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Impact of Assumptions Concerning Containment Failure on the Risk from Nuclear Power Plants

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ABSTRACT

We describe the containment failure mode and release category assumptions used in the seismic risk study of the Zion nuclear power plant, which was performed by the Seismic Safety Margins Research Program (SSMRP). We then, for the dominant accident sequences, reassign containment failure modes and release categories based upon current thinking. We recalculate the seismic risk from the Zion facility using the new assumptions. Lastly, we discuss the impact of the new assumptions on the results and the relevance of the assumptions to value/impact analyses.

INTRODUCTION

In 1978, the United States Nuclear Regulatory Commission began the Seismic Safety Margins Research Program at Lawrence Livermore National Laboratory. The primary goals of the SSMRP were to develop tools and data *bases for evaluating the risk of earthquake induced radioactive releases from* commercial nuclear power plants. In order to perfect and demonstrate SSMRP methods, a seismic risk assessment was performed for the Zion Nuclear Power Plant, a twin 1040 MWe Pressurized Water Reactor facility located on Lake Michigan 40 miles north of Chicago, Illinois.

Limited demonstration calculations were made as part of Phase I of the SSMRP. The calculations were completed in February, 1981. A 9-volume final report was issued during 1981-1982. The containment failure modes and release categories are discussed in the report for the systems analysis portion of the project [1]. The Zion plant seismic risk assessment was completed in October 1982 and reported in November 1983 [2]. All references to the SSMRP report in this study are for the Phase II results and final methodology.

The general methodology employed in the SSMRP is a familiar one in the probabilistic risk assessment field. Using the general design of the plant as a guide, analysts defined a set of initiating events which could result from an earthquake at the Zion site. There were seven of these initiating events: 1) Reactor Vessel Rupture; 2) Large LOCA; 3) Medium LOCA; 4) Small LOCA; 5) Small-small LOCA; 6) Class 1 Transient; and 7) Class 2 Transient. Each of the events is capable of initiating reactor accident sequences which lead to a core melt and a release of radioactivity from the plant.

For each initiating event, an event tree was defined by the analysts based upon the safety systems at the plant, which are designed to mitigate the effects of reactor accidents. The event trees define the combinations of successes and failures of safety systems which make up the various accident sequences. A total of 219 accident sequences were defined and evaluated in the study. Of these, 178 lead to a core melt.

DEFINITION OF TERMS

Containment Failure Modes:

The SSMRP defined 5 ways in which the containment could fail. These five failure modes are represented by the first five letters of the Greek alphabet: ALPHA, BETA, GAMMA, DELTA, and EPSILON.

ALPHA: Reactor Pressure Vessel Steam Explosion

In this mode, the molten core contacts water in the vessel. This produces a steam explosion which fractures the reactor pressure vessel and disperses large amounts of core material into the containment atmosphere. The result is a sudden, large increase in containment atmosphere pressure and temperature which could fail the containment structure. Additionally, energetic missile fragments may be produced which can fail the containment spray equipment and, possibly, penetrate the containment.

BETA: Containment Leakage

In this mode, one or more of the normal penetrations into the containment fail to seal properly, thereby providing a leakage path for the radioactivity. This mode includes the passage of radioactivity from the containment to the outside via normal piping which may not be isolated effectively.

GAMMA: Hydrogen Detonation

In this case, hydrogen which has accumulated in the containment building over the course of the accident is ignited. This ignition produces a rapid temperature and pressure spike which ruptures the containment.

DELTA: Containment Overpressure

In this mode, the gradual buildup of pressure within the containment atmosphere results in a failure of the containment walls. This pressure can be due to the steam being generated by the degraded core as well as by other processes, especially the production of hydrogen and carbon dioxide during a core/concrete interaction.

EPSILON: Containment Basemat Melt Through

In this mode, the molten core, which has melted through the bottom of the pressure vessel and come to rest on the basemat floor beneath the vessel, eats completely through the containment basemat. Once it has done so, it continues to move through the supporting soil for several feet before finally coming to a halt.

Release Categories:

In addition to the containment failure modes, the SSMRP specified what the severity of the radioactive release would be given a particular accident *sequence and containment failure mode. These release categories are numbered* 1 through 7, each one representing a different type of release. Table I lists the release categories along with the public exposure assumed to be associated with them by the SSMRP [4].

Table I

Public Consequences of the
WASH-1400 Release Categories

Release Category	man-rem per Release
1	5.4E+6
2	4.8E+6
3	5.4E+6
4	2.7E+6
5	1.0E+6
6	1.5E+5
7	2.3E+4

ORIGINAL CONTAINMENT FAILURE ASSUMPTIONS

In the SSMRP, the assignment of the containment failure modes and release categories for each of the accident sequences was based largely upon the analyses from WASH-1400, the Reactor Safety Study [3]. This was possible because the WASH-1400 study included an analysis of a Pressurized Water Reactor whose safety systems were similar to those at the Zion Nuclear Power Plant. In fact, the SSMRP event trees list, for each accident, an equivalent accident sequence definition from the WASH-1400 study.

Table II below lists the most probable accident sequences from the Base Case of the SSMRP. (The Base Case is one of several case studies made and represents the best point estimate of seismic risk at Zion.) Together, these eight accident sequences account for an annual probability of core melt of 3.0e-6, which is 85% of the total core melt annual probability of 3.5e-6.

Table II

Dominant[a] SSMRP Accident Sequences

	Initiating Event	Accident Sequence	Definition	Probability
1)	Class 2 Transient	T2-4a	$\underline{K}$ L B $\underline{P}$ $\underline{Q}$ C	1.3e-6
2)	Small-small LOCA	S2-35	$\underline{K}$ L C F	4.1e-7
3)	Small LOCA	S1-21	$\underline{K}$ C $\underline{D}$ $\underline{J}$ F $\underline{H}$	3.4e-7
4)	Small LOCA	S1-28	$\underline{K}$ C D F	3.2e-7
5)	Large LOCA	A-13	$\underline{C}$ D $\underline{E}$	2.3e-7
6)	Reactor Vessel Rupture	R-7	C F	1.6e-7
7)	Large LOCA	A-28	C D F	1.3e-7
8)	Small-small LOCA	S2-21	$\underline{K}$ $\underline{L}$ C $\underline{D}$ $\underline{J}$ F $\underline{H}$	1.2e-7

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[a] Based upon contribution to core melt frequency.

Key to Accident Sequence Definitions:

B = Bleed & Feed System (B&FS)
C = Containment Spray Injection System and Containment Fan Cooler System - Injection Phase (CSIS & CFCS(I))
D = Emergency Coolant Injection (ECI)
E = Containment Fan Cooler System - Recirculation Phase (CFCS(R))
F = Residual Heat Removal System (RHRS)
H = Emergency Coolant Recirculation (ECR)
J = Emergency Core Functionability
K = Reactor Protection System (RPS)
L = Auxiliary Feedwater System & Secondary Steam Relief
P = Safety/Relief Valves - Open (S/RV-O)
Q = Safety/Relief Valves - Reclose (S/RV-R)

Note: $\underline{X}$ - underscore implies system success.

Table III below lists the eight dominant accident sequences identified in Table II along with the containment failure and release category assumptions made during the SSMRP. For each of the eight dominant accident sequences, the probability of the various containment failure modes is given along with the release category assumed for that containment failure mode. For example, the fifth entry, A-13 (Large LOCA sequence #13) is assumed to have a 1% chance of failing the containment via the ALPHA mode. In that case, there would be a category 3 release. Likewise, A-13 is assumed to have a 99% chance of failing the containment via the EPSILON mode, with a category 7 release resulting in that case. Finally, the BETA mode of failure was considered possible, but had less than a 1% chance of occurrence.

Note that, for each accident sequence, the containment failure mode probabilities are normalized to 1.0. This reflects the assumption by the SSMRP that, given an accident sequence that leads to a core melt, containment failure must occur at some point.

Table III

SSMRP Containment Failure Mode Assumptions for Dominant Accident Sequences

	Accident	Containment Failure Mode Assumptions				
	Sequence	ALPHA	BETA	GAMMA	DELTA	EPSILON
1)	T2-4a	1(.01)		2(.24)	2(.56)	6(.19)
2)	S2-35	1(.01)	2(*)	2(.12)	2(.04)	7(.83)
3)	S1-21	1(.01)			3(.99)	
4)	S1-28	1(.01)			7(.49)	7(.50)
5)	A-13	3(.01)	5(*)			7(.99)
6)	R-7	1(.06)	2(*)	2(.91)	2(.03)	
7)	A-28	1(.01)	4(*)		7(.49)	7(.50)
8)	S2-21	1(.01)	6(*)		3(.99)	

Note: a * implies less than .01 probability of occurence.

SSMRP RESULTS

Using the above assumptions regarding containment failure modes, release categories, and public doses resulting from radioactive releases, the SSMRP calculated the seismic risk, in man-rem/yr, from the Zion Nuclear Power Plant. This risk was found to be 9.6 man-rem/yr.

The seismic risk found at Zion is unquestionably small. If the seismic risk at Zion is truly on the order of 10 man-rem/yr, then we need not concern ourselves with the seismic integrity of the plant. Unfortunately, all probabilistic risk assessments contain some degree of uncertainty. The SSMRP Zion study is no exception.

We are uncertain about both the core melt frequency and the public risk at Zion. The SSMRP Phase II report [2] contains the results of an uncertainty calculation which was performed as an integral part of the Zion seismic risk assessment. The uncertainty calculation resulted in a 90th percentile core melt frequency 8.e-04/yr, i.e., there is a 90% probability that the actual core melt frequency is 8.e-04/yr or less. This value is roughly a factor of 200 larger than the mean value of 3.6e-6/yr.

We cannot say how the total risk scales with increasing core melt probability in the uncertainty study. For a single accident sequence, the probability of core melt is merely a linear factor in the expression for man-rem/yr. Thus, if the probability of the accident sequence increases by a factor of 5, then so does the man-rem/yr risk from that accident sequence. However, as total core melt probability increases, the relative contributions from the various accident sequences may change, causing the risk in man-rem/yr to scale in an unpredictable fashion.

Nevertheless, given that a core melt frequency estimate 200 times larger than the mean is within credible limits, and given that the uncertainty study performed in the SSMRP did not involve many facets of the methodology, including the systems analysis and the containment failure assumptions, we can see that it is important to reexamine the consequence models used in the SSMRP in light of the experience gained since the WASH-1400 study was performed.

REVISED CONTAINMENT FAILURE ASSUMPTIONS

Using results available to us from the ongoing source term assessments at the U.S. NRC, as well as other experience gained in the years since the WASH-1400 study was performed, particularly the Three Mile Island accident, we have updated the assumptions of containment failure probabilities and release categories. Table IV presents the results of our reassessment.

Table IV

Revised SSMRP Containment Failure Mode Assumptions

	Accident	Containment Failure Mode Assumptions				
	Sequence	ALPHA	BETA	GAMMA	DELTA	EPSILON
1)	T2-4a		2(.01)		7(.79)	7(.20)
2)	S2-35		2(.01)		7(.79)	7(.20)
3)	S1-21		2(.01)	2(.01)	3(.98)	
4)	S1-28		2(.01)		7(.79)	7(.20)
5)	A-13		5(.01)			7(.99)
6)	R-7	1(.01)	2(.01)		6(.78)	7(.20)
7)	A-28		2(.01)		6(.79)	7(.20)
8)	S2-21		2(.01)	2(.01)	3(.98)	

In general, we notice that the probability of having ALPHA, GAMMA and EPSILON containment failure modes is now smaller. In contrast, the BETA and DELTA mode probabilities have increased. Notice that, as before, we assume that containment failure must occur, i.e., the total probability of containment failure is normalized to 1.0 for each accident sequence.

Notice also, that, for some accident sequences, the release categories have decreased in severity for a given containment failure mode. This reflects the effects of delaying containment failure upon the severity of release.

RESULTS USING REVISED ASSUMPTIONS

Recalculating the seismic risk at Zion using the assumptions given in Table IV yields a value of 3.6 man-rem/yr. Comparing against the original SSMRP risk value of 9.6 man-rem/yr, we see that the best estimate of seismic risk has decreased by 6 man-rem/yr because of our new assumptions. The probability of core melt is, of course, not affected by the assumptions and, thus, does not change.

Table V below presents the contribution to risk from each of the dominant accident sequences, using both the original and revised containment failure assumptions. Notice that, under the original assumptions, over half of the total seismic risk was contributed by the Class 2 Transient sequence T2-4a. Under the revised assumptions, this sequence is almost neglible. Consequently, we find that almost all of the risk is contributed by only two sequences: Small LOCA sequence S1-21, and Small-small LOCA sequence S2-21.

Please note that the total of 8.6 man-rem/yr risk from the dominant sequences examined is less than the total seismic risk of 9.6 man-rem/yr, the difference being the contribution of the remaining 170 accident sequences studied in the SSMRP.

Table V

Risk Contribution from Dominant[a] Accident Sequences

	Initiating Event	Accident Sequence	Contribution to Risk (man-Rem/yr) Original	Revised
1)	Class 2 Transient	T2-4a	5.1	0.1
2)	Small-small LOCA	S2-35	0.3	0.0
3)	Small LOCA	S1-21	1.8	1.8
4)	Small LOCA	S1-28	0.0	0.0
5)	Large LOCA	A-13	0.0	0.0
6)	Reactor Vessel Rupture	R-7	0.8	0.0
7)	Large LOCA	A-28	0.0	0.0
8)	Small-small LOCA	S2-21	0.6	0.6
		TOTAL:	8.6	2.5

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[a] Based upon contribution to core melt frequency.

CONCLUSIONS

The original point estimate of seismic risk at Zion of 9.6 man-rem/yr is too low to be of any concern. Thus, what we are primarily concerned with is the possibility that the containment failure mode and release category assumptions would, upon being updated, induce a sizable increase in the estimated risk from the facility. Certainly, one of the most obvious conclusions which can be drawn from the results is that this is not the case.

The other conclusion we can draw relates to the effects of containment failure mode and release category assumptions upon value/impact assessments.

Relevence to Value/Impact Assessments

In 1983, a value/impact assessment was performed to determine the effects of proposed changes to the U.S. NRC Standard Review Plan sections 3.7.1, 3.7.2 and 3.7.3, dealing with seismic design criteria [5]. As part of that assessment, a study was made of the effect upon seismic risk of strengthening the Refueling Water Storage Tank (RWST). It was found that strenghtening the tank actually increased the seismic risk at the hypothetical PWR being studied. This result was directly attributed to assumptions concerning the containment failure modes and release categories which would follow the defined accident sequences.

Briefly, the phenonmenon which was observed was the following. As the RWST was strengthened, the probability of having successful Emergency Coolant Injection increased. However, the stronger RWST had no impact on the probability of successful Emergency Coolant Recirculation or heat removal from containment. Thus, strengthening the RWST only served to insure a supply of water with which to produce steam in the containment. This served to increase the likelihood of containment overpressure, the DELTA mode, followed by rather severe releases.

In contrast, a failure to inject emergency coolant resulted in a "dry" reactor cavity. Thus, when the core melts through the reactor vessel, it reacts only with the concrete basemat, eventually ending with an EPSILON mode of failure, which is thought to have generally less severe consequences than the containment overpressure mode.

Table V above shows that the majority of the seismic risk under the new containment failure assumptions arises from sequences S1-21 and S2-21. Each of these sequences is characterized by successful Emergency Coolant Injection followed by unsuccessful heat removal from containment. Thus, under the new assumptions, we would expect that we would see the same type of relationship between risk and RWST strength as for the hypothetical PWR.

Clearly, there are a great deal of assumptions operative in the analysis; for example, the assumption that a failure to have successful emergency coolant injection results in a "dry" reactor cavity. If there is a total failure of the ECI system pumps, then this may be a valid assumption. If, instead, a partial pumping failure results in classifying the injection phase a failure, then we might still have a considerable volume of water available in the reactor cavity.

Another major assumption involves the severity of release which follows when the containment fails due to steam overpressurization. It is not clear whether the presence of large amounts of steam in the containment atmosphere at the time of rupture will act to improve or worsen the degree of radioactive release. Clearly, this assumption would impact the results of the above analysis.

At present, the U.S. NRC is engaged in a major reassessment of the source term from a nuclear power plant accident. When this work is completed, it may be possible to obtain more definitive results from value/impact assessments which involve consequences other than core melt frequency.

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