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MULTIPLE SYSTEM RESPONSES and INTERACTION ISSUES: ADEQUACY of TREATMENT in IPE/IPEEE SUBMITTALS

by

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ABSTRACT

Safety issues related to multiple systems interaction effects are assessed and summarized relative to their treatment within several **I**ndividual **P**lant **E**xamination (IPE) and Individual **P**lant **E**xamination for **E**xternal **E**vents (IPEEE) submittals. Investigative results indicate that systems interaction issues, particularly for support system cross-dependencies, are best treated using PRA methods rather than alternate **S**eismic **M**argins **M**ethods (SMM) and **F**ire **I**nduced **V**ulnerability **E**valuation (FIVE) techniques.

I. INTRODUCTION

The underlying design philosophy for nuclear power plants has always been one of redundancy and diversity in vital and engineered safety systems. Nevertheless, elusive cross-system interactions and human-equipment dependencies are inherent to complex systems, which can ultimately defeat multiple/independent pathways for safe reactor shutdown. The accident at Three Mile Island (TMI-2) and the Browns Ferry fire provide examples of such cross-system interactions. Inadvertent shutoff of the high pressure injection system (HPIS) during maintenance procedures (a human error) exemplifies a human-equipment dependency, while loss of HPIS in conjunction with the stuck-open relief valve (a cross-system interaction) resulted in insufficient core cooling and eventual meltdown. The mutual destruction of power and control cables to the decay heat removal and emergency core cooling (ECC) systems during the Browns Ferry fire exemplify another cross-system interaction, which could have been averted by adequate cable separation to redundant safety trains. Ref. [1] provides additional examples of system-interaction events which compromised plant safety and which has lead to long history of discussions by the Advisory Committee on Reactor Safeguards (ACRS) members in this area. The issue came to a head in the early years following the TMI-2 accident, while the committee was hearing proposed remedies to a number of **U**nresolved **S**afety **I**ssues (USI), namely:

USI A-17: Systems Interactions in Nuclear Power Plants,

USI A-46: Seismic Qualification of Equipment in Operating Plants
USI A-47: Safety Implications of Control Systems

10 CFR 50.48: Fire Protection Rules

10 CFR 50.49: Equipment Qualification

10 CFR 50(R): Guidelines used in the Standard Review Plan

ACRS members expressed the concern that an issue-by-issue approach to resolution and lack of coordination to assess cross-relationships among issues, could lead to oversight of potentially significant safety problems. In response to these concerns, the NRC staff initiated the Multiple System Responses Program (MSRP) in 1986. Early efforts were performed by the NRC staff at the Nuclear Operations Analysis Center (NOAC) located at Oak Ridge, and centered on the identification of cross-relation/multiple-system interactions associated with the above six issues. From these six parent issues were born the twenty-one MSRP issues[2] listed in Table 1. Table 1 also shows how each issue is treated in the regulatory process[3], where it is noted that all issues are deemed to be covered under the scope of existing Generic Issues (GI) and other NRC actions, or to be addressed in the Individual Plant Examination (IPE) and the Individual Plant Examination of External Events (IPEEE) programs.

In the fall of 1995, the ACRS requested this author to investigate the treatment of IPE/IPEEE designated MSRP issues within several representative IPE/IPEEE submittals, the results of which are summarized here.

II. SCOPE OF SURVEY

The investigation centered on an examination of the 4 IPE/IPEEEs listed in Table 2. The Callaway and Diablo Canyon submittals, which have similar plant characteristics but employed somewhat different IPEEE methodologies, were reviewed in detail to compare the extent of coverage of the MSRP issues. The Callaway IPEEE was based on the Seismic Margins Methodology (SMM) and Fire Induced Vulnerability Evaluation (FIVE) approaches to identify potential plant vulnerabilities, while Diablo Canyon made use of probabilistic risk assessment (PRA) techniques. The WNP-2 and Catawba IPEEEs were also examined for three concerns which received considerable prior ACRS scrutiny, namely (a) The Effects of Fire Suppression System Actuation on Non-Safety and Safety Related Equipment Interactions-Issue 13, (b) Seismically Induced Relay Chatter-Issue 19, and (c) The Effects of Hydrogen Line Ruptures-Issue 21. Investigative results are summarized in this paper, first however SSM, FIVE, and PRA techniques are reviewed.

III. SEISMIC ANALYSIS METHODS

Two techniques to assess seismic vulnerabilities are: (a) the seismic PRA and (b) Seismic Margins Method. The basic elements of the PRA approach are:

(a) A *Seismic Hazards Analysis*: to identify the probability of occurrence of seismic events,

(b) *Equipment/Structural Fragility Analysis*: to identify the probability of failure or malfunction of plant components,

(c) *Plant Logic Analysis*: makes use of event and fault trees to estimate the progression of component and system failures

(d) *Reduced Containment Analysis*: to identify unique seismic vulnerabilities analysis.

Table 1. Multiple System Responses and Interaction Issues

Issue	Potential Safety Issue	Suggested Resolution[a] 1	2	3
1	Common Cause Failures Related to Human Errors		X	X
2	Non-Safety/Safety-Related Control System Effects		X	X
3	Failure Modes of Digital Computer Control Systems	X		
4	Specific Scenarios Not Covered in USI A-47	X		
5	HVAC Degradation on Control/Safety Systems	X		
6	Failure Modes from Degraded El. Power Sources	X		
7	Failure Modes from Degraded Comp.-Air Systems	X		
8	Potential Effects of Untimely Component Operation	X		
9	Propagation of Environments Associated with DBEs	X		
10	Heat/Smoke/Water Propagation Effects from Fires	X		
11	Synergistic Effects of Harsh Environments	X		
12	Environmental Qualification of Seals/Gaskets Packing/Lubricants for Mechanical Equipment	X		
13	Effects of Fire Suppression System Actuation on Non-Safety Related and Safety-Related Equipment			X
14	Effects of Flooding and/or Moisture Intrusion on Non-Safety Related and Safety-Related Equipment		X	X
15	Seismically-Induced Spatial/Functional Interactions			X
16	Seismically-Induced Fires			X
17	Seismically-Induced Fire Suppression System Actuation			X
18	Seismically-Induced Flooding			X
19	Seismically-Induced Relay Chatter			X
20	Evaluation of Earthquake Magnitudes Greater than the Safe Shutdown Earthquake			X
21	Effects of Hydrogen Line Ruptures			X

(1) Embodied in existing Generic Safety Issues or other NRC actions; (2) To be addressed in IPEs; (3) To be addressed in IPEEEs

Table 2. Plant Characteristics for Evaluation of MSRP Issues

Plant/Rating	Commercial Operation	Vendor/Type	Containment	IPEEE Method
Callaway/3545 MWt	Apr. 1985	WE/4-loop PWR	Large-dry	SMM/FIVE
Diablo Canyon/3338 MWt	Mar. 1986	WE/4-loop PWR	Large-dry	PRA
Catawba/3411 MWt	Jun. 1985	WE/4-loop PWR	Ice Condenser	PRA
WNP-2/3323 MWt	Dec. 1984	GE/BWR-5	Mark-II/Inert	PRA

System interactions are generally revealed in the Plant Logic Analysis, which illustrate the consequences of various structural and component failures. The initial step includes development of "dependency tables", indicating how failure of a support system (electric power, controls, cooling water) impacts equipment in other support or front-line systems. Event trees are constructed from such dependency tables, from which information on cascaded or system-system interactions is abstracted.

The alternate Seismic Margins Method (SMM) is based on a screening approach[4], which primarily relies on plant walkdowns to identify component, system, and human error vulnerabilities important to reactor shutdown and seismic ruggedness. Two SMM approaches have been developed. Using the NRC method, plant safety must be assured by attainment of reactor subcriticality and early emergency core cooling. The EPRI (Electric Power Research Institute) method is based on a systems success path[5] approach, which evaluates the capacity of components required to bring the plant to a stable shutdown.

IV. FIRE ANALYSIS METHODS

Two somewhat different methods are used to assess fire related plant vulnerabilities: (a) the fire PRA and (b) the Fire Induced Vulnerability Evaluation (FIVE). A fire PRA is similar in its basic structure to that for seismic analysis, and includes an assessment of potential component and system degradation due to smoke and heat generation effects. The FIVE method[6] was developed by EPRI as an alternative to the fire PRA, and is directed at implementation by plant personnel experienced with overall plant operation, fire hazards, and protection features, as opposed to being conducted by the PRA analysist. The methodology provides plant personnel with walkdown guidelines to identify potential fire related vulnerabilities for plant equipment, cabling, and components necessary to achieve safe shutdown. Guidance for use of the FIVE methodology is provided in EPRI-TR-100370[6] and NUREG-1407[4]. With this background, findings are summarized relative to coverage of the multiple system responses program (MSRP) issues noted from examination of several IPE/IPEEE submittals.

V. IPE/IPEEE SURVEY RESULTS

Table 3 summarizes results for the Callaway[7,8] and Diablo Canyon[9,10] IPE/IPEEEs. The first column denotes the various MSRP issues deemed to be dealt with in the IPE/IPEEE program, while the second and third provide a simple "yes or no" answer as to review findings. As indicated all IPE/IPEEE delegated MSRP issues were addressed to some degree in both submittals, thus the central question relates to the depth of coverage for the PRA (Diablo Canyon) versus SMM/FIVE (Callaway) approaches.

Results from this limited comparison indicate that MSRP system-system interaction issues, appear best treated using PRA-based IPEEE methods. An example is provided by the assessment of seismic spatial/functional interactions (Issue-15), which include dust generation and compressed air line failures. In the Diablo Canyon seismic-PRA model, dust effects are considered as part of the seismic human actions analysis, where a human failure multiplication factor of 30 was used for seismic events greater than 2.5g to account for the adverse dust effects on human performance.

Table 3. MSRP Safety Issues and Proposed Deposition Method

Issue (Where to be Addressed)	Diablo Canyon IPE	Diablo Canyon IPEEE	Callaway IPE	Callaway IPEEE
1) Human-Error Common Cause Failures (IPE/IPEEE)	yes	yes	yes	no
2) Non-Safety/Safety Control System Dependencies (IPE/IPEEE)	yes	yes	yes	yes
13) Fire Suppression System Actuation Effects on Non-Safety/Safety Equipment (IPEEE)	--	yes	--	yes
14) Flooding/Moisture on Effects on Non-Safety/ Safety Equipment (IPE/IPEEE)	yes	yes	yes	yes
15) Seismic Spatial/Functional Interaction Effects (IPEEE)	--	yes	--	yes
16) Seismic-Induced Fires (IPEEE)	--	yes	--	yes
17) Seismic-Induced Fire Suppression System Actuation (IPEEE)	--	yes	--	yes
18) Seismically-Induced Flooding (IPEEE)	--	yes	--	yes
19) Seismic Relay Chatter (IPEEE)	--	yes	--	yes
20) Evaluation of Earthquake Magnitudes Greater than Safe Shutdown Earthquake (IPEEE)	--	yes	--	yes
21) Effects of Hydrogen Line Ruptures (IPEEE)	--	yes	--	yes

The Diablo Canyon PRA model also includes failure analysis of mechanical support systems, such as the switch-gear ventilation system, compressed air supply for instrumentation, control room HVAC, and component cooling water. Consideration of seismic related dust effects/air supply failures was not evident from inspection of the Callaway IPEEE, although several fixes to fire extinguisher mounting brackets were made as a result of the walkdown process, which would broadly fall under spatial/functional interactions.

System interactions are evaluated from "dependency tables" developed in support of a PRA model. Table 4 provides a simplified example of a support-to-support system dependency table abstracted from the Diablo Canyon submittal. For example failure of the 480KV Bus-1 would disable the group-A switchgear vent fans, the group-C control room fans, and operation of the compressed air source for instrumentation. Delineation of such support-system interactions is not evident from review of the Callaway IPEEE, where the FIVE approach only requires verification that the plant can be brought to safe shutdown during fire related events. Such examples indicate that system interaction effects, particularly cross-interactions among secondary or support systems, are best treated using PRA methods rather than from SMM/FIVE analysis.

A limited review of the WNP-2 and Catawba PRA based IPEEEs was also performed, to assess coverage of three MSRP issues which received considerable prior ACRS scrutiny (Relay Chatter-19, Spurious Fire Control Actuation-13, Hydrogen Line Ruptures-21). Both relay chatter and fire system actuation were adequately covered, however treatment hydrogen line ruptures was not noted from inspection of either IPEEE. It is interesting to note that the limited fixes identified in the Diablo Canyon IPEEE, may be partially attributed to "quantified" estimates of core damage frequency provided by a PRA based-IPEEE. Damage frequencies of 4.0E-5/yr (seismic) and

Table 4. Support-System to Support-System Dependency Table

Failed Support System	Impacted Support System								
	Switchgear Vent Fans			Control Room Vent Fans			Instrument Comp. Air		
	A	B	C	A	B	C		A	
480KV Bus-1	X					X		X	
480KV Bus-2		X			X				
480KV Bus-3			X	X					
Diesel Gen-1	X			X					
Diesel Gen-2		X			X			X	
Diesel Gen-3			X			X			

2.7E-5/yr (fire) were estimated, which are below the criterion of 1.0E-4/yr for which remedial action would be required. On the other hand, the qualitative indications of plant vulnerabilities provided by the SMM/FIVE methods (Callaway IPEEE) may have lead to perceived greater vulnerabilities requiring remedial action, including the following:

- Mounting modifications to hand-held fire extinguishers to avoid impact on safety equipment during a seismic event.

- Additional equipment anchors identified from seismic related plant walkdown efforts.

- Removal of unsecured carts, filing cabinets, and testing equipment from the control room to avoid impact on safety related equipment during a seismic event.

- Initiation of training programs to insure that chain hoists would be properly positioned to avoid impact on safety related equipment during a seismic event.

- Development of a Severe Accident Management Guidance (SAMG) plan to mitigate against cabinet fires and identification of appropriate recovery actions.

VI. CONCLUSIONS

Although the IPE/IPEEE-MSRP issues were found to be addressed in the Callaway (SMM/FIVE) and Diablo Canyon (PRA) submittals, variances were evident, which appear related to differences in methodology employed. Weaknesses for the Callaway SMM/FIVE approach pertain to a more limited treatment of non-safety equipment and multiple-system interactions effects. For example consideration of seismic associated dust effects and compressed air line failures (Issue-15: Spatial/Functional Interactions) was not evident from the inspection of the Callaway IPEEE; however these effects were treated in the Diablo Canyon seismic PRA. From the limited examination of the four IPE/IPEEE submittals reviewed here, one is lead to the conclusion that multiple-system interaction effects, around which the MSRP issues center, are best treated using PRA techniques. It is interesting to note that a much earlier study on systems interactions[1], which emphasized methods for identification of cross-system dependencies, concluded that event tree/fault methods in general provide a better indication of such cross-system interactions than either plant walkthroughs or stand-alone fault trees; a conclusion that is supported here.

A noted problem area common to both FIVE and fire-PRA methods, relates to lack of documentation on fire vulnerabilities associated with hydrogen line ruptures (Issue-21). In addition to incorporation of the MSRP issues into NUREG-0933[13], specific IPE/IPEEE guidance to address these weaknesses may be warranted. It is also noted that the original intent of the MSRP project was to encompass *a wide breadth of hidden safety issues* not being considered in NRCs' resolution of safety concerns on an issue-by-issue basis. Shortly after its inception the scope of the MSRP project was limited to an identification of safety issues which might reside within six specific issues being reviewed by the ACRS in the early

1980s. Twenty-one additional issues were born from these six, which remained the focus of MSRP discussions ever since. Returning to the original intent and philosophical foundation of MSRP, the notion of closure may be inappropriate, where insights into systems interactions are a natural outcome of knowledge continuously gained through accumulated experience. Changes in plant design or upgrades may likewise expose new systems interaction concerns. As a matter of organizational convenience and expedience, incorporation of MSRP issues into the framework of the Generic Safety Issues Program[13] and IPE/IPEEE process may be useful and appropriate. The best assurance against adverse systems interactions leading to a serious compromise of plant safety is through continued vigilance and attention to plant safety.

DISCLAIMER

The views expressed in this paper are solely those of the author, and do not necessarily reflect those of the ACRS or NRC.

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