D effort does not result from a more detailed analysis of the common mode errors, although different methods of analysis are possible; rather, the increase in level of effort is due to the manner in which the possible common mode errors are identified.

To determine the impact of additional effort in this topic area the common mode errors evaluated in the PRAs were decoupled and fault independence was assumed. The resulting changes to the dominant accident sequences formed the basis for the selection of the impact levels. Changes in core melt frequency were also estimated for this topic.

The evaluation of common mode failures in the three PRAs that considered this type of error did not significantly affect the identification of dominant accident sequences nor did it affect the core melt frequencies more than 10 percent. Only in one, PRA-6, was the order of the dominant sequences even slightly rearranged (a level 2 impact). The results for this topic area are presented in matrix form in Figure 3.10.

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	II III V				
B	I	VI			
C					
D	IV				
E					

Figure 3.10 Effort-Impact Profile
Topic Area: Common Mode Analysis

PRA-1: Effort B; Impact 1

Common mode human errors were considered on a case-by-case basis in PRA-1. Engineering judgment was used to select particular actions which were felt by the analysts to be susceptible to common mode failure and have potential for contributing to the results. The errors were quantified by constructing THERP trees as specified in NUREG/CR-1278 (Reference 4). Even though the detailed THERP models were used for quantification, the use of judgment in the selection of the errors to be quantified kept the overall level of effort very low, at level B. This method resulted in a substantial increase in the combined unavailabilities of the components affected by these common mode human errors (two groups of sensors); however, these errors still did not appear as contributors to the dominant sequences. Thus, the impact of this topic is level 1.

PRA-2, PRA-3, PRA-5: Effort A; Impact 1

There was no common mode human error analysis performed in PRA-2, PRA-3 or PRA-5. This represents the least amount of effort for this topic area and is a level A effort. By definition this is a level 1 impact.

PRA-4: Effort D; Impact 1

Common mode human errors were considered in PRA-4 in a somewhat detailed way. For any set of dependent operator tasks, during normal operation or accident progression, a level of dependency was determined based on the nature of the tasks. The error rate for each subsequent dependent task was calculated from the non-dependent error rate adjusted for the dependence level as defined in equations in NUREG/CR-1278. The increase in the level of effort for this topic is D. These common mode human errors did not constitute a significant contribution to any sequences, and therefore no effects on the results were noted. The impact of this topic is level 1.

PRA-6: Effort B; Impact 2

In PRA-6, common mode human errors during normal operation, such as the miscalibration of a logic circuit or the failure to reclose bypass valves after test, and during accident conditions, such as failure to open motor-operated valves in the low and high pressure recirculation system, were considered. Nondetailed human error analysis was used to assign probability values for these kinds of events. Thus, the increase in the level of effort was judged to be B. Consideration of these common mode human errors resulted in a slight rearrangement of some dominant accident sequences. Thus, the impact of the additional effort is a level 2.

Common mode errors evaluated at the level of effort found in PRAs 1, 4 and 6 had virtually no impact on the dominant accident sequences. Although a sample size of 3 is admittedly small, the results clearly suggest that this topic need not be given high priority in future PRAs.

3.1.11 R - Treatment of Recovery

This topic refers to the treatment of possible operator recovery actions. Options range from not considering any faults or actions to be recoverable to considering a wide range of human errors, actuation faults, and individual component faults to be recoverable. (The treatment of the recovery of offsite power is not considered here. That recovery affects the frequency of initiating events.)

Three levels of effort were identified for the treatment of recovery in the PRAs. For the baseline level of effort A, no faults or outages are treated as being recoverable. When a PRA evaluated the possibility of recovery from human errors and automatic actuation systems failures only, the increase in effort is to level C. Finally, a level D effort includes an assessment of the actions required for recovery from human faults, actuation system failure, and individual component faults for which the potential for recovery exists.

To assess the impact of the different treatments of recovery on the dominant accident sequences the dominant and non-dominant sequences were re-evaluated with no credit given for recovery. Whenever a fault's failure probability had been modified by a recovery factor, the recovery factor was eliminated.

Recovery had more impact than any other topic. It was treated in all six PRAs, although the recovery actions identified in PRA-2 are treated, in this study, as human actions during accident conditions. In four of five cases the treatment of recovery resulted in a significant change in the selection of dominant sequences, regardless of the amount of effort used in the analysis. In these cases, consideration of recovery reduced the estimated core melt probabilities by factors ranging from about 7 to 34. Only in PRA-6 did the consideration of recovery not result in changes to the core-melt frequency. Results for this topic area are presented in matrix form in Figure 3.11.

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	II				
B					
C		VI		I	V
D					III IV
E					

Figure 3.11 Effort-Impact Profile
Topic Area: Treatment of Recovery

PRA-1: Effort C; Impact 4

In PRA-1 recovery was treated using a simplified model. Recovery credit during accidents was given only for actions which were covered by written procedures. Recovery was limited to functional recovery by the operator, that is, bypassing the need for failed components by activating alternate systems or components. (This includes recovery of initiation faults by manually operating components). No credit was given for recovering failed components. The recovery actions were quantified by using a strictly cognitive (i.e., time dependent) error model. No detailed task analysis was performed. This is a level C increase in effort. This treatment of recovery resulted in reducing the frequencies of a number of sequences, reordering the dominant sequence list. Three sequences were reduced to non-dominance when recovery actions were considered. The recovery actions that had the largest impact were recovery of low pressure injection actuation faults and the recovery from an operator error in performing manual depressurization. The three sequences reduced to non-dominance were not any of the most dominant sequences but rather three of the least dominant of the dominant sequences. Thus, the impact for this topic on the analysis is level 4.

PRA-2: Effort A; Impact 1

Some operator actions that can be performed during accident conditions at plant 2 can be interpreted as recovery actions. However, these actions are generally the manual operation of redundant systems, not the recovery of a failed system. For this report a restricted definition of recovery is being used. Recovery actions are those actions taken by an operator to bring into service a component which has failed to perform its function. This definition would not include the type of operator actions, during the accident, evaluated in PRA-2. Other than the operator actions to bring redundant systems on line, no recovery actions are evaluated in PRA-2. This is the minimum effort possible and is a level A effort for the treatment of recovery in PRA-2. By definition this is a level 1 impact.

PRA-3: Effort D; Impact 5

Recovery was treated in a very detailed manner in PRA-3. Recovery was considered for both functional recovery and individual component fault recovery. Credit was given for action both inside and outside the control room. Functional recovery credited the operator with being able to bypass the need for failed components by activating alternate systems. Component recovery credited the operator with being able to restore unavailable equipment, depending on the reason for its being unavailable. NUREG/CR-1278 was used as the basis for the human recovery reliability quantification. The increase in level of effort for this topic is D. This had a profound effect on the results. The number of dominant sequences was reduced by a factor of 2. The most dominant sequence prior to the consideration of recovery was a small-small LOCA with a high pressure injection failure. After recovery was considered, this sequence was not a dominant sequence. Thus, the impact of this topic is level 5.

PRA-4: Effort D; Impact 5

Recovery was also treated in detail in PRA-4. Recovery was considered for both functional recovery and recovery of individual component faults. Functional recovery was handled using detailed human factors models for all cases where the operator could recover from a failure by taking actions, primarily from the control room, which could bypass the need for the failed equipment. In addition, credit was taken for operator actions to actually recover pieces of failed equipment. This was done by using historical data to calculate the fraction of failures which could be considered easily recoverable. The increase in level of effort for this topic is D. As for PRA-3, the effort had a profound effect on the results in that a number of sequences which would have otherwise been dominant were reduced to nondominance by consideration of recovery. These sequences were primarily loss of offsite power initiated transients that involved failure of the auxiliary feedwater system. These sequence frequencies were reduced by a factor of approximately 2. Thus, the impact for this topic is level 5.

PRA-5: Effort C; Impact 5

Operator errors and actuation system faults were the two types of faults considered to be potentially recoverable in PRA-5. When either of these two types of faults appeared in a dominant sequence cut set, a recovery factor was used to modify the cut set frequencies. The recovery factor was determined by several considerations. These included the amount of time available to perform the recovery task, where the recovery task had to be performed, and whether a procedure existed which called attention to the recovery action. Based on these factors a probability of nonrecovery was assigned to the potentially recoverable faults. (Analysis showed that not all human errors and actuation faults were recoverable.) This is a level C increase in effort for the treatment of recovery in PRA-5. Again, as for PRA-3 and PRA-4 a number of sequences were reduced to nondominance because of the quantification of recovery. However for plant 5 the sequences that were reduced to nondominance were eliminated because of recovery of faults in the long term cooling system. (Recovery reduced seven such sequences to nondominance.) The impact of this topic is level 5.

PRA-6: Effort C; Impact 2

In PRA-6, recovery was considered in the quantification of loss of offsite power sequences and some human actions. The recovery of human actions were included in fault trees as opposed to the sequences. The level of effort in this case is judged to be C. This resulted in a change in placement of one dominant accident sequence. Thus, the impact of this level of effort on the overall results is categorized as level 2.

The importance of treating recovery in all future PRAs clearly is strongly supported by this analysis. It is important not only because it is highly likely to have a large impact, but because the impact is consistently in the direction of reducing estimates of risk. Not to consider the possibility of recovery in a future PRA would be to ignore the PRA objective of favoring realism over conservatism in matters of risk.

3.1.12 AC - Modeling of AC Power Systems

This topic refers to the level of detail in the PRA concerning the modeling and quantification of the AC power support system. Options range from using failure probabilities from previous studies for each AC power train to developing and using detailed systems models. The baseline level of effort A was defined as using past PRA models of AC power systems, which indicate a heavy reliance on diesel failures as the dominating fault (e.g., $3x10^{-2}$ per train). A level C effort is to use simple, nondetailed models like block diagrams or top level fault trees to assess AC power unreliability. This level analysis will result in the identification of the major system components and support system interfaces. Since detailed fault trees are not produced not all system components are modelled. Detailed fault trees are constructed for a level E effort. These fault trees include all system components and should identify all support system interfaces. The increase in effort from level C to level E is a result of the increased detail of the fault tree model and the resulting increase in the number of components modelled.

To evaluate the impact of additional effort on the dominant sequences and the core melt frquency each PRA was re-evaluated assuming a baseline effort. The baseline effort assumes a $3x10^{-2}$ per train per demand failure probability for the AC power system. The more detailed models resulted in higher failure probabilities due to the identification of additional AC power faults. In determining the impact of additional effort, all dominant cut sets containing AC power faults were reduced to a set of cut sets that contained only diesel failures.

All six PRAs performed more than the minimal effort for this topic area. Only two PRAs showed any impact and only one, for which a level E increase in effort was performed, resulted in a change to the list of dominant sequences. The results for this topic area are shown in matrix form in Figure 3.12. Although the treatment of the AC power systems did impact the selection of dominant sequences, it had very little impact on the calculated core melt frequencies. No core melt frequency changed by more than a factor of 1.5 due to additional effort in this topic area.

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A					
B					
C		I	IV		
D					
E	II III VI			V	

Figure 3.12 Effort-Impact Profile
Topic Area: Modeling of AC Power Systems

PRA-1: Effort C; Impact 2

In PRA-1 the emergency electric power system was modeled in a simplified fault tree format. The level of detail of the model indicated that the analyst's knowledge of the system helped to avoid the need to model every detail of system design. This generally assumes that no subtleties in system design (i.e., things the analyst would not be expecting or which he had never seen before) exist. This is a level C increase in effort. This analysis resulted in some change in the probability of AC system failure as compared to using generic system failure probabilities and this resulted in the movement, or reordering, of one dominant sequence. Thus, the impact of this topic is level 2.

PRA-2: Effort E; Impact 1

PRA-2 constructed a detailed fault tree model for the emergency AC power system. The fault tree model included all safety related buses, breakers and AC power system logic components. This detailed model represents a level E effort for the modeling of AC power systems. The detailed model did not result in a noticeable change in the list of dominant accident sequences. This is a level 1 impact.

PRA-3: Effort E; Impact 1

The electric power system in PRA-3 was modeled with a very detailed fault tree analysis. All individual components in the system were included explicitly on the fault tree, as were all component dependencies. This is a level E increase in effort. This analysis does not identify any unexpected contributors to system failure, and the overall failure rates obtained did not differ from generic values. Thus, there was no noticeable effect on the dominant sequences; the impact of this topic is therefore level 1.

PRA-4: Effort C; Impact 3

In PRA-4 the electric power system was modeled in much the same way as in PRA-1, but the impact was greater in that a number of the dominant sequences were reordered. Some additional AC power faults were identified that affected the LOSP sequences. Therefore, these sequences became more dominant than if a baseline effort had been performed. However, the difference was not significant enough to alter the sequences in the dominant sequence list. The impact for this topic in PRA-4 is level 3.

PRA-5: Effort E; Impact 4

PRA-5 developed a very detailed model of the AC power system. It included all safety-related buses, breakers, or other electrical components, and AC power system logic components (relays, relay contacts, timers, etc). This detailed model is a level E increase in effort for the modeling of plant power systems. By using this detailed model several AC component faults were found that contributed significantly to the frequency of several dominant sequences. Without the detailed model a few of the dominant sequences would not have appeared to be dominant. As in PRA 4 the sequences most affected were LOSP sequences. The sequences most affected were three of the less dominant of the dominant sequences. (The additional faults contributed approximately 20-30% of the value of these sequence frequencies.) For this topic area the extra effort resulted in a level 4 impact.

PRA-6: Effort E; Impact 1

A detailed model of the electric power system was developed using fault tree analysis in PRA-6. The increase in the level of effort in developing this detailed fault tree is E. The results of the detailed analysis of the AC power system were similar to the generic results both in terms of major contributors to the unavailability of the system and failure probability of various parts of the system. Thus, there was no noticeable effect on the dominant accident sequences. The impact of this topic is level 1.

3.1.13 L - Modeling of Logic (Actuation) Systems

This topic refers to the level of detail in the PRA concerning the modeling and quantification of the logic actuation systems. The options are very similar to those for AC power (AC), ranging from using past studies to detailed modeling of the system. The baseline level of effort, level A, was defined as using past PRA models of logic systems which yield an unreliability of approximately $3x10^{-3}$ per train. A level C effort is to use simple nondetailed models such as block diagrams or top level fault trees to assess logic system unavailability. As in the case of AC power, the increase in effort from level C to level E results from increased detail of the fault tree model and the associated increase in the number of components modeled.

The impact of additional effort for this topic area was determined in much the same manner as for the topic area AC. "Generic" actuation logic unavailabilities were substituted for the actual faults found through the use of more detailed models. The changes in the dominant accident sequence list defined the impact for this topic area.

As with the modeling of AC power systems all PRAs performed more than the minimal effort. Two of the PRAs found failures in the logic systems that resulted in the increased dominance of some accident sequences. One of these two PRAs constructed a detailed logic model while the other used a simplified fault tree method. The results for this topic area are presented in matrix form in Figure 3.13.

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A					
B					
C	IV			I	
D					
E	II VI	III		V	

Figure 3.13 Effort-Impact Profile
Topic Area: Modeling of Actuation Logic Systems

PRA-1: Effort C; Impact 4

The logic systems were modeled in a simplified fault tree format in PRA-1 with considerable reliance placed in the analyst's knowledge of the system. The decision not to model every detail of the system implies that subtleties in system design were not expected. This is a level C increase in effort. This analysis resulted in a significant change in the probability of logic systems failure as compared to using generic system failure probabilities and had a noticeable effect on the dominant sequence results. Two lower order dominant sequences, which would have been nondominant had generic system failure probabilities been used, were raised to the dominant sequence list. The impact was due to actuation faults that could affect the operation of the long term cooling system. Thus, the impact of this topic is level 4.

PRA-2: Effort E; Impact 1

The logic (actuation signal) systems at plant 2 were modeled in detail. The fault tree consists of failures at the relay and sensor level and the system is modeled from the sensors to the valve and pump motors. The detailed logic system model is a level E effort for PRA-2. Logic system faults did not significantly contribute to any of the dominant accident faults. Thus, the impact of the extra effort in this topic area is level 1.

PRA-3: Effort E; Impact 2

In PRA-3 the logic systems were modeled in a very detailed fault tree analysis. All individual components in the system were included explicitly on the fault tree, as well as all component dependencies. The increase in the level of effort for this topic is E. This analysis resulted in identifying certain initiation signals having an order of magnitude higher failure rate than generic values. The overall logic train failure rates were only slightly higher, however, and only resulted in a minor reordering of a few sequences on the dominant sequence list. Thus, the impact for this topic is level 2.

PRA-4: Effort C; Impact 1

In PRA-4 the logic systems were modeled in a simplified fault tree format at a level similar to that of PRA-1. This analysis resulted in some change in the probability of logic system failure as compared to using generic system failure probabilities; however, this had no noticeable effect on the dominant sequence results. Thus, the impact for this topic is level 1.

PRA-5: Effort E; Impact 4

The logic systems in plant 5 are modeled to the same level of detail as the AC power system. The logic channels are modeled to the relay and relay contact level from the sensors all the way to the valve and pump motors. This detailed model of the logic systems is a level E effort for PRA-5. Because of the detailed logic system modeling performed in this PRA some system dependencies were found that would not have been found had a generic model been used. An AC power failure that propagated through the logic system for the emergency service water system and failed long term cooling was found due to the extra effort for this topic area. This hard-wired dependency resulted in two sequences being identified as dominant sequences. (They are two of the least dominant of the dominant sequences.) Therefore the impact for this topic is a level 4.

PRA-6: Effort E; Impact 1

The logic systems in plant 6 were modeled in a very detailed fashion using fault tree analysis. Thus, the level of effort in this case is E. The results of the detailed analysis of the logic systems were similar to the generic results both in terms of major contributors to the unavailability of the system and failure probability of various parts of the system. Thus, there was no noticeable effect on the dominant accident sequences. The impact for this topic is level 1.

3.1.14 CC - Common Cause

This topic refers to the level of effort expended in the PRA to perform hardware common cause failure analysis. The options range from not considering hardware common cause failures at all to performing detailed, comprehensive analyses of hardware common cause failures.

Three levels were identified for the treatment of common cause failures among components. The baseline level of effort, level A, was defined to be no effort at all, i.e., no common cause analysis was performed. A common cause analysis performed on a few components identified by engineering judgment to be susceptible to common cause failures is a level B effort. A consistent common cause analysis using nuclear experience data to identify and assess the common cause contributions requires a level C effort. The impact of a common cause analysis was evaluated by identifying the common cause failures modeled in each PRA and re-evaluating the sequences assuming no common cause linkage between the failure of separate components. The change in the dominant sequences resulting from this decoupling of failures defines the impact.

In the four PRAs where common cause failures were considered no new dominant sequences were found. The consideration of common cause resulted only in a rearrangement of the dominant sequences. The results for this topic area are shown in matrix form in Figure 3.14. Of the nine topic areas for which changes in core melt frequency were estimated, this area consistently had the least impact. Additional efforts caused no more than a 20 percent change in core melt frequency.

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	I V				
B	IV	III VI			
C			II		
D					
E					

Figure 3.14 Effort-Impact Profile
Topic Area: Common Cause Analysis

PRA-1: Effort A; Impact 1

Common cause failures were not considered in the analysis of PRA-1. This is a baseline level of effort for this topic so the impact is of level 1.

PRA-2: Effort C; Impact 3

A common cause model was developed for every set of redundant mechanical components in PRA-2. For each set of redundant components an independent failure probability was calculated for one component and a conditional failure probability was assigned to the remaining components. This is essentially a beta-factor method. This methodology was used for all potential mechanical common cause systems in plant 2. The use of a common cause model for all redundant components is a level C effort. While the treatment of common cause failures did increase the failure probabilities of some systems, especially the core spray system and the IC makeup system, it did not affect the selection of the dominant sequences. It did, however, cause some reordering of the dominant sequences. Some of the sequences containing failure of the two systems mentioned had a frequency factor of 2 or more larger than they would have had no common cause analysis been performed. This is a level 3 impact.

PRA-3: Effort B; Impact 2

Common cause failures were considered in the analysis on a case-by-case basis in PRA-3. Engineering judgment was used to select particular components which were felt by the analysts to be susceptible to common cause failure and to have the potential to contribute to the results. Historical generic data on the number of common cause failures recorded throughout U.S. nuclear power plants were used to quantify these cases by classical analysis. This is a level B increase in effort. Only one component pair was identified in this study, and it resulted in a minor increase in frequency for a sequence which was already dominant. Thus, the impact of this topic is level 2.

PRA-4: Effort B; Impact 1

Common cause failures were considered in the analysis of PRA-4 on a case-by-case basis with engineering judgment used to select particular components for consideration. A beta-factor approach was used to quantify the common cause effects. The increase in the level of effort for this topic is B. The common cause effects were generally small, even in an absolute sense, and were distributed among all of the sequences. This resulted in a slight, and in some cases immeasurable, increase in sequence frequencies across the board, but no apparent reordering. Thus, the impact for this topic is level 1.

PRA-5: Effort A; Impact 1

PRA-5 did not perform any common cause analysis. By definition this is a level A effort for this topic area, and a level of impact of 1.

PRA-6: Effort B; Impact 2

The possibility of failure of components due to common cause was considered in PRA-6 on a case-by-case basis using engineering judgment. Only one component pair was found to be susceptible to common cause failure and its failure probability was increased based on historical data. The increase in level of effort in this case is judged to be B. Consideration of this common cause failure resulted in a slight rearrangement of dominant accident sequences. Thus, the impact of this level of effort on the overall results is categorized as level 2.

3.1.15 DB - Component Reliability Data Base

This topic covers the type of data base used in the PRA. The options range from using generic data only for quantifying component faults to using sophisticated Bayesian analysis techniques employing both plant-specific and generic data. Three levels of effort were identified to characterize the types of data bases used in PRAs. The baseline level of effort, level A, is to use generic data only, e.g., WASH-1400 data or the IREP data base. The C level of effort is to use generic data for most faults, augmented by plant-specific data, classically treated, for a few important fault types. The use of both generic and plant-specific data employing a Bayesian treatment of the data requires a level E effort. To evaluate the impact of the varying levels of effort the differences between generic data values and the plant-specific component failure probabilities were identified. Where significant differences existed the impact on the dominant sequences was evaluated. This evaluation was more qualitative than most of the other evaluations of impact levels.

The use of plant-specific data, either classically or modified in some way, did not appreciably affect the results of any of the PRAs. The highest level of impact was a level 2. The results for this topic area are shown in matrix form in Figure 3.15.

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	I VI				
B					
C	III V	II			
D					
E	IV				

Figure 3.15 Effort-Impact Profile
Topic Area: Component Reliability Data Base

PRA-1: Effort A; Impact 1

Strictly generic data were used for component failure rates in PRA-1. This is an A level of effort and thus has an impact of level 1.

PRA-2: Effort C; Impact 2

The data base for PRA-2 consisted primarily of plant-specific data, supplemented by generic data, not necessarily from WASH-1400, where the analysts determined it was necessary. The plant-specific data were used directly in all cases. That is, the data were not used to modify generic data but were used instead of generic data. The use of a plant-specific data base for PRA-2 is a level C effort. Approximately one-fourth of the dominant sequences were affected by the use of plant-specific data. The plant-specific data resulted in only minor changes in the ranking of these sequences. Therefore the impact of the additional effort in this topic area is level 2.

PRA-3: Effort C; Impact 1

The data base for PRA-3 included both generic and plant-specific data on component failure rates. Plant-specific data were obtained from plant maintenance reports and the Nuclear Plant Reliability Data System. Classical analysis was used to determine failure rates from the plant-specific data. A statistical significance test based on the binomial distribution was used to determine if the difference between plant-specific data and generic data for each component was meaningful in a statistical sense. If it was, the plant-specific data was used. The increase in level of effort for this topic is C. In most cases, it was found that the plant-specific failure rates were not significantly different from the generic values. The values which were different only affected components which were minor contributors to system failure, so that the system failure rates, and therefore the sequence frequencies, were not significantly altered. Thus, the impact for this topic is level 1.

PRA-4: Effort E; Impact 1

The data base in PRA-4 combined both generic and plant-specific data by the use of a two-stage Bayesian technique. Baseline generic data were utilized to formulate the prior estimates for the first Bayesian step. These were updated using generic data from other plants similar to the one being studied to generate posterior estimates. The distributions determined from this step constituted the prior distributions for the second Bayesian step. These were updated using plant-specific data from the plant being studied to develop the posterior estimates of the failure rates. The increase in level of effort for this topic is E. While the values of component failure rates were changed somewhat in the absolute sense, the changes were not significant and there was virtually no change in the relative values. The effect on the sequences appears to be virtually nonexistent, even to the extent that we do not believe that any sequences were reordered. Thus, the impact of this topic is level 1. This discussion does not apply to the use of this technique for initiator frequencies.

PRA-5: Effort C; Impact 1

Generic data from several data sources comprise most of the data base for PRA-5. The primary source of component failure data was WASH-1400. A plant-specific data search was performed for components that were deemed to be significantly different from the components used to construct the generic data base. Failure probabilities for these components were derived using classical point estimates, as opposed to a Bayesian technique. This is a level C increase in effort for the generation of a data base. This limited use of plant-specific data had no impact on the ranking of dominant accident sequences. Therefore the impact is a level 1.

PRA-6: Effort A; Impact 1

A generic list of component failure rates was used in PRA-6. No plant-specific data were considered in the quantification process. This is the baseline level of effort, level A. The impact of this level of effort on the overall results is categorized as level 1.

The difference between levels C and E for this topic are substantial in terms of viewpoint and philosophy as well as level of effort. With only one PRA performing a level E analysis, caution should be used in generalizing the low impact result observed here to other reactors.

3.1.16 DFP - Use of Demand Failure Probabilities

This topic refers to the treatment of demand failure probabilities from a generic data base for components that have very long test periods (i.e., on the order of a refueling cycle). The options include use of the demand failure probability directly from the generic data base, a baseline effort and therefore a level A effort; and developing failure rates from the generic demand failure probabilities which are then used with the long test period to quantify the component fault, a level C effort.

In those cases where the failure rate was derived from demand failure probabilities the dominant sequences were examined to identify those cut sets that contained components with long test intervals. Then the demand failure probabilities were used for these components and the dominant accident frequencies recalculated. The resulting changes to the dominant sequence list formed the basis for the selection of the level of impact.

Only PRA-5 performed more than the baseline effort for this topic area. In that case, the modification of the data had a large impact on the selection of dominant accident sequences. The results for this topic area are presented in matrix form in Figure 3.16.

Impact On Ordering of
Dominant Sequences

Increase In Absolute
Level of Effort

	1	2	3	4	5
A	*				
B					
C					V
D					
E					

* I, II, III, IV, VI

Figure 3.16 Effort-Impact Profile
Topic Area: Use of Demand Failure Probabilities

<u>PRA-1, PRA-3, PRA-4, PRA-6: Effort A; Impact 1</u>

Demand failure probabilities were utilized directly from the data base in PRA-1. No modifications were made for long test periods. The level of effort for this topic is level A, the baseline level. Thus, the impact of this topic is level 1. PRA-3, PRA-4 and PRA-6 also fall into the same effort-impact category.

PRA-2: Effort A; Impact 1

This topic area is not completely appropriate for PRA-2. Since plant-specific data were used in nearly all cases it was not necessary for the analysts to modify the data to reflect differences between the test intervals used to develop generic data and the test intervals for various components in plant 2. The use of plant-specific data reflects the differences in component failure probabilities based on different test intervals provided the data is analyzed and grouped accordingly. For PRA-2, the level of effort for this topic area has been assigned to level A. Thus, the impact is a level 1 impact.

PRA-5: Effort C; Impact 5

PRA-5 modified the data in the generic data base. In many cases the data in WASH-1400 are presented in the form of demand failure probabilities based on failure data for components with monthly test intervals. This PRA used that data but derived a failure rate from the failure probability and used plant-specific test intervals to produce point estimate failure probabilities. Therefore, in addition to the actual modification of the available data, the additional effort in this PRA for this topic area consisted of an evaluation of the test procedures at plant 5 to determine the actual test intervals for all components. This is a level C increase in effort. The use of this technique resulted in a large increase in the importance of the AC power system at plant 5 because many components are tested only during the integrated loss of offsite power test performed during refueling outages. At least three of the dominant loss of offsite power sequences are dominant because this data modification was performed. This results in a different perception of the dominant sequences and plant weaknesses for plant 5. The impact for plant 5 for this topic area is a level 5 impact.

The core melt frequency resulting from this treatment of data in PRA-5 was found to increase by a factor of 2.

Even though the one example of extra effort led to a large impact for this topic, we do not conclude that the extra effort is warranted. Aside from the fact that the sample size is small, this topic is an example, like aggregation of initiating events, of a case where extra effort does not necessarily imply a better result. The topic was included in recognition of the fact that demand failure probabilities derived from experience may be influenced by the usual time between demands, surveillance intervals, in the component population. The WASH-1400 and IREP data bases are presumably representative of populations subjected predominantly to 30 day surveillance intervals. The problem is that the dependence of demand failure probabilities on surveillance interval is not known. The approach taken in PRA-5, which was to treat the failure probabilities of components subject to long surveillance intervals as being directly proportional to the surveillance interval, was simply a way of being more conservative, typically by an order of magnitude or more, in face of the uncertainty.

The lesson to be drawn from this topic is that using conservatism as a substitute for dealing rationally with uncertainty can have a large impact, perhaps to the point of yielding distorted and misleading results. The ultimate solution in this case is to reduce the uncertainty through more careful collection and analysis of data.

3.1.17 MVM - Use of Means Versus Use of Medians

This topic refers to whether the component faults in the PRA were quantified using mean or median failure rate and demand failure probability data. It was assumed for this topic area that the level of effort resulting from the use of either means or medians is a baseline effort, the assumption being that the data is available in both forms. Therefore, both levels of effort are level A efforts. The impact level was determined by comparing the mean values used in the one PRA that used means to the median values. The absolute change in the frequency of the dominant sequences was not the important consideration, however. The relative change in the order of the dominant sequences, or the elimination or discovery of a dominant sequence, was the only criteria used to determine the level of impact.

Only PRA-4 chose to use means rather than medians. The selection of mean values had an impact on the core melt frequency but did not appreciably impact the ranking of the dominant sequences. The results for this topic area are presented in matrix form in Figure 3.17.

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	*				
B					
C					
D					
E					

* I, II, III, IV, V, VI

Figure 3.17 Effort-Impact Profile
Topic Area: Use of Means Versus Use of Medians

PRA-1, PRA-2, PRA-3; PRA-5: Effort A; Impact 1

PRA-1, PRA-2, PRA-3 and PRA-5 utilized medians (actually, in many cases "point estimates" or "best estimates" were used without the implication of a distribution) for their evaluation of estimated sequence frequencies. This is a baseline level of effort and has an impact of level 1.

PRA-4: Effort A; Impact 1

PRA-4 utilized means rather than medians in its evaluation of point estimate sequence frequencies. The selection of one parameter over the other has no effect on the level of effort, since we would expect that either would be equally accessible in whatever data base is being utilized. The level of effort for this topic is A. The effect on the component data is to cause an increase in all the probabilities and rates. The increase is somewhat higher for those components whose failure rates have a greater uncertainty, but the difference is not significant. Thus, while the absolute values of the sequences are slightly modified, there is no measurable effect on their relative values. The impact of this topic is level 1. This discussion does not apply to the use of this technique for initiator frequencies.

PRA-6: Effort A; Impact 1

Median values with error factors were used for all component failure probabilities in PRA-6. The system unavailability values were presented as means with 90% upper and lower bound values. The level of effort in this case is the baseline, level A. The impact of this level of effort on the overall results is categorized as level 1.

3.1.18 SSC - System Success Criteria

This topic refers to how the system success criteria were determined in the PRA. Two levels were identified that represent options for determining system success criteria. The baseline level, a level A effort, is to use the system success criteria identified in the FSAR. The second level is to perform realistic, plant-specific phenomenological analyses to determine system success criteria. This is a level C effort. The impact of modifying system success criteria was determined by substituting the more rigorous success criteria for the modified criteria, where possible. The modified criteria were generally less restrictive than FSAR criteria.

Four of the six PRAs used realistic calculations, as opposed to licensing criteria, for the determination of the success criteria for at least some systems. In two of these PRAs the more realistic success criteria resulted in the elimination of some sequences from the list of dominant accident sequences. The results for this topic area are presented in matrix form in Figure 3.18.

PRA-1: Effort C; Impact 1

Plant-specific system success criteria were utilized rather than just the licensing criteria from the FSAR in PRA-1. The increase in the level of effort for this topic is C. Using these plant-specific criteria results in the reduction of certain system failure rates under certain conditions. However, in this study none of the reductions affected any of the systems which contributed to dominant sequences. Thus, the impact of this topic is level 1.

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	II VI				
B					
C	I	V		III IV	
D					
E					

Figure 3.18 Effort-Impact Profile
Topic Area: Evaluation of System Success Criteria

PRA-2: Effort A; Impact 1

The system success criteria adopted for PRA-2 were based on FSAR data. No new analysis was performed to determine possibly more realistic criteria. This is, by definition, a level A effort with a level 1 impact.

PRA-3, PRA-4: Effort C; Impact 4

In PRA-3 plant-specific system success criteria were utilized rather than just the licensing criteria from the FSAR. This resulted in the reduction of certain system failure rates. One sequence (pertaining to ATWS) became nondominant because failure of the RPS was not assumed to lead directly to a core melt following a loss of the power conversion system; the high pressure injection system was also required to fail. This sequence would have been a dominant sequence had FSAR system success criteria been used. Thus, the impact of this topic is level 4. The effort was of level C. This characterization is also true of PRA-4, although the sequence found to be nondominant was nondominant because the analyst allowed the possibility of using a feed and bleed method to cool the core if the auxiliary feedwater system failed.

PRA-5: Effort C; Impact 2

The system success criteria for some of the mitigating systems were modified (from FSAR criteria) based on realistic calculations in PRA-5. The changes in the success criteria usually involved a reduction in the number of redundant trains necessary to perform a particular function. For this topic area, PRA-5 exerted a level C increase in effort. Using plant-specific criteria resulted in the reordering of some of the less dominant sequences. This is a level 2 impact.

PRA-6: Effort A; Impact 1

In PRA-6 the system success criteria were directly taken from the FSAR; no plant-specific analysis was performed. This corresponds to baseline level of effort, A. The corresponding impact on the overall results is categorized as level 1.

3.1.19 TM - Treatment of Test and Maintenance Outages

This topic refers to how test and maintenance outage contributions were modeled in the PRA.

Three levels of effort were identified as options for quantifying test and maintenance outage contributions in PRAs. The baseline level of effort, level A, is to use generic data for maintenance frequencies and test and maintenance outage times. The increase in effort to a B level of effort requires the use of generic data for all of these parameters except repair times, which are evaluated using plant-specific data. The final level of effort, level D, is to use plant-specific data for all of the parameters. To determine the level of impact for the PRAs that exerted additional effort in this topic area, the calculated test and maintenance outage unavailabilities were replaced by the generic values. The effect this replacement had on the dominant sequence list determined the level of impact.

Five of the six PRAs performed at least some plant-specific analysis of test and maintenance unavailabilities. Only in two PRAs did this result in even a minor reranking of the dominant accident sequences. The results for this topic area are presented in matrix form in Figure 3.19.

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	I				
B	V				
C					
D	II III	IV VI			
E					

Figure 3.19 Effort-Impact Profile
Topic Area: Treatment of Test and Maintenance Outages

PRA-1: Effort A; Impact 1

Generic test and maintenance unavailabilities were used in PRA-1. No attempt was made to perform any plant-specific analysis. The level of effort for this topic is A. This is a baseline level of effort with impact of level 1.

PRA-2: Effort D; Impact 1

Plant-specific maintenance histories were used to develop unavailabilities for test and maintenance outages in PRA-2. A comprehensive review of the maintenance records was used to produce different unavailabilities for similar components that had not failed at the same rate. This effort represents the highest level of effort to determine test and maintenance outage unavailabilities, even though part of the effort could be attributed to the use of plant-specific data. The effort PRA-2 exerted to determine test and maintain outage unavailabilities represents a level D increase. The use of plant-specific maintenance histories does not appear to have resulted in any significant changes to the list of dominant accident sequences. Therefore the level of impact is level 1.

PRA-3: Effort D; Impact 1

PRA-3 did substantial analysis of test and maintenance unavailability. Component out-of-service probabilities were based on the actual historical out-of-service times determined by searching through the plant test and maintenance records. This is a level D increase in effort. While most of the components had outage probabilities which were not greatly different from available generic values, there were a few which had significantly different plant-specific values. These changes did have some effect on the overall system unavailabilities, but it was very small. What little effect it did have was distributed over most of the sequences, so that the sequences were not even changed enough to reorder them relative to the other dominant sequences. Thus, the impact of this topic is level 1.

PRA-4: Effort D; Impact 2

PRA-4 engaged in basically the same type of effort as PRA-3, with very similar effect on component outage probabilities. The change in the test and maintenance contribution to system unavailability as a result of this did not have a very large effect on the overall system unavailabilities. The only effect was that a few sequences were changed enough to reorder them relative to the other dominant sequences. The impact of this topic is level 2.

PRA-5: Effort B; Impact 1

In PRA-5 maintenance outages were quantified by using generic failure rates and plant-specific repair times for each type of component, e.g., batteries, valves, and pumps. The additional effort used to quantify maintenance outages qualifies this as a level B increase in effort. This treatment of test and maintenance outages resulted in almost no change in system unavailabilities and therefore no change in the dominant accident sequence rankings. This is a level 1 impact.

PRA-6: Effort D; Impact 2

An extensive effort was spent in calculating system unavailabilities due to test and maintenance outages in PRA-6. Plant-specific test and maintenance durations were analyzed using a distribution to calculate mean values for the test and maintenance durations. The same process was used for calculation of mean test and maintenance frequencies. The increase in the level of effort for this topic is judged to be D. The final parameters used for calculation of test and maintenance outages were, in most cases, close to the generic values. The impact of this effort was a minor rearrangement of the dominant accident sequence and is categorized as level 2.

3.1.20 EQ - Environmental Qualification

This topic refers to how environmental qualification of equipment was modeled in the PRA. The options range from not considering environmental effects on equipment to developing equipment failure probabilities for environments that exceed the equipment specifications. The baseline effort is to not consider the environmental qualification issue, a level A effort. A level B effort consisted of using engineering judgment to qualitatively select components that are subjected to severe environments. A third level, a level C effort, requires the calculation of environmental conditions in various locations throughout the plant. Equipment exposed to severe environments is assumed to fail. A fourth level of effort, level E, also exists. For this level of effort the environmental conditions are calculated and modified failure probabilities are used for components exposed to the severe environments, rather than using the assumption that the component will fail. The impact of additional effort is evaluated by removing all environmental considerations from each PRA. The impact is derived from the rearrangement of the dominant accident sequences.

Environmental qualification considerations were evaluated in three of the six PRAs. In two of the PRAs this had no impact on the ranking of the dominant accident sequences. However, in the third PRA environmental considerations determined the most dominant sequences. The results for this topic area are presented in matrix form in Figure 3.20.

Impact On Ordering of
Dominant Sequences

Increase In Absolute
Level of Effort

	1	2	3	4	5
A	I, III IV				
B	V VI				
C					II
D					
E					

Figure 3.20 Effort-Impact Profile
Topic Area: Environmental Qualification

PRA-1, PRA-3, PRA-4: Effort A; Impact 1

Phenomenological interactions with severe environments (e.g., exposure to LOCA environment) were not considered in PRA-1, PRA-3 or PRA-4. For each of these PRAs the level of effort for this topic was therefore level A. This level implicitly assumes that these interactions are not important. If any significant interactions were present they would have been missed. This is a baseline level of effort, thus it has an impact of level 1.

PRA-2: Effort C; Impact 5

In the performance of PRA-2, the analysts did consider the impact of systems operating in environments beyond the system design limits. Any component that was exposed to an environment more severe than that for which it was designed was assumed to fail with a probability of one. As part of PRA-2, calculations were performed to determine the environment to which components inside containment would be exposed during any LOCA or transient-induced LOCA accident sequence. If this environment exceeded the design limits of components before the components were required to operate, a failure probability of one was assigned to that component for that accident sequence. This is a level C effort for this topic area for PRA-2. The environmental effects considered in this PRA resulted in several sequences being added to the dominant sequence list. The most dominant sequences for plant 2 were the most dominant as a result of the consideration of environmental effects on the depressurization system and the core spray system. In all, seven dominant accident sequence frequencies were raised 2 orders of magnitude due to environmental effects on these two systems. None of these sequences would have been dominant had environmental effects not been considered. Because of the increased frequency of these sequences, some other sequences (particularly ATWS sequences) do not appear as dominant sequences. This is a level 5 impact.

PRA-5: Effort B; Impact 1

The analysts performed a review of equipment location in PRA-5. Part of the intent was to determine what major pieces of equipment were subject to adverse environmental conditions during an accident, e.g., the LOCA environment inside containment. No equipment was found to be in such a location. This effort is a level B effort and had no impact on the system unavailabilities and therefore no impact on the dominant accident sequences. The effort for PRA-5 had a level 1 impact.

PRA-6: Effort B; Impact 1

In PRA-6 environmental qualification was considered in one case where two of the containment spray recirculation system pumps that are located inside the containment were assumed to fail at a higher rate due to common post-accident environment. A dependence factor was used based on engineering judgment. This is judged to be a level B increase in effort. Only one dominant sequence was effected by this assumption. This did not result in any change in the ordering of the dominant accident sequences. Thus, the impact of this topic on the overall results is categorized as level 1.

3.2 CALCULATION OF CORE MELT FREQUENCY CHANGES

This search for insights into PRA methods has so far focused on impacts related to dominant accident sequences, either as a change in the ranking of dominant accident sequences or as a change to the sequences that are considered dominant. For nine of the topic areas, the change in core melt frequency resulting from an increased effort was examined in addition to the evaluation of the impact as discussed in Section 3.1.

The nine topic areas for which this analysis was performed are: use of demand failure probabilities (DFP), common cause analysis (CC), analysis of common mode human errors (CM), modeling of the AC power systems (AC), treatment of recovery (R), treatment of the post accident heat removal phase (PAHR), identification of initiating events (IIE), human errors during normal operation (HN), and human errors during accident conditions (HA).

Some of the topic areas for which this analysis was not performed could be expected to have some impact on the calculated core melt frequency. For example, the treatment of the three topic areas of mean versus median (MVM), frequency of initiating events (FIE), and data base (DB) could potentially impact the calculated core melt frequency. The use of mean rather than median values throughout a PRA could result in an increase in the calculated core melt frequency, although probably not by more than a factor of 2. The use of plant-specific data, for both initiator frequencies and component failure rates, could result in either an increased or decreased core melt frequency. (In particular note the discussion of FIE in the previous section for PRA-4 in which it was noted that the frequency used for some initiators differed from generic values by an order of magnitude.)

However, the criterion for selecting the topic areas for this portion of the analysis was that the information to recalculate the core melt frequency, assuming the minimal effort for the topic area, had to be available from all six PRAs. This criterion was not met for those topic areas not included in this analysis, including the three quantification topic areas discussed above.

For each of the nine topic areas selected, the dominant accident sequence frequencies were recalculated assuming a baseline effort, as defined in Sections 3.1.1-3.1.20, for the topic area. For example, the requantification of the topic area IIE required a reevaluation of the initiators used in each PRA. In the reevaluation only generic initiators, those from EPRI NP-801, were considered. This represents a baseline level of effort. The dominant accident sequences initiated by events other than generic events were eliminated from the PRA results. The frequencies of the remaining accident sequences were screened and the change in the total core melt frequency calculated. A similar process was used to calculate the change in the total core melt frequency calculated in each PRA for the remaining eight topic areas. The requantified core melt frequencies were used to find the factor by which the increased topic area effort changed the plant core melt frequency.

The factor by which each plant core melt frequency changes is presented in Table 3.1. In this table, a positive number means that the plant core melt frequency increased due to the additional effort for the associated topic area. A negative number means the plant core melt frequency decreased. For example, in PRA-1 the plant core melt frequency increased by a factor of 1.1 due to the additional effort in the topic area AC. A plant core melt frequency change of +1.0 or -1.0 indicates a negligible increase or decrease, respectively, in the plant core melt frequency. In Figure 3.21 these same results are presented in a form similar to that used in Section 3.1. The increase in the absolute level of effort is correlated to a range of factors by which the core melt frequency changes for each PRA and topic. The PRAs are identified in this figure by arabic numerals.

Table 3.1. Factors By Which Core Melt Frequencies Were Changed Due to Increased Topic Area Efforts

	Core Melt Change Factor[1]					
Topic Area	PRA-1	PRA-2	PRA-3	PRA-4	PRA-5	PRA-6
AC	+1.1	-1.0	+1.2	+1.3	+1.5	+1.0
CC	N/A	+1.1	+1.2	+1.1	N/A	+1.0
CM	1.0	N/A	N/A	1.0	N/A	+1.1
DFP	N/A	N/A	N/A	N/A	+1.9	N/A
HA	-4.1	+1.2	-7.9	-11	+1.9	-1.3
HN	1.0	-2.2	1.0	N/A	-1.4	-3.3
IIE	+1.1	+1.3	+1.9	+1.1	+1.0	N/A
PAHR	1.0	+1.2	N/A	N/A	N/A	N/A
R	-9.3	N/A	-6.7	-12	-34	-1.0

[1] A positive number indicates the additional effort resulted in an increase in the core melt frequency; a negative number indicates a decrease. A number with no sign indicates no noticeable effect.

[illegible] ly topic area where an increased effort consistently results in more [illegible] a factor of 2 change in the core melt frequency is recovery. In four [illegible] the five plants where additional effort was exerted for this topic ar[illegible] the core melt frequency changed by a factor of more than five. Three [illegible] he five performed a level C increase in effort in which recovery of actuation faults and operator errors was considered. The remaining two PRAs considered recovery from these faults as well as the possibility of recovery from individual mechanical component faults, a level D increase in effort. The single largest impact on the core melt frquency did not occur in one of the two plants that performed a level D effort. This impact was due, in part, to particular plant strengths and weaknesses. Prior to the consideration of recovery most of the dominant accident sequences included failure of the long term cooling systems. This plant has multiple long term cooling systems that allow many options for the recovery of these systems.

The increased effort in the topic area treatment of human errors during an accident can impact the core melt frequency by more than a factor of 2 but not as consistently as the increased effort in treating recovery and certainly not to the same degree as recovery. The additional effort for this topic area involved nondetailed human error analysis, level of effort C, and a detailed human error analysis, level of effort E, versus the baseline effort of using screening values. (This differs from recovery where the baseline effort is to not consider recovery.) No single type of

Figure 3.21 Level of Effort versus Core Melt Frequency Impact for Nine Selected Topic Areas

Increase in Absolute Level of Effort	Factor By Which Core Melt Frequency Changes				
	1-2	2-3	3-10	10-20	20-50
A	CC 1,5 CM 2,3,5 HN 4 IIE 6 DFP 1,2,3,4,6 PAHR 3,4,5,6 R 2				
B	CC 3,4,6 CM 1,6 IIE 4 PAHR 1,2				
C	AC 1,4 CC 2 DFP 5 HA 6,2 HN 1,5 IIE 1,2,3,5 R 6	HN 2	HN 6 R 1		R 5
D	CM 4		R 3	R 4	
E	AC 2,3,5,6 HA 5 HN 3		HA 1,3	HA 4	

human error resulted in the change in the core melt frequency at all six plants, but there was a dominant human error at each of the plants. In the PWRs this error tended to be a failure to perform the switchover from injection to recirculation cooling.

A one-to-one correlation between the core melt frequency change results and the dominant core melt sequence impact results does not exist. Several of the topic areas in which an additional effort can impact the selection of the dominant sequences have no greater effect on the core melt frequency than topic areas in which an additional effort does not impact the selection of dominant sequences. For example, additional effort for the topic areas common cause and the modeling of AC power systems have different impacts on the selection of dominant accident sequences; however, their effect on the core melt frequency is approximately the same. Additional effort in both topic areas changed the core melt frequency by a factor of less than 2.

4.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This study has indicated the wide variety of safety analysis and reliability techniques involved in performing a PRA. Table 2.1 listed 20 of the most important methodological topic areas which must be addressed. In addition, the table outlined the related levels of effort that have been used in PRAs for treating each topic area. The baseline level of effort, represented by the "A" category in Table 2.1, was established as the minimum that can be performed and still have the analysis considered a reliability assessment. For some of the topics, the baseline effort represents WASH-1400, the state-of-the-art circa 1974; for other topics, the baseline efforts are less detailed than in WASH-1400. Many new techniques and approaches have since been developed. Alternative approaches within each topic area are represented by the levels of effort (levels A-E) shown in Table 2.1. In planning a PRA, the selection of the level of effort to be expended for each topic area is not trivial; it can have significant impact on the resources required to perform the study and on the acceptability of the results. The objective of this study was to develop an understanding of which of the topic areas has had the largest payoff when expanded analyses, above the baseline, were performed and to suggest guidance on which topic areas should be seriously considered for expanded levels of effort when undertaking a PRA.

We first summarize our observations by grouping the topics according to the degree of impact for effort expended. The first group includes topics which have been observed to have a high impact (and therefore are very important) but can be addressed with only moderate increases in effort above the baseline.

Moderate Effort - High Impact Topics

- Recovery (R)
- Identification of Initiating Events (IIE)
- Logic System Analysis (L)
- Human Errors During Normal Operation (HN)
- System Success Criteria (SSC)
- Frequency of Initiating Events (FIE)

- Environmental Qualification (EQ)
- Common Cause (CC)

Among these topics, recovery is especially important because failure to consider it always leads to overconservation, sometimes by large margins. This is contrary to one of the most important motivations for performing probabilistic analyses. Careful consideration of human errors, during normal operation or otherwise, is important for a similar reason in that overly conservative screening values of failure probabilities can distort results if not followed up by more thorough analyses for dominant sequences.

The high impact observed for logic system analysis (L) is somewhat correlated with low or moderate effort treatment of recovery (R). Extensive treatment of recovery tends to increase emphasis on operator actions and reduce the relative importance of automatic actuation systems. Thus, the pressure of logic system analysis in this group probably tends to overstate its relative importance.

Topics in the second group also have had high impact but require larger efforts. Their importance makes it essential to consider them as high priority topics in future PRAs.

Large Effort - High Impact Topics

- Human Errors During Accidents (HA)
- Analysis of AC Power (AC)
- System Dependency Analysis (SDA)

Three of the four PRAs employing the highest levels of effort in treating human errors during accidents (HA) exhibited high impacts. Only two PRAs employed the highest effort in hardwired system dependency analysis (SDA) but the impact in both cases was high enough to justify placing the topic in this group. The placement of AC power analysis (AC) in this group is much more tenuous in that only one of four high level efforts led to a high impact; in fact, the other three showed no impact from the increased effort. We include the topic in this group because the high impact observed in the one case demonstrates the possibility and illustrates the potential for a high level of impact from enhanced effort, particularly in plants of atypical design (as may be found in some older plants, the exceptional case noted here being an example). The AC topic could have been placed in the low impact group which follows, but we felt this could be a misleading indication of the topic's potential importance. We should also note that there is evidence of coupling between the AC and SDA topics. Detailed treatment of AC power is unlikely to show high impact if hardwired system dependency analysis is not also performed in detail. This is consistent with what one would expect.

The third group to be highlighted here includes topics in which moderate or large efforts above the baseline level have had very little impact on the outcomes of the six PRAs. This does not mean they can be ignored. It simply suggests they can be adequately treated with nominal levels of effort.

Large Effort - Low Impact Topics

- Data Base (DB)
- Common Mode (CM)
- Test and Maintenance (TM)
- Systems Interaction Analysis (SIA)
- Aggregation of Initiating Events (AIE)

The fourth group is comprised of four topics for which the sample size was too small to permit defensible conclusions. The topics are: means vs. medians (MVM), demand failure probability (DFP), event tree techniques (ET), and post accident heat removal (PAHR). Again, these topics are not to be ignored. They are, in fact, quite fundamental.

In order to translate our empirical observations into guidance for allocating analytical resources in future PRAs, we have prepared a "Suggested PRA Effort-Impact Profile" as shown in Figure 4.1. This indicates a suggested level of effort commensurate with an expected level of impact from the six PRAs considered. It was developed from a composite effort-impact profile for all PRAs and topics (presented in Appendix B as Figure B.7) by attempting to identify the level of effort for each topic that resulted in the largest marginal increase in impact. A considerable amount of the

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	DB SIA TM				
B		CM		FIE	
C		AIE	AC CC	L HN SSC	R IIE EQ
D					
E				SDA AC	HA

Figure 4.1 SUGGESTED PRA EFFORT-IMPACT PROFILE

analysts' judgment was also required. The profile chart itself is rather cryptic; to provide explicit guidance, the level of effort scale must be retranslated back into the level definitions given individually for each topic area in Table 2.1. The results of this exercise are shown in Table 4.1. Analysis of AC power (AC) appears twice because, as noted above, the impact will depend upon the amount of effort expended in other topic areas, specifically systems dependency analysis (SDA). A large effort (several man months) may not be justified if a less rigorous approach is used in evaluating system dependencies. Moreover, as indicated by the earlier discussion, our suggestion of an extensive fault tree effort encompassing the entire emergency power distribution system (i.e., circuit breakers and logic relays in addition to diesels or other power sources) stems more from the potential impact than from the expected impact. The greater effort is more important for older plants. A more moderate (less detailed) effort might well be acceptable for newer, more standardized, plants.

The suggested effort for analyzing hardwired system dependencies (SDA) would entail extensive fault tree analysis and the use of a large scale Boolean analysis code to analyze individual accident sequences considering both system failures and system successes. It would require about 2-6 additional man months of effort beyond the baseline. The main benefit would be much greater confidence that subtle hardwired system interactions had been identified. The full Boolean analysis also explicitly indicates sequence-level cutsets, i.e., failure modes at the plant level, which yields better insight into plant vulnerabilities.

The topic for which the highest level of effort is most clearly indicated is that of human errors during accidents (HA). As noted earlier, the usual screening approach to treating human errors generally leads to overconservation. The high impact of greater efforts stems from the tendency for estimates of error probabilities to decline (from screening or scoping values) upon detailed examination of the actions and circumstances associated with specific tasks. Human error probabilities vary by up to two orders of magnitude for different actions, or for similar actions under different conditions, e.g., loss of coolant accidents vs. loss of offsite power. This leads to greater realism in terms of quantitative estimates of core melt probability and risk and in terms of understanding plant vulnerabilities. There is less likelihood that true dominant accident sequences

Table 4.1 Suggested Levels of Effort Derived From Empirical Effort - Impact Analysis

	Topic Area		Suggested Level of Effort
IIE -	Identification of Transient and LOCA initiators	C.	Use generic initiator data plus plant-specific data.
FIE -	Determination of frequency of transient and LOCA initiators	B.	Use generic data augmented by classical use of plant-specific data.
ET -	Event tree modeling techniques	A. B.	Use small systemic event trees, or Use large event trees including global human actions.
SDA -	System hardwired dependency analysis	E.	Use Boolean reduction code.
SIA -	System interaction analysis	A.	Do not perform an analysis based on engineering insights.
PAHR -	Treatment of the past accident heat removal phase	B.	Use realistic accident lengths based on sequence requirements.
HN -	Human errors during normal operation	C.	Use non-detailed human error analysis.
HA -	Human errors during accident progression	E.	Use detailed human error analysis.
CM -	Common mode human error analysis	B.	Use an analysis based on engineering judgement.
R -	Treatment of recovery	C.	Consider the recovery of human errors and actuation faults.

	Topic Area		Suggested Level of Effort
AC -	Modeling of AC power systems	C. E.	Use non-detailed system models, or Use detailed system models (see Note 1).
L -	Modeling of logic systems	C.	Use simple non-detailed system models.
CC -	Common cause analysis	B.	Select components for analysis using engineering judgement.
DB -	Selection of component data base	A.	Use generic data.
DFP -	Use of demand failure probabilities	C.	Consider effect of long test intervals on component failure probabilities.
MVM -	Use of means vs use of medians	A.	Use mean failure rates, or Use median failure rates.
AIE -	Aggregation of initiating events	C.	Use functional aggregation of transient initiators.
SSC -	Determination of system criteria	C.	Use plant specific, realistic, analysis to determine appropriate system success criteria.
TM -	Modeling of test and maintenance	A.	Use generic unavailabilities.
EQ -	Environmental qualification	C.	Consider environmental effects on components, calculate environmental conditions encountered.

Note 1: Choice of detail can depend upon the level of effort expended in other topic areas, particularly SDA. If the suggested SDA level of effort (level E) is used, the suggested level of effort for the topic area AC is level C

will be masked by sequences where probability estimates are artificially high. The extra effort called for involves performing task analyses for specific acts, consideration of "performance shaping factors," and systematic estimation of composite error probabilities using methods such as THERP trees. Operational errors such as failure to reconfigure pumps and valves for recirculation or failure to manually depressurize would typically dominate. The detailed analyses should, of course, follow a screening analysis to minimize wasted effort on unimportant errors. The amount of effort involved might range from one to six man months depending on the number of tasks requiring detailed analysis.

The four topics for which the PRA sample size was too small to permit firm conclusions are omitted from the suggested profile. These, together with topics for which the baseline or low levels of effort are suggested, should be reconsidered on a case-by-case basis in light of the particular history or characteristics of a plant under consideration for a PRA. The appropriate level of effort for these topics probably should be left to the discretion of the analysts.

It should be noted that level C efforts require only modest resource commitments beyond those required for levels A and B. For topics in the low-impact category, it may well be desirable and cost effective to expend the level C efforts in that they may provide greater confidence in the results of a PRA.

Nine topics were examined with impact measured in terms of their influence on core-melt frequency. This analysis strongly confirmed the importance of recovery (R) and human errors during the course of an accident (HA). None of the other topics considered had a significant effect on core-melt frequency. This suggests that much of the value in applying extra effort comes from illuminating the relative importance of potential accident sequences and thereby gaining more insight and understanding of plant vulnerabilities.

The above recommendations are based upon a limited sample size of six PRA studies. One question which continually arose in performing the analysis was whether the conclusions were representative of PRA topic areas in general or whether the results were biased by the specific set of PRAs being analyzed. To develop an indication of the quality of the results, two attempts were made to characterize the topic areas in terms of the robustness of the conclusions.

First, a systematic attempt was made to prioritize topics within major effort-impact groupings on the basis of the numbers of PRAs falling in each group. For example, for the topic "recovery," there were 4 high impact cases out of 5 for which an effort greater than the baseline effort was made. This can be considered conclusive of the topic's importance insofar as the six-PRA sample permits. Similarly, "human errors during accidents" rated 4 of 6 while "identification of initiating events" rated 3 of 5. Other topics in the high impact groups exhibited lesser degrees of robustness, ranging down to 1 of 3 for "common cause." Presentation and discussion of these results are contained in Appendix A. Similar characterizations are provided for the low impact topics and for those for which the sample sizes were too small to permit firm conclusions.

A second attempt to illuminate the quality of the results was made in terms of the perceptions of the analysts most deeply involved in extracting detailed information from the six PRAs. Their perceptions are generally consistent with the more systematically generated assessments described above though they do not always follow directly.

The results for two high-impact topics are believed likely to be highly representative in the sense that similar results would be observed from any other set of PRAs. These are: Recovery (R) and Human Errors During Accidents (HA). Specific human errors of importance in the topic HA might vary among different categories of plants, e.g., PWRs vs BWRs, but the topic calls for expanded effort for virtually all existing light water reactors.

System Dependency Analysis (SDA), with two-of-two PRAs in the high effort-high impact category, warrants the suggested full scale Boolean analysis; that the impact will always be high is much less certain. Three PRAs showed no impact from a less thorough (hand vs. computer) Boolean reduction analysis.

Human errors during normal operation (HN) has the potential for high impact but may vary widely from one plant to another. The topic is probably always worthy of added effort because the likelihood of high impact cannot be reliably predicted, for example, on the basis of reactor type. With respect to human errors, an issue raised during the study was whether our assessments of impacts might have been biased in some sense because of the consistent choice of 0.01 as the scoping value for human error probability by the six PRAs, the implication being that 0.01 might be a poor choice. In principle, a different choice might have led to somewhat different results in individual PRAs. However, from the basic idea of a scoping analysis, a poor choice would be one that is too small. With a better, i.e., larger, choice, our assessments would have indicated higher impacts. But since we have already classified the human error topics in the high impact category, our results would not change in any essential way.

Common mode (CM) analysis, a topic of frequent concern from a methodological point of view, appears generally not to be a high priority topic. Additional effort may be warranted in some cases, but this need not be assumed automatically.

Expanded levels of effort for many topics will not necessarily have high impact on the results except for reactor-specific reasons such as anomalies in the plant, plant vintage, or reactor type. Topic areas which fall in this category include: Analysis of AC Power (AC), Equipment Qualification (EQ), Identification of Initiating Events (IIE), Frequency of Initiating Events (FIE), Data Base (DB), Test and Maintenance (TM), Logic System Analysis (L), and System Success Criteria (SSC). These topic areas are expected to have large impact on the results only for specific circumstances. FIE, DB and TM will only come into consideration if there are unique features that are not normally considered in existing PRAs or if there have been a significant number of previous problems (event precursors) at the plant. Detailed logic system analysis (L) is probably only important for older vintage plants designed when integrated systems were first being developed.

Specific topic areas in this category need to be addressed by analysts who can make reasonable judgments as to the need for expanded analysis based upon specific knowledge of the plant.

In addition to the above categories, a few of the topics were either indeterminant or had some unique characteristic which set them apart from the others. For example, the appropriate level of effort for System Dependency Analysis (SDA) is strongly dependent upon the level of effort and detail used in other topics and in fault tree analysis generally. Common Cause (CC) analysis used in the six PRAs was not at the current state-of-the-art so the results are of questionable value. System Interaction Analysis (SIA) is not well defined; its impact is likely to be highly dependent upon the skill and experience of the analyst and therefore is not easily represented in this analysis.

Certain basic assumptions are generally common to all PRAs. For example: faults are assumed to be binary with no credit given for partial success; no credit is taken for success paths not described in plant procedures; no "miracles" are allowed. The present study did not address these assumptions. Other more specific assumptions, however, could affect the relative outcomes of different PRAs. Rather than treat assumptions as a general topic in itself, we tried to represent major assumptions in the specification of levels of effort. To illustrate, a possible assumption is that operator errors are not recoverable. This assumption is implicit in the baseline level of effort for the topic of recovery (R), which is not to consider recovery actions. A higher level of effort implies removal of the assumption. The impact of the assumption is therefore reflected in the collective results for the topic of recovery. While we cannot assure completeness, we believe the impact of most major assumptions that have been made at the present level of interest are probably reflected at least to some extent in the assessments.

The method used in performing this analysis - defining a specific list of topics, establishing a baseline approach or level of effort for each, and then determining the impact of increased levels of effort employed in the PRA - provided an excellent method for reviewing a PRA. The method assured that there would be a detailed evaluation of all areas in the study. Not only are the topics highlighted, the analyst has to develop a detailed understanding of the dominant accident sequences and the impact of the methods or levels of effort on the results.

To indicate the thoroughness of this review process, errors were found in every one of the six PRAs studied. Two of the errors found had significant impact on the results. The first of these involved sequence quantification. An operator action following a loss of offsite power involved shutting down high pressure injection pumps. This operator error, the failure to shutdown the pumps, was applied to a station blackout sequence. Under this condition the operator error is not a credible event since the pumps could not operate during station blackout, the cut sets containing this error cannot exist. Had these cut sets been handled properly one dominant sequence would have been eliminated. The second error was a Boolean reduction problem in that two redundant dominant sequences were quantified. This represented 25% of the dominant sequences and had a significant impact on the results.

The other errors found were minor and had little impact on the results. Examples included small mathematical quantification errors and errors in determining the frequencies of some initiating events. Additional problems were found in failure to consider system successes in analyzing individual accident sequences.

As can be seen, the method used to assess the impact of the topic areas provided an excellent mechanism for review of the PRA. In addition, the results from this study on what topic areas have significant impact should provide direction to the review process and help in allocating the review resources to areas where there is potential payoff.

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Appendix A

PRIORITIZATION OF TOPIC AREAS

In order to obtain some insights into the appropriate level of effort for each topic, an attempt was made to prioritize the topic areas in terms of impact obtained for the level of effort expended. The topic areas were partitioned into three classes:

- Topics that exhibit high impact for moderate and large levels of effort
- Topics that exhibit small impacts for the level of effort applied
- Topics for which the data size was too small to draw even tentative conclusions about impacts from higher than baseline levels of effort

Table A-1 shows the list of topics for which higher than baseline levels of effort resulted in relatively high impacts. "High impact" is defined to be impact levels 3, 4, and 5. The eleven topic areas in this category are listed in the left hand column. The topics are listed approximately in their prioritized order, with the highest priority topic (recovery) listed at the top. The second column lists the number of high impact cases observed (x) and the number of cases where an effort greater than the baseline effort was made to perform the topic area (y). Thus, for recovery, four cases were found to have high impact out of a total of five cases where the level of effort applied to the topic was greater than the baseline level of effort. The topic areas in Table A-1 are ranked primarily according to this fraction, i.e., for recovery the primary ranking index is 4/5. The third column, Remarks, gives an indication of the actual impacts achieved for the levels of effort expended on the topics. Thus, for the topic area "Identification of Initiating Events" (IIE), the high impact cases were levels 4 and 5, and these were achieved with levels of effort B and C. The information in this column was used to break ties in the primary ranking index. Thus the topic areas "Human Errors during Normal Operation" (HN), and "System Hardwired Dependency Analysis" (SDA), both have primary ranking indices of 2/5. The topic HN is ranked higher than SDA because, for

TABLE A-1

TOPICS THAT EXHIBIT HIGH IMPACT FOR MODERATE AND LARGE LEVELS OF EFFORT

Topic Area	X/Y	Remarks
Recovery (R)	4/5	High impact cases (levels 4 and 5) were levels of effort C and D
Human errors during accident (HA)	4/6	Three of four high impact cases were level of effort E
Identification of initiating events (IIE)	3/5	High impact cases (levels 4 and 5) were levels of effort B and C
Frequency of initiating events (FIE)	2/4	High impact cases (level 4) were levels of efforts B and C
System success criteria (SSC)	2/4	High impact cases (level 4) were level of effort C
Human errors during normal operations (HN)	2/5	High impact cases (levels 3 and 4) were level of effort C
System hardwired dependency analysis (SDA)	2/5	High impact cases (levels 3 and 4) were level of effort E
Environmental qualification (EQ)	1/3	High impact case (level 5) was level of effort C
Actuation system analysis (L)	2/6	High impact cases (level 4) were levels of effort C and E
AC power system analysis (AC)	2/6	High impact cases (levels 3 and 4) were levels of effort C and E
Common Cause (CC)	1/4	High impact case (level 3) was level of effort C

Legend: X = number of high impact cases

Y = number of cases where an effort greater than the baseline effort was made

HN, impact levels 3 and 4 were achieved with level of effort C, while for topic SDA impact levels 3 and 4 were achieved with level of effort E, a significant increase in the level of effort over level C.

Table A-2 lists the topic areas categorized as exhibiting small impacts for the levels of effort expended. The topic areas are listed in the left-hand column, approximately in an order that emphasizes least impact for the level of effort expended. Thus, for the level of effort expended, "Test and Maintenance" showed somewhat less impact than "Data Base." The second column shows the ranking index, number of low impact cases versus the number of cases where an effort greater than the baseline effort was made to perform the topic. The third column, Remarks, gives an indication of the impacts obtained for the levels of effort expended in each topic. The rankings in this case are very weak. In only one case (AIE) was a high impact observed for a greater than baseline level of effort, and in this case there appears to be a deficiency in the methodology that results in the high impact (as noted in Section 3.1).

Table A-3 shows the topic areas for which insufficient data was available in the sample of PRA's studied to draw conclusions about the impact versus level of effort. These topics are not arranged in any particular order. The Remarks column lists additional information about the few cases that were not the baseline level of effort. These topics are categorized in Table A-3 because most of the PRA's applied only the baseline level of effort to them.

Care must be exercised in interpreting the results shown in Tables A-1, A-2, and A-3. The small sample size limits their usefulness. A large sample size could easily result in a different ranking of the topics listed in Table A-1, or topics in Table A-2 moving to Table A-1 due to cases where high impacts are observed for the topics in Table A-2. Nevertheless, although the ranking in Table A-1 could change, the topics listed here have been observed to, in at least one case, exhibit a large impact from application of a level of effort greater than the baseline level.

TABLE A-2

TOPICS THAT EXHIBIT SMALL IMPACT FOR LEVEL OF EFFORT APPLIED

Topic Area	X/Y	Remarks
Test and maintenance (TM)	5/5	Four of five low impact cases (levels 1 and 2) were level of effort D. Remaining case was impact 1, level B
Data base (DB)	4/4	Impact levels 1 and 2 for levels of effort C and E
Common mode human errors (CM)	3/3	Impact levels 1 and 2 for levels of effort B and D
Systems interaction analysis (SIA)	3/3	Impact levels 1 and 2 for level of effort C. No PSA did highest level of effort
Aggregation of initiating events (AIE)	4/5	Impact levels 1 and 2 for levels of effort C and E. One high impact case (impact 4 for effort E), due to failure to recognize a dominant accident sequence because of lack of initiating event aggregation

Legend: X = number of low impact cases

Y = number of cases were an effort greater than baseline effort was made

TABLE A-3

TOPICS FOR WHICH DATA SIZE WAS TOO SMALL TO DRAW CONCLUSIONS

Topic Area	X/Y	Remarks
Means versus medians (MVM)	6/6	All level of effort A
Demand failure probability (DFP)	5/6	Only level of effort case greater than A was level C which resulted in impact 5
Event trees (ET)	5/6	Only level of effort case greater than A was level B, which resulted in impact 2
Post accident heat removal (PAHR)	4/6	No PRA did highest level of effort. Two cases did level of effort B resulting in impacts 1 and 3

Legend: X = number of cases that did level of effort A

Y = total number of cases

Appendix B

EFFORT-IMPACT ASSESSMENTS ARRANGED BY PRA

This section recasts the results of the analysis by PRA. These results are the same as those presented in Section 3.0 and therefore are not presented at the same level of detail. More specific information on how a PRA treated each topic area can be found in the appropriate topic area discussion in Section 3.0.

The results for each PRA are presented in matrix form in Figures B.1 through B.6. In these matrices the topic areas are referred to using the designators presented in Section 1.0. A composite matrix showing all the results for this study is presented in Figure B.7. In this matrix the topic area designators are used and the plants are referred to by their assigned number. For example, R-3,4 appears in location D-5. This represents a level D increase in effort and a level 5 impact for the topic area recovery for PRA-3 and PRA-4.

B.1 PRA-1 Methodology Study Results

This section summarizes the results of the examination of the methodology used in PRA-1. The results are presented in terms of the additional efforts above the baseline effort utilized in performing the PRA and the impacts of these efforts on the analysis. The results are shown in matrix form in Figure B.1.

This PRA put additional effort above the baseline into a number of the methodological topic areas evaluated. Extensive evaluation of plant-specific initiating events was performed (level C). Classical statistics were used to develop plant-specific initiating event frequencies from plant historical data (level B). The initiating events were aggregated functionally based on their effects on plant mitigating systems, which resulted in the need to evaluate a moderate number of event trees (level C). Hardwired system dependencies were identified directly by the analysts for support system interfaces, although some computer aided reduction was performed, with bounding calculations used to evaluate the potential contributions of nonsupport system dependencies (level C). System interactions other than

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	CC DB DFP ET EQ MVM TM				
B	CM PAHR	FIE			
C	HN SDA SIA SSC	AC AIE IIE		L R	
D					
E				HA	

Figure B.1 Effort-Impact Summary Matrix for PRA-1

Impact On Ordering of
Dominant Sequences

Increase In Absolute
Level of Effort

	1	2	3	4	5
A	CM SSC DFP ET MVM R				
B			PAHR	FIE	
C	SDA SIA	DB	CC	HA HN IIE	EQ
D	TM				
E	AC AIE L				

Figure B.2 Effort-Impact Summary Matrix For PRA-2

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	CM DFP ET EQ FIE MVM PAHR SIA				
B		CC			
C	DB	AIE		SSC	IIE
D	TM				R
E	AC HN	L	SDA	HA	

Figure B.3 Effort-Impact Summary Matrix for PRA-3

Impact On Ordering of
Dominant Sequences

Increase In Absolute
Level of Effort

	1	2	3	4	5
A	DFP EQ HN MVM PAHR SIA				
B	CC	ET		IIE	
C	L SDA		AC	FIE SSC	
D	CM	TM			R
E	DB	HA	AIE		

Figure B.4 Effort-Impact Summary Matrix for PRA-4

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	CC SIA CM ET MVM PAHR				
B	EQ FIE TM				
C	DB IIE	AIE SSC	HN		DFP R
D					
E				AC L SDA	HA

Figure B.5 Effort-Impact Summary Matrix For PRA-5

Impact On Ordering of Dominant Sequences

Increase In Absolute Level of Effort

	1	2	3	4	5
A	AIE DB DFP ET FIE IIE MVM SDA SSC				
B	EQ	CC CM			
C		HA HN R SIA			
D		TM			
E	AC L				

Figure B.6 Effort-Impact Summary Matrix for PRA-6

IMPACT ON ORDERING OF DOMINANT SEQUENCES

INCREASE IN ABSOLUTE LEVEL OF EFFORT

	1	2	3	4	5
A	AIE-1 CC-1,5 CM-2,3,5 DB-1,6 DFP-1,2,3,4,6 ET-1,2,3,5,6 EQ-1,3,4 MMM-1,2,3,4,5,6 PAHR-3,4,5,6 FIE-3,6 HM-4 IIE-6 R-2 SDA-6 SIA-3,4,5 SSC-2,6 TM-1				
B	CC-4 CM-1 EQ-5,6 FIE-5 PAHR-1 TM-5	CC-3,6 CM-6 ET-4 FIE-1	PAHR-2	FIE-2 IIE-4	
C	DB-3,5 HM-1 IIE-5 L-4 SDA-1,2,4 SIA-1,2 SSC-1	AC-1 AIE-1,3,5 DB-2 HM-6 HA-6 IIE-1 SSC-5 SIA-6 R-6	AC-4 CC-2 HM-5	FIE-4 HA-2 HM-2 IIE-2 L-1 R-1 SSC-3,4	DFP-5 EQ-2 IIE-3 R-5
D	CM-4 TM-2,3	TM-4,6			R-3,4
E	AC-2,3,6 AIE-2 DB-4 HM-3 L-2,6	L-3 HA-4	SDA-3 AIE-4	AC-5 HA-1,3 L-5 SDA-5	HA-5

Figure B.7 Effort-Impact Composite Results hardwired were evaluated on a case-by-case basis using engineering judgment (level C). Plant-specific system success criteria rather than FSAR criteria were used (level C). Human errors during normal operation were evaluated using a simplified error model based on NUREG/CR-1278 without detailed THERP analysis (level C). Human errors during accident progression were evaluated using detailed THERP modeling techniques from NUREG/CR-1278 (level E). Common mode human errors were evaluated on a case-by-case basis, using engineering judgment to select which of these errors would be evaluated (level B). The AC power and control logic systems were modeled using simplified fault trees (level C). Recovery credit was evaluated only for functional recovery covered by written procedure by using a strictly cognitive (time-dependent) recovery model (level C). A plant-specific analysis was performed to determine the length of the post accident heat removal phase (level B).

The impact of the additional efforts discussed above varied from topic to topic. Some had a great impact while others had no impact at all. The impact ranking of the topic areas for which additional effort was expended, from greatest impact to least impact, were as follows:

Impact 5
    None

Impact 4
    Human errors during accident conditions
    Recovery
    Modeling of logic systems

Impact 3
    None

Impact 2
    Identification of initiating events
    Frequency of initiating events
    Aggregation of initiating events
    Modeling of AC power systems

Impact 1

System hardwired dependency analysis
Systems interaction (other than hardwired) analysis
Human errors during normal operation
Common mode human errors
System success criteria
Treatment of the post-accident heat removal phase

B.2 PRA-2 Methodology Study Results

This section summarizes the results of the examination of the methodology used in PRA-2. The results are presented in matrix form in Figure B.2.

This PRA put additional effort into a number of the methodological topic areas evaluated. Extensive evaluation of plant-specific initiators was performed (level C). The frequencies of these initiating events were determined using both generic data sources and plant-specific information (level B). Very little aggregation of the initiating events was performed, resulting in the need to evaluate a relatively large number of event trees (level E). Hardwired system dependencies were identified primarily by the analysts for support system interfaces (level C). Other types of systems interactions were identified by using engineering judgment to select appropriate areas of study (level C). Detailed fault tree models were developed for both the AC power systems (level E) and the actuation logic systems (level E). Human errors during accident conditions were evaluated using nondetailed task-oriented models (level C). The evaluation of operator errors during normal operation was handled in a similar manner (level C). Plant-specific data were used; generic data were used only if insufficient plant data were available (level C). Plant-specific test and maintenance histories were used to develop outage unavailabilities (level D). The impact of environments beyond design limits on component failure probabilities was considered on a case-by-case basis using engineering judgment (level C). Common cause failures were evaluated for all common cause systems (level C). A plant-specific analysis was performed to determine the length of the post accident heat removal phase (level B).

The impact ranking of the topic areas for which additional effort was expended, from greatest impact to least impact, were as follows:

Impact 5
- Environmental qualification

Impact 4
- Frequency of initiating events
- Identification of initiating events
- Human errors during normal operations
- Human errors during accident conditions

Impact 3
- Treatment of the post-accident heat removal phase
- Common cause

Impact 2
- Type of data base

Impact 1
- System hardwired dependency analysis
- Systems interaction (other than hardwired) analysis
- Test and maintenance outages
- Modeling of AC power systems
- Modeling of actuation logic systems
- Aggregation of initiating events.

B.3 PRA-3 Results

This section summarizes the results of the examination of the methodology used in PRA-3 in terms of both the additional efforts above the baseline utilized in performing the analysis and the impacts of this effort on the analysis. The results are shown in matrix form in Figure B.3.

This study put additional effort into a number of the methodological topic areas evaluated. Extensive evaluation of plant-specific initiating events was performed (level C). The initiating events were aggregated functionally based on their effects on plant mitigating systems, which resulted in the need to evaluate a moderate number of event trees (level C). Hardwired system dependencies were included directly on the fault trees and evaluated by Boolean reduction on a computer (level E). Plant-specific realistic success criteria were developed rather than using licensing criteria (level C). Very detailed human error models based on NUREG/CR-1278 were developed for both human errors during normal operation (level E) and human errors during accident progression (level E). The AC power and control logic systems were modeled using very detailed component level fault trees (level E). Very detailed analysis of recovery considering functional and component recovery both inside and outside the control room was performed (level D). Classical analysis with a statistical significance test was used to incorporate plant-specific component failure data into the analysis (level C). Common cause component failures were handled on a case-by-case basis, with generic historical failure data used for those components which the analysts judged to be susceptible to common cause failure (level B). Finally, historical plant-specific out-of-service times were used to develop test and maintenance unavailabilities (level D).

The impact ranking of the topic areas for which additional effort was expended, from greatest impact to least impact, were as follows:

Impact 5
- Recovery
- Identification of initiating events

Impact 4
- System success criteria
- Human errors during accident conditions

Impact 3
- System hardwired dependency analysis

Impact 2
- Common cause modeling
- Aggregation of initiating events
- Modeling of logic systems

Impact 1

- Type of data base
- Test and maintenance
- Human errors during normal operation
- Modeling of AC power system

B.4 PRA-4 Results

This section summarizes the results of the examination of the methodology used in PRA-4. The results are shown in matrix form in Figure B.4.

In PRA-4, additional generic initiating events above those identified in WASH-1400 were included (level B). A two-stage Bayesian technique utilizing two levels of generic data and one level of plant-specific data was used for both initiating event frequency (level C) and component failure rates (level E), and means instead of medians were used for the point estimate calculations (level A). Many event trees were evaluated since the use of FSAR event categories resulted in very little aggregation of initiating events (level E). The event trees evaluated included functional operator actions and support systems (level B). Hardwired system dependencies were identified and isolated by the analysts outside of the fault tree process (level C). Plant-specific realistic system success criteria were developed instead of using licensing criteria (level C). Very detailed human error models based on NUREG/CR-1278 were developed for both human error in response to accidents (level E) and common mode human error (level D). The AC power and control logic systems were modeled using simplified fault trees (level C). Very detailed analysis of recovery, which considered functional and component recovery both inside and outside the control room, was performed (level D). Common cause component failures were handled on a case-by-case basis, with a beta-factor approach being used for those components which were judged by the analysts to be susceptible to common cause failure (level B). Finally, historical plant-specific out-of-service times were used to develop test and maintenance unavailabilities (level D).

The impact ranking of the topic areas for which additional effort was expended, from greatest impact to least impact, were as follows:

Impact 5
- Recovery

Impact 4
- Identification of initiating events
- Frequency of initiating events
- Aggregation of initiating events
- System success criteria

Impact 3
- Modeling of AC power system

Impact 2
- Event tree types
- Test and maintenance
- Human errors during accident conditions

Impact 1
- System hardwired dependency analysis
- Common mode human errors
- Modeling of logic systems
- Component reliability data base
- Use of means vs. medians
- Common cause modeling

B.5 PRA-5 Methodology Study Results

This section summarizes the results of the examination of the methodology used in PRA-5. The results are shown in matrix form in Figure B.5.

This study put additional effort into a number of the methodological topic areas evaluated. An evaluation of plant-specific initiators was performed (level C). Plant-specific event frequencies were calculated for some of the initiators (level B). Functional aggregation of initiators was performed, resulting in the evaluation of a relatively small number of event trees (level C). The hardwired system dependency analysis was performed using detailed fault trees and the quantification of sequence level (as opposed to system level) cut sets (level E). A generic data base was used, augmented with plant-specific data (level C). Generic data was used for test and maintenance unavailabilities with the exception that plant-specific repair times were used (level B). Failure rates were derived from the demand failure probabilities, found in generic data, for components with long test intervals (level C). Plant-specific system success criteria were used for some systems (level C). Screening values were used in the quantification of human errors that can occur during normal operation (level C). Detailed analyses were performed for human errors during the accident progression, at least for those that appeared in dominant cut sets when a screening value was used (level E). Recovery actions that could be taken from the control room or accessible areas were considered; the recovery of failed equipment was not (level C). Detailed fault tree models were constructed for the AC power system (level E) and the actuation logic systems (level E). Environmental evaluation considerations were evaluated on a case-by-case basis using engineering judgment (level B).

The impact ranking of the topic areas for which additional effort was expended, from greatest impact to least impact, were as follows:

Impact 5
    Use of demand failure probabilities
    Recovery
    Human errors during accident conditions

Impact 4
    Modeling of AC power systems
    Modeling of actuation logic systems
    System hardwired dependency analysis

Impact 3
    Human errors during normal operation

Impact 2
    Aggregation of initiating events
    System success criteria

Impact 1

- Environmental qualification
- Frequency of initiating events
- Test and maintenance outages
- Component reliability data base
- Identification of initiating events

B.6 PRA-6 Methodology Study Results

This section summarizes the results of examination of the methodology used in PRA-6. The results are shown in matrix form in Figure B.6.

Engineering judgment was used to select the systems for which a common cause analysis would be performed (level B). Common mode human errors were evaluated on a case-by-case basis, engineering judgment was used to determine when these common mode errors would be considered (level B). Nondetailed human error analysis was performed for human errors during normal operation (level C) and for human errors during the accident progression (level C). Recovery of actuation faults and operator errors was considered (level C). Detailed fault tree models were constructed for the AC power system (level E) and the actuation logic systems (level E). Plant-specific test and maintenance outage information was used (level D). System interactions other than hardwired were evaluated on a case-by-case basis using engineering judgment (level C). When to consider operation of equipment outside design limits was determined using engineering judgment (level B).

The impact of the additional effort discussed above varied from topic to topic. The impact ranking of the topic areas for which additional effort was expended, from greatest impact to least impact, were as follows:

Impact 5

- None

Impact 4

- None

Impact 3

- None

Impact 2

- Common cause
- Common mode
- Human errors during accident conditions
- Human errors during normal operation
- Systems interaction (other than hardwired) analysis
- Recovery
- Test or maintenance outages

Impact 1

- Environmental qualification
- Modeling of AC power systems
- Modeling of actuation logic systems

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(2 84)
NRCM 1102,
3201, 3202

U.S. NUCLEAR REGULATORY COMMISSION

BIBLIOGRAPHIC DATA SHEET

SEE INSTRUCTIONS ON THE REVERSE

1. REPORT NUMBER *(Assigned by TIDC, add Vol. No., if any)*
NUREG/CR-3852

2. TITLE AND SUBTITLE
Insights Into PRA Methodologies

3. LEAVE BLANK

4. DATE REPORT COMPLETED

MONTH	YEAR
August	1984

5. AUTHOR(S)
D. GALLAGHER AND OTHERS

6. DATE REPORT ISSUED

MONTH	YEAR
August	1984

7. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
SCIENCE APPLICATIONS, INC.
P.O. BOX 1303
1710 GOODRIDGE DRIVE
McLEAN, VIRGINIA 22102

8. PROJECT/TASK/WORK UNIT NUMBER

9. FIN OR GRANT NUMBER
FIN B0783

10. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS *(Include Zip Code)*
Division of Safety Technology
Office of Nuclear Reactor Regulation
U. S. Nuclear Regulatory Commission
Washington, D. C. 20555

11a. TYPE OF REPORT
TECHNICAL REPORT

b. PERIOD COVERED *(Inclusive dates)*
SEPT. 1983--JUNE 1984

12. SUPPLEMENTARY NOTES

13. ABSTRACT *(200 words or less)*

This report describes the results of a survey of six probabilistic risk assessments to determine the impact of different aspects of the methodology on dominant sequence ordering and core-melt likelihood. The results indicate that effort should be given to human error analysis, system dependency analysis, and modeling of AC power systems.

14. DOCUMENT ANALYSIS – a. KEYWORDS/DESCRIPTORS
PRA METHODOLOGY
CORE-MELT FREQUENCY
DOMINANT ACCIDENT SEQUENCES

b. IDENTIFIERS/OPEN ENDED TERMS

15. AVAILABILITY STATEMENT

16. SECURITY CLASSIFICATION
(This page)
UNCLASSIFIED
(This report)
UNCLASSIFIED

17. NUMBER OF PAGES

18. PRICE

UNITED STATES
NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555

120555078877 1 1AN
US NRC
ADM-DIV OF TIDC
POLICY & PUB MGT BR-PDR NUREG
W-501
WASHINGTON DC 20555