

EARTHQUAKE ENGINEERING PROGRAMS AT THE LAWRENCE LIVERMORE LABORATORY*

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ABSTRACT

This paper presents an overview of the earthquake engineering programs at the Lawrence Livermore Laboratory (LLL).

INTRODUCTION

In support of the U.S. Nuclear Regulatory Commission (NRC), LLL conducts research and provides technical assistance in three broad areas: waste management, nuclear-material safeguards, and safety. Although the safety program addresses many different safety aspects of nuclear facilities, analysis of the effects of earthquakes receives the most funding--about \$5 million annually. We also perform earthquake engineering studies for the U.S. Department of Energy, but on a smaller scale.

Ultimately, we are helping the NRC to answer such questions as how well can a facility withstand seismic forces, and how high is the risk of radiation release following an earthquake? To do this, our programs have focused on two major areas:

- Evaluation and improvement of current seismic engineering design methods.
- Case reviews of specified facilities and sites for seismic vulnerability.

Included herein are numerous references to reports that document our work. These reports reflect our technical judgments. They should be viewed as contractor reports to the NRC that represent only partial input in the formulation of NRC staff positions.

Our major earthquake engineering program in the first area above is called the Seismic Safety Margins Research Program, which we describe in the first part of this paper along with its predecessor, the Seismic Conservatism Program, and a related short-term program, Task 10 of Task Action Plan A-40, that recommends revisions in NRC seismic design criteria. Next, we describe progress in our major effort in the area of case reviews--the Systematic Evaluation Program, which reviews eleven older operating nuclear reactors. Assessments of several nonreactor facilities, including LLL buildings, are also presented. Finally, we discuss several other research efforts, including our findings on the advisability of seismic scram systems for nuclear power plants.

ASSESSMENTS OF CURRENT SEISMIC DESIGN METHODS

The seismic threat to nuclear power plants causes special licensing problems for the NRC partly because:

- Earthquakes can affect all safety systems simultaneously, thus

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defeating redundancy.

- Seismic safety assessments and designs are based largely on analyses that have little experimental verification.

In dealing with conventional structures, past earthquake engineering practice has focused on preventing the collapse of a structure and given little attention to the survival of piping systems, equipment, and components. However, in nuclear power plants, certain safety systems must operate during and after an earthquake; thus, new requirements are placed on the design. To ensure safety against the seismic threat, the NRC has set forth regulations, guides, standards, and licensing review procedures that establish seismic criteria for nuclear power plant design. The criteria collectively define a seismic methodology chain that departs from conventional earthquake engineering practice in detail and complexity to meet the nuclear plant requirements.

The seismic methodology chain is considered sufficiently conservative to ensure safety, despite the lack of experimental verification. This is because conservative estimates are usually made at each link in the chain to account for uncertainties, and these conservative estimates are likely compounded in successive links to produce an overly conservative final design. For example, the strongest plausible earthquake is presumed to occur and produce the largest ground motion at the free field of the site. This motion is coupled to the bedrock and the building foundation to produce the worst possible forces and stresses. Such responses are compared to conservative estimates of the fragility of each structure or component to determine its survivability. Often in such a design process, the real safety issue of potential radioactive release is never addressed in the context of a systems assessment.

Started in January 1978, our Seismic Safety Margins Research Program (SSMRP) is developing probabilistic methods that predict the behavior of nuclear power plants during earthquakes more realistically than does present seismic design methodology. The program grew out of an evaluation we did in 1977 (Ref. 1) and two recent projects--the Seismic Conservatism Program, discussed below, and an evaluation of the reserve capacity in power plant braced frames.² These and another related program that we undertook to identify and quantify the conservatism in the NRC's Standard Review Plan³ and Regulatory Guides are discussed in detail below.

Seismic Conservatism Program⁴⁻¹⁵

The Seismic Conservatism Program was the first step in our evaluation of current seismic design methodology. While recognizing that the best approach is by way of a systems model, we investigated the individual links in the chain as sources of conservatism because of the urgent need for timely assessments. For many links, we were able to quantify conservatism in a single number that can be thought of as measuring our assurance that the required conservatism is being achieved, rather than the extent of the conservatism itself. In some areas, we also attempted to quantify by how much the NRC seismic safety requirements are exceeded. In all, we investigated ten likely sources of conservatism, briefly summarized below.

R.G. 1.60 Design Response Spectrum.⁵ NRC Regulatory Guide (R.G.) 1.60 (Ref. 16) specifies a design spectrum that, together with the peak horizontal acceleration at the site, serves as the criterion for seismic

safety evaluations. This spectrum has a broader band of frequencies than can be expected from most real earthquakes. Our evaluation of the conservatism that can be traced to this spectral breadth suggests that there is more conservatism than desired at both low and high frequencies.

Synthetic Time Histories.^{4,6} Certain aspects of seismic design call for a time history, and its spectrum must envelop that specified by R.G. 1.60. We estimated the conservatism that arises in the process of developing these synthetic time histories to be about 10 to 15% more than required.

Soil-Structure Interaction.⁸ Soil-structure interaction (SSI) is the phrase used to describe the interaction of massive structures like a nuclear power plant with the earth during an earthquake. This interaction modifies the free-field earthquake motion; therefore, the motion of the base of structures (which is required for subsequent safety evaluation) is obtained from SSI analyses. SSI continues to be one of the most controversial seismic issues. This study attempted to infer conservatism in SSI methods, by comparing motions recorded at the Humboldt Nuclear Power Plant during the June 7, 1975, Ferndale, California, earthquake with SSI analyses. Though we found areas of conservatism and nonconservatism in floor spectra, the results were inconclusive.

Three Components of Earthquake Motion.⁹ Earthquake ground motion at any point has three translational components of motion. We considered the square-root-of-the-sum-of-the-squares method for combining seismic responses for each component of motion. We found floor spectra that were 1.5 to 4 times the value calculated using other acceptable methods of combination.

Broadening of Spectral Peaks.¹⁰ The R.G. 1.60 design spectrum is modified by SSI and structural response as the earthquake motion is transmitted to various parts of the structure. Response spectra are calculated at different support points, then used as input loads for piping and equipment design. Typically, these spectra have peaks (the frequencies of which are characteristics of SSI and structural response) that amplify R.G. 1.60 spectra. These peaks are broadened to account for uncertainties in modeling and material properties. We evaluated the NRC broadening requirement and found that typical floor spectra should be smoother than those commonly used; that is, peaks should be lowered and valleys raised.

Nonlinear Structural Response.¹² When strong earthquakes are specified for nuclear power plant seismic design, the response of the structures is likely to be nonlinear, whereas the structures are typically designed assuming a linear response. This study evaluated the consequences of the linear assumption on floor response spectra. Here, too, we concluded that such spectra should be smoother than is common.

Subsystem Response.¹³ Subsystems, such as piping, are supported on the major structure at several points. These points may have different response spectra, and the envelope of the spectra at the various points is used in design. By closely studying a specific pipe-and-frame system, we estimated the conservatism in this approach to be a factor of 1.5. Other analyses could lead to much larger factors.

Damping.⁷ During earthquake excitation, structures lose energy by various mechanisms (which ensures that the vibrations eventually die down). These losses are characterized in structural analyses by a parameter called damping. Our preliminary investigation suggests that the sensitivity of structural response to changes in damping is less than expected. We are doing more work in this area.

Structural and Mechanical Resistance.¹¹ This study was a literature review on a number of topics. For example, design specifications define certain allowable stresses in steel, based on minimum mill test requirements. However, mill test reports show that the minimums are typically exceeded. Such sources of conservatism were quantified at between 10 and 20% from documented test results.

Design Controlled by OBE Response.¹⁴ Typically, the peak acceleration of the operating basis earthquake (OBE) is half that of the safe shutdown earthquake (SSE). The allowable stresses and load combinations used in design for these two different earthquake levels are different, and frequently the OBE, rather than the SSE, controls the design. The SSE is safety related, but the OBE is usually not considered so. In those cases where the OBE controls the design, the structure is stronger than required for safety purposes, if we consider only the requirements of the SSE. Evaluation of this conservatism on the basis of actual nuclear power plant seismic designs was inconclusive because we found examples in which the OBE both did and did not control the design.

From these studies we reached several general conclusions:¹⁵

- Where several links of the seismic methodology chain can be put together, the estimate of the overall conservatism is greater than might be expected on the basis of the individual results. This was the case in our study of a method that accounts for three-dimensional ground motion. This conclusion confirms our high expectations for the systems approach being used in the SSMRP project.

- Statistical methods are necessary in developing realistic design criteria. Indeed, probabilistic appraisals of design methods give a clearer picture than the quantified conservatisms that we relied on in several studies.

- Increased conservatism in seismic design criteria has not clearly increased overall safety. Some scenarios suggest that increasing seismic conservatism beyond a certain point could lead to reduced safety from nonseismic effects. The location of this point is unclear, as are the seismic tradeoffs. What is clear is that these tradeoffs have not been directly and authoritatively recognized in the development of seismic safety requirements.

Seismic Safety Margins Research Program^{17,18}

The objectives of this program are to develop an improved seismic safety design methodology and to develop a methodology to perform earthquake risk assessments of nuclear facilities. Risk will be measured by various failure probabilities and by the probability of release of radioactive materials.

As discussed above, the historical approach in seismic safety addresses each element of the seismic methodology chain independently. Since there is uncertainty in each element, conservative assumptions are usually, though not always, made, and the final result is a summation of several worst-case scenarios. Such results, therefore, give unrealistic safety characterizations. Our approach integrates the elements of the seismic chain, including:

- Earthquake characterization
 - Earth-structure coupling
 - Structural dynamic response
 - Combination of nonseismic loads
 - Local failure
 - Systematics of how local failures could combine and lead to a release.
- Each element will be characterized realistically and probabilistically, rather than conservatively and deterministically.

Significant advances in technology will be required to meet the objectives. A three-phase program has been developed, and the results of Phase I will be used to determine priorities on and direct research in Phase II. This research will be used to improve the methodology. Phase II could become quite large if the required validation experiments include areas such as earth-structure coupling, where massive structures and high-explosive testing are involved. Phase III will develop the improved seismic safety methodology, based on the results of Phases I and II.

Seven key projects constitute the Phase I program, which will extend through 1980. Each is briefly described below.

Plant/Site Selection Project. The Zion Nuclear Power Plant, Unit #1, owned by Commonwealth Edison Company, Chicago, Illinois, has been selected as a baseline design for systems analysis.

Seismic Input Project. The goal of this project is to develop a probabilistic statement of the seismic hazard, or the reciprocal of the seismic hazard, the return period. (Plots of return period show the time between earthquakes that result in a given earthquake source parameter such as peak ground acceleration vs the source parameter.) It is important to define the seismic hazard accurately and realistically, because all failures are conditional on the occurrence of an earthquake of a certain size, and the overall probability of release is essentially obtained by integrating the seismic hazard with the failure probabilities. In addition, because the seismic input occurs first in the seismic methodology chain, uncertainties in the seismic input propagate through the entire chain and may significantly affect uncertainties in the probability of release. The basic approach to specifying seismic input can be classified as "Bayesian"--an approach that incorporates Monte Carlo techniques.

Soil-Structure Interaction Project. This project will develop relationships for calculating the earth-structure coupling effect. In contrast with methods that produce conservative results for design purposes, the methodology must be as realistic as possible and, ultimately, incorporate nonlinear response characterization.

Structural Building Response Project. This project deals with the methodology to be used for structural building response. The final goal is to determine structural building response. Output from the soil-structure interaction project (in terms of time history or frequency at the foundation base) will be used as input into our structural building model. The building response can be studied in terms of stress, strain, displacement, velocity, and acceleration. Realistic damping and nonlinear response behavior will be major areas of development.

Subsystem Response Project. This project deals with the methodology to be used for subsystem structural response. For the SSMRP, the term subsystem denotes those components and systems for which behavior during a seismic event may be decoupled from the major structural response. Typically, the mathematical model used for the major structural response will include only the mass effects of the subsystem and will produce the support motions to be applied for subsystem seismic qualification. The goal of this task is to develop responses to be used in the systems analysis model discussed below. Again, nonlinear response effects will require major development.

Fragility Definition Project. The goal of this project is to develop component and structural fragility curves that describe the probability of failure of a component or structure in a specific input environment. In Phase I of the SSMRP, the fragility definition will be based on available information; testing will not be carried out. For components, performance qualifications are usually based on nondestructive dynamic tests or on analyses. Therefore, for most components, it is difficult to define a realistic fragility curve. Since we expect failure test data to be limited, it may be necessary to collect information from outside the nuclear industry to expand the data base, and to apply engineering judgment where data are scanty or lacking. Subsequent phases will involve experimental programs to refine fragility estimates.

Systems Analysis Project. The systems analysis project comprises two parts. The first involves the specification and development of an overall computational procedure for the seismic methodology and event tree/fault tree models developed for this program. This procedure will, among other things, generate the probability of radioactive releases caused by seismically induced events in nuclear power plants. The second part of the project will deal with the construction and evaluation of the event tree/fault tree model of a nuclear power plant (Zion) subjected to a seismic event.

The computational procedure is divided into two parts--response calculations and systems calculations (Fig. 1). The response calculations follow the first four tasks of Phase I; that is, building and subsystem response, which will ultimately be nonlinear, is derived from probabilistic seismic input and realistic soil-structure interaction. In the systems calculations, results of the response calculations are combined with nonseismic loads and known component fragilities in a component failure analysis to generate functional relationships between failure probabilities and given response parameters such as displacement or stress. These relationships are the input for the event tree/fault tree model, which is based on the structure, system, or component under investigation.

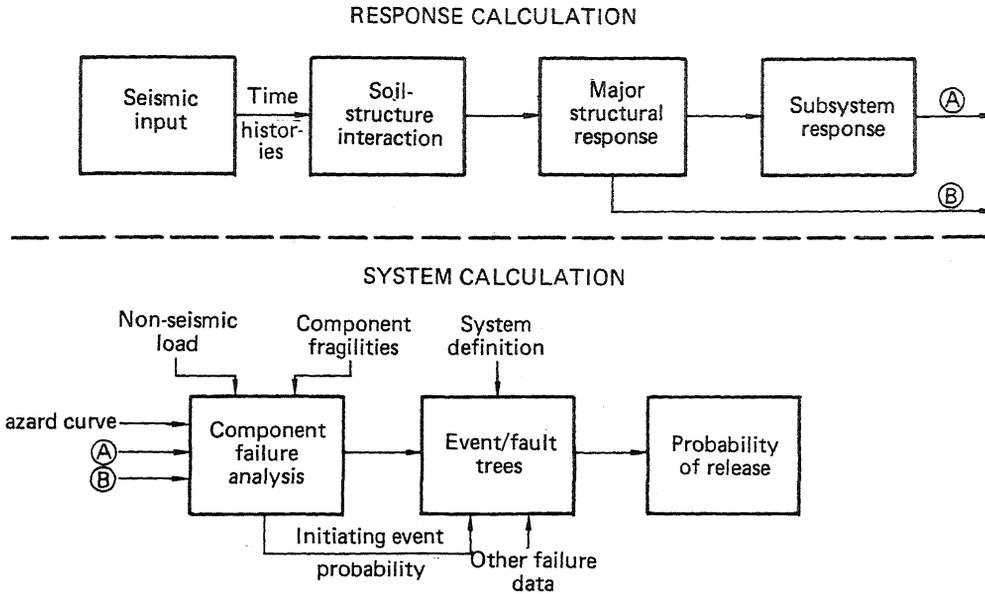


FIG. 1. The planned overall computational procedure for the Seismic Safety Margins Research Program will generate the probability of radioactive releases caused by seismically induced events in nuclear power plants. The procedure has two parts: response and system calculations.

Figure 2 is a detailed representation of the systems calculation. Note that the event tree network is initiated by failure of a critical element in the nuclear steam supply system (NSSS), while the fault tree is a model of a given engineered safety feature (ESF) system (e.g., an auxiliary feedwater system), the failure of which is one event in the event tree network. As shown, the probability of radioactivity release depends on both the probability of a failure in the NSSS (an initiating event) and the probability of failures in the ESF systems.

Task Action Plan A-40/Task 10

NRC Task Action Plan A-40 (TAP A-40) was developed to identify and quantify the conservatism in the NRC's Standard Review Plan³ and Regulatory Guides. Task 10 of TAP A-40 recommends changes that will keep these criteria in step with the state of the art in seismic design until results are obtained from the Seismic Safety Margins Research Program. The results of Task 10 will also help the NRC staff to review existing plants under the Systematic Evaluation Program discussed below.

Most studies of the engineering response characterization of structures and components are complete, while studies of seismological characterization of ground motion are incomplete as of this writing. The report issued on the completed studies¹⁹ contains recommendations based on the philosophy that performance specifications for structures and equipment should be the ultimate goal, not procedural specifications.

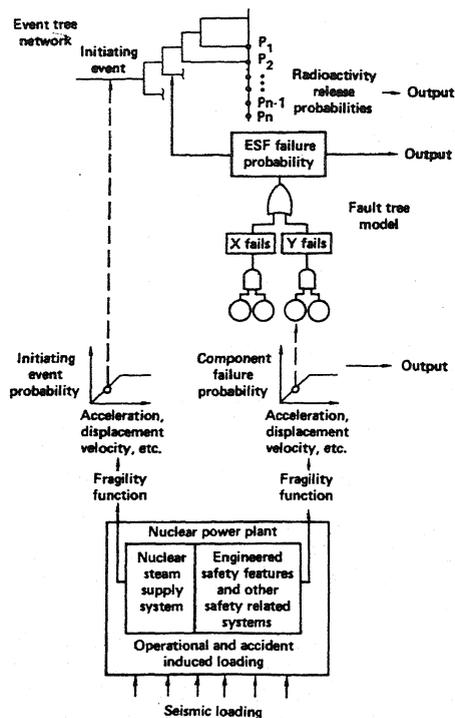


FIG. 2. A detailed representation of the systems calculation. Note that the event tree network is initiated by failure of a critical element in the nuclear steam supply system (NSSS), while the fault trees model engineered safety feature (ESF) systems. The probability of radioactivity release depends on the probabilities of failure for the NSSS and the ESF systems.

Specifically, the report recommends:

- Changes in the specification and application of ground motion for the design of structures and equipment.
- Significant changes to the philosophy and specifications for soil-structure interaction analysis.
- More specific guidelines for the seismic design and analysis of special structures such as buried pipes, conduits, and aboveground vertical tanks.
- Specific criteria for the combination of high-frequency modal response.
- The allowance of limited amounts of inelastic energy absorption in the design response of Category I structures.
- Revision of damping values for design, based on the type and condition of the structure and the stress levels of interest.
- Direct generation of in-structure response spectra for equipment design.
- Accounting for uncertainties in the generation of in-structure response spectra through multiple analyses with variation of parameters and

through the use of probabilistic in-structure response spectra generated on the basis of nonexceedance criteria. The requirement to broaden spectra is thereby eliminated.

- The option to use randomly selected multiple time histories (real or synthetic) for time-history analysis.
- Reduction in the number of operating basis earthquake (OBE) cycles required for design.
- In-situ testing of selected aspects of nuclear power plants.

The last recommendation above--that nuclear power plant structures be tested--reflects LLL's judgment that confidence in design methods can be increased by correlating analytical prediction techniques with experimental observations of response characteristics such as frequencies of vibration, mode shapes, and damping. Along these lines, LLL has performed a study that evaluated the applications of system identification techniques to nuclear power plant structures and subsystems.²⁰ These experimental techniques involve exciting a structure and measuring, digitizing, and processing the time-history motions that result. The data can be compared to parameters calculated using finite element or other models of the test systems to verify the model and analysis procedures that were used to design the structures. Work was done in three main areas:

- Examination of the feasibility of safely exciting a nuclear power plant structure and accurately recording the resulting time-history motions.
- Analytical qualification of a particular set of LLL computer programs for use in extracting the model parameters from the time histories.
- Study of how these extracted model parameters can be used best to evaluate structural integrity and analyze nuclear power plants.

CASE REVIEWS

Systematic Evaluation Program

Structural Studies. The Systematic Evaluation Program (SEP) consists of a plant-by-plant limited reassessment of the safety of eleven older operating nuclear reactors. Phase I of the SEP developed a comprehensive list of topics of safety significance that collectively affect a plant's capability to respond to various design basis events. LLL then evaluated the seismic analysis methods available for the SEP.²¹ In September 1978, the NRC staff commissioned a Senior Seismic Review Team (SSRT) of recognized seismic design experts under the direction of Nathan M. Newmark of the University of Illinois and charged the SSRT with the following responsibilities:

- To develop the general philosophy of review, setting forth seismic design criteria and evaluation concepts applicable to the review of older nuclear plants, and to develop an efficient, yet comprehensive review process for NRC staff use in subsequent evaluations.
- To assess the safety of selected older nuclear power plants relative to those designed under current standards, criteria, and procedures, and to define the nature and extent of retrofitting to bring these plants to acceptable levels of capability if they are not already at such levels.

As a first step in Phase II of the SEP, the SSRT performed a limited reassessment of the seismic design of the Dresden Nuclear Power Station, Unit 2, near Chicago, Ill. The reassessment focused generally on the reactor coolant pressure boundary and on those systems and components necessary to shut down the reactor safely and to maintain it in a safe shutdown condition following a postulated earthquake. Unlike a design analysis, the reassessment was limited to structures and components deemed representative of generic classes. Conclusions and recommendations about the ability of selected structures, equipment, and piping to withstand the postulated earthquake were presented.²²

The review concept was not based upon demonstrating compliance with specific criteria in the Standard Review Plan or Regulatory Guides because individual criteria do not generally control broad safety issues. However, current licensing criteria were used with respect to the level of design they dictate, and baselines from which to measure relative safety margins to support the broader integrated assessment. Therefore, the seismic resistance capability of the Dresden 2 facility was compared in a qualitative fashion to that dictated by the "intent" of today's licensing criteria with the objective of demonstrating acceptable levels of safety and reliability.

LLL was represented on the SSRT and supplied much of the engineering expertise for the reassessment of Dresden 2. Moreover, the reassessment of the other ten reactors for the SEP is an ongoing LLL project. Completion of the reviews of four of the plants is scheduled for 1980.

Site Specific Spectra Study. Part of the SEP reassessments is the specification of the seismic hazard for each site--another ongoing LLL study. A realistic site specific spectrum is not easy to develop because the spectra at a specific site are functions of the following variables:

- Earthquake magnitude and source parameters
- Hypocentral distance
- Region of country
- Travel path
- Site soil column
- Site topography.

The problem is compounded by a lack of data, which is of considerable importance in the eastern United States where the affected region for a given seismic energy differs significantly from that for the same seismic energy in the western United States. Thus, data obtained in the West must be extrapolated to eastern conditions. Even using worldwide data, we expect broad gaps in the data base for many sites, epicentral distances, and earthquake magnitudes.

The site-specific approach differs from the method of generically specifying the Safe Shutdown Earthquake spectral envelope, which is now used for new facilities. This current methodology, which is often termed a deterministic approach, has problems that arise because it does not explicitly keep track of various probabilities. These difficulties can be overcome by using probabilistic methodologies to estimate the seismic hazard at a site. These methods are attractive but controversial. The many assumptions that must be made can cause the results of various

investigators to differ significantly. We studied the problems associated with such methodologies and did the following:²³

- Outlined various methodologies that may reasonably define seismic hazard.
- Identified the major assumptions that can lead to significant variations in the predicted hazard.
- Provided guidance to appropriate choices of parameters.
- Presented possible corrections that can extend the meager earthquake data base for sites located in the eastern United States.

For the SEP sites, we recommended the use of a "Bayesian" method that incorporates various interpretations of the same data. Our report²³ was directed toward sites in the eastern United States because all but one of the plants under review as part of SEP are located east of the Rocky Mountains.

In an unrelated and previous site-specific study, we analyzed response spectra for the Diablo Canyon Nuclear Power Plant site on the central California coast. As the plant neared completion, geologists found evidence that a nearby fault may be part of a major fault system. If so, the original Design Basis Earthquake (DBE) would be inadequate. We studied the site geology and found significant site effects that would lessen the impact of this new hypothesis. In particular, the level of ground motion at the plant resulting from a nearby major earthquake would have lower amplification factors than those specified in NRC regulatory guides. This reduction results partly from the fact that the sandstone at the site is underlaid by a less-competent mudstone layer and partly from soil-structure interactions. We concluded that a larger-magnitude DBE should have little effect on the reactor design if the increase stems from greater fault rupture length rather than increased stress drop.²⁴

Nonreactor Facilities

As part of its relicensing activities, the NRC asked LLL to assess the seismic vulnerability of several fuel reprocessing facilities. Groundwork for these assessments had been laid several years ago when we evaluated:

- The structural integrity and possible failure modes of a mock mixed-oxide fuel fabrication plant.²⁵
 - Methods for seismic analysis of nuclear fuel processing plants, using two actual and one planned nuclear fuel plants.^{26,27}
- Our recent assessments are discussed below.

Nuclear Fuel Services, Inc., West Valley, N.Y. We assessed the seismic integrity of the reprocessing facility operated by Nuclear Fuel Services, Inc., at West Valley, N.Y. The assessment began with a seismic analysis of the process building.^{28,29} Next, we analyzed the neutralized liquid-waste tanks located north of the building and the fuel receiving station adjacent to the process building.^{30,31} Our final report presented our analysis of two acid liquid-waste tanks located next to the neutralized liquid-waste tanks.³² These reports all present discussions of the approaches we took in performing the analyses as well as descriptions of the facilities, our modeling and analysis techniques, failure criteria, results, and conclusions.

Five Commercial U.S. Plutonium Fabrication Plants. We performed seismic assessments of five commercial U.S. plutonium fabrication plants licensed by the NRC before Sept. 2, 1971, when regulations were changed. The NRC is evaluating the facilities to determine the effects on them of three adverse natural phenomena--earthquake, flood, and high wind--and will use the results of the evaluation in license renewal reviews to determine how much retrofitting, if any, each facility needs for adequate protection of the public against adverse natural phenomena. The facilities include:

- Westinghouse Plutonium Fuels Development Laboratory, Cheswick, Penn.
- Babcock and Wilcox Facility, Leechburg, Penn.
- Battelle Memorial Institute, Columbus Laboratories West Jefferson Site, West Jefferson, Ohio
- Exxon Mixed Oxide Fuel Plant, Richland, Wash.
- Atomics International Nuclear Materials Development Facility, Santa Susana, Calif.

Our seismic assessment had three parts:³³

1) Documentation of the structural condition of each facility and its critical equipment.

2) Analysis of the seismic hazard (i.e., determination of peak ground acceleration vs return period for each site).

3) Analysis of seismic capacity (i.e., peak ground accelerations at which critical structures and equipment fail) based on material properties from (1) and seismic input from (2).

Results of the assessment comprised partial input for the overall natural hazards study by the NRC.

Department of Energy Programs. Our programs for the U.S. Department of Energy (DOE) involve:

- Development of seismic hazard criteria for all DOE sites in the United States.
- Seismic evaluation of some 17 LLL buildings that house nuclear materials.

The goal of the first program is to develop uniform design criteria for seismic, tornado, and extreme-wind hazards at the various DOE sites--a program similar to the natural hazards evaluation of commercial plutonium processing plants discussed above. To date, we have established which DOE sites are to be assessed and identified the critical facilities at each. We plan to develop models, analyze them for response to peak ground accelerations and wind loadings, and thus evaluate the existing criteria for the design of critical facilities at each DOE site.³⁴

We are also evaluating the seismic vulnerability of critical facilities at the LLL complex in Livermore, California, and at the test sites near Tracy, California, and Las Vegas, Nevada. Our general approach was presented in a paper to the 6th World Earthquake Engineering Conference.³⁵ Today, we have completed the evaluations of most of the critical facilities. Our review of LLL's plutonium facility was, perhaps, the most extensive effort.³⁶ We found that, with scheduled modifications, the structures and ventilation systems will be able to withstand an earthquake characterized by a peak ground acceleration of 0.8 g, and glove boxes can withstand 1.0 g. In view of the site seismicity and geology, we conclude that the earthquake-related risk to the public from a release of plutonium from this facility is essentially zero. However, we

are doing more field studies to further confirm our belief that potential offset beneath the building is not credible, including:

- A major trenching and drilling survey of the LLL site.
- Installation of additional seismographic stations to pinpoint epicenters within 0.5 km, rather than 5 km, as is now possible.
- Installation of strong-motion accelerographs.
- Additional geophysical exploration using such techniques as high-resolution seismic reflection surveying, magnetometer surveying, and dipole-dipole resistivity mapping.

OTHER WORK

The major research projects discussed above often overshadow other seismic research efforts at LLL that contribute greatly to the major projects as well as to the state of the art of earthquake engineering. We have performed basic investigations into many areas, including:

- Effective mass and damping of submerged structures³⁷
- Seismic analysis of large pools³⁸
- Comparison of finite element and lumped mass methods for calculating soil-structure interaction in nuclear power plants.³⁹

We also have ongoing programs in the following areas:

- Evaluation of structural and equipment performance in heavy industrial structures that have experienced major earthquakes.
- Assessment of seismic instrumentation needs and establishment of procedures for post-OBE inspections.
- Development of a plan for post-earthquake inspections.

Advisability of Seismic Scram

Another study for the NRC assessed the value of seismic trip (scram) systems on commercial nuclear power plants.⁴⁰ Previous studies had addressed the feasibility of providing a seismic trip system,⁴¹ but the final report considered the advisability of such systems by addressing five topics:

- The likelihood that existing plant instrumentation will cause a trip during an earthquake.
- The consequences of spurious reactor trips caused by a seismic trip system.
- The consequences of tripping during an earthquake.
- The advantages of a controlled shutdown during an earthquake.
- The desirability of allowing nuclear power plants to continue to generate power during an earthquake.

We assessed the risk in each of these specific areas through a generalized fault tree analysis. Using estimated data, we compared fault trees for nuclear reactors with and without seismic trip systems. The quantification of the fault trees made possible a comparison between the risks of plants with and without seismic trip systems, and between earthquake-caused risk and other accident risks. We found that seismic trip systems would have a small and undetermined effect on risk due to nuclear reactor accidents and may indeed increase the risk to society from an earthquake.

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