SYSTEMS ANALYSIS METHODS USED IN THE SEISMIC SAFETY MARGINS RESEARCH PROGRAM

G. E. CUMMINGS, J. E. WELLS
Lawrence Livermore Laboratory, University of California, P.O. Box 808, Livermore, California 94550, U.S.A.

Summary

In order to provide insights into the seismic safety requirements for nuclear power plants, a probabilistic based systems model and computational procedure have been developed. This model and computational procedure will be used to identify where data and modeling uncertainties need to be decreased by studying the effect of these uncertainties on the probability of radioactive release and the probability of failure of various structures, systems, and components. From the estimates of failure and release probabilities and their uncertainties the most sensitive steps in the seismic methodologies can be identified. In addition, the procedure will measure the uncertainty due to random occurrences, e.g. seismic event probabilities, material property variability, etc. We will be discussing the elements of this systems model and computational procedure, the event-tree/fault-tree development, and the statistical techniques to be employed.

1. Introduction

Lawrence Livermore Laboratory is currently engaged in work on a large multiyear seismic research program for the U.S. Nuclear Regulatory Commission (NRC), Office of Nuclear Regulatory Research, entitled the Seismic Safety Margins Research Program (SSMRP) [1]. In this paper we present the systems analysis methods used in the program.

The systems analysis project of the SSMRP is composed of two parts. The first part involves the specification and development of an overall computational procedure encompassing the seismic design and using event-tree/fault-tree methodology. This procedure will have as it's output the probability of failure of structures, systems, and components and probability of radioactive releases caused by seismically induced events in nuclear power plants.

The second part of the systems analysis project will deal with the construction and evaluation of the event-tree/fault-tree model to be used in the computational procedure.

2. Computational Procedure

2.1 Seismic Calculational Chain

The computational procedure described in this section will encompass the entire seismic calculational chain from the seismic input to the probability of radioactive release for a set of release categories. This calculational chain is illustrated in figure 1. Block one, seismic input, processes the regional seismic characteristics, source parameters, site modification factors, and other seismic related input and generates as output a free field ground motion. This free field motion is then used as input into block two, soil structure interaction. Together with the underlying soil data and reactor structure information, a base-mat motion is calculated. The base-mat motion is then used as input into the major structural response block along with the appropriate structural information. The major structural response information obtained from this block is then used as input either to the subsystem response or in the component failure analysis. The subsystem response block calculates the local response on the "critical" components. During the component failure analysis phase the "critical" component responses are compared with the component fragility functions to determine the component probabilities of failure. These probabilities of failure are used as input into the system fault tree.

System failure probabilities calculated from the fault trees are input into event trees to determine the probability of radioactive release.

2.2 Probabilistic Techniques

The computational procedure described in this paper requires the linking of complex methodologies. To measure the variability in our model, a non-deterministic method of representing and combining existing and any proposed methods is required. This requires the use of techniques such as Monte Carlo simulation, modeling random and systematic uncertainties, stratified sampling, and sensitivity analysis. These probabilistic techniques will be discussed in this section.

2.2.1 Monte Carlo Simulation

The use of Monte Carlo simulation [2] will permit the development of probability density functions (PDF) for the critical variables of concern in the computational procedure. In Monte Carlo simulation a trial consists of selecting a random value that is weighted to fit the specified input distributions. A large number of trials then produce a precise estimate of the probable systems behavior for the range of variability specified for the independent variables.

It is possible to apply the Monte Carlo Techniques to our computational procedure in several ways. One way is to loop over the entire systems model or use an inner and outer loop if random and systematic uncertainties are to be kept separate [3]. Another approach is to modularize the procedure so that any Monte Carlo simulation operates over only part of the model. This has the advantage of flexibility and should save on running time but makes sensitivity studies more cumbersome. Still another approach would be to make a series of deterministic runs covering all ranges of the input variables and then use experimental design techniques to determine means and confidence limits for the output variables.

2.2.2 Random and Systematic Uncertainty

Two categories of uncertainties are recognized, systematic and random. A systematic uncertainty represents bias in the models or input variable distributions which could be reduced with more information. Random uncertainties have to do with variabilities in basic parameters over which the analyst has little control. Improved models will not reduce random uncertainties.

The component fragility curves in fig. 2a can be used to further illustrate the difference between random and systematic uncertainties. The solid line represents the best estimate of failure. All the systematic uncertainties are then reflected on the component failure curve by the dashed lines.

2.2.3 Stratified Sampling

Stratified sampling concepts [4] will play an important role in the analysis because of the number of Monte Carlo Trials required. Stratified sampling allows us to direct these random choices to the areas of most concern, thereby reducing the number of Monte Carlo trials required.

These techniques can be used, for example, in the case where sampling over a seismic source parameter such as magnitude is desired. In order to make the analysis more efficient, you should direct the samples to the area of concern. This can be done by dividing the variable of concern, magnitude in our example, into sub-groups or "strata" and then sample appropriately from each stratum [see fig. 2b].

One drawback in the stratified sampling concept is that in order to select in a stratified manner one needs prior information on the appropriate split required of the parameter's population. Initially, good engineering judgment will be required. After the initial runs are made a study of the data generated should be used as a basis for further decisions on how to split up the parameter population.

2.2.4 Sensitivity Studies

One of the primary uses of the computational procedure is to assess the relative impact different components, systems, input variables, and modeling elements will have. The computational procedure must provide us insights into modeling and data needs. There are several methods available. One would be to construct the partial derivative of the output variables with respect to a given input variable. Another method would sample input variables at various places within their systematic error bands to determine the resulting variation in the output variables.

3. Event-Tree/Fault-Tree Development

3.1 Background

A number of seismic safety studies [5] have been made of nuclear power plants. In most cases, these studies were based on failures of specific critical components and/or sub-systems [7]. One study which analyzed the seismic safety of a complete nuclear power plant (Diablo Canyon) [8] used an event-tree/fault-tree representation of the reactor systems to predict failure and radioactive release probabilities due to seismic events. The event-tree/fault-tree methodology used was based to a large extent on WASH 1400 [9] results.

In SSMRP we wish to have as complete a measure of the consequences of seismically induced failure as possible. For this reason, we are using and event-tree/fault-tree representation of an existing nuclear power plant (Zion I) in order to conduct our studies. We have extended the techniques developed in WASH 1400 and the Diablo Canyon Study to the needs of our program, which are not to come up with a quantitative measure of risk, but rather to provide a measure to help establish research priorities and conservatism in current design.

3.2 Event-tree/Fault-tree Methodology

Event trees are used to identify important accident sequences which can lead to radioactive releases. For our program, we are initially only considering sequences which can lead to core melt since most of the radioactive material resides inside the fuel elements and cannot be released unless the core melts.

An event tree is constructed for each of several initiating events, e.g., loss-of-coolant-accidents of various sizes and reactor transients caused by such occurrences as loss of offsite power. The outcomes of such initiating events are determined by the operation of systems which have an effect on the event. Figure 3a shows an event tree whose initiating event is a pipe break leading to a loss-of-coolant accident. Three systems which effect the outcome of this accident are the emergency core cooling systems (ECCS), fission product removal system, and the containment. The successful operation or failure of each system determines the accident sequence and the multiplication of system failure probabilities (P_i) determines the accident sequence probabilities. The type of release is determined for each accident sequence and the probabilities of sequences with like releases are summed to give the total release probability for that type release. For our program, the first three WASH 1400 PWR release categories will be used since these represent the major-contribution to risk.

The failure probabilities (P_i) for the systems included in the event trees are determined by constructing fault trees for these systems. Figure 3b shows a simple fault tree of an auxiliary feedwater system. Failure probabilities are assigned to the basic events (circles or diamonds) on the fault tree and the top event (system failure) probability calculated from the Boolean representation of the tree. The basic event probabilities are determined by the computational procedure either by calculation or direct input.

3.3 Use of Event Trees and Fault Trees by SSMRP

The following steps are being used to develop the event-tree/fault-tree model of the Zion nuclear power plant.

a. Initiating events for those accident sequences which might lead to core melt are identified, e.g. LOCA, transient.

b. The systems which effect the course of the accidents caused by these initiating events are determined, e.g. auxiliary feedwater system, residual heat removal system.

c. Functional and system event trees are constructed for each initiating event so that accident sequence probabilities can be calculated.

d. Approximate quantitative methods are used to rank the important accident sequences so that systems needing detailed fault tree analysis can be identified.

e. Fault trees are constructed for each important system listed on the event trees so that system failure probabilities can be calculated.

f. An event tree describing potential containment failure modes is developed to help determine the type of release from each accident sequence. This event tree is made conditional on the occurrence of a seismically induced accident.

Figure 4 pictorially shows how the event trees and fault trees are used by SSMRP. Seismic responses of structures, systems, and components are calculated and compared to fragility functions to determine probabilities of failure. These failure probabilities are input to the event trees and fault trees to determine radioactive release probabilities. Both the failure probabilities and release probabilities and the uncertainty in these probabilities will be used to meet program objectives.

This application of event-tree/fault-tree methodology to seismic safety concerns is a major extension of WASH 1400 techniques. Problems concerning the statistical dependence between events and data insufficiencies are more acute than for a random failure analysis like WASH 1400. In order to come up with a useful analysis we are carefully building from what has been learned in other such studies and trying to concentrate on areas of high interest and sensitivity to our program. By constructing the event trees and fault trees conditional on the seismic event some of the concern about dependencies is removed. In addition, bounding techniques will be used to bracket the problem and more detailed common cause analyses will be used in critical areas and where data permits.

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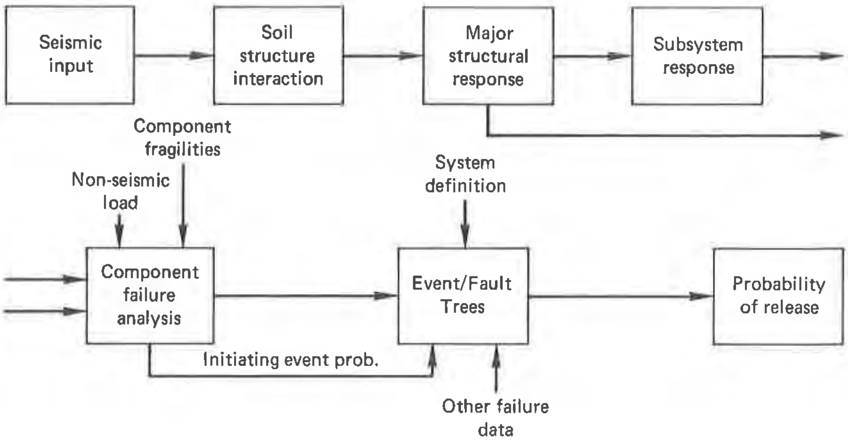

Figure 1. Computational Procedure Overview

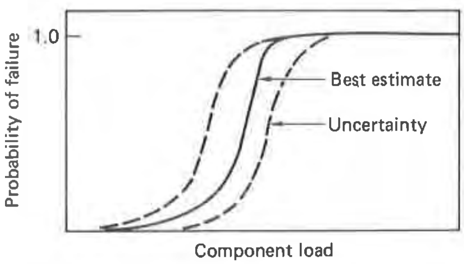

Figure 2a. Example Component Fragility Function

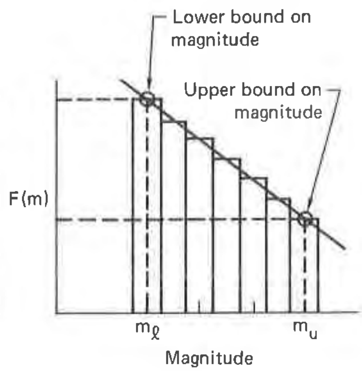

Figure 2b. Stratified Sampling Example

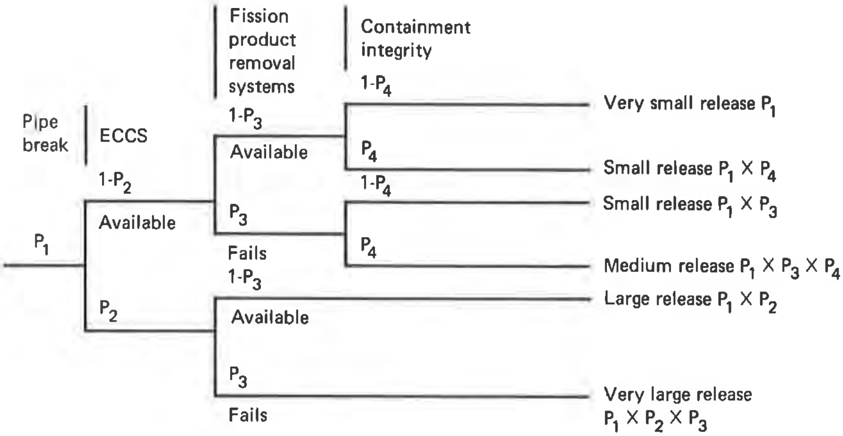

Figure 3a. Event Tree

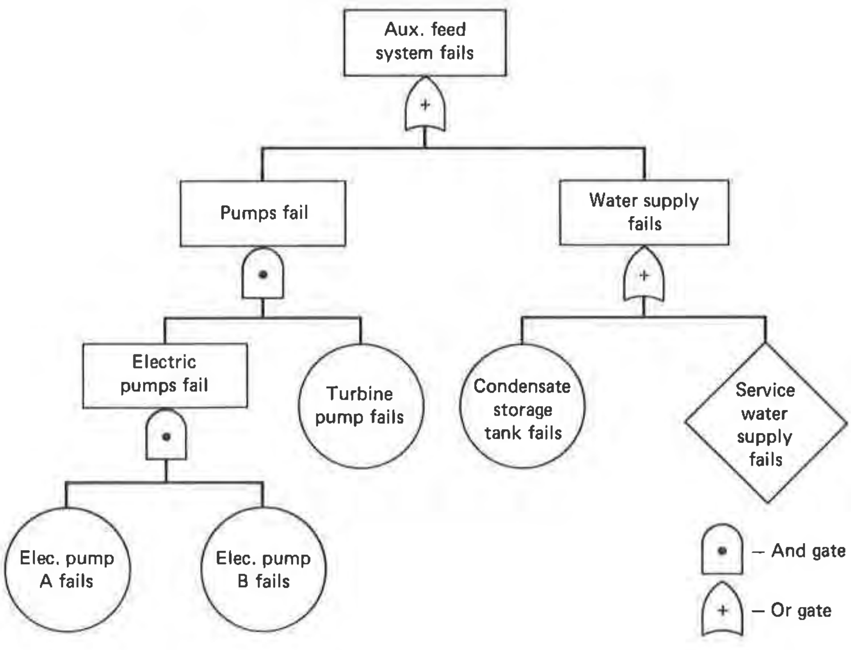

Figure 3b. Simple Fault Tree of the Auxiliary Feedwater System

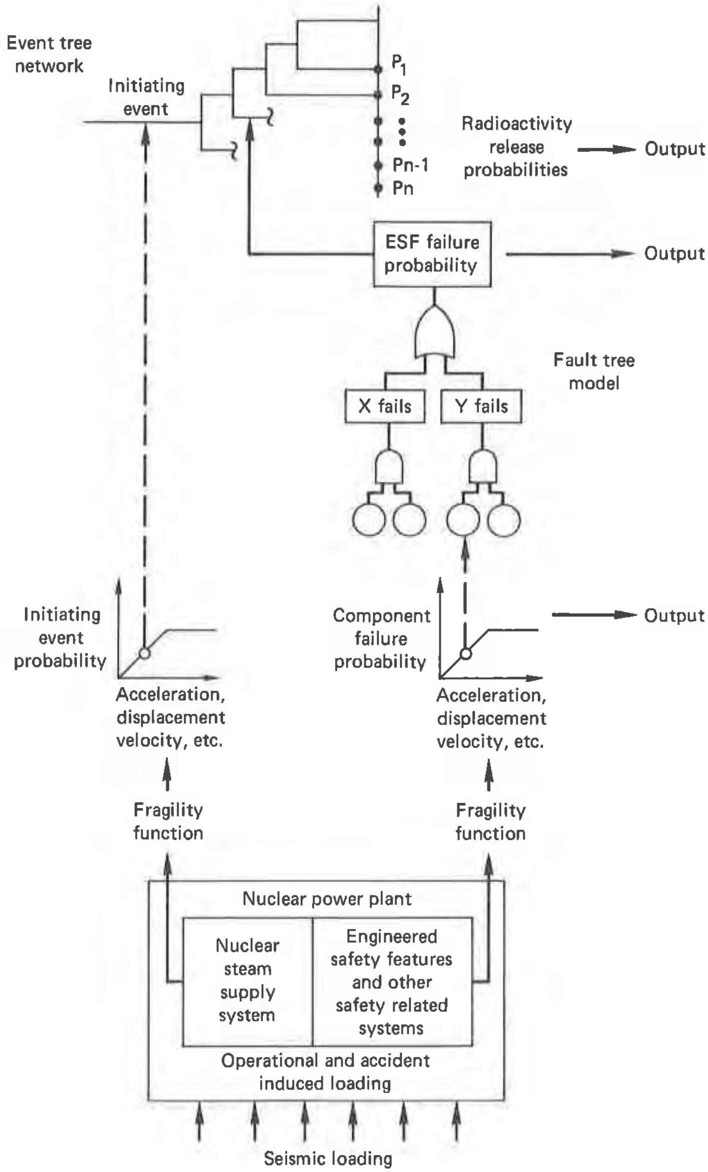

Figure 4. Use of Event Trees and Fault Trees by SSMRP