Results from the Application of Systems Analysis Techniques to the Study of Reactor Seismic Safety

G.E. Cummings, J.E. Wells
University of California, Lawrence Livermore National Laboratory, P.O. Box 808, L-90, Livermore, California 94550, U.S.A.

J.M. Hudson, J. Gasca
J.H. Wiggins Company, 1650 South Pacific Coast Highway, Redondo Beach, California 90277, U.S.A.

Summary

Systems and structural analysis techniques are being employed to calculate failure and radioactive release probabilities in an effort to provide insights into the seismic safety of nuclear power plants. An event-tree/fault-tree model of a nuclear power plant has been constructed and is being used to calculate these probabilities. Failure data for use in this model is generated from responses calculated by structural analysis codes using earthquake time histories as forcing functions. These responses are applied to fragility functions which describe the failure probability of a component as a function of the response it sees. A description is given of the event-tree/fault-tree model that has been constructed and preliminary system failure probabilities using this model are presented.

This work was supported by the U.S. Nuclear Regulatory Commission under a Memorandum of Understanding with the U.S. Department of Energy.

1. Introduction

Lawrence Livermore National Laboratory is currently engaged in work on a large multi-year seismic safety research program for the U.S. Nuclear Regulatory Commission entitled the Seismic Safety Margins Research Program (SSMRP) [1,2]. In this paper we discuss the systems analysis aspects of the program.

The systems analysis task [3] is to determine component, system, and structural failure probabilities resulting from seismic events at nuclear power plants. These probabilities are calculated by means of a computer code called SEISIM (Seismic Evaluation of Important Safety Improvement Measures). Also calculated are accident sequence probabilities and the radioactive release probabilities resulting from these accident sequences. The calculated probabilities are used to determine dominant events and rank the importance of systems, structures, and components, to seismic safety. These and other SEISIM results are used to meet the objectives of the SSMRP.

In this paper we will be discussing the SEISIM code and the event and fault tree system descriptions used by the code. Preliminary results from an analysis of the Zion I Nuclear Power Plant are also discussed.

2. Computational Procedure

2.1 Description

A flowchart of the computational procedure used in the SSMRP is shown in Fig. 1. Basically, the computations are carried out in two stages as shown in the figure. The responses of equipment and structures to a set of earthquake time histories are calculated by a computer code called SMACS (Seismic Methodology Analysis Chain with Statistics) [4]. In turn, failure and release probabilities are calculated in SEISIM [5,6] based on these responses. Other inputs required by SEISIM include fragility functions, random event probabilities, event trees, fault trees, and seismic occurrence data. Fragility functions are cumulative probability functions of component or structural capacity as a function of local response. Event trees describe the accident sequences; fault trees describe the system failure modes.

Failure probabilities of components and structures are calculated using the distribution functions of their responses (formed from SMACS output) and fragilities. Figure 2 illustrates this procedure. The failure probabilities thus calculated are applied to the fault trees to calculate system failure probabilities. In the same way, initiating event probabilities are calculated from logical descriptions of the initiating events. Finally, these initiating event and system failure probabilities are applied to the accident sequence logic to determine release sequence probabilities as a result of the initial set of earthquake time histories. This is shown by the following equation and also illustrated in Fig. 3.

$$P(\text{release seq.} \mid \text{eq.}) = P(\text{initiating event}) \times P(\text{accident seq.}) \times P(\text{containment failure})$$

The accident sequence coupled with the containment failure mode determines the release category (type and quantity of release) to which each release sequence belongs.

The radioactive release probabilities for each release category are determined by summing the probabilities of all release sequences in that category. These

probabilities are conditional on the occurrence of the earthquake. Conditional probabilities are calculated for earthquakes of various sizes as defined by their peak ground acceleration. The unconditional probabilities are then calculated by integrating over the range of earthquakes.

2.2 Probabilistic Techniques

Various options are planned for SEISIM. These options reflect choices between analytical or Monte-Carlo computation of failures and probabilistic or binary evaluation of the event and fault trees (Monte-Carlo options only). The results reported here were calculated using the analytical computation option. This restricts the distribution functions describing responses and fragilities to normal or lognormal types. A unique feature of the code is that the user is allowed to input correlation coefficients between fragilities. Correlations between responses are automatically accounted for in the way the responses are calculated and input to SEISIM.

The outputs of SEISIM are to be used to evaluate seismic risk at nuclear power plants and to help in determining important areas for further research. In order to prioritize research needs and guide the regulatory process concerning seismic safety, dominance ranking of sequences, systems, and components is provided by SEISIM. Sequence dominance is determined from the probability of occurrence of the sequences in each release category. System and component rankings are in proportion to their contribution to occurrence of the sequence.

A further capability is provided by SEISIM which allows the computation of numerical partial derivatives of the output with respect to selected input variables. This routine will help in performing sensitivity analyses.

3. Event-Tree/Fault Tree Development

Eight event trees were constructed during the initial phase of SSMRP [7]. These trees were drawn up for the Zion I Nuclear Power Plant at the time of its construction. One of the eight event trees represents possible containment failure modes and is used, conditional on a core melt accident sequence, to determine the probability of that accident sequence resulting in one of seven release categories. Reactor pressure vessel rupture, four different sized primary loop pipe breaks, and two types of transient events serve as initiating events for the other seven event trees. From these seven event trees, 141 core melt accident sequences were derived.

The large loss-of-coolant accident (LOCA) event tree is shown in Fig. 3. The initiating event for this tree is a large pipe break (>6 in. dia.) in the primary coolant loop. The systems used to control the accident and mitigate its effects are listed across the top. These include the Containment Fan Cooler System (CFCS), Emergency Core Cooling Systems (ECI, ECR), and the Residual Heat Removal System (RHRS). ECF is not a system. It is defined as the ability of ECI to cool the core, given that ECI is successful. The small greek letters represent containment failure modes. The number of letters denotes the number of possible containment failure modes for each accident sequence. Failure modes are steam explosion (α), leakage (β), hydrogen burning (γ), over-pressure (δ), and basemat melt-through (ε). The equivalent WASH-1400 [8] accident sequences are given in the right hand column.

Fault trees were constructed for seven systems (including supporting systems)

required for quantification of the event trees. The systems were selected on a priority basis after referring to previous seismic risk studies [9]. They included the Auxiliary Feedwater System (AFWS), Emergency Core Cooling System (ECCS) (contains four systems), Service Water System (SWS), and Electric Power System (EPS). Failure probabilities for other systems were either assumed equivalent to the failure probabilities of key components or estimated from other data.

Common cause failures and systems interactions were considered in constructing the fault trees. The common cause failure environment induced by the earthquake was accounted for by the methodology previously described. The number of basic events and single and double cut sets for each fault tree is listed in Table 1.

The event-tree/fault-tree quantification process within SEISIM computes an upper bound on the probability of the accident sequence. The minimal cut sets were obtained from the fault trees by using the fault tree evaluation code SETS [10].

4. Demonstration Calculation

To demonstrate the utility and validity of the SSMRP methodology, a demonstration calculation using Zion I as the basis is being conducted. Results from these calculations are currently being generated. Sensitivity studies will be next undertaken in order to assess the uncertainty in the probability values generated. For the current calculations, modeling and random uncertainties have been combined. In the sensitivity studies it is planned to separate these two types of uncertainties.

Since the purpose of the initial set of calculations was to demonstrate the methodology, various assumptions and estimates were used. Data for human errors, test and maintenance errors, failure probabilities for systems without fault trees, small LOCA initiating event probabilities, containment failure mode probabilities, and the assignment and nature of release categories were all taken from other studies [8,9]. Not all piping systems described in the fault trees were modeled. This in no way affects the validity of the methodology but does lend uncertainty to the calculated probabilities.

Results were calculated for six different peak acceleration intervals (30 time histories in each interval) ranging from 0.15 g to > 0.90 g. System failure probabilities are listed in Table 2. These probabilities are conditional on the earthquakes.

5. Conclusions

The demonstration calculations establish the viability of the technique just described to calculate failure probabilities. Calculation of accident sequence and release probabilities are underway. With these results, dominance rankings will be used to prioritize contributors to seismic safety and so indicate where further investigation is warranted.

Careful analysis of the results and their comparison with other studies will be necessary to give credance to their validity. Sensitivity studies will be used both to rank the importance of input variables and to assess the uncertainties in the results calculated.

References

[1] Smith, P. D., et al., "Seismic Safety Margins Research Program Plan," UCID-17824, Lawrence Livermore National Laboratory, Livermore, CA, August, 1978.

[2] Smith, P. D., et al., "An Overview of Seismic Risk Analysis for Nuclear Power Plants," UCID-18680, Lawrence Livermore National Laboratory, Livermore, CA, September, 1980.

[3] Cummings, G. E. and Wells, J. E., "Systems Analysis Methods Used in the Seismic Safety Margins Research Program," Transactions of the 5th International Conference on Structural Mechanics in Reactor Technology, Berlin, Germany, Paper K3/2, 1979.

[4] Johnson, J. J., et al., "Seismic Response Calculations for the U.S. NRC Seismic Safety Margins Research Program," Transactions of the 6th International Conference on Structural Mechanics in Reactor Technology, Paris, France, Paper K16/5, 1981.

[5] Collins, J. D. and Hudson, J. M., "SEISIM Design Concept," Report No. 78-1645-2, J. H. Wiggins Co., Redondo Beach, CA, January, 1981.

[6] Hudson, J. M., Gasca, J. D., "SEISIM Option 1 Users Manual," Report No. 80-1366-2, J. H. Wiggins Co., Redondo Beach, CA, January, 1981.

[7] Garcia, A. A. and Kelly, J. E., "Seismic Safety Margins Research Program (Phase I) Project VII Systems Analysis Event Tree Development and Construction," Report No. SAI-003-74-RE, Science Applications, Inc., Bethesda, MD, August, 1979.

[8] Nuclear Regulatory Commission, "Reactor Safety Study - An Assessment of Accident Risks in Commercial Nuclear Power Plants," WASH-1400 (NUREG-75/04), National Technical Information Service, October, 1975.

[9] "Seismic Evaluation for Postulated 7.5 m Hosgri Earthquake, Units 1 and 2, Diablo Canyon Site, Vol. V: Analysis of the Risk to the Public from Possible Damage to the Diablo Canyon Nuclear Power Station from Seismic Events," U.S. Nuclear Regulatory Commission Docket Nos. 50-275 and 50-323, Pacific Gas and Electric Co., San Francisco, CA.

[10] R. B. Worrell and D. W. Stack, "A SETS User's Manual for the Fault Tree Analyst," SAND77-2051, Sandia Laboratories, Albuquerque, New Mexico, November, 1978.

TABLE 1. Fault Tree Characteristics

System	Basic Events	Single Cut Sets	Double Cut Sets
Auxiliary Feedwater System (AFWS)	778	13	448
Service Water System (SWS)	172	0	310
Safety Injection System (SIS)	248	55	2058
Residual Heat Removal System (RHRS)	298	13	2894
Charging System (CHG)	384	138	1509
Accumulators (ACC)	58	0	1014

TABLE 2. Conditional System Failure Probabilities

Earthquake Interval (g)	AFWS	SWS	SIS*	CHG*	RHRS*	ACC
0.15-0.30	8.4E-3	6.7E-5	4.7E-2	1.4E-1	4.8E-1	3.8E-4
0.30-0.45	1.4E-1	1.8E-3	1.2E-1	5.8E-1	9.0E-1	4.2E-3
0.45-0.60	3.0E-1	1.4E-2	2.6E-1	8.2E-1	9.6E-1	2.1E-2
0.60-0.75	5.9E-1	1.2E-1	5.0E-1	9.8E-1	9.8E-1	1.3E-2
0.75-0.90	8.6E-1	4.9E-1	7.5E-1	~ 1.0	~ 1.0	2.6E-1
> 0.90	~ 1.0	9.3E-1	9.9E-1	~ 1.0	~ 1.0	9.9E-1

*Injection phase; loss of one of two pumps causes failure

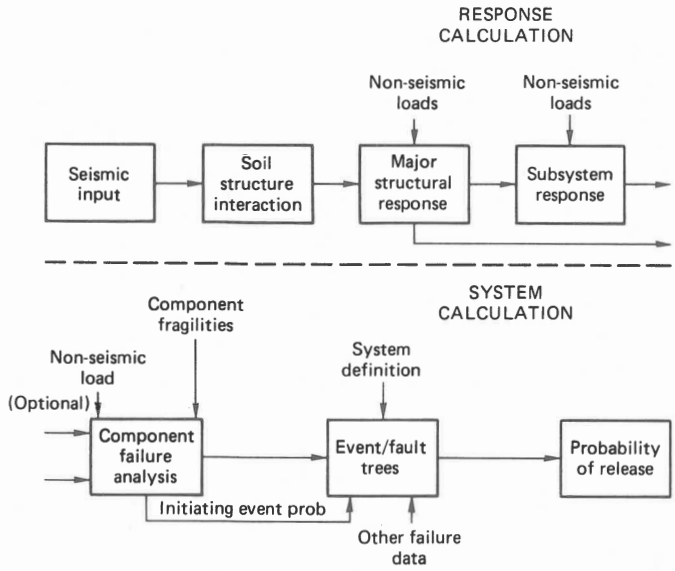

Figure 1. Flow Chart of the SSMRP Computational Procedure

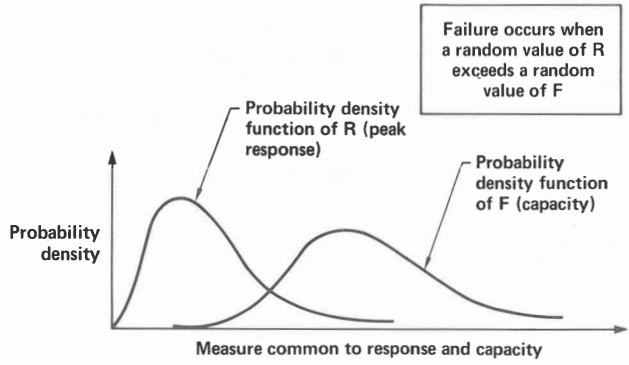

Figure 2. SEISIM Method for Computing Component Failure Probabilities

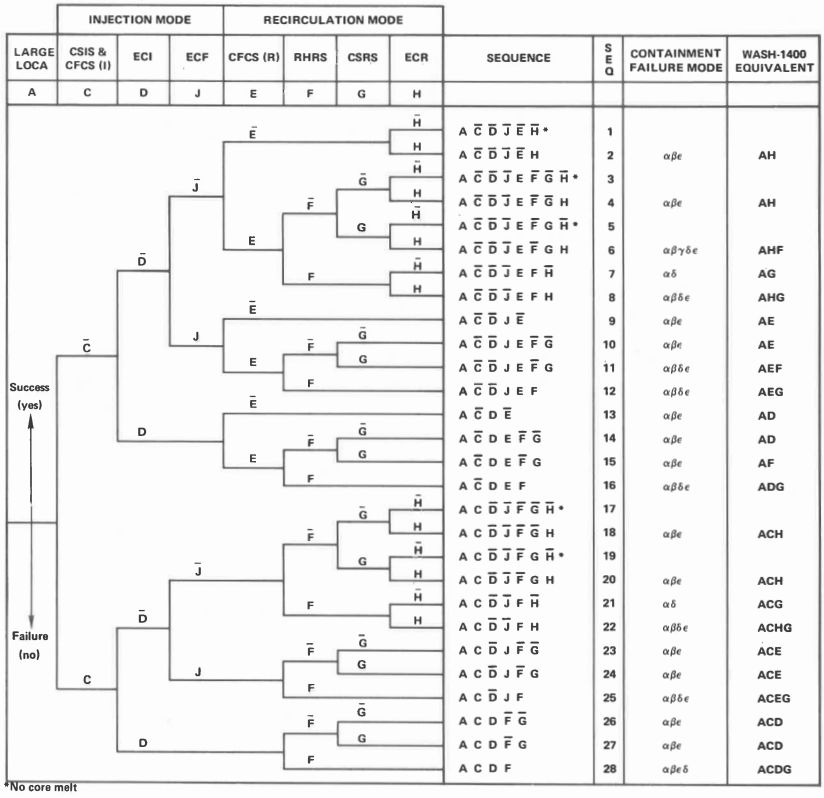

Figure 3. Zion Large (A) Loca Event Tree