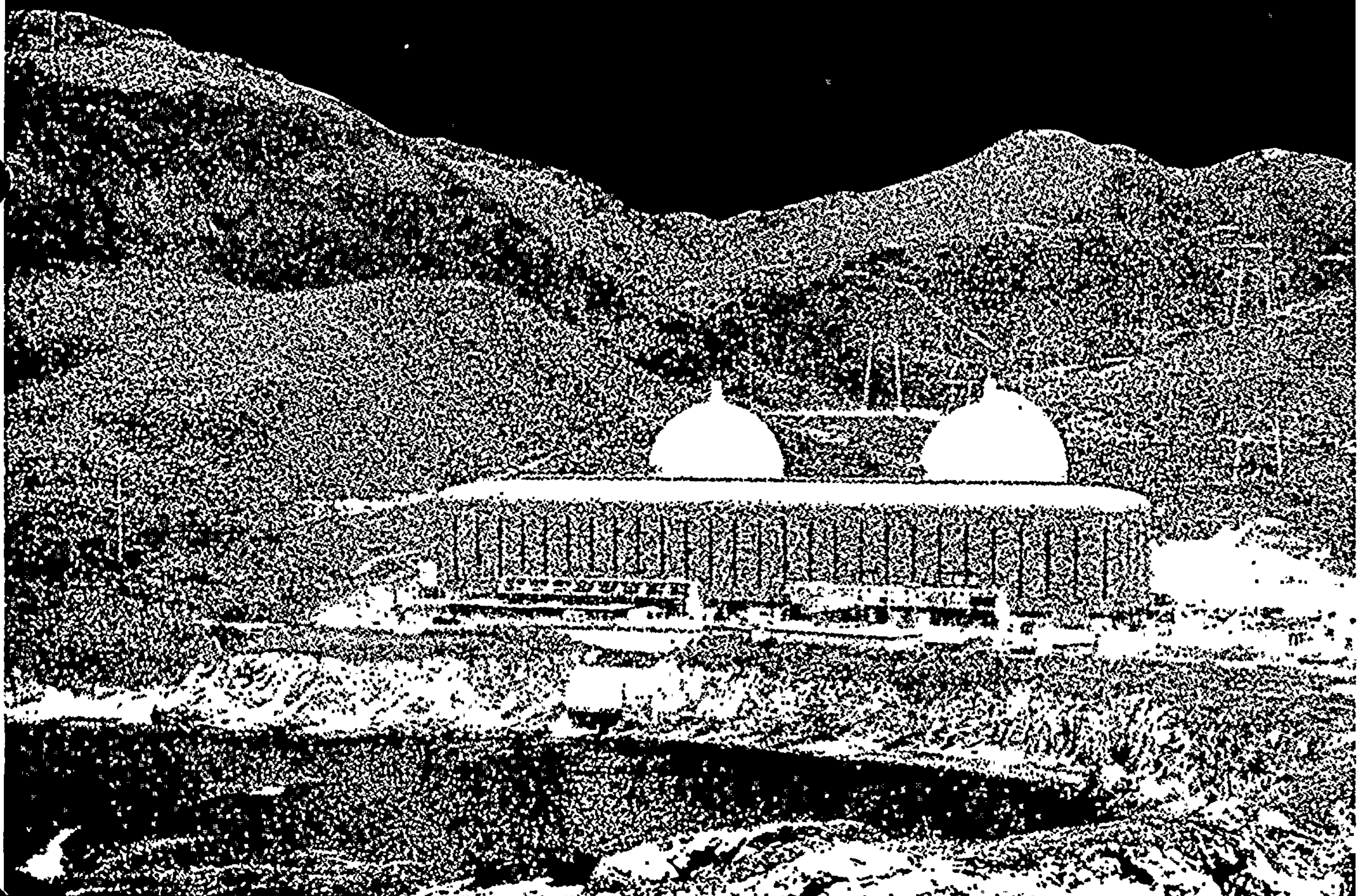
LONG TERM SEISMIC PROGRAM

PROGRAM PLAN

JANUARY 1985

PACIFIC GAS AND ELECTRIC COMPANY
Diablo Canyon Power Plant
Docket Nos. 50-275 and 50-323



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1. INTRODUCTION

1.1 BACKGROUND

On February 23, 1984, the U.S. Nuclear Regulatory Commission (NRC) Staff proposed a license condition for the Diablo Canyon Power Plant (DCPP) based in part on the Advisory Committee on Reactor Safeguards' (ACRS) letter of July 14, 1978, which recommended that "...the seismic design of Diablo Canyon be reevaluated in about 10 years taking into account applicable new information." In addition, differing interpretations of the geologic setting of the region near the plant have been put forth during the past several years. As a result, the following License Condition was added to the operating license for DCPP:

1. PG&E shall identify, examine, and evaluate all relevant geologic and seismic data, information, and interpretations that have become available since the 1979 ASLB hearing in order to update the geology, seismology, and tectonics in the region of the Diablo Canyon Nuclear Power Plant. If needed to define the earthquake potential of the region as it affects the Diablo Canyon Plant, PG&E will also reevaluate the earlier information and acquire additional new data.

2. PG&E shall reevaluate the magnitude of the earthquake used to determine the seismic basis of the Diablo Canyon Nuclear Plant using the information from Element 1.

3. PG&E shall reevaluate the ground motion at the site based on the results obtained from Element 2 with full consideration of site and other relevant effects.

4. PG&E shall assess the significance of conclusions drawn from the seismic reevaluation studies in Elements 1, 2 and 3, utilizing a probabilistic risk analysis and deterministic studies, as necessary, to assure adequacy of seismic margins.

PG&E shall submit for NRC Staff review and approval a proposed program plan and proposed schedule for implementation by January 30, 1985. The program shall be completed and a final report submitted to the NRC three years following the approval of the program by the NRC Staff.

PG&E shall keep the Staff informed on the progress of the reevaluation program as necessary, but as a minimum will submit quarterly progress reports and arrange for semi-annual meetings with the staff. PG&E will also keep the ACRS informed on the progress of the reevaluation program as necessary, but not less frequently than once a year.

In order to comply with these conditions, Pacific Gas and Electric Company (PGandE) has developed the Long Term Seismic Program (LTSP) that is described in detail in this Program Plan.

1.2 OBJECTIVES

The primary objective of the LTSP is to comply with the seismic license conditions set forth above. This objective will be accomplished by investigating relevant technical areas in the field of geology and assessing earthquake magnitude and ground motion both by empirical and numerical methods. Such ground motion will then be utilized for the 3-D soil-structure interaction analysis to develop the motion at the structural foundation level and also to perform deterministic evaluation, as necessary. Seismic hazard analysis will also be performed to define the probabilistic ground motion with their associated uncertainties. The results of the hazard analysis, along with the fragility analysis, will provide input to the probabilistic risk assessment (PRA).

2. LTSP ORGANIZATION, ADMINISTRATION, AND SCOPE

2.1 PROGRAM ORGANIZATION

2.1.1 Program Team

The LTSP will be conducted by a program team that will administer and coordinate the work being performed by technical consultants. The main technical subject areas to be investigated are represented in the program organization (Figure 2.1-1). PGandE management and responsibility for the program rests with the Vice President of Engineering. The Program Manager, assisted by three Assistant Program Managers, has the responsibility for program definition and implementation. Other members of the program team will have responsibility for quality assurance, cost and schedule, and day-to-day administration.

PGandE has selected prime investigators to perform activities associated with various elements of the Program Plan. These prime investigators have considerable experience in their respective areas of expertise. Earth Sciences Associates (ESA) has been selected to perform the geologic investigation, under the direction of Dr. Douglas Hamilton. Dr. Hamilton has been involved with the site geology at Diablo Canyon since 1972 and had the prime responsibility for offshore studies in 1974-1975, and 1978. ESA has also performed regional investigations for other commercial and military facilities in central and northern California, including studies of earthquake hazards for major dam sites. ESA will utilize the services of Ogle Petroleum, Inc. as a subcontractor, thereby gaining additional expertise in the Santa Maria Basin region.

TERA, under the direction of Mr. Larry Wight and Dr. Stewart Smith, will perform seismological investigations. TERA performed numerous studies developing estimates of maximum earthquake magnitude and associated ground motion for various sites based on historical data and application of

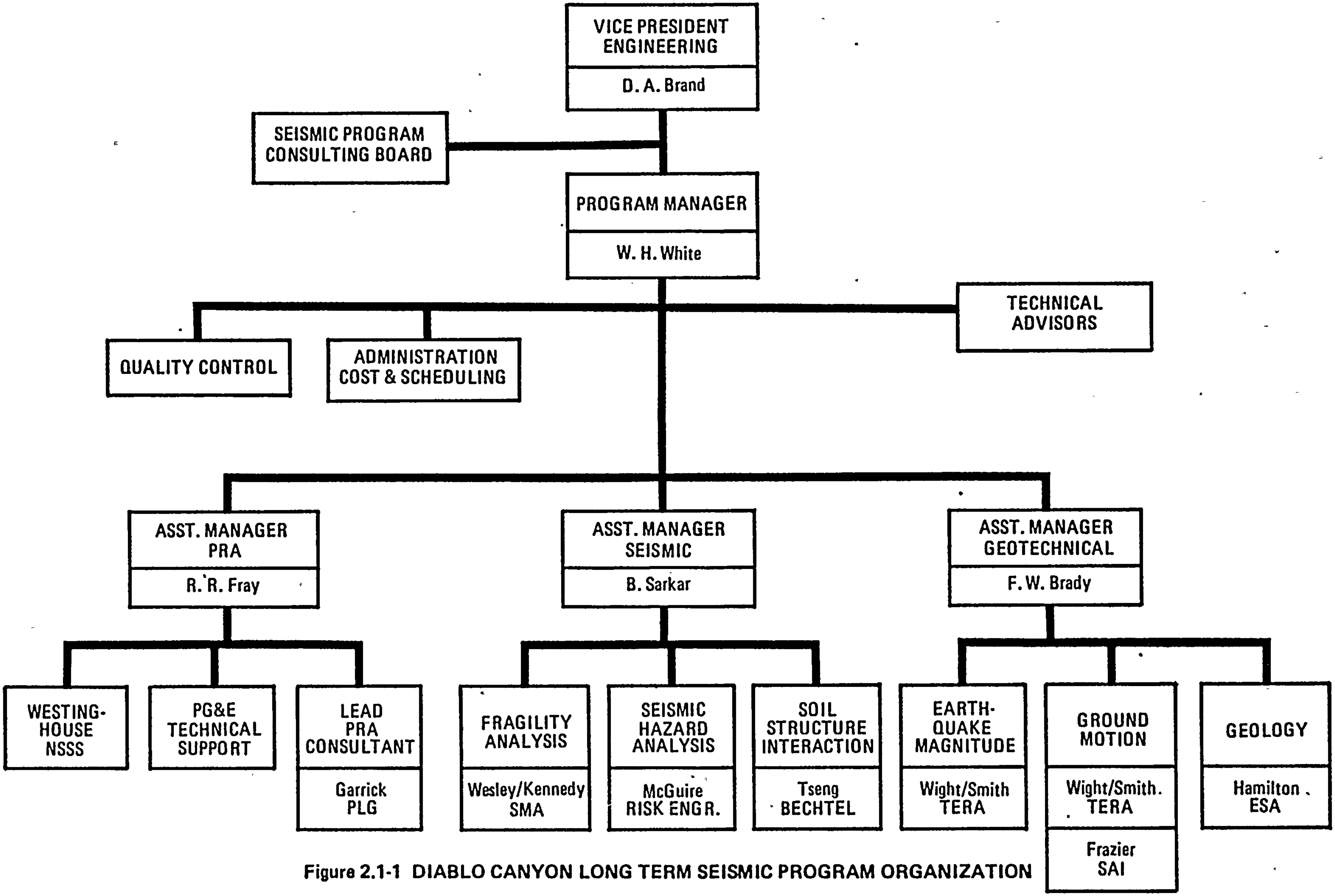


Figure 2.1-1 DIABLO CANYON LONG TERM SEISMIC PROGRAM ORGANIZATION

statistical techniques. The San Onofre Nuclear Generation Station (SONGS) is but one example of where state-of-the-art prediction methods were employed. Another recent project addressed the seismic hazard at the Vallecitos Nuclear Center. In that project, statistical and probabilistic tools were used extensively.

Science Applications International Corporation (SAIC) will investigate ground motion using numerical modeling techniques under the direction of Dr. Gerald A. Frazier and Dr. Thomas C. Bache. Dr. Frazier was previously associated with TERA/DELTA where he directed numerical modeling studies for San Onofre and Diablo Canyon. Dr. Bache has performed numerous seismological studies during the past decade. In addition, Professor Donald V. Helmberger will act as a consultant for this effort.

The soil-structure interaction (SSI) analysis will be performed by Bechtel Power Corporation (Bechtel) under the direction of Dr. Wen Tseng. Bechtel has taken a leading role in developing SSI techniques and has performed SSI analyses on many power plants.

Risk Engineering, under the direction of Dr. Robin McGuire, will develop the seismic hazard analysis. Dr. McGuire has considerable experience in this area from developing these relationships for numerous nuclear power plant sites. He has also examined and published research on seismic hazard and its uncertainties in the California plate margin environment.

Structural Mechanics Associates (SMA) will develop the fragility curves for the structures and equipment under the direction of Drs. Don Wesley and Robert Kennedy with the assistance of PGandE and Bechtel. In addition to the successful development of such information for other plants, SMA has published numerous research papers in this field.

Pickard, Lowe and Garrick (PLG) will perform the probabilistic risk assessment under the direction of Dr. John Garrick. PLG has extensive experience in this field, having completed 15 full-scope PRAs for nuclear power plants throughout

the world. PLG has continually advanced the methodology of PRA, including the initial development of the seismic analysis methodology in risk assessments.

2.1.2 LTSP Program Consulting Board and Technical Advisory Groups

The LTSP Consulting Board and the Technical Advisory Groups (TAGs) are key elements of the LTSP organization. The primary function of the consulting board is to provide guidance to PGandE (and the prime investigators) to assure that the objectives of the NRC license condition are achieved and that relevant theories have been considered. This will be accomplished by having the consulting board review results as they become available and to suggest priorities of program elements and allocation of resources. The Board will, therefore, have a strong influence on the program as the work progresses. The members of this board are: Thomas M. Leps (Chairman), Clarence A. Allen, Bruce C. Bolt, C. Allin Cornell, Cole R. McClure, and H. Bolton Seed.

The technical advisors will work individually or in small groups (ranging from two to four persons) with individual prime investigators to review their scope of work and to advise in the development of technical solutions, as shown in Table 2-1.

2.1.3 Quality Assurance Program

The LTSP will be conducted in accordance with the applicable requirements of PGandE's Quality Assurance Program. This program, which is described in the Diablo Canyon FSAR, Chapter 17, has been reviewed and accepted by the NRC. The program description identifies the industry standards and regulatory guides to which PGandE has committed.

The LTSP quality assurance program will consist of two distinct components. The first will include activities performed by PGandE and the Diablo Canyon Project (DCP). Currently, all engineering activities, including those performed by DCP, are controlled by the requirements of PGandE's Engineering Department Nuclear Engineering Manual (NEM).

Table 2-1

TECHNICAL ADVISORY GROUPS

Technical Area	Technical Advisors
Geology	Clarence A. Allen Cole R. McClure Thomas M. Leps Richard Holt
Earthquake magnitude and ground motion	Bruce A. Bolt Thomas M. Leps J. Carl Stepp
Soil-structure interaction	H. Bolton Seed William Hall
Fragility analysis	William Hall Robert Kennedy
Hazard analysis	C. Allin Cornell Robert Kennedy
Probability risk assessment	C. Allin Cornell Robert Kennedy

The second component involves activities performed by LTSP prime investigators. These activities will be conducted under QA programs appropriate to their scope of work or they will be required to comply with existing DCP requirements. PGandE will develop and specify, as a part of each contract, the QA requirements for each prime investigator. Where a separate QA program is required, PGandE will review the prime investigator's program to assure compliance with PGandE's QA program.

2.2 INTERACTION OF LTSP WITH NRC

PGandE's licensing organization within the Nuclear Power Generation Department will be the contact on the LTSP with the NRC and, through the NRC, with the various NRC consultants, the U.S. Geological Survey (USGS), and the ACRS.

The following sections describe the formal program mechanisms for maintaining a working relationship between PGandE and the NRC on the LTSP.

2.2.1 Quarterly Progress Reports To NRC

Quarterly progress reports will be submitted to the NRC. The first report will be submitted at the end of the fourth month following NRC approval of the program plan, and will reflect the progress and status of the LTSP as of the end of the month preceding the reporting month.

2.2.2 Semiannual Progress Meetings With NRC

Semiannual progress meetings, starting six months after approval of the program plan, will be held with the NRC and their consultants.

2.2.3 Annual Progress Meetings With ACRS

Annual progress meetings, starting at least six months after approval of the Program Plan, will be held with the ACRS and their consultants.

2.3 DYNAMIC NATURE OF LTSP

As events concerning the Diablo Canyon seismic design over the past 2 decades have shown, any successful long term seismic program must be structured to accommodate change. That is, there must be inherent flexibility in the program to allow changes in direction necessitated by developing facts and emerging theories. In recognition of this fact, the program plans for each of the eight technical areas (Sections 3 through 10) are, therefore, not intended as absolutes. Indeed, some of the planned activities may be abandoned as unnecessary or of little value, while other activities may be substituted and/or added as better methods of achieving the objectives of the LTSP. This will be done after consultation with the consulting board. Importantly, any significant changes in direction will be set forth in the quarterly reports to the NRC and, where practicable, be discussed in advance in meetings between the NRC and the LTSP.

2.4 PROJECT SCHEDULE

A Milestone Summary Schedule indicating completion of major events is shown in Figure 2.4-1 The schedule shows the overall requirements of the program and is the basis for general project planning and control. The project schedules will be regularly maintained to provide status information. Significant schedule changes will be reported in the LTSP quarterly reports to the NRC.

LINE NO.	DESCRIPTION	SCHEDULE
	MILESTONE	PROG… PLA… SUBMIT… TO N… ▽ ; FINAL PROGRAM REPORT ▽
	YEAR	1984 … 1988
	MONTH	SEP OCT NOV DEC JAN ‖ DEC JAN FEB MAR APR MAY JUN JUL AUG
1	SUMMARY	PHASE I
2		
3		
4		
5	GEOLOGY	Y
6		
7		DRAFT RPT. FINAL REPORT INPUT
8		
9		
10		
11	EARTHQUAKE MAGNITUDE	(SEE NOTE
12		
13		FINAL REPORT INPUT
14		
15		
16	GROUND MOTION-EMPIRICAL	(SEE NOTE
17		
18		
19		
20		IES FINAL REPORT INPUT
21		
22	GROUND MOTION-NUMERICAL	(SEE NOTE
23		
24		
25		
26		DRAFT RPT. FINAL REPORT INPUT
27		
28		
29–31	SOIL-STRUCTURE INTERACTION (INCL. DCP SUPPORT TO FRAGILITY)	(SEE NOTE
32		DRAFT RPT. FINAL REPORT INPUT
33		
34		
35	SEISMIC HAZARDS ANALYSIS	(SEE NOTE
36		
37		
38		
39		
40		
41		
42	FRAGILITY ANALYSIS	(SEE N…
43		
44–45	PROBABILISTIC RISK ASSESSMENT	(SEE N…
46		
47		&E REVIEW PREP FINAL REPORT ISSUE FINAL REPORT
48		

NOTES:

1. THE OVERALL SCHEDULE DATES ARE BASED UPON THE LICENSING CONDITION 2.C.(7) DATED NOVEMBER 2, 1984.
2. DELETED
3. THE SCOPE OF EACH PROGRAM PRESENTED HERE IS CONSISTENT WITH THE INFORMATION CONTAINED IN THE PROGRAM PLAN DATED JANUARY 30, 1985.
4. EVALUATION OF EMPIRICAL, AND SEISMIC HAZARD GROUND MOTIONS BY THE TECHNICAL ADVISORS IS AN ON-GOING ACTIVITY.
5. DIABLO CANYON PROJECT SUPPORT/INTERFACE TO ALL PROGRAM ELEMENTS HAS NOT BEEN SHOWN ON THIS SCHEDULE.
6. ITERATIONS INCLUDES TIE-INS TO OTHER TECHNICAL PROGRAMS AS REQUIRED AND FINALIZATION OF RESULTS.
7. PROGRAM ELEMENTS OTHER THAN GEOLOGY WILL START UPON NRC PROGRAM APPROVAL.

TI APERTURE CARD

Also Available On Aperture Card

LEGEND:

—— SCHEDULED ACTIVITY

—— ON-GOING ACTIVITY

8502130391-01

…IC CO. …ROGRAM

TITLE: MILESTONE SUMMARY SCHEDULE

FIGURE 2.4-1

3. GEOLOGICAL INVESTIGATION

3.1 INTRODUCTION

The geologic investigations program described in this section is designed to respond directly to Condition 2.C.(7).(1). of the operating license for DCPP, and to provide appropriate geological and geophysical data where needed by prime investigators working on aspects of the DCPP LTSP responding to the other license conditions. For convenience of reference, License Condition 2.C.(7).(1). is repeated here:

> PG&E shall identify, examine, and evaluate all relevant geologic and seismic data, information, and interpretations that have become available since the 1979 ASLB hearing in order to update the geology, seismology and tectonics in the region of the Diablo Canyon Nuclear Power Plant. If needed to define the earthquake potential of the region as it affects Diablo Canyon Plant, PG&E will also reevaluate the earlier information and acquire additional new data.

The program for geologic investigations is based on the current understanding by PGandE and its consultants of geologic and tectonic conditions in the region of the power plant. It also reflects work done between 1965 and the present together with discussion, guidance, and comments received from the NRC, ACRS, and USGS, and their respective consultants. The basis for PGandE's understanding is briefly reviewed in Section 3.2, and the succeeding discussions of the geology element Tasks A, B, and C. Presentations and discussions that are relevant to the program are described herein, together with letters and memoranda from NRC and ACRS Staff and consultants (listed in Table 3-1).

Table 3-1

MEETINGS AND COMMUNICATIONS THAT PROVIDE
BACKGROUND FOR DIABLO CANYON LTSP
GEOLOGY INVESTIGATION

Date	Meeting/Communication	Geoscience Participants/Authors
05-07-84	Memorandum--Status of Draft Elements for the Diablo Canyon License Condition	R. Jackson (NRC Geosciences Branch)
05-08-84	Meetings in Bethesda--NRC	NRC Geosciences Branch and consultants; PGandE and consultants
05-18-84	Memorandum--Summary of NRC Meeting with PGandE regarding revalidation of Program for seismic design basis	
05-24-84	Memorandum -- "Preliminary Summary and Evaluation of Article Containing New Information or Interpretation of Faults in the Near Offshore of Central Coastal California (Including Hosgri Fault Near Diablo Canyon)."	R. Jackson (NRC Geosciences Branch)
05-24-84	Meeting in Los Angeles--ACRS Subcommittee for Diablo Canyon	ACRS Geology Consultants; NRC Geosciences Branch; PGandE and consultants; J. Crouch
06-14-84	Meeting in Washington, D.C. --ACRS	ACRS; NRC Geosciences Branch; PGandE and consultants; J. Crouch
06-20-84	Letter--ACRS report on Diablo Canyon Power Plant	Letters regarding May 24 meeting from ACRS Geology consultants B. M. Page, G. A. Thompson, and J. C. Maxwell
06-20-84	Field trip to Diablo Canyon and vicinity; review of Diablo Canyon site exploration data	NRC Geosciences Branch; PGandE and consultant

Table 3-1 (Continued)

Date	Meeting/Communication	Geoscience Participants/Authors
10-04-84	Meeting in Bethesda--NRC	NRC Geosciences Branch and consultants; PGandE and consultants
11-14-84	Letter--NRC Meeting with PGandE Seismic Reevaluation Program for Diablo Canyon. Attached letter from D. B. Slemmons to Dr. Steve Brocoum, Geosciences Branch	NRC Geosciences comments regarding PGandE program as discussed at October 4, 1984 meeting. Dr. Slemmons' comments regarding PGandE program as discussed at October 4, 1984 meeting
11-15-84	Meeting in Bethesda--NRC	NRC Geosciences Branch and consultants; PGandE and consultants
12-07-84	Letter--NRC meeting with PGandE on seismic reevaluation program for Diablo Canyon	NRC Geosciences Branch comments regarding PGandE program as discussed at November 15, 1984 meeting, with additional comments regarding October 4, 1984 meeting
01-10-85	Meeting in Bethesda--NRC	NRC Geosciences Branch and consultants; PGandE and consultants

3.2 BACKGROUND

The original geological evaluation of the DCPP site was established on the basis of detailed mapping, extensive trenching, and structural analysis performed by Dr. R. H. Jahns beginning in 1965 and documented by him in a series of reports docketed in the Diablo Canyon Units 1 and 2 PSAR and FSAR (Ref. 1). This work confirmed the absence of capable faults within the plant site and its immediate vicinity.

An initial study of the offshore region between the Estero Bay to San Luis Obispo Bay coastline and the Santa Lucia Bank region located some 30 miles west of the coastline was performed by the USGS in 1969. The results of this study provided one basis for the USGS testimony supporting the application by PGandE in 1970 for a construction permit for Diablo Canyon Unit 2.

The geology of the area around the site has been studied and mapped by several individuals at various times. The most detailed geologic map available was prepared by Dr. Clarence Hall and released in 1973 as USGS Map MF-511 (Ref. 2). This map was docketed with Appendix 2.5C to the Diablo Canyon Units 1 and 2 FSAR revision of 1974 (Ref. 3). Information demonstrating the absence of faulting or other deformation of the Quaternary marine and nonmarine deposits that overlie the uplifted terrace bench along the coast between Point Buchon and Point San Luis, at points north and south of the plant site, was acquired during studies by PGandE in 1973 and by the California Division of Mines and Geology (CDMG) in 1978.

A comprehensive review of the regional geology around the Diablo Canyon site was undertaken by PGandE in 1973, in connection with preparation of the project FSAR. This effort included a review of published sources as well as previous and then-current research, including investigations of offshore geology by Shell and other oil companies and by Dr. Eli Silver, then of Scripps Institute and the USGS. The initial submittal of the FSAR, in 1973, contained a map, cross-sections, and discussion of the zone of faulting a few miles offshore from Diablo Canyon. The information available at that time

chiefly derived from the 1971 article, "Hydrocarbon Potential of Northern and Central California Offshore," by Hoskins and Griffiths of Shell Oil Company (Ref. 4).

Subsequent to PGandE's filing of the Diablo Canyon FSAR in 1973, the NRC commissioned the USGS to make a survey of the offshore region along the central California Coast between Point Sal on the south and Cape San Martin on the north. This survey was carried out in late 1973 by the USGS research vessel George V. Kelez. In December 1973, PGandE commissioned surveys of the same offshore region extending north and south from the vicinity of Diablo Canyon. The latter surveys were accomplished using two marine geophysical contractors, BBN Geomarine Services, Inc. and Aquatronics, Inc., and were performed mainly during the first half of 1974. Data from the USGS and PGandE surveys were exchanged and two independent detailed interpretations of geology in the offshore region along the coastline were developed from the resulting combined set. The PGandE interpretation, with supporting data from both sets, was docketed in an amendment to the Diablo Canyon FSAR in 1974. The USGS interpretation, which was substantially the same as the one by PGandE, was released in 1974 as USGS Open File Report 74-252, "Marine Geology between Cape San Martin and Point Sal, South-central California Offshore," by H. C. Wagner (Ref. 5). The name Hosgri for the offshore fault zone was assigned in the latter report.

Additional investigations were requested by the NRC following its review of the submittals made in 1974. Topics of concern to the NRC that were specifically concerned with geology included:

- The maximum earthquake that can be expected on faults of various ranks within the San Andreas system.
- The nature of the southerly termination of the Hosgri Fault and its relationship to the Transverse Ranges.
- The relationship of the Hosgri Fault to the San Simeon Fault.

- o The geology of the source region of the 7.3M earthquake that occurred in the offshore region south of Diablo Canyon in 1927.

The investigations that responded to these requests included acquisition of new offshore geophysical data and gaining access to two extensive data sets acquired by the USGS in 1972 but not previously open filed. Additionally, several lines of high quality 5-second penetration multichannel (CDP) seismic reflection data were purchased from Western Geophysical Company. Most of these lines were located in the offshore region south of Point Sal, but one was located across the Hosgri Fault nearly opposite from Diablo Canyon. This enhanced data set provided the basis for another supplement [Appendix 2.5E (Ref. 6)] to the Diablo Canyon FSAR, which PGandE filed in 1975.

During 1975-1978, interpretations were developed by several individuals, notably Clarence Hall of UCLA, Steven Graham and William Dickinson of Stanford, and Eli Silver of UC Santa Cruz, which indicated that the Hosgri Fault was part of a major branch of the San Andreas fault system and that approximately 100 km of right lateral strike slip had occurred along the faults of this branch during Neogene Time. The basis for this interpretation lay chiefly with proposed correlations of various stratigraphic units found in isolated onshore outcrop areas thought to be on opposite sides of the fault trend. No additional offshore work was involved in development of the interpretation. Graham and Dickinson further proposed that the approximately 115 km of Neogene slip indicated in their interpretation accounted for part of the discrepancy in cumulative right lateral offset along the San Andreas fault between northern California, where some evidence indicates approximately 550 km of right slip since Cretaceous time, and southern California, where the evidence seems to preclude more than about 300 km of right slip since pre-Cretaceous time.

Interpretations and results of research by most geologists who had worked on problems of faults along the San Gregorio-Hosgri trend were presented in a symposium entitled, "San Gregorio-Hosgri Fault System--Implications for the Tectonic Development of the Central California Continental Margin," given

during the Geological Society of America (GSA) Cordilleran Section Meeting in 1977. Several of the papers from the symposium were subsequently published in CDMG Special Report 137 (Ref. 7).

By the time of the ASLB hearing for Diablo Canyon Units 1 and 2 in 1978, an additional, extensive set of geophysical data covering the offshore region opposite from, and north and south of, Diablo Canyon had become available and was purchased and interpreted by PGandE. This data set, consisting of 810 miles of high quality wave-equation migration processed multichannel (CDP) seismic reflection records, covered the region through which any southerly extension of the Hosgri Fault would have to pass. A modified interpretation of the geology of the offshore region between Point Sal and Point Arguello was presented with PGandE's prefiled direct testimony for the ASLB hearing. Another data set covering the southernmost part of the offshore Santa Maria Basin was acquired by Fugro Inc., working under contract to the USGS and PGandE. Results from this survey, which involved use of the towed high-resolution SONIA system, improved definition of both the southern end of the Hosgri fault and of the offshore Lompoc anticline. The latter structure had previously been identified by PGandE as the likely source of the 1927 Lompoc earthquake. PGandE's position that the Hosgri Fault system was not a major continuous strike slip branch within the San Andreas Fault system was challenged during the hearing by technical witnesses for intervenors, but was supported by the NRC witnesses and accepted by the ASLB.

Since 1978, several government-sponsored geophysical surveys have been made of parts of the offshore Santa Maria Basin. In 1979, R. Leslie of UC Santa Cruz, working under Eli Silver, acquired shallow high-resolution data for the offshore area between Point Estero and San Simeon Point. Leslie interpreted a data suite that included his own records and other previously available data as showing a direct join between the San Simeon and Hosgri faults. This interpretation was released as a USGS Open File Report (Ref. 8) and was used as one basis for a motion in 1980 by intervenors to have a reopened hearing on seismic issues; however, the interpretation was challenged by PGandE and was not accepted as an issue by the Appeal Board. Nonetheless, the interpretation

showing a connecting link between the San Simeon and Hosgri faults has been shown on several USGS maps of the region released since 1978.

In 1980, USGS Open File Report 80-229, "Seismotectonic Setting of Santa Barbara Channel Area, Southern California," (Ref. 9) was released. This report was centered around Point Conception at the west end of the Santa Barbara Channel, where a liquefied natural gas facility was proposed, but it also encompassed the southernmost part of the Santa Maria Basin and included discussion of the 1927 Lompoc earthquake. A reference to the USGS report in a 1980 NRC Staff affidavit responding to a motion by intervenors to reopen the Diablo Canyon hearing on seismic issues, led to a question by the ASLAB regarding the statement made in the Open File Report concerning the probable source of the 1927 earthquake. This statement--"...existing evidence suggests association of the 1927 (7.3M) Lompoc earthquake with an east dipping reverse fault such as the one near Santa Lucia Bank, the offshore Lompoc, or a similar fault 10 km to the south that offsets the sea floor."--reflected additional study of the source region of this event, and seemed to indicate a modification of the previous USGS view that the 1927 earthquake probably originated on the Hosgri Fault. This was further indicated in ASLAB testimony by the USGS regarding this issue.

The USGS has developed two independent fault and geohazards maps of the Santa Maria Basin since 1978. The first, prepared by McCulloch and others of the Marine Geology Branch was released as part of USGS Open File Report 80-1095 (Ref. 10). It incorporated data from a new set of single channel air gun seismic reflection lines across the basin and the Santa Lucia Bank area bordering it on the west, with previously available USGS data. The second, prepared by Richmond and Burdick of the USGS Conservation Division, was developed from a new set of single- and multi-channel seismic reflection records acquired in 1980 by Fairfield Industries, under contract with the USGS. The Richmond and Burdick map has been released as USGS Open File Report No. 81-318 (Ref. 11). The most recent offshore research by the USGS in the region of Diablo Canyon involved a survey of the newly designated Offshore Economic Zone using the GLORIA side scan sonar system. This survey provided

imagery of the deep ocean floor and extended far enough shoreward to include the Santa Lucia Bank fault. Preliminary results of this survey were presented at the 1984 GSA meeting in Reno (Ref. 12) and the fall 1984 American Geophysical Union (AGU) meeting in San Francisco (Ref. 13).

In addition to the USGS work, an extensive body of work has been done by and for the petroleum industry since 1978 in the offshore Santa Maria Basin, in connection with exploration for petroleum and assessment of geohazards that could affect petroleum development. The petroleum industry work has generally proceeded through a series of phases, as follows:

a. Pre-bid exploration, typically involving acquisition and study of a variety of data in order to assess petroleum discovery prospects in the region of a future lease sale. The study usually proceeds from a general review of the entire lease sale area to more detailed studies of sites considered to have significant potential for discovery and production of petroleum. The initial regional studies often involve use of purchased seismic data shot by a geophysical company on speculation or as part of a group-financed effort. More detailed coverage may then be acquired in areas of potential bidding interest as interpretations are tested and refined and as bids are prepared.

b. Following the lease sale, holders of lease blocks must have geohazards studies prepared, usually by an independent contractor, and approved by the USGS Minerals Management Service (MMS) prior to undertaking actual subsurface exploration. The geohazards study is performed according to specifications issued by the MMS. A specific study is required for each lease block, covering the entire block. A multi-sensor suite of data is acquired, including multi-channel CDP seismic reflection records to about 0.6 seconds depth. The data are interpreted and a report, with supporting data, is filed with the MMS. This material becomes part of the public record.

c. Following approval of the geohazards study and issuance of required

permits by the MMS, the operator of a lease block can begin drilling to test for the presence of hydrocarbons and, if any are found, determine their properties (API gravity, sulfur content, etc.), quantity, and reservoir characteristics. The drilling is done from a ship-mounted rig capable of operating in the maximum water depth in the area of interest (about 1,200 feet in the lease sale 53 area). Following a discovery, additional wells are usually drilled in order to define the limits of the producing zone(s) and determine reserves. Basic data from the wells, including lithologic and electric logs, must be filed with the MMS and the California State Division of Oil and Gas (DOG). Most of this information becomes public 2 years after it is filed. Information from many of the wells drilled in the lease sale 53 area will become public early in 1985.

Various aspects of faults along the San Gregorio-Hosgri trend have been studied since the Diablo Canyon ASLB hearing of 1978-79. Onshore regions traversed by the San Gregorio and San Simeon faults have been studied in varying levels of detail by Weber and Lajoie (Ref. 14), Weber and Cotton (Ref. 15), and Weber and others (Ref. 16). Slip rate along the San Andreas Fault south and north of its apparent junction with the San Gregorio Fault was investigated by Hall, Nelson, and Fowler (Ref. 17) and Cotton, Hall, and Hay (Ref. 18), respectively. The overall geology, history of displacement, and neotectonics of the San Gregorio-Hosgri trend have been described in papers by Hamilton and Willingham (Ref. 19) and Hamilton (Ref. 20). Clark and others (Ref. 21) described stratigraphic features along the trend of the San Gregorio Fault between Point Lobos (south of Monterey Bay) and Point Reyes, and proposed a movement history based on correlations between units exposed at various points along this trend. As noted in the following discussion for Task B, Minster and Jordan (Ref. 22), Crouch, et al. (Ref. 23), Bird and Rosenstock (Ref. 24), and Humphreys and Weldon (Ref. 25) all have recently described tectonic models that specify particular rates and directions of slip on faults of the overall San Gregorio-Hosgri trend. Clark and others (Ref. 21) have recently released a map with accompanying data tabulation (Ref. 26) that summarizes the results obtained from studies of Quaternary

fault slip at points along faults throughout California, including the San Gregorio and San Simeon Faults.

The setting and tectonics of coastal central California were discussed in articles by Page and by Hall in the volume, "The Geotectonic Development of California," (Ref. 27). Both articles accepted the concept of large-scale Neogene right slip along the San Gregorio-Hosgri trend of faulting. Hall's interpretation of the geotectonic development of the Santa Maria Basin involves an origin of the basin as a pull-apart structure in a fault system that transferred movement from the Hosgri to the Santa Ynez fault (first presented in Hall, 1977).

Since the 1978-79 ASLB hearings, other studies have been concerned with the geology of the Santa Barbara channel, Western Transverse Ranges, and Santa Maria-Santa Ynez onshore regions. Beginning in 1977, Dames and Moore carried out studies of a proposed liquefied natural gas facility at Point Conception (Ref. 28). Although most of the work was site-specific (including extensive study of post-terrace age bedding plane faulting at the site), an examination of the regional earthquake hazard to the site led to formulation of the concept of a Santa Ynez River Fault as an important geologic feature and component of the Santa Ynez Fault system [e.g., Sylvester and Darrow (Ref. 29)]. This feature corresponds in location, if not in tectonic function, to the Lompoc-Solvang Fault previously proposed by Hall (Ref. 30).

The Santa Ynez Fault itself was the subject of several recent studies (Refs. 31-34). The ESA and Dames and Moore studies included detailed mapping and trenching work to define the late Quaternary movement history and provide bases for estimating the earthquake potential of the Santa Ynez Fault and other faults in the region.

The results of research by several individuals and groups were presented in a symposium entitled, "Neotectonics of the Western Transverse Ranges," held during the 1982 Cordilleran Section Meeting of the GSA (Ref. 35). More recently, an interpretation of the structure associated with the Santa Ynez

River fault, based on gravity data, was presented (in abstract only) by Up de Graff (Ref. 36).

The foregoing review of studies relevant to the problem of characterizing the geologic setting of the Diablo Canyon site is presented as background for an introduction to the program of geologic investigations in support of the Diablo Canyon LTSP. The Geologic Investigation is organized into three main Tasks, as follows:

- o Task A - site and regional data collection, processing, and interpretation
- o Task B - evaluation of tectonic model
- o Task C - seismic source characterization

Each of the three tasks is discussed, and presented as a detailed outline of work items, in the following sections. It should be noted that, while work on some aspects of the tasks must be carried out sequentially, some will be done concurrently and the objectives of the overall LTSP will be kept in mind throughout the performance of the program.

3.3 SITE AND REGIONAL DATA COLLECTION, PROCESSING, AND INTERPRETATION

The general objective of this Task is the fulfillment of the overall charge to PGandE in License Condition 2.C.(7).(1). A program has been developed that will provide the most current data base for characterizing the regional setting of the site and of all seismogenic tectonic features that may be relevant to an evaluation of the seismic hazard at the site. This effectively requires study of a region encompassing a considerable part of south-central California and extending from the offshore continental slope on the west to the Basin and Ranges province on the east. Focal elements of progressively broader scope in this study are:

- The Hosgri Fault
- The neotectonics of the Santa Maria Basin region
- The relationship and neotectonics of the southern Coast Ranges structures to those of the western Transverse Ranges
- The distribution of strain within the boundary between the Pacific and North American plates, especially around the latitude of south-central California

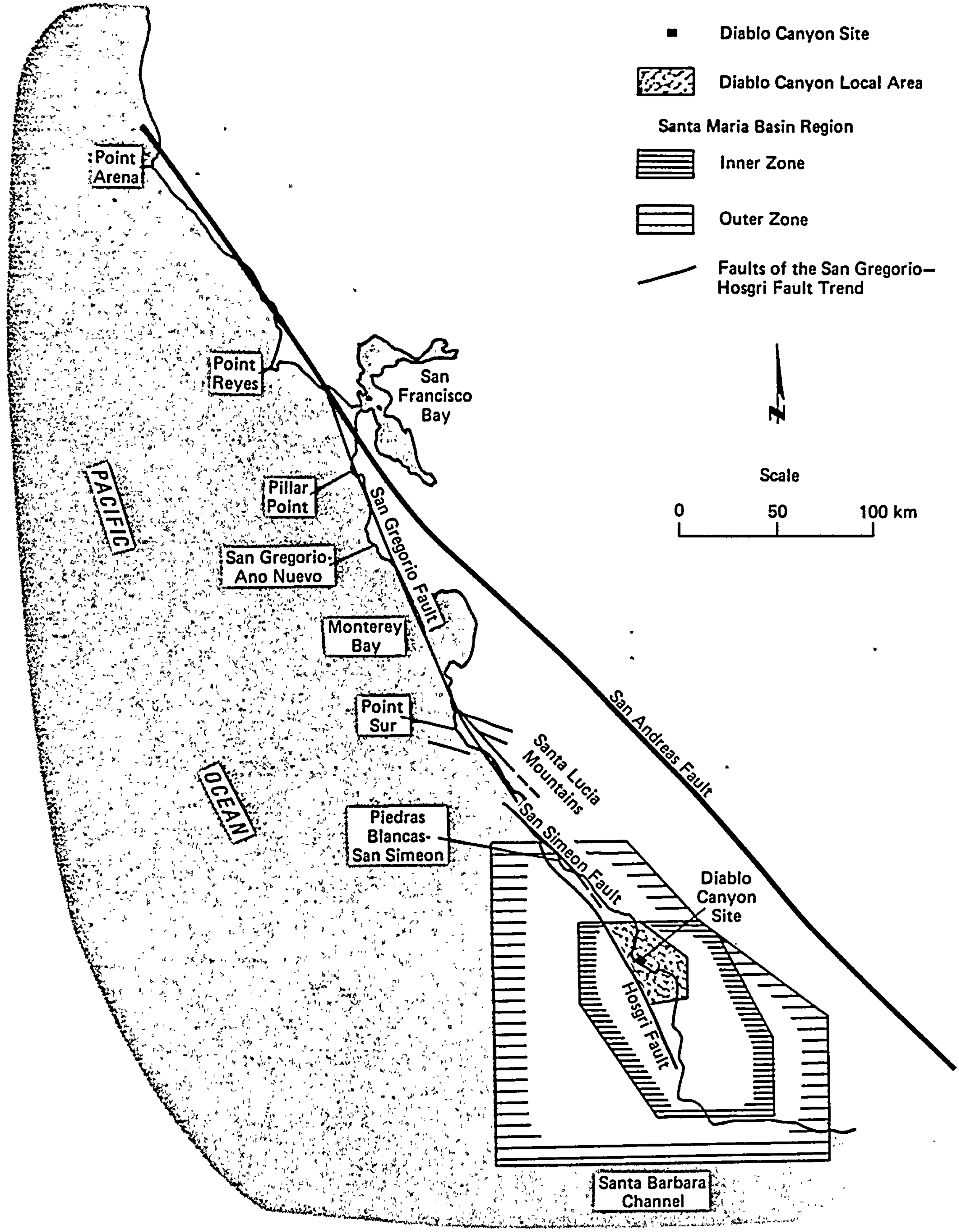
In order to facilitate the conduct of the proposed study, it has been organized into five geographic zones, as follows:

- Site
- Local area
- Santa Maria Basin region (onshore and offshore)
- San Gregorio-Hosgri Fault trend
- Pacific-North American Plate boundary (continental slope offshore to Basin and Range province) only for the purposes of the tectonic model

The first four zones are shown on Figure 3.3-1. The fifth is shown generally on Figure 3.3-2.

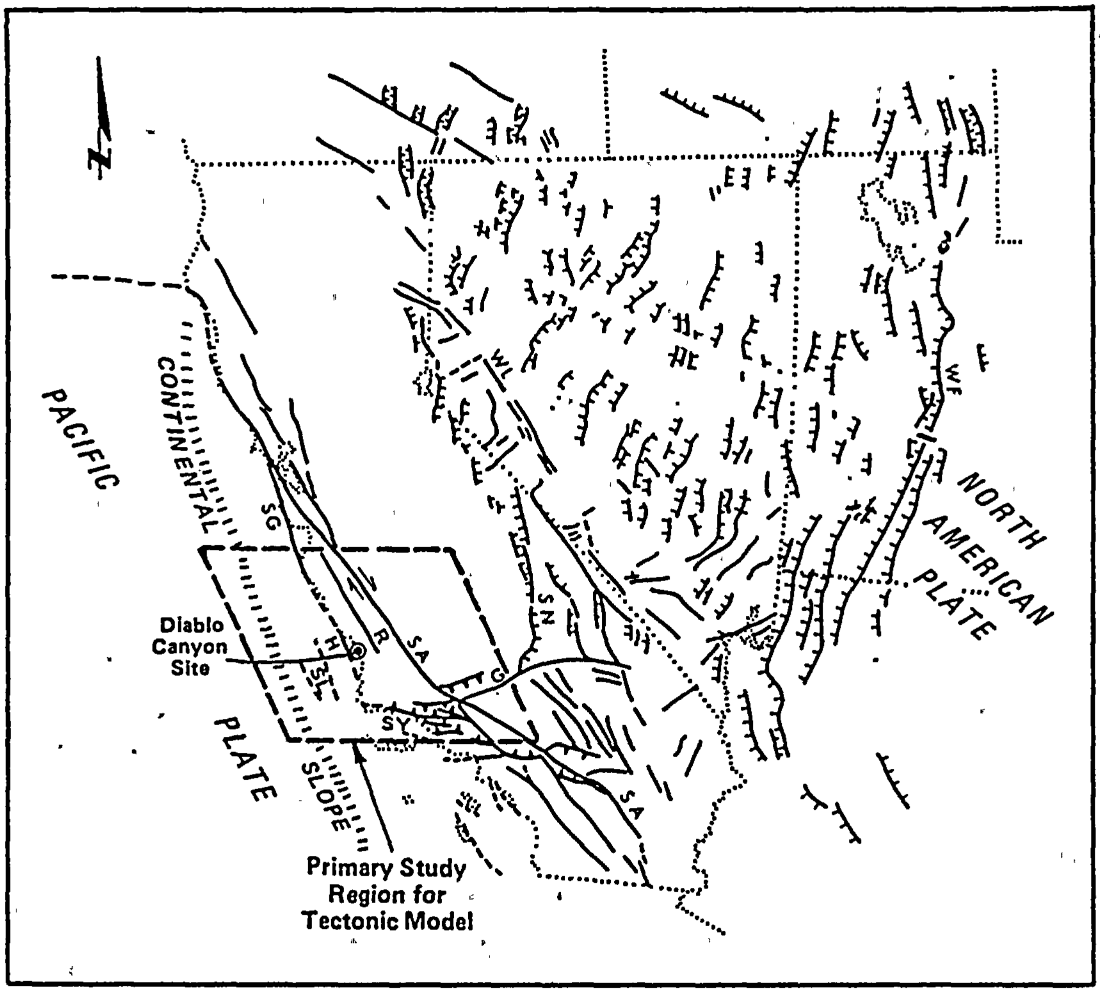
Considerations that were regarded as having special importance in the formulation of the Task A Program were the following:

- The assessment of seismic hazard to Diablo Canyon is presently understood to depend chiefly on the understanding of the seismic capability of the Hosgri Fault, including its neotectonic behavior, geometry near the site, and place in the regional tectonic setting.



AREAS FOR GEOLOGIC INVESTIGATIONS

Figure 3.3-1



Map Showing Major Quaternary Faults
within the Pacific - North American
Plate Boundary Region
(modified from Minster
and Jordan, 1984)

SL – Santa Lucia Bank
SG – San Gregorio
H – Hosgri
R – Rinconada
SY – Santa Ynez

SA – San Andreas
G – Garlock
SN – Sierra Nevada
WL – Walker Lane
WF – Wasatch Front

- An understanding of the Hosgri Fault can be achieved only in the context of an understanding of the geology and neotectonic history of the Santa Maria Basin region, and the latter understanding is, in turn, necessary for understanding the overall tectonic model operative in the region.

- Understanding of the Hosgri Fault will also require resolution of ambiguities and conflicting theories regarding the overall San Gregorio-Hosgri Fault trend.

With these considerations in view, it was noted that since the time of the 1979 Diablo Canyon ASLB hearings, no overall study of either the Hosgri Fault or the Santa Maria Basin region, based on current data (especially petroleum industry seismic and drilling data), has been published. For this reason, major elements of the Task A program involve acquisition and interpretation of a comprehensive selection of such data, rather than reliance on previous interpretations.

The sub-items that comprise Task A, are identified in the outline below. The areas to be investigated are shown on Figure 3.3-1.

1. Identify, examine, and evaluate all existing relevant (offshore and onshore) geologic, geophysical, geodetic, and remote sensing data, information, and interpretations.

   Five subsets of data, information, and interpretations will be reviewed.

The subsets involve progressively widening areas of coverage extending away from the Diablo Canyon site. They are:

- Site

- Local area

- Santa Maria Basin region (onshore and offshore)

- San Gregorio-Hosgri Fault trend
- Pacific-North American Plate boundary (continental slope offshore to Basin and Range province) for tectonic model

2. Obtain geologic, geophysical, geodetic, and remote sensing data necessary to supplement the existing data base.

   a. Required data will be obtained by means including the following:

      - Purchase
      - Exchange
      - Research of published material
      - Research of unpublished available data
      - New surveys and programs carried out in support of the LTSP

   b. Types of data to be reviewed, acquired, and interpreted include the following:

      - Multichannel deep seismic
      - Shallow high resolution seismic
      - Side scan sonar (including GLORIA system)
      - Fathometer
      - Refraction
      - Deep well

- o Shallow well (e.g., water wells) and borehole
- o Gravity
- o Magnetic
- o Remote sensing including conventional, false color infra red, and low sun angle aerial photography
- o Geodetic
- o Surface and subsurface geologic
- o Soil
- o Paleontologic
- o Paleomagnetic
- o State of stress
- o Heat flow
- o Geohydrologic
- o Topographic/bathymetric

3. Process geophysical and other data of items 1. and 2. above, by application of current techniques as necessary:

   a. Processing of multichannel deep seismic data will be designed for optimization of events of special interest. Defining fault planes within and splaying from the central part of the Hosgri Fault zone, and tracing such faults' down dip, will be a prime objective of such

processing. Other prime objectives will include identifying fault surfaces within and beneath folds, and identifying faults lying along or at a low angle to bedding.

b. Areas of consideration in seismic data processing may include velocity analysis, statics corrections, deconvolution/wavelet recovery, suppression of multiples, and filtering parameters. Other factors and techniques applicable in processing multichannel seismic data will be considered when appropriate.

c. Extended recorrelation of onshore multichannel deep seismic data will be employed to increase the time section to at least mid-crustal depth, in order to search for evidence suggestive of decollement structures beneath the Santa Maria Basin.

d. Processing to facilitate interpretation of other data will be undertaken as necessary (e.g., computer enhancement of digitized remote sensing imagery).

4. Interpret data to establish geologic conditions for areas of interest in characterizing the local and regional geologic setting of Diablo Canyon. Specific programs of interpretation will be undertaken for the following: site area; local area; Santa Maria Basin region; and San Gregorio-Hosgri Fault trend. These areas are shown on Figure 3.3-1, and elements of the program of interpretation for each area are outlined below.

a. Site area

o Review sea cliff exposures along the site shoreline, noting specifically any microstructures indicative of tectonic transport, and relationships of deformation to volcanic intrusive bodies.

- o Compile and integrate relevant surface and subsurface geologic data for the site; present data at suitable scale in map and cross-section form.

- o Analyze bedrock structural data to assess the pattern of post-Miocene deformation at site, and to provide a basis for relating this pattern to larger scale local and regional structures.

- o Develop map and cross-sections showing marine terrace wave-cut bench surfaces, shoreline angles, and distribution of terrace deposits, to the extent permitted by available and accessible data. The results will be used for comparison and correlation with data for marine terraces extending along the coastline north and south of the site and located elsewhere along the coastline of central California.

b. Local area

(1) <u>Onshore</u>

- o Review geologic mapping by different workers; compare recorded data and stratigraphic/structural interpretations, including evidence of unconformities.

- o Perform field mapping as needed to resolve discrepancies, fill gaps, and record data on microstructures.

- o Study Edna and San Miguelito Fault zones, noting especially any evidence indicating fault geometry and style, history, and recency of movement.

- o Study subsurface geology by means of oil well, water well, and any other available borehole logs, and the multichannel deep seismic lines in the Santa Maria Valley Region.

- Review the structural style and history of deformation of the San Luis Range-Pismo synclinorium on the basis of macro and micro structures, including deformed unconformities.

- Evaluate evidence for the rapid variations in thickness of stratigraphic units shown in the cross-sections presented by Hall (Ref. 2). Attempt construction of balanced cross-sections through the synclinorium.

- Study the marine terrace extending southward from the site; integrate results with terrace data from the site and from CDMG Open File Report OFR 78-17 LA by George Cleveland (Ref. 37), and other data relating to the terrace extending northward from the site toward Morro Bay. Evaluate results for evidence of post-terrace age deformation in the local area.

- Develop bases in local sampling and age dating or correlation with age-dated terraces elsewhere by soil stratigraphy or other means, for establishing the age of at least the main marine terrace surfaces in the local area.

(2) <u>Offshore</u>

- Review interpretation of complete integrated set of relevant geophysical, bathymetric, and sampling data, for area between the Hosgri Fault zone and the landward-most extent of data between the south half of Estero Bay and San Luis Obispo Bay. Review and reinterpretation will be concerned with both bedrock and Quaternary geology, including bedrock stratigraphy and structure, sequence and distribution of Quaternary deposits, sea floor morphology (especially submerged terrace escarpments and any morphologically expressed folding or warping), and, in

particular, relationships among these features that could indicate Quaternary tectonism.

- o If the above review and reinterpretation indicates a necessity, conduct new multisensor survey including side scan sonar, which would extend as close as feasible, accounting for navigation hazards and kelp beds, to the shoreline; integrate results into above reinterpretation.

(3) Offshore-Onshore Transition

- o Compare offshore map data from local area (Task 4.b.) offshore program with surface and subsurface stratigraphic and structural data from local area onshore program to establish relationship between stratigraphic units and structural features recognized in the two adjacent environments. The relationship between offshore and onshore features will be tested along the coastline extending from Morro Bay past Diablo Canyon to Avila Bay, and from Avila Bay south across the north half of the Santa Maria Valley coastline. The subsurface in the latter onshore area will have been studied through integrated interpretation of well logs and deep seismic lines.

- o Evaluate continuity of anomaly patterns indicated in airborne magnetic and gravity data extending across the offshore-onshore interface.

- o Evaluate results of the onshore, offshore, and offshore-onshore local area programs especially for indications of thrust faulting, which could be represented by listric down dip flattening of the Hosgri Fault and/or by imbrication within the ground east of the Hosgri. Criteria to be used may include, but will not be limited to, the following:

- Outcrop or intercept of low angle fault
- Reversal of age sequence in stratigraphic section
- Repetition of lithology of down hole E-log signatures
- Anomalous thickness of section
- Evidence for crustal shortening without adequate fold or reverse fault geometry to balance cross-sections
- Asymmetry of anticlinal folds
- Disharmonic structure with more deformed over less deformed
- Structural back-tilting of upthrown fault block, indicating listric form of fault
- Irregular and especially sinuous or curving and discontinuous trace of fault and form of any associated scarps
- Direct representation in seismic reflection records
- Character of potential field (gravity and magnetic) anomaly

c. Santa Maria Basin region

Inner zone, offshore (area of OCS Lease Sales 53 and 73; petroleum exploration and development region, extending shoreward into 3-mile limit; includes central and southern part of Hosgri Fault):

(1) Regional offshore basin study

- o Potential field studies:

  - Integrate available potential field data into unified interpretation; continue all data downward or upward to same datum; check for internal consistency and mis-ties; create gravity and magnetic maps.

  - Invert model data to bring potential field interpretations into conformance with seismic data interpretations.

- o Seismic reflection data interpretation:

  - Interpret new suite of deep (6 sec) and intermediate (1-2 sec) seismic reflection records, using available well ties to establish stratigraphic control; identify structural features and trends; develop structural contour maps for two horizons throughout study area; derive isochron and/or isochore maps between contoured horizons.

  - Interpret combined suite of relevant high-resolution data to define shallow depth and sea floor surface expression of structural and stratigraphic features; integrate any available shallow sampling data.

  - Integrate potential field, deep-intermediate seismic, and shallow-surface seismic maps; identify potentially seismogenic tectonic features for consideration and further study in Tasks B and C.

(2) Hosgri Fault Study

- o Process multichannel seismic lines crossing the fault zone to optimize data for delineation of fault planes and fault-related deformation.

- o Interpret deep and intermediate seismic lines to establish structure of the fault zone to the maximum depth permitted.

- o Perform potential field modeling studies to establish correlation between gravity and magnetic expression and seismic reflection expression of the fault zone.

- o Interpret combined suite of all high-resolution seismic and bathymetric data in order to define any shallow subsurface and surface expression of the fault zone.

- o Correlate any earthquake epicentral, hypocentral, focal mechanism, isoseismal, coseismic geodetic, and tsunami data with structural data from seismic and potential field data.

- o Relate interpretation of fault geometry to data regarding geometry of other faults in the region and to results of onshore deep crustal seismic study.

(3) Inner zone, onshore

Subsurface interpretation:

- o Well log study--Tie all available logs of onshore wells into cross-sections within a fence diagram; review logs especially for evidence indicative of thrust faulting.

- o Conventional seismic study--Interpret several multichannel

deep seismic lines crossing the major structural trends and basins in the area to confirm existence and establish subsurface form of faults and folds at least within the Neogene section; identify seismostratigraphic units through ties to wells.

- Potential field study--Perform modeling study of available potential field data; correlate resulting interpretation of geologic structure with results of well log and seismic studies.

- Deep crustal seismic study--Interpret deep seismic lines that have been subjected to extended recorrelation processing (to yield COCORP-equivalent time-depth section); determine whether patterns of reflecting events that could be indicative of near-horizontal decollement structures can be identified at intermediate crustal depths (approximately 5-15 km); compare crustal model indicated by deep seismic study with models that accord with potential field data.

(4) Inner and outer zone, onshore

Surface interpretation:

- Remote sensing and aerial photograph study of region, noting especially:

  - Geomorphic expression of faults and associated tectonic features.

  - Geomorphic anomalies suggestive of local folding, warping, uplift, or subsidence.

- Review of available mapping data.

- o Reconnaissance checking and mapping to understand and confirm interpretations or fill gaps.

- o Local detailed mapping, section measurements, and sampling.

- o Limited shallow subsurface studies to determine sense and orientation, recency, and recurrence characteristics of fault slip, and rate of movement at selected locations.

Marine and river terrace study:

- o Review and check mapping and available age-dating studies; identify areas of possible significance for studying late Quaternary tectonism.

- o Study relationship of terrace surfaces and deposits to possibly young tectonic features.

(5) <u>Inner Zone, Offshore-Onshore Transition</u>

- o Extend offshore-onshore program from Task 4.b. to include entire Task 4.c. offshore-onshore interface.

- o Acquire and review any relevant data from offshore-onshore studies by others done in support of applications for oil delivery pipelines from offshore wells to onshore facilities or similar projects.

(6) <u>Outer Zone, Offshore</u>

- o Santa Lucia Bank-Continental Slope:

  - Interpret open-filed seismic data to establish fault and structural pattern and fault structural characteristics;

compare with surface pattern indicated in GLORIA side scan sonar images.

- Interpret available gravity and magnetic data for region; model data to test postulated structure beneath the continental slope and its possible relationship to faults of the Santa Lucia Bank system.

- Integrate earthquake epicentral, hypocentral, and focal mechanism data into interpreted structural and local tectonic model.

o Northern Offshore Santa Maria Basin, including northern Hosgri Fault and central and southern San Simeon Fault:

  - Extend interpretation of offshore Santa Maria Basin inner zone, as based on multichannel deep and intermediate seismic data, with well ties, shallow high-resolution seismic data, and potential field data, northward to limit of study region using available multichannel and single-channel seismic coverage and potential field data.

  - Interpret subsurface goemetry of, and structural relationship between, Hosgri and San Simeon Faults, using available intermediate depth multichannel seismic data and modeling of gravity and magnetic data, supplemented by reinterpretation of integrated set of single-channel, high-resolution seismic data covering the zone between these faults; also consider any available earthquake epicenter, hypocenter, and focal mechanism data. Evidence for late Quaternary surface displacements along the northern Hosgri and San Simeon faults will be sought in high-resolution shallow records.

d. San Gregorio-Hosgri Fault trend studies

(1) <u>Onshore</u>

o Review relevant geologic studies, mapping data, geophysical data, subsurface data, geodetic data, and remote sensing data for onshore areas along the San Gregorio-Hosgri Fault trend (Pillar Point, San Gregorio-Ano Nuevo, Point Sur, and Piedras Blancas-San Simeon Point). Review and reinterpretation will be concerned with both bedrock (stratigraphy and structure) and Quaternary geology. Particular aspects of the review will emphasize:

- Structural form of both principal faults within the zone, and related subsidiary faults.

- Pattern of fault traces indicating degree of continuity of faulting at the present level of exposure.

- Stratigraphic units that may be correlatable from place to place to provide indications of or constraints to cumulative fault slip over various increments of time.

- Late Quaternary features and relationships that may provide evidence of sense and rate of slip or of other related deformation such as warping or folding. Relationships of fault and fold features to uplifted marine terrace surfaces and deposits are recognized as being especially important in such studies. Age dating of terraces in each of the onshore areas will be reviewed and, if necessary, efforts will be made to improve or add to existing data. Both absolute dating and dating relative to rate of uplift vs. chronology of glacioeustatic changes in sea level will be attempted.

- Paleoseismic evidence of specific episodes of fault displacement.

- o Review geologic studies as above for inland regions adjacent to the San Gregorio-Hosgri Fault trend which may play a role in distribution of deformation associated with faults of the trend. The Santa Lucia Mountains within the southern Coast Ranges are recognized as a prime objective, since Compton (Ref. 38) has documented extensive compressional deformation there, Dibblee (Ref. 39) has proposed this deformation as a mechanism for transfer of right lateral strain between the San Gregorio and Rinconada Faults, and Hamilton (Ref. 20) has mapped splays from the south end of the San Gregorio Fault that extend into the northern Santa Lucias. The role of evident rapid late Quaternary uplift of the Santa Lucia Mountains opposite the San Simeon Fault in the tectonics of the San Gregorio-Hosgri Fault trend, will also be examined.

- o Review stratigraphic studies from onshore regions adjacent to the reach of the San Andreas Fault north of its apparent junction with the San Gregorio Fault (especially west of the fault, i.e., Point Reyes, Bodega Head, Fort Ross-Gualala-Point Arena regions) for evidence proposed as indicative of various amounts of cumulative lateral slip through various increments of time.

- o Review any available studies of late Quaternary rate of slip (including geodetic data) along the San Andreas Fault at points south and north of its apparent junction with the San Gregorio in order to determine whether there is evidence of a significant contribution of right slip by the San Gregorio Fault to the combined fault system.

- Review the pattern of structural deformation and geomorphic uplift in the vicinity of the apparent junction of the San Andreas and San Gregorio Faults, in order to evaluate whether there is evidence of merging or interference of two right slip faults undergoing roughly similar rates of slip [as shown, for example, in the vicinity of the convergence of the San Jacinto and San Andreas Faults (Ref. 40)].

(2) Offshore

- Review available studies and non-proprietary geophysical data (shallow and deep seismic reflection, aeromagnetic, gravity) covering offshore reaches of the San Gregorio-Hosgri Fault trend from Ragged Point (north of the Santa Maria Basin offshore study area) northward to Bolinas Bay; interpret data to develop a map of the offshore parts of the fault trend and determine the dip of faults within the trend wherever possible.

- Review available evidence of sea floor fault zone morphology and late Quaternary landform and stratigraphic relationships along the zone, in order to determine extent, sense, orientation, and rate of late Quaternary age movements of faults within the trend.

(3) Overall

- Compile available seismicity studies and historical and instrumentally-recorded seismicity data, including hypocentral depth and focal mechanism determinations for the coastal region along and adjacent to the trend; correlate data with fault data to the extent possible in order to determine pattern of contemporary stress relief through seismic activity along the zone.

5. Identify potential seismic source features according to criteria discussed under Task C below.

3.4 EVALUATION OF TECTONIC MODEL

The Task A program of geologic and geophysical data acquisition, processing, and interpretation outlined above is designed to identify the existing body of data, interpretation, and theory, and supplement this as necessary to allow development of a generally applicable tectonic model for the region.

Various and diverse tectonic models that might bear upon the identification and evaluation of potential seismic sources near Diablo Canyon have been proposed over the last three decades. Among the first unified tectonic models proposed for the central California region was that for the San Andreas Fault system developed by Hill and Dibblee (Ref. 41). This showed the San Andreas right lateral fault, and Garlock and Big Pine left lateral faults, as principal shears within a conjugate strain system responding to regional north-south oriented horizontal compression. Dibblee (Ref. 39) subsequently described a history of right lateral slip along the Rinconada Fault, within the southern Coast Ranges, and indicated a tectonic model for transfer of right lateral strain from the San Gregorio Fault to the Rinconada Fault.

Several papers presented in the early 1970s applied concepts of the (then) recently formulated theory of plate tectonics to the origin and movement history of the San Andreas Fault. Atwater (Ref. 42) and Atwater and Molnar (Ref. 43) showed how progressive change from a subduction to a transform boundary occurred as the Farallon plate and spreading ridge was obliquely subducted beneath the North American Plate, resulting in the establishment of the San Andreas Fault. Silver (Ref. 44) described the relationship of the San Andreas transform fault to the Mendocino triple junction, and Larson et al. (Ref. 45) and Moore and Buffington (Ref. 46) showed how multiple transform offsets of the East Pacific Rise spreading ridge north of the Rivera triple junction resulted in the opening of the Gulf of California about 5 million years ago and in consequent acceleration in rate of slip along the San Andreas

Fault. A recent addition to knowledge about the timing of the opening of the Gulf of California is given in Curray and Moore (Ref. 47).

In 1973, Davis and Burchfiel (Ref. 48) characterized the Garlock Fault as an intracontinental transform which separated ground on the north that was being pushed west by an expanding Basin and Ranges, from a relatively stable Mojave Desert block on the south. The Davis and Burchfiel tectonic model corresponded generally to one presented in PGandE's 1975 FSAR Appendix 2.5E (Ref. 6) supplement, in the section entitled, "2.17--Discussion and Arguments for Determining the Maximum Earthquake That Can be Expected on Faults of Various Ranks Within the Southern Coast Ranges Province of the San Andreas System." In 1979, Greenhaus and Cox (Ref. 49) reported the results of their paleomagnetic study of middle Miocene intrusive volcanic rocks of the Morro Rock-Islay Hill complex in the Los Osos and San Luis Obispo Valleys. They suggested that the indicated clockwise rotation of 27 to 76 degrees of these rocks could have occurred as rotation within a right lateral shear strain system. Paleomagnetic evidence of even larger clockwise rotation in the Western Transverse Ranges and Channel Islands, together with the concept of large-scale right slip on faults north of the Transverse Ranges such as the Hosgri and Rinconada Faults, was interpreted by Luyendyk and others (Ref. 50) as explainable in terms of the deforming plate made up of sliding blocks. Crouch (Ref. 51) presented evidence for northward migration and subsequent rotation and emplacement of the terrain now represented as the Western Transverse Ranges. Another tectonic model, which was illustrated by a deforming plate made up of hexagonal elements, was described in Hill (Ref. 52).

A series of modeling studies of relative movement along faults in central and southern California performed by Bird and his colleagues was described in articles beginning in 1980 (Refs. 53 and 54). Their most recent paper (Ref. 24) presents a kinematic model for regional deformation that includes an attempt at reconciling the rate of slip assigned to the Hosgri Fault in a majority of published reports, with observed consequent deformation in the Western Transverse Ranges. They conclude that the indicated (majority opinion) slip rate on the Hosgri Fault produces about three times the level of deformation that can be observed in the Western Transverse Ranges.

Humphreys and Weldon (Ref. 25), however, have recently described a tectonic model in which coastal faults, identified as those of the San Gregorio-Hosgri trend in central California and as probably including the Newport-Inglewood, Palos Verdes, and San Clemente faults in southern California, define a mini-plate boundary, along which they consider nearly all Pacific-North American relative plate motion not represented in the 35 mm/yr movement of the central part of the San Andreas Fault zone to occur. Using the Minster and Jordan (Ref. 55) RM-2 value of 56 mm/yr for the total interplate relative motion, Humpreys and Weldon thus assign approximately 20 mm/yr right slip to the coastal faults, with the locus of movement stepping east from north to south at the Transverse Ranges, and being accommodated there by north-south compression across the Ventura basin. The Humpreys and Weldon interpretation employs only latest Quaternary slip values and so, if valid, would indicate a contemporary high rate of right slip--nearly two-thirds that of the rate on the San Andreas itself north of the Big Bend--on the Hosgri Fault.

Analyses of past and present plate motion in the region that includes coastal central California have been made by Minster and Jordan (Refs. 22, 55, and 56) and by Engebretson and various coworkers (Refs. 57-59). Minster and Jordan (Ref. 55) determined rate and direction of instantaneous plate motion for plates and relative motion along plate boundaries worldwide. Their results led them to note in 1980 (Ref. 56) that in central California the azimuth of relative movement along the plate boundary is closer to the strike of the San Gregorio Fault than that of the San Andreas Fault where the two are adjacent, and that the apparent deficit in rate of slip on faults of the recognized main San Andreas Fault zone, therefore, could well be accounted for by a relatively high rate of slip on the San Gregorio. In 1984 (Ref. 22), they presented the results of an analysis of vectors and rates of slip along a traverse that extended from the central California coast to the east edge of the Basin and Ranges province. These results, when compared with their previous RM-2 value of 56 mm/yr relative movement between the Pacific and North American plates, led to their concluding again that a significant fraction of the total RM-2 value, which they estimated as 6-25 mm/yr, was occurring on faults west of the San Andreas. They further indicated that the deviation in azimuth of the

central San Andreas trend from the plate boundary azimuth predicted by their model should result in there being a significant component of compression normal to the fault trend as well as strike slip along it.

Engebretson (Ref. 57) analyzed plate motions along the northeast Pacific margin back in time to the Mesozoic Period. He showed that changes in rate and azimuth of plate motion had occurred in this region at various times, most recently at a time within the last 2-5 million years. This latest change, as identified by Cox and Engebretson (Ref. 59), apparently coincided with an upsurge of compressional and strike slip tectonism along the central Pacifc North American plate boundary, as described in Page and Engebretson (Ref. 58) and as noted by Stein (Ref. 60).

In 1978, Hadley and Kanamori (Ref. 61) analyzed crustal velocities in the region of the Transverse Ranges and San Andreas Big Bend. Their results, showing horizontal layers of contrasting velocity that seemed to pass beneath the San Andreas and Garlock Faults without interruption, to end along a north-northwest trend beneath the Mojave Desert, when taken with data from several earthquake focal mechanisms from south and west of the 1971 San Fernando aftershock zone that showed anomalously deep, low-dipping sources, led them to conclude that some form of subregional detachment structure must exist in central California. Their data and ideas were subsequently used in tectonic model analyses by Yeats (Ref. 62) and Crouch et al., (Ref. 23), among others.

Yeats (Ref. 62) interpreted the regional relationships of the Western Transverse Ranges to the terrain to the north and south in terms of what he called flake tectonics, wherein he regards the Transverse Ranges as a broad wedge that is being thrust out over the bordering regions. Crouch et al. (Ref. 23) present an interpretation of decollement tectonics applied to the southern Coast Ranges as well as, apparently, the Western Transverse Ranges. They call upon decollement along an approximately 10-km deep aseismic detachment zone, occurring in response to the east-west compression predicted by Minster and Jordan (Ref. 22), as the tectonic model operative in the region

of the Hosgri Fault and other structural features lying west of the central reach of the San Andreas. To support this interpretation, they cite Hadley and Kanamori, Minster, and Jordan, many previous studies of geologic structures throughout the southern Coast Ranges, and their own interpretation of seismic reflection records across the Hosgri Fault which show it as an east-dipping listric thrust. From this, they conclude "...that suggested late Cenozoic right-slip offsets on northwest-trending faults in onshore and offshore central California may be overstated and that late Cenozoic basin morphology in central California may be due largely to compression rather than exclusively to wrench-style tectonics." In fact, the interpretations of the Hosgri Fault they have shown would seem, if valid, to structurally and stratigraphically preclude more than a kilometer or so of either right slip or thrust movement having occurred along it since Upper Miocene time.

In addition to the studies cited above, and many others that are less directly pertinent, other work that is relevant to understanding the tectonic model and fault behavior in the Diablo Canyon region is currently under way.

New articles are published nearly every month (Refs. 63-67). Meetings of societies devoted to any of several branches of the geosciences can be expected to contribute richly to the flood of information (e.g., AAPG-SEPM San Diego, 1984; GSA Reno, 1984; and AGU San Francisco, 1984). Presentations as diverse as studies of the mechanics and kinematics of both overthrust and strike slip faulting, reconstruction of plate movements opposite western North America, tomographic representations of the crustal velocity structure beneath the Transverse Ranges and southern California, studies of crustal extension and fault slip in the Basin and Ranges province, structural cross-sections based on oil well logs in the Ventura Basin, and imagery of the continental slope and deep ocean floor from the GLORIA system, have been featured at the meetings mentioned above during 1984.

Some of the information and the interpretations seem contradictory (e.g., Crouch et al., thrust faulting along the coast vs. Humphreys and Weldon, strike slip faulting in the same place) but none can be ignored and all may

contribute to the understanding of the geology of the region around Diablo Canyon and the tectonic model that describes and predicts the dynamics of structural deformation there.

The final step in the tectonic model evaluation subtask is the screening of structural features located within reasonable distances of Diablo Canyon to identify those which could represent seismic sources relevant to assessing seismic risk at the site. Available data suggests that such sources will, at minimum, include the Hosgri Fault, at least two large fold structures that deform the sea floor within the offshore Santa Maria Basin, the Santa Lucia Bank System of faults, several of the largest faults in the Southern Coast Ranges and Western Transverse Ranges, and the central reach of the San Andreas Fault.

The sub-items that comprise Task B are identified in the annotated outline below.

1. Assess and synthesize relevant data relating to structure/tectonics from each of the five geographic/geologic study areas: site, local area, Santa Maria Basin, San Gregorio-Hosgri trend (Figure 3.3-1), and that part of the Pacific-North American plate boundary which influences the tectonic behavior of south central California (Figure 3.3-2) fault and fold orientations, style of faulting and folding, complexity of faulting, rate of deformation, epicentral locations and focal mechanisms of earthquakes, state of stress measurements, heat flow data, geodetic data, studies of the lower crust and mantle, and apparent relationship to plate boundaries and interplate motion (including data relating to extensional and strike slip deformation in the Basin and Ranges province).

   o Identify and fill (within the scope of Task A) gaps in the existing structural/tectonic data that might be critical for evaluating existing tectonic models and/or constructing new models.

   o Prepare a first approximation tectonic model for the region surrounding Diablo Canyon.

2. Analyze and evaluate existing proposed tectonic models that relate to each of the five geographic/geologic study areas, particularly as these models identify and characterize any potential seismic sources that could be capable of producing strong ground motion at the Diablo Canyon site. Establish degrees of confidence for the various models or parts of models based upon their congruence with the data synthesized in this investigation (Task B.1.).

   Focus in particular upon determining the nature and slip history of the Hosgri Fault. Existing tectonic models variously postulate that the Hosgri Fault exhibits behavior ranging all the way from dextral strike-slip movement as one end member to regional low angle thrust movement as the other extreme.

3. Using the refined data set and the analysis of existing tectonic models, choose and/or construct refined model(s) that best characterize the tectonic regime of the region pertinent to the Diablo Canyon site. It is anticipated that the model(s) will focus upon tectonic behavior and patterns for different time intervals as, for example, the late Quaternary (the neotectonic regime) and for several intervals during the Tertiary. Relict structures will be identified and characterized. Models will also be developed at various scales ranging from the local structural domain that encloses the Diablo Canyon site to the regional plate boundary scale.

4. Using the refined tectonic model(s):

   o Make regional assessment of fault and fold orientations: style, length, and complexity of faulting, relationship of folds to faults, and rate and pattern of late Quaternary deformation as represented in the model to identify and characterize potential seismic source features important to Diablo Canyon.

   o Separate, on the basis of age and orientation, relict structures

(folds, faults, and intrusive bodies) that were created during previous stress regimes from those formed or likely to be active during the present regime.

5. Evaluate the predictive capability of tectonic model(s) generated during this investigation to aid in analyzing seismotectonic conditions relevant to Diablo Canyon.

3.5 SEISMIC SOURCE CHARACTERIZATION

Structural features that may have seismic capability of sufficient magnitude to affect assessments of seismic risk to Diablo Canyon will be identified in connection with work done in Task A (specifically subtask A.5). The criteria to be employed in making such identification will be as follows:

- The feature must be large enough to generate an earthquake of significant magnitude according to a preliminary estimate based on generalized source dimension to magnitude relationships or other criteria that may be appropriate.

- The estimated earthquake associated with a feature must be large enough to result in relatively strong ground motion at Diablo Canyon, at a source-to-site distance corresponding to the actual distance of the feature from Diablo Canyon, and/or

- It is considered that detailed characterization of the indicated seismic source structure is necessary to achieve adequate understanding or documentation of some aspect of the tectonic model.

The varied and transitional geology and tectonics of the region around Diablo Canyon are such that a variety of approaches will be required to adequately characterize the seismic source structures of the region found to be significant in the context of the Diablo Canyon LTSP. Some major factors that will influence the characterization process include:

a. <u>Nature of surface exposure</u>

The Santa Maria Basin region is partly onshore and partly offshore. Among larger mapped faults in the region, at least the main part of the Hosgri Fault, all of the Santa Lucia Bank fault system, and the offshore Lompoc anticline and fault are exposed only on the sea floor. The San Simeon, Lions Head, Honda, and south branch of the Santa Ynez faults are exposed both on- and offshore. Other larger faults of the region are mostly or entirely onshore.

b. <u>Style and orientation of faulting</u>

The style of faulting and the orientation of faults varies throughout the region of interest. In general terms, faults of the southern Coast Ranges tend to be of northwesterly strike, those of the Santa Maria Valley to be west-northwesterly, and those of the Western Transverse Ranges to be nearly east-west, but exceptions exist in all regions. In terms of style, surface morphology clearly indicates a significant component of right lateral strike slip for some segments of larger faults in the Southern Coast Ranges and of left lateral strike slip for some segments of larger faults in the Western Transverse Ranges. But steep to low angle reverse movement is well documented on other faults as well as on different reaches of the strike slip faults in the same regions. Some tectonic models propose right lateral strike slip movement on some faults of the Santa Maria Valley transition region, but available field and subsurface evidence shows predominantly reverse or thrust movement. Earthquake focal mechanisms generally indicate right oblique reverse movement except in the northern Santa Lucia Mountains, near Monterey Bay, where some shocks have been generated by nearly pure right lateral strike slip faulting.

c. <u>Possible low angle detachment faulting at mid-crustal depth</u>

The tectonic model proposed by Crouch et al. (Ref. 23) envisions the

existence of a subhorizontal aseismic detachment zone or regional decollement at a depth of about 10 km, beneath the Southern Coast Ranges. If such a feature exists, the question of whether it is truly aseismic or whether earthquakes of significant magnitude may occur on it from time to time must be addressed. If evidence is found that a regional decollement does (or could) exist, and is potentially seismogenic, it will be necessary to make an assessment of the likely location and characteristics of potential earthquakes that might be generated along it.

d. <u>Folds or other forms of deformation not expressed by fault rupture at the surface or at shallow crustal depth, as indicators of seismic capability</u>

The recent occurrence of the $6.7M_L$ Coalinga earthquake demonstrated that, under some conditions, seismogenic processes may be reflected at the surface by active folding or warping rather than by faulting. This consideration was emphasized by Stein and King (Ref. 66). Hill (Ref. 68) suggests that the Coalinga earthquakes of 1983 might have been caused by the process of folding via the mechanism of bedding-plane (flexural) slip. He speculates that when bending occurs on long and deep fold limbs like those at Coalinga, flexural slip might be delayed by friction long enough to produce a large elastic rebound with an associated property-damaging earthquake. Mechanisms involving flexure and movement along bedding plane faults have also been proposed for the 1892 Vacaville-Winters ($6.4M_L$ and $6.2M_L$) earthquakes in northern California (Refs. 69 and 70). The seismogenic potential of folding is of special significance to the LTSP Geologic Investigation because active folds are known at several locations in the Santa Maria Basin region and because Crouch et al. (Ref. 23) note that the style of faulting such as they attribute to the Hosgri zone may be accommodated by ductile deformation near the surface. Identification, characterization, and seismic evaluation of features that may be indicators of seismogenic capability will, therefore, be of special importance in the context of the present study.

Several approaches to quantifying estimates of future earthquake capability of individual faults and of predicting future seismic behavior within specified regions have been developed during the past 20 years. For the case of individual faults, empirical relationships have been developed based on study of various fault parameters recognized in connection with known earthquakes (Refs. 71-76).

In 1982, a Chapman Conference sponsored by the AGU was held to bring together current understanding of fault behavior and the earthquake generation process. Discussions focused upon the spatial and temporal behavior of faults, especially with regard to earthquake recurrence and magnitude, fault zone geometry, and the mechanical and physical properties of fault zones that control the rupture process. Significant papers to emerge from this conference include Aki (Ref. 77), Thatcher (Ref. 78), and Schwartz and Coppersmith (Ref. 76), among others.

For interpreting preserved evidence of past fault movements, as is done in connection with paleoseismicity studies, factors such as age of displacements, completeness, and representativeness of preserved evidence (e.g., scarp height, scarp length, ratio of scarp height or lateral deflection to actual maximum surface offset, etc.) must be evaluated. An issue that has been raised in connection with some cases where the geologic relationships indicate a possibility of surface displacement generated by flexural slip faulting is that of whether the observed fault offsets may have occurred as more or less aseismic slip. Such a suggestion has been made by Yeats et al. (Ref. 62). Yeats recently (Ref. 63) described a case where geomorphic evidence allowed making a determination that the observed offset had occurred rapidly, hence probably with an associated earthquake.

Investigations of paleoseismic evidence associated with surface faults have mostly been done under terrestrial conditions where detailed exposures can be developed and studied in artificial exposures. A number of examples of such investigations have been published (Refs. 79-81) and many others exist in consulting reports. Some investigations, however, have been concerned with

submerged fault exposures. Evidence of sea floor displacements, while seldom observable in the same level of detail as in the case of terrestrial displacements, actually can be more extensively preserved, especially if not affected by eroding bottom currents. Also, if deposition continues after the displacement has occurred, evidence of it may be well preserved and, where units of contrasting seismostratigraphic character are involved, may register clearly in high-resolution reflection records. Past studies of the Hosgri Fault have revealed an example of a probable sea floor scarp along one strand (Ref. 82) and other examples of sub-sea floor offsets (Ref. 83).

Other studies have attempted to relate earthquake magnitude to overall rate of fault slip within some period of steady state behavior (Refs. 84 and 85) and to seismic moment as defined by area of slip along the fault plane during a single event (Refs. 86-88).

The recent occurrence of the $6.7M_L$ Coalinga earthquake focused attention on the fact that earthquakes of significant magnitude can occur at locations where recent tectonism is expressed by folds or perhaps by other nonfault-related deformation rather than by surface faults. King and Stein (Ref. 89) and Stein and King (Ref. 66) have analyzed the deformation that accompanied this earthquake, and through comparison of this with the long-term growth of the Coalinga Anticline Ridge, have deduced a recurrence interval for earthquakes of equivalent magnitude. Other instances interpreted as representing comparable examples of earthquake-associated surface folding, uplift, and subsidence were cited by Stein and King and in Dr. D. B. Slemmons' letter of October 20, 1984 to Dr. Steve Brocoum of the NRC Staff. Examples where earthquakes have been attributed to flexural slip or other strain release associated with folding include the 1892 Vacaville-Winters earthquake in northern California (Refs. 69 and 70) and the Coalinga and other earthquakes (Ref. 68). Since several active folds are presently known in the Santa Maria Basin region, and others may be identified during the course of the LTSP study, characterization of the maximum earthquake and the earthquake recurrence interval for these features will also be required. The basic approach presently envisioned for this will be to employ analytical techniques

similar to those discussed by Stein and King (Ref. 66) for their study of the Coalinga earthquake and by Stein and Thatcher (Ref. 90) for the 1952 Kern County earthquake. Basic data employed will have to be geologic [except for such geodetic data as has been recovered for the 1927 Lompoc earthquake (Ref. 91), and direct sea floor deformation information that may be reconstructed from study of the tsunami from the same event].

The geologic data will concern form and dimensions of surface deformation, and near-surface and deeper structural form of underlying features. Deep seismic data may reveal information about underlying faults and potential field data may show evidence of crustal discontinuities or other anomalies. In some cases, correlation between geomorphic, drilling, and seismic data may allow determination of the rate and history of fold growth [e.g., Beaudry and Klink (Ref. 92), for the offshore Lompoc anticline].

Objectives of Task C will be: (1) provide necessary geologic data for use in determining maximum earthquake magnitude in Task 2, and (2) develop independent estimates of earthquake magnitude and recurrence interval from analysis of paleoseismic and other geologic data. The estimates developed within the scope of the Task 1 Program will be made according to procedures corresponding to those noted above or to other procedures that may be developed to address particular situations encountered during the Program. Evaluation of the seismic capability of any broad-scale, low-angle, detachment structure that may be identified is an example of a possible need for development of new techniques.

The sub-items that comprise Task C are identified in the annotated outline below.

1. Make best estimate and assess uncertainty associated with geologic characteristics of potential seismic source features in Task B, Item 5 significant to evaluation of maximum magnitude and other geologically-related earthquake characteristics including:

a. Total fault length

b. Segmentation/continuity/sinuousity

c. Orientation and sense of slip

d. Fold dimensions, depth, orientation, history of growth, and relationship to faults

e. Rate and pattern of Neogene and late Quaternary (including contemporary geodetic) rate of slip or other deformation (including geologically young folding, warping, uplift, etc.)

f. Correlation with earthquake epicenters, foci, and focal mechanisms

2. Review current understanding of relationships between characteristics of tectonic features (including faults, folds, decollement, etc.) and earthquake generation worldwide.

3. Relate characteristics in Item 1. above to estimates of maximum or characteristic magnitude, recurrence interval, and other behavior of seismologic interest.

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4. EARTHQUAKE MAGNITUDE

4.1 SCOPE

This section discusses the review and analysis of data pertinent to the determination of the maximum earthquake magnitude for the Hosgri (and any other relevant faults). The parameters that the analysis techniques include are fault and rupture geometry, deformation rate, and seismicity.

The incompleteness of seismologic and geologic records for geologic structures often necessitates application of a variety of empirical techniques for evaluation of the maximum credible earthquake magnitude which could be associated with those structures. These techniques are based on the analysis of a data base compiled from observations of recent earthquakes which provide one or more data points relating earthquake magnitude to various fault parameters. Application of these techniques does not lead to a unique estimate. Therefore, the estimation of uncertainty associated with each evaluation becomes important.

In order to assure that the resulting estimates are meaningful, the selected data base to be analyzed should be well-suited to the geologic and seismological conditions under study. Also, care must be exercised to assure that all data represent the same clearly defined physical parameters. These restrictions will be necessary in order to be able to interpret uncertainties purely in a statistical context, with no inherent biases in data.

The approach to be followed in this evaluation of maximum earthquake magnitude emphasizes the uniformity of the data base and the consistency of procedures used in the evaluation of regression coefficients, relating earthquake magnitude to various fault parameters. Application of these concepts to a data base, site-specific to DCPP, is described in Section 4.3. This section also addresses the distribution of magnitudes derived from the use of different fault parameters.

Section 4.2, on the other hand, is concerned with the compilation and review of source parameters and fault deformation rates, obtained from geologic studies described in Section 3, for their consistency with the site-specific data base used for the prediction of the DCPP maximum magnitude earthquake. An integral element of Section 4.2 is the evaluation of the range of uncertainties associated with various fault parameters derived for individual faults which may be relevant to DCPP. This information is helpful for ranking the resolution power of individual fault parameters. It also provides input to the task identified in Section 4.3.7 for the evaluation of the compounded uncertainty of the final magnitude estimate.

4.2 DATA INPUT PREPARATION

4.2.1 Total Fault Length

The main objective of this task is to integrate the available data pertinent to the style and geometry of faulting near DCPP in order to estimate the length of relevant faults. The data will be examined for their consistency with the historical and ongoing seismic activity. The interrelation of the regional structural features with the tectonic forces produced by the Pacific - North American plate interactions, as provided by the geologic studies in Section 3, will be reviewed in light of the prevailing regional seismicity pattern.

Procedures used by different investigators for assigning total length to the Hosgri and other relevant faults will be compared in order to ensure a uniform approach, compatible with the site-specific data base. The effects of different fault types will be investigated for prediction of the maximum magnitude earthquake associated with each relevant structure resulting from the geologic studies in Section 3.

4.2.2 Rupture Length and Area

Previously reported rupture lengths and areas of faulting associated with past

earthquakes determined by geologic or paleoseismologic considerations will be reviewed for the consistency of definitions and uniformity of assumptions employed. The data will be classified according to fault type, proximity to the plate margin, and deformation rate.

The available hypocentral data files for the Coast Ranges and offshore area of central California will be reviewed in order to evaluate the depth to the base of the seismogenic zone and its possible local variation. This information, together with that regarding depth of basement, will provide an estimate for the width of the rupture zone. Geologic information concerning the geometry of faulting in the area, resulting from geologic investigations in Section 3, will be applied to estimate the maximum rupture width. Consideration will be given to possible variations along the strike of the fault.

The procedures for converting total fault length to rupture length under different stress conditions will be reviewed and those most applicable to relevant faults will be selected. The assumption that rupture length is the same as surface rupture will be further investigated with seismological evidence for smaller strike-slip offsets and reverse ruptures.

The rupture length and width and their uncertainty will be estimated for relevant faults, based upon studies from Section 3. With the estimations of rupture length and width available, the rupture area for relevant faults will be evaluated. The compounded uncertainty associated with these parameters will be estimated.

The procedures for converting rupture area to earthquake magnitude will be reviewed. The uniformity of definitions and consistency of assumptions in estimation of rupture area will be examined. The most representative subset of the data base for evaluation of regression coefficients and their uncertainties will be identified.

4.2.3 Maximum Displacement Per Event

The data on the inferred displacements resulting from the geologic and

paleoseismology studies discussed in Section 3 will be reviewed and the information necessary for the best estimate of maximum displacements and its uncertainty for the Hosgri and other relevant faults will be selected. The sense of slip on individual faults will be characterized.

The maximum displacements will be compared against seismological data obtained in studies of historical seismicity and microearthquake activity. The maximum displacements will be compared with earthquake recurrence relations and slip-rate estimates. The sense of estimated slip will be contrasted against earthquake focal mechanisms and other source parameters derived for data and investigations of relevant regional earthquakes.

4.2.4 Moment Magnitude

Having estimated rupture area and displacement per event, the information will be used for estimation of corresponding seismic moment. The technique requires evaluation of average slip on the rupture surface. The technique will ensure an estimation of average displacement and its associated uncertainty consistent with the maximum displacements derived in Section 4.2.3 for the potentially relevant faults around DCPP. Finally, the geometrical movement, LWD, in which L is length, W is width, and D is average offset per event, will be determined.

Given that the moment itself is a product of several uncertain parameters, the sources and magnitudes of uncertainty in estimations of fault parameters will be characterized. When appropriate, teleseismic information will be used to constrain moment estimation.

4.2.5 Slip Rate

Slip rate can be utilized to determine maximum magnitude. This is based on establishing a link between seismic moment as a geologic constraint and earthquake statistics. This concept will be applied to the slip rate estimates for relevant faults as an independent estimate of magnitude.

The regional deformation rate as a whole and slip rate data for relevant faults as determined in the studies described in Section 3 will be reviewed. Geologically determined parameters will be compared against the current rate of seismicity, and the integrated slip rates against the current estimates of direction and rate of plate motion.

4.2.6 Historical Seismicity

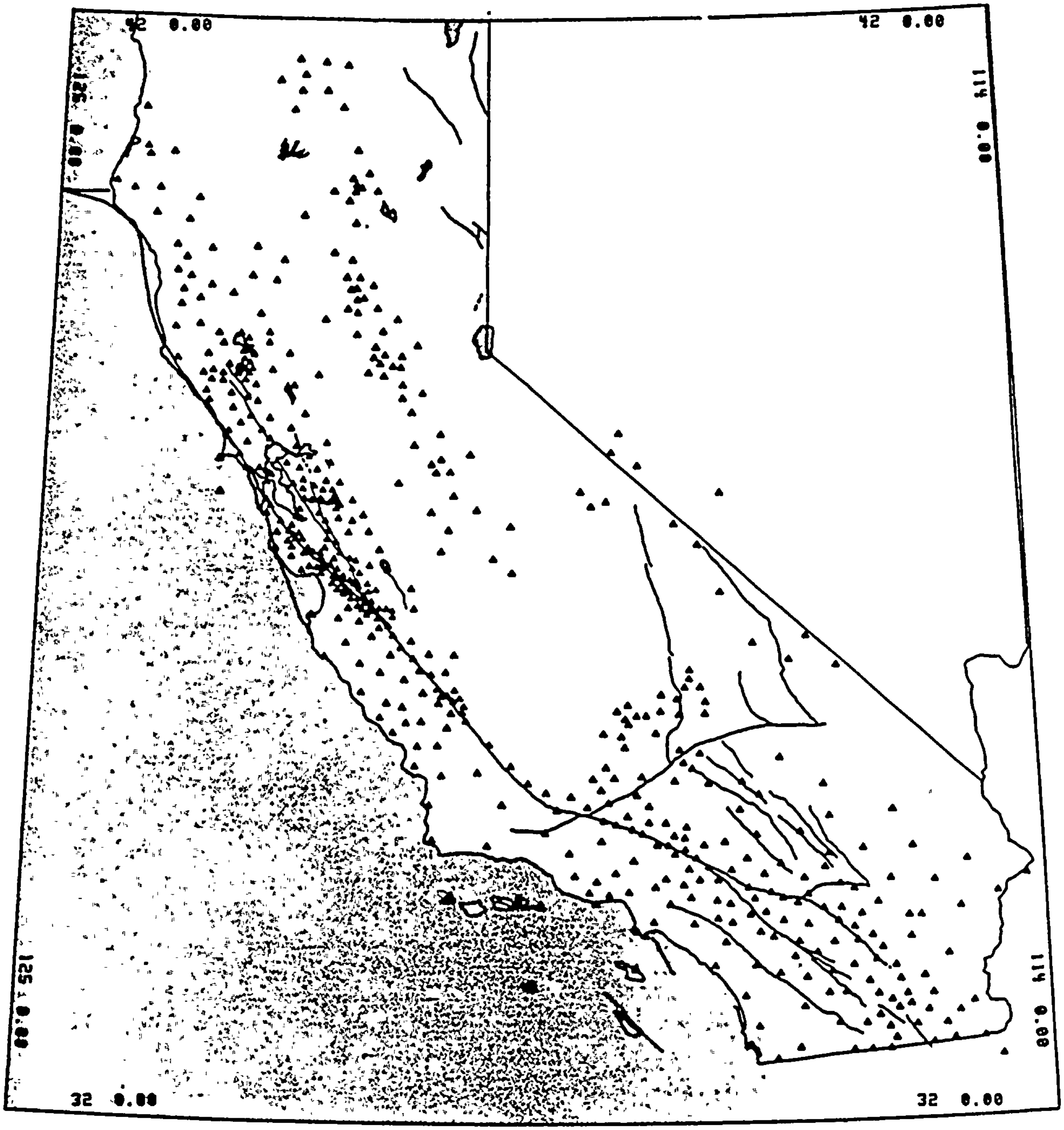
Available catalogs of instrumentally-located earthquakes as well as intensity reports will be reviewed in order to establish the background regional seismicity pattern. Recent regional earthquakes which occurred after the 1980 ALAB hearings will receive particular attention.

The seismological evidence, including tsunami data, associated with the 1927 Lompoc earthquake will be reanalyzed for its location, magnitude, and focal mechanism, and the results of the geological and geophysical studies described in Section 3, will be integrated in order to identify the most probable causative structure, with the objective of establishing the relationship of this seismic event to the regional tectonic model.

The reported focal mechanisms for recent offshore earthquakes will be reviewed with particular attention directed toward an assessment of the uncertainty of the solution. The results of this effort will be used, in conjunction with results from Section 3, to address the spatial variation of stress and the corresponding pattern of deformation.

4.2.7 Microearthquake Analysis

With the recent expansions of CALNET (a statewide seismographic network of nearly 500 seismic monitoring stations operated by the U.S. Geological Survey in California), the current capability to detect smaller events has been improved over that of the 1970s. As seen in Figure 4.2-1, the area of interest to this study lies in the transition zone between central and southern California subarrays, and has a somewhat more sparse distribution of



Networks of seismographic stations in California deployed in seismogenic areas and near active faults.

FIGURE 4.2-1

stations. Nevertheless, the improved capability is expected to permit the location of hypocentral coordinates of onshore events, with magnitudes as low as 2, with substantially higher confidence than before. The same type of improvements may be expected for offshore events which are not too far from the coastline. Utilizing these improvements, a detailed study will be made of the seismicity pattern which emerges from the spatial distribution of microearthquakes within a 30 km radius of DCPP.

4.3 CALCULATION OF MAGNITUDES

It is reasonable to assume a priori that different deformation parameters may not be equally suitable for application to every geologic circumstance. Investigation of the range of applicability of various deformation parameters is, therefore, expected to constitute an important component of this investigation. The same is true with the procedural steps and their underlying assumptions for application to subsets of data. The intent is to analyze the sensitivity of both segregation and regression procedures to the derivation of regression coefficients and the resulting predictions. These sensitivity analyses are expected to provide selections of the candidate data sets and preferred procedures towards application of different observed parameters for the estimation of maximum magnitude and its associated uncertainty. Various statistical approaches for final estimates and their overall uncertainty range based on different scenarios will then be tested on individual estimates.

4.3.1 Reevaluation of Existing Data

The existing data files, consisting of earthquake magnitudes and fault parameters used in previous regression models, will be reviewed. The data bases used in a number of recent studies will be compared for their similarities and differences. The uniformity of definitions for magnitude scale and for geologic parameters will be examined. Selection and rejection criteria for merging and subgrouping different data sets under definition of a unified magnitude scale will be developed. The existing data will be reviewed

for fault type. Regional source characteristics, such as those manifested in the different attenuation behavior of intensities with distance, and for tectonic environment as implied in the intraplate-interplate association of the source, will be incorporated.

4.3.2 Acquisition of New Data

Recent technical literature and available unpublished reports will be reviewed for identification of additional earthquakes associated with faulting in order to obtain new data which would meet the selection criteria. The results of ongoing studies such as those directed towards slip rate evaluation of Quaternary faults in California and satellite laser ranging (SLR) experiments for potential inclusion in the data base will be reviewed.

4.3.3 Applicability Criteria for Screening Data

It is important to exercise prudence in the development of candidate data sets for application to specific faults. In order to facilitate the screening process, a coding scheme will be developed similar to the one used in the empirical ground motion study (Section 5). This scheme will be useful in sorting and winnowing data for specific geologic conditions and in the selection of a candidate data base. It also provides a means of testing the applicability of data parameterization procedures, similar to those which proved successful in the empirical ground motion analysis.

4.3.4 Statistical Approaches for Application to the Screened Data

Previous regression models and their underlying statistical basis will be reviewed. The application of these models to subsets of the expanded data base will be examined. Alternative functional forms and combinations of variables for application to the data will be developed and the standard deviations in each test compared. Alternative partitioning of the data will be examined and the sensitivity of the results to the reallocation of lower

quality data will be evaluated. Nonlinear regression techniques, as well as other alternative regression schemes will be considered and tested against the objective of reducing the standard deviations of the regression.

4.3.5 Sensitivity Analyses

The impact of introducing weighting schemes to account for the level of confidence in the quality of data on the regression coefficients will be studied. Categories with insufficient data points may be consolidated into broader categories. Statistical outliers of each data set will be examined in light of specific faulting circumstances which may distinguish it from the rest.

4.3.6 Estimation of Magnitude

This sub-section describes how the adopted procedures will be applied to the candidate data sets for the evaluation of maximum magnitudes. As a merging point of Sections 4.2 and 4.3, the best estimate of geologic parameters for each candidate capable fault (based on geologic and seismologic considerations) will be applied to the selected regression model for those parameters. The magnitudes so derived will be compared with a subset of worldwide data within the magnitude and distance range appropriate for DCPP. The results of this comparison will be placed in the context of regional tectonic characteristics. The calculated maximum magnitudes and the associated uncertainties will be evaluated for their significance in establishing an overall magnitude for relevant faults near the site.

Procedures for application of total fault length criteria to estimation of the maximum earthquake magnitude for the Hosgri and other relevant faults in the vicinity of DCPP will be reviewed. The expected uncertainties in the assigned magnitudes resulting from total length estimation will be evaluated. Predicted rupture lengths and areas for relevant faults obtained from the application of different geologic or seismologic considerations will be compared and used with appropriate regression models for the estimation of

maximum magnitude and their range of uncertainty. In order to evaluate maximum magnitudes and the associated uncertainty, regression models consistent with tectonic characteristics of the region and nature of faulting will be used. Maximum moment magnitudes and the associated uncertainties for sources located on the Hosgri fault and other relevant faults will be evaluated. Previous studies in which slip rate has been used for determination of characteristic or maximum earthquake magnitude will be evaluated. The underlying reasoning in the context of the present study will be examined and the most appropriate procedure for the application of the data obtained from the studies described in Section 3 will be determined.

4.3.7 Analysis of the Distribution of Results

A synthesis for the earthquake magnitude will be developed for DCPP. Each of the fault parameters studied in the previous sections provides a best estimate of maximum magnitude and uncertainty. Hence, for each relevant fault a synthesis must be developed to provide an overall best estimate and uncertainty measure of the upper magnitude.

Several weighting schemes based on the level of confidence in the data and predictive ranking of parameters under desired geologic conditions, as described in previous studies, will be investigated. Statistical procedures will be considered. The results will consist of estimations of the maximum magnitude earthquake and the uncertainties associated with those estimations on a quantifiable basis, synthesizing the various parameters addressed in this study.

5. EARTHQUAKE GROUND MOTION BY EMPIRICAL ANALYSIS

5.1 SCOPE

This section presents the approach for empirically determining the earthquake ground motion at DCPP. The approach is founded on a statistical analysis of existing near-source earthquake ground motion data. In addition, studies will be performed in subjects related to interpretation of ground motion records including, but not limited to, dense array studies, phasing between horizontal and vertical peaks, and characteristics of time histories.

5.2 DATA BASE DEVELOPMENT

5.2.1 Establish Selection Criteria

Since the conditions associated with the DCPP are near-field strong ground motion, selection criteria are required to allow sufficient quality data for meaningful predictions. The range of the data must be broad enough to address concepts such as the scaling of ground motion amplitudes with magnitude and distance. In this respect, certain data beyond the near-field (about 50 km) will be included to address magnitude and distance scaling, and the variations of site and source parameters with distance. The inclusion of individual earthquakes will be based on the availability of reliable information on fault location, fault surface rupture, or aftershock distributions relative to the distance of the recording sites.

5.2.2 Update Data Base

An extensive near-source strong-motion data base has been developed (TERA Corporation) which includes the 1979 Imperial Valley earthquake, all the available North American near-source recordings through about 1980, and several significant foreign records including Gazli, USSR, and Tabas, Iran. Since the development of this data base, there have been several significant

western U.S. earthquakes. The data base update will build upon the existing data base with the inclusion of available western U.S. recordings which meet the selection criteria. Additionally, several large near-source events occurring outside North America have been identified for which sufficient quality information may be available. These will also be investigated against the selection criteria and for the availability of sufficient source and site information, and will be added where possible. Table 5-1 presents a partial list of the earthquakes identified. Since these are significant events, processed data are available for many of them. For those records not previously processed, the available records will be gathered for in-house processing. In addition to the incorporation of new earthquakes, the current data will be reviewed against recent studies and updated accordingly.

Current digitization and processing techniques which have been applied to ground motion data will be reviewed and evaluated. Existing data have been processed with techniques varying from hand to laser digitization, and with various integration techniques. Furthermore, the dynamic characteristics of the recording instruments have implications for techniques of instrument correction. These considerations will be reviewed for the potential biases existing in currently processed data and their potential impact on the analysis. Where determined necessary, records will be reprocessed. Additionally, unprocessed film records will be digitized and processed by the preferred methods.

5.2.3 Earthquake Data Characterization

In preparation for the regression analysis, the data will be reviewed and classified according to earthquake source characteristics. Consistent with the existing data base, information will be collected on magnitude, fault type (focal mechanism), and the geometry of the sources to be converted to source-to-site distance. Additionally, information on rupture configuration will be compiled for use in the computation of the potential for focused seismic energy at the recording sites.

Table 5-1

ANTICIPATED NEW NEAR-SOURCE ACCELEROGRAPH DATA

Location	Date	Magnitude
Tangshan, China	July 27, 1976	7.8
Guerrero, Mexico	March 14, 1979	7.6
San Juan, Argentina	November 23, 1977	7.4
Caldiran, Turkey	November 24, 1976	7.3
Urakawa-Oki, Japan	March 21, 1981	7.3
Offshore Trinidad, California	November 8, 1980	7.2
Gazli, U.S.S.R.	March 1, 1984	7.1
Montenegro, Yugoslavia	April 15, 1979	6.9
Campania-Basilicata, Italy	November 23, 1980	6.9
Gulf of Corinth, Greece	February 24, 1981	6.8
Lice, Turkey	October 13, 1975	6.7
Izu Peninsula, Japan	January 14, 1978	6.7
Milford Sound, New Zealand	May 4, 1976	6.6
Friuli, Italy	May 6, 1976	6.5
Coalinga, California	May 2, 1983	6.5
Thessaloniki, Greece	June 20, 1978	6.4
Mexicali Valley, Mexico	June 9, 1980	6.3
Halls Valley, California	April 24, 1984	6.2
Mammoth Lakes, California	May 25, 1980	6.1
Livermore, California	January 24, 1980	5.9
Westmoreland, California	April 26, 1981	5.6
Southern California	February 25, 1980	5.5
Monterey, California	January 22, 1984	5.3
Mesa de Andrade, Mexico	December 7, 1976	5.0

5.2.4 Recording Sites Data Characterization

Information on instrument location (e.g., ground level, embedded, abutment of dam), instrument housing, site surficial geology, and topography will be collected and the data classified accordingly. Additionally, the azimuth of the station from the rupture front will be determined for use in investigating directivity effects on both the amplitudes of ground motion and its influence on the uncertainty. Changes in shear wave velocity underlying the recording stations will also be assessed to study its effect on peak ground velocity (PGV) and lower frequency spectral ordinates.

5.3 MODEL DEVELOPMENT

Appropriate regression models will be developed for the mean horizontal and vertical components of peak ground acceleration (PGA), PGV, and the 10, 5, and 1 Hz response spectral ordinates. The 10, 5, and 1 Hz ordinates are chosen to model the changing characteristics of response spectral ordinates with decreasing frequency. It is anticipated that, due to the divergent nature of these ground motion parameters and the range of frequencies represented, the models will vary significantly. The information gathered and regression models developed from investigation of these three frequencies will then be applied, in Section 5.3.1 of the Program, to obtain predictions for DCPP at a sufficient number of spectral ordinates to adequately characterize the shape of the response spectra between 20 and 1 Hz.

5.3.1 Evaluation of Regression Biases

Applicable weighting schemes will be evaluated, including the analysis of alternate weighting procedures and the sensitivity of results to those methods. Application of weighting schemes usually involves decisions concerning those portions of the data to be emphasized in the regression. Other methods have been developed to partially compensate for the influence of well-recorded events without application of a priori weighting schemes. These and alternate methods will be explored, including the application of various weighting schemes.

5.3.2 Development of Functional Form

Functional forms will be developed to minimize the standard error, to provide stability at the extremes of the data, to model physical characteristics of earthquake sources, and to allow for the treatment of data biases.

5.3.3 Treatment of Site and Source Parameters

Addressing the effects of site and source parameters is an important consideration in minimizing the uncertainty while providing predictions appropriate to the site. Eliminating or correcting systematic biases in the data is necessary to model various physical considerations such as the saturation of PGA with magnitude.

The average bias associated with the reverse fault data as opposed to other fault types will be evaluated. In order to apply this information directly to ground motion predictions, various considerations affecting this issue will be investigated. For example, the sense of movement associated with most earthquakes is usually a mixture of strike slip, reverse, or normal faulting. Furthermore, the variations in stress between the interplate and intraplate environments as well as variations in depth of rupture will be investigated for their influence on the analysis. Also, the influence of fault type in the different frequency domains will be investigated.

The influence of earthquake source directivity on the amplitude of recorded ground motion will be investigated. This influence on the uncertainty will be examined by attempting to evaluate the bias associated with the directivity factor.

The treatment of site effects is important in minimizing the uncertainty and for predictions appropriate to the site. For example, certain subsets of data produce results significantly different for PGAs than those produced by data from sites more comparable to DCPP site conditions. Subsets of data which would not be comparable would include those from sites located on shallow soil

deposits over rock, those located in areas of steep topographic relief or on abutments of dams, and those located in large structures. The influence of these data subsets will be analyzed with the inclusion of the new data and results will be compared to the previous analyses. The results from the studies of source and site effects will then be applied to the screening and analysis of the data to eliminate groups of data which may compromise the goodness of fit.

5.3.4 Special Studies Affecting the Analysis

The choice of distance definition has an impact on the ground motion predictions and the uncertainty. Furthermore, the analysis of the saturation of ground motion amplitudes with magnitude also relies heavily on the choice of distance definition. Thus, the definitions of distance will be reviewed against their physical basis and applicability, and their influence on the uncertainty. The choice of distance definition will also be reviewed against its impact on predictions for DCPP, the phenomenon of magnitude saturation, and the variation of its influence with frequency.

Magnitude scaling with distance will be studied in order to characterize the sensitivity of ground motion amplitudes to changes in magnitude and the concept of an upper bound to those amplitudes.

Previous studies have indicated that the character and amplitude ground motion recorded on soil can be a strong function of the weight and base area of the pad upon which the sensor is placed, as well as the soil underlying the instrument pad. This issue will be reviewed with respect to its potential impact on the free-field ground motion predictions for Diablo Canyon and the feasibility for quantitatively addressing this potential bias in the free-field predictions.

5.3.5 Uncertainty and Sensitivity of the Results

The quantification of uncertainty for the conditions applicable to Diablo

Canyon will be emphasized in this program. The sensitivity of results to changes in functional form, weighting scheme, data selection criteria, and characterization of site and source parameters, will be tabulated. Variations of the standard deviation with magnitude, distance, and other parameters will be investigated and other methods of expressing the uncertainty will be explored.

5.4 ANALYSIS AND EMPIRICAL INTERPRETATION OF EARTHQUAKE RECORDS

5.4.1 Regression Analyses

Site-specific regression results will be generated for the mean horizontal and vertical components of PGA and PGV. The three representative models for the 10, 5, and 1 Hz spectral ordinates will be applied to a sufficient number of spectral ordinates to adequately characterize the shape of the response spectrum between 20 and 1 Hz at 5 percent damping. Results of these analyses will be compared with similar studies conducted by other investigators, and with those of theoretical and numerical studies.

5.4.2 Dense Array Studies

Acceleration time histories recorded by one- and two-dimensional dense arrays will be analyzed for the purpose of estimating the base reduction of ground motion as a result of incoherence of the high frequency components. Additional data sets will be located for other source-site conditions and from two-dimensional arrays such as the SMARTI array in Taiwan.

Under certain assumptions regarding the stiffness of foundations, the coherent portion of acceleration time histories recorded across dense arrays can be utilized for construction of time histories for different rotation components to which the foundation is subjected, including rocking and torsion. This procedure will be applied to data sets across the same array to evaluate the peak rotation amplitudes and their possible magnitude-dependent behavior.

The spatial reduction of high frequency coherence of the impinging seismic energy will result in the modification of ground motion by large foundations with a behavior similar to a low-pass filter. The concept originally suggested by Newmark for nonvertical incidence to high-frequency waves may be further accentuated by the observed high frequency incoherence. With the expansion of the data base for observation across dense arrays, a wider empirical data base will be available for better quantification of this effect. In this task, previous empirical estimates of base averaging effects on PGA and PGV as a function of foundation dimension will be reviewed as additional new data becomes available.

5.4.3 Phasing Between Horizontal and Vertical Peaks

The phasing of the three components within a record will be studied in a selected number of time histories. Distribution of the time of occurrence of the largest peaks between both two and three directions will be presented on a probabilistic basis. Additionally, correlation of the results with magnitude, distance, and fault mechanism will be investigated to determine any potential trend.

5.4.4 Character of Time Histories

A selected number of time histories and response time histories for single-degree-of-freedom systems of given damping and frequencies will be evaluated for strong motion duration, energy content, frequency content, and peak decay. Several definitions of each of these quantities will be tested. The objective of this effort is to characterize the nature of free field accelerograms that could occur at DCPP in order to better constrain the input to the soil-structure interaction calculation.

6. EARTHQUAKE GROUND MOTION BY NUMERICAL ANALYSIS

6.1 OBJECTIVE

An earthquake modeling study will be conducted to reevaluate the ground motion at the Diablo Canyon site using numerical analysis. The study will use current information about the local geology and the earthquake-generating capacity of faults in the area to determine the range of ground motions that could result from maximum magnitude, earthquake scenarios.

Ground motions determined from this study will be decomposed into the composite of incoming wave components that impinge on the various structures and cause base motions. The packages of incoming wave types, thus determined, will be used as input for analyses of soil-structure interaction effects.

New data have become available since the last formal review of seismic issues for DCPP. Recent developments that merit special consideration include alternate interpretations of the local geology as related to the Hosgri Fault, some 5 to 6 kilometers offshore. Also, there is important new information in recordings of recent earthquakes, most notably the 1983 Coalinga, the 1984 Morgan Hill, and the several Mammoth Lakes earthquakes. Further, in the past few years, an improved understanding has been gained of earthquake processes, for example, the increase in the source strength with increasing depth.

In summary, the earthquake modeling study will be performed to accomplish the following objectives:

- Reevaluate the ground motion at the Diablo Canyon site
- Use current information about earthquakes to update earlier analyses.
- Provide answers to important technical questions about earthquake ground motion for conditions relevant to Diablo Canyon

- o Evaluate the range of ground motion effects that are plausible, and estimate the probability that these effects may occur for each earthquake that is postulated
- o Decompose the predicted ground motion into the various components of incoming waves for input to analyses of soil-structure interactions

6.1.1 Approach

Credible predictions of earthquake ground motion must be closely tied to recordings of past events. Since these recordings were obtained under circumstances that are not the same as at the site of interest, some form of extrapolation is required to obtain site-specific estimates of ground motion. The numerical modeling approach is designed to accomplish this extrapolation to conditions at Diablo Canyon, using the most relevant information currently available from earthquake theory and from the recorded data.

A large data base of strong motion recordings has now been collected. Strong ground shaking has been recorded at close distances to dozens of different earthquakes, and these span the range of source mechanisms: strike slip, normal, and reverse (thrust). The size of these recorded earthquakes varies from events too small to pose a serious hazard (magnitude < 4) to potentially damaging earthquakes with subsurface fracture extending over tens of kilometers (magnitude > 6 and a few > 7). Over 100 recordings of strong ground motion are now available for establishing important trends and illustrating the diversity of effects that can occur.

Extrapolation from motions recorded elsewhere to conditions relevant to the Diablo Canyon site requires some means for characterizing the earthquake recordings using relevant parameters, such as earthquake magnitude and distance to the causative fault. Because these two parameters are insufficient for describing conditions that govern earthquake recordings, the data appear to be highly variable. Thus, extrapolation to site-specific conditions results in a broad range of predicted motions. Also, the

uncertainty increases when extrapolating to conditions not well covered by the available earthquake recordings.

A more complete characterization of the recorded data can serve to significantly reduce the uncertainties and provide the means for realistic predictions of ground motion based on conditions present at the site. The parameters that govern recorded motions are of two types: those that characterize the earthquake source, and those that characterize the propagation of waves from the source to the recording station. For example, magnitude is a parameter that characterizes the amplitude of low-frequency motions generated by an earthquake. Additional parameters are needed to characterize the higher frequency source effects manifested in the strong motion recordings. For example, earthquake fracture that spreads toward a recording site results in higher levels of ground motion than the opposite conditions with fracture extending away from the site. Other characteristics of the source that can significantly influence recordings include slip mechanism (strike slip, normal, reverse), orientation, depth, fracture extent, stress drop, fracture velocity, and local irregularities in the fracture process.

Recorded motions are strongly influenced by wave propagation effects; distance being the most important. The remaining path effects depend on the local geology, and account for a variation of about a factor of two in earthquake recordings. Both wave theory and recordings of small earthquakes can be used to characterize path effects and reduce uncertainty associated with extrapolation from earthquake recordings to conditions at DCPP.

It is concluded that reliable extrapolation of earthquake ground motions can be accomplished using a numerical model to account for the many influential, but site-specific, source and path effects. A consideration is required of what earthquake theory is available for accomplishing this task, namely computational methods for modeling faulting and subsequent wave propagation through the earth. The methods for simulating seismic waves are remarkably advanced and serve to provide a refined characterization of the detailed

subsurface geology. The literature provides numerous examples of computer-generated seismograms that closely mimic recordings of earthquakes and explosions. For frequencies above a few Hz, the theory cannot match, in detail, recorded motions. However, it is adequate to model the important characteristics. The earthquakes of greatest importance for this study produced many aftershocks which were recorded at most of the same stations that recorded the main event of interest. These recordings provide the basis for establishing the validity of methods used to represent the effects of wave propagation.

The capability to accurately model waves through the earth has enabled the determination of the gross rupture process from low-frequency recordings. Most of the earthquakes that produced multiple recordings in the near-field have been analyzed and the results described in the professional literature. Independent studies of the same earthquake provide comparable models for the progression of rupture and appear able to resolve large variations in fault offset over distances of a few kilometers. When these source characteristics are used for calculating ground motions through a representative earth model, results are obtained that closely resemble the recorded motions for frequencies below 1-2 Hz.

A similar representation for the high-frequency recordings can be obtained using, for example, the likely hypothesis that high frequency waves are produced in the source region near the leading edge of the crack, as determined from recorded motions below about 1 Hz. By using the information derived from low frequency recordings in this way, the source of high-frequency waves can be determined in a straightforward manner. This step serves to distill information contained in the earthquake recordings into its most elementary form for extrapolation to conditions at the site.

The numerical model is designed to be quite analogous to conventional empirical methods. The functions to be fitted to the data are those ground motions produced at the recording stations by the small regions of the source that make up the extended area of faulting. The unknown parameters to be

determined empirically characterize the source strength at the crack tip as it passes through the various small regions. A goodness-of-fit criteria is introduced to provide a quantitative measure for differences between the motions produced by the model and those recorded during the earthquake. The parameters that best characterize the production of high-frequency waves can be determined by constraining the model to best match the recorded motions in the sense provided by the goodness-of-fit criteria. As with conventional empirical methods, differences between the recorded motions and those obtained from the model will appear as unexplained data scatter. However, because the model includes the effects that most influence the earthquake recordings, the unexplained data scatter is expected to be much less than that from conventional methods that consider only earthquake magnitude and distance to the causative fault.

Once the path effects have been removed from the relevant earthquake recordings, equivalent source representations will have been determined and site-specific conditions can be extrapolated. The results of several researchers, including the previous modeling work performed by DELTA for the Diablo Canyon project, indicate remarkable similarities in the high-frequency source characteristics for different earthquakes. For example, it appears that the average production of high-frequency waves per unit area of the source is essentially a constant for earthquakes in California, and hence, independent of the earthquake magnitude. Other researchers have found the same result. Such generic representations of the source will be established and tested by predicting additional earthquake recordings. These tests of the generic source representation will be performed using the prediction procedures to be applied at the Diablo Canyon site. Variances with the recorded motions provide the measure of prediction uncertainty, expressed as a statistical distribution about the median prediction of response spectrum. Using these procedures, extrapolation of recordings can be made to the distances of interest for the Diablo Canyon site with the highest level of confidence that can be achieved with current understanding of earthquakes.

6.1.2 Introduction

The numerical modeling capability to be used will build upon the experience of DELTA, a former subsidiary of TERA Corporation. Between 1976 and 1982, computer programs were developed and used for simulating earthquake ground motions. The approach to earthquake ground motion estimation that motivated that work is similar to the approach intended for the Diablo Canyon Project. The approach was to: (1) develop a computer model for simulating earthquake ground motion and subsequent wave propagation; (2) normalize the model by matching recordings from several earthquakes; and (3) estimate site-specific motions by changing the model parameters to be appropriate for the site. This was a revolutionary approach at the time it was begun (1976), and the DELTA group and their consultants (mainly from the University of California at San Diego) had to develop many of the key elements of the numerical simulation models. Also, they were forced to confront many of the key questions about fault physics and travel path effects, often without much prior work to provide guidance.

Since then, earthquake ground motion science has moved strongly in the direction pioneered by this earlier work. There is now a better understanding of the various elements required for simulating earthquake ground motions, and these elements are widely understood and appreciated. What hasn't been done is to assemble the new technology into a complete package for modeling earthquakes and to use this capability to represent and extend the empirical data base. The objective is to accomplish this.

In this section, the important features of the DELTA model are reviewed and the limitations of that model are identified. Some of the important progress made during recent years that has allowed the limitations of the DELTA model to be overcome is reviewed and accurate and credible ground motion estimates are developed for the DCPP site.

6.1.3 Review of DELTA Model

The DELTA work was originally done to evaluate ground motion criteria for Unit 1 of the San Onofre Nuclear Generating site and was later used in a similar way for Units 2 and 3 and for the Diablo Canyon site; the basic concept was to:

- Develop numerical models capable of simulating (on the computer) the earthquake fault process and the propagation of the myriad of seismic waves from the fault to the sites of interest

- Normalize and validate the numerical model by matching recordings from several earthquakes over the frequency band from 0 to 30 Hz

- Change the model parameters to represent the suite of postulated events at the site of interest and predict the associated ground motions

This concept is illustrated schematically in Figure 6.1-1. The fault was represented by a rectangular fault plane. The rupture initiates at a point on the fault surface and spreads at a rupture velocity taken to be a fraction of the local shear-wave velocity. In the example in the Figure, the rupture wavefront is distorted because the local shear wave velocity is lower at the top of the fault surface.

The slip function was prescribed on each element of the fault plane, using the form described in Figure 6.1-2. The time of rupture initiation at any element is controlled by the rupture velocity. The S_∞ was chosen so the fault has the moment for the earthquakes of interest. The rise time was taken to be the time it takes for a shear wave to traverse the fault width, which is the result obtained by finite difference calculations of fault propagation. The remaining parameter is the initial slip velocity which was determined from high frequency recordings and found to be the same for all earthquakes that were modeled.

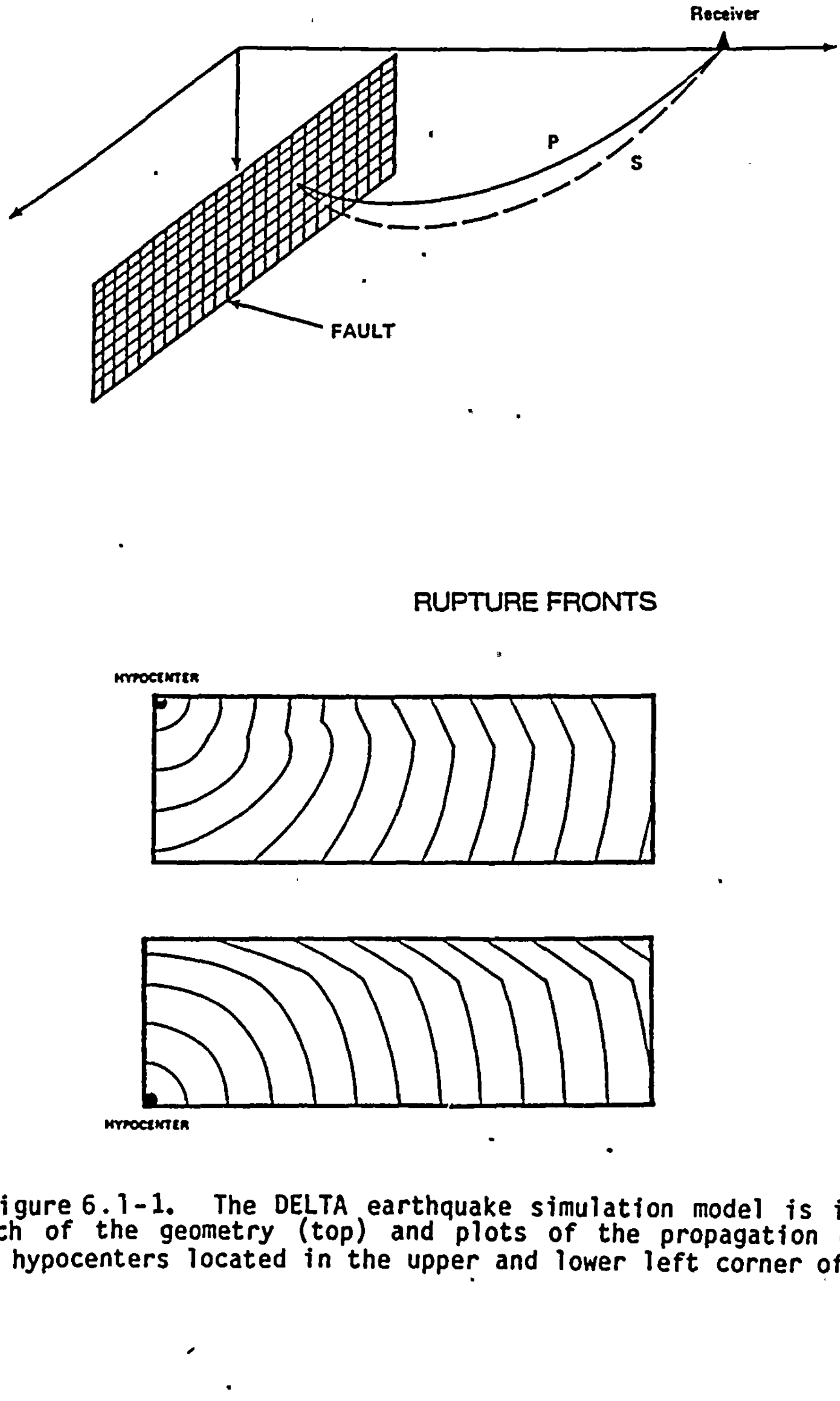
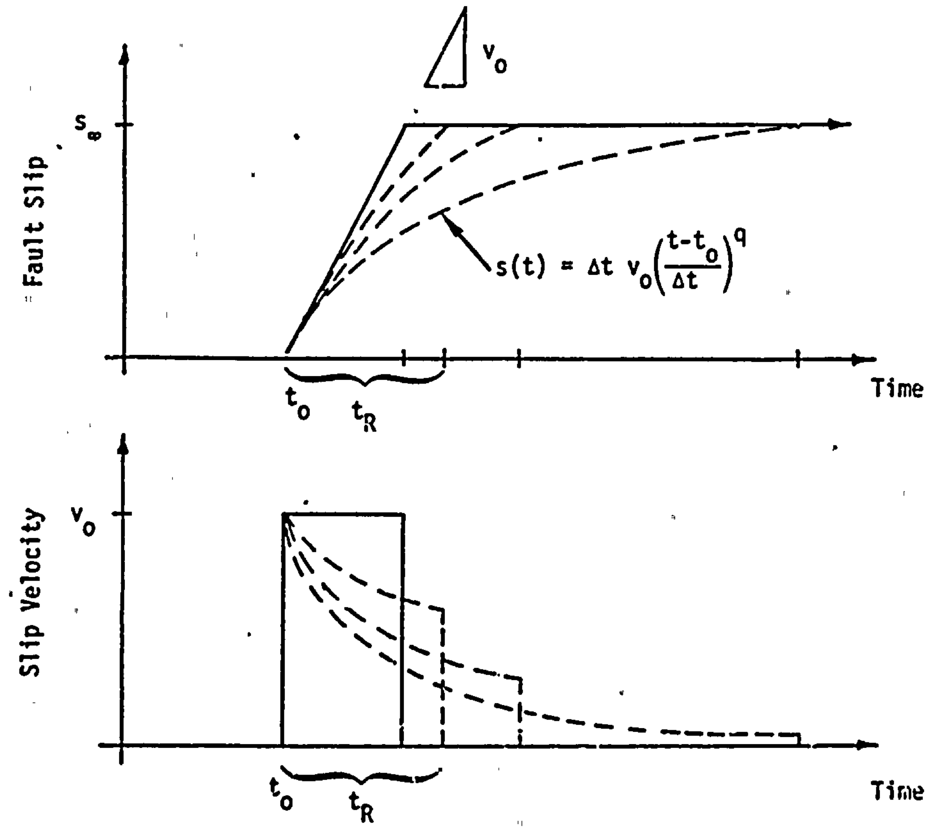


Figure 6.1-1. The DELTA earthquake simulation model is illustrated by a sketch of the geometry (top) and plots of the propagation of rupture fronts for hypocenters located in the upper and lower left corner of the fault segment.

DELTA'S THREE-PARAMETER SLIP FUNCTION



v_o = initial slip velocity ∿ dynamic stress drop

s_∞ = Final fault offset ∿ static stress drop

t_o = time of rupture initiation

t_R = rise time (duration of slip at a point)

$= \dfrac{s_\infty}{v_o}$ for a simplified two-parameter model.

Idealized slip function in which $q = [\ln(s_\infty/\Delta t\ v_o)]/\ln(t_R/\Delta t)$ is assigned to cause $s(t = t_o + t_R) = s_\infty$. Note that $q = 1$ for $t_R = s_\infty/v_o$, thus yielding a simplified two-parameter slip function.

Figure 6.1-2. The DELTA three-parameter slip function is plotted for several choices of the parameter V_R. The other parameters are V_o and S_∞. The Δt is the time step, which was .025 seconds for the DELTA calculations.

To compute seismograms, the slip function on the fault must be convolved with Green's functions which represent the propagation of seismic waves from the fault to the receiver. For the DELTA calculations, the source-path geology was represented by a plane-layered earth model chosen to be consistent with the known geological structure. A program for calculating the complete solution for waves in this structure was used. The important parameters for the propagation calculations were the velocity and Q (anelastic attenuation factor) as a function of depth.

The earthquake faulting process is not characterized by a smooth and constant rupture velocity on a plane. Also, plane-layered models can only approximately represent the complex, heterogeneous earth. Some means for representing these complexities must be included to obtain realistic ground motions. In the DELTA model, the irregularities in the faulting and wave propagation were represented by including several kinds of randomness in the model, including:

- Micro irregularities

  Rupture times for 50-m irregularities within a 1-km segment were randomly distributed about the gross rupture time for the segment. The degree of randomness varied inversely with rupture time.

- Macro irregularities

  - The time for rupture initiation in each segment was delayed beyond the arrival time of the gross crack by a random number with a two-thirds confidence of not exceeding one second

  - The orientation of rupture in each segment was modified by random numbers with a two-thirds confidence of not exceeding 20, 20, and 10 degrees for the strike, rake, and dip, respectively, of the slip vector

- The tip of the crack migrated through each segment in a direction that deviates from the gross direction of rupture propagation by a random number with a two-thirds confidence of not exceeding 30 degrees

- The horizontal particle motion computed at the receiver station from each rupture segment was altered in direction by a random number with a two-thirds confidence of not exceeding 30 degrees

The last item under macro irregularities is included to simulate some of the effects of scattering of waves from heterogeneities encountered along the travel path.

The DELTA model accounted for the effect of many of the key parameters controlling earthquake ground motion. In particular, it includes:

- o Fault geometry
- o Fault orientation
- o Rupture velocity
- o Source directivity (focusing)
- o Static and dynamic stress drop
- o Travel path geology (plane-layered)

Thus, it was used to assess the effect of variations in these gross parameters.

The model was normalized to ground motion data for many earthquakes (1976 Brawley, 1940 and 1979 Imperial Valley, 1933 Long Beach, 1966 Parkfield and 1971 San Fernando). The comparison was in terms of observed and predicted response spectra. Several examples are shown in Figure 6.1-3.

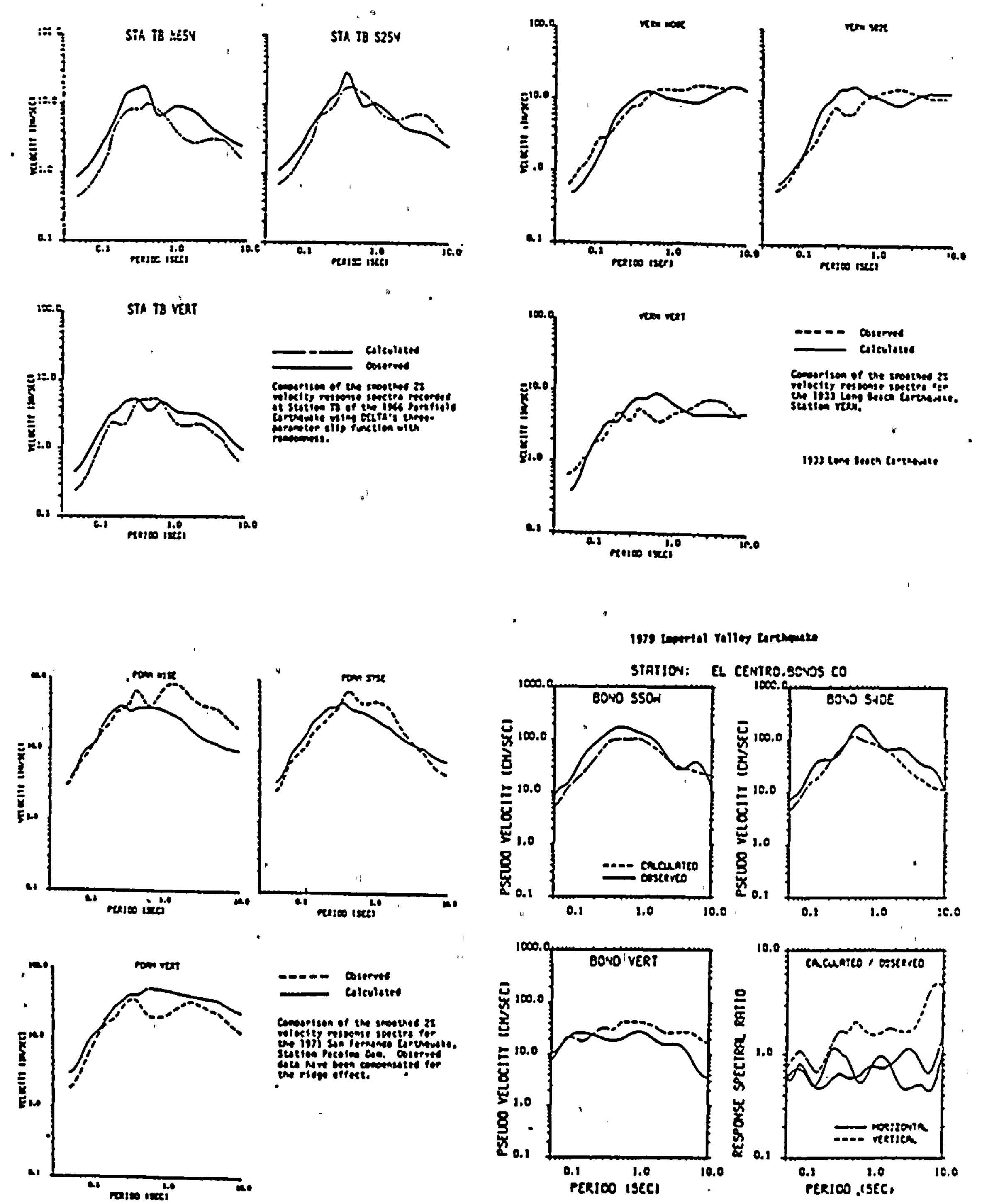


Figure 6.1-3. Calculated and observed ground motions are compared in terms of smoothed 2% velocity response spectra. These are four of the many comparisons done to normalize the DELTA model.

In simulating these events, the event-specific fault geometry and orientation and the moment were input. The appropriate path geology and station locations were used. Otherwise, all earthquakes were the same. That is, the same slip function, rupture velocity (90% of the local shear wave speed), and specification of randomness were used.

The DELTA model represented a great step forward in earthquake ground motion estimation because it was shown to match recorded ground motions rather well for several different events, despite the fact that it had so few earthquake-specific source parameters.

It was used to obtain site-specific predictions for the San Onofre and Diablo Canyon sites by varying the source parameters within the range specified for earthquakes postulated on the faults relevant for those sites.

While the DELTA model was successful, especially in view of the fact that it provided new insights to ground motion estimation, the model had some limitations which can now be overcome. Briefly discussed, these are:

- Representation of slip heterogeneity

  The DELTA model used the same slip function everywhere on the fault, mainly to reduce the number of free parameters. It is now known that earthquake fracture is more complex and is characterized by heterogeneous faulting processes. However, earthquakes in California have characteristic source heterogeneities which can be determined and included in the model. This model improvement will enable more rigorous explanation for recorded motions and reveal important information about the earthquake source, such as how the source strength varies with depth.

- Representation of path heterogeneity

  The DELTA model did not include a physical basis for representing

wave scattering along the path. This is known to be important. Theories for representing scattering are now available and can be included.

- Model normalization

The DELTA model was normalized to earthquake data in terms of the seismic moment and response spectra. However, there are robust features of earthquakes revealed by longer period (>0.5 seconds) data, and these were not used. Many of the key earthquake parameters can be fixed by these data, leaving only a select few parameters for representing the high frequency motions.

- Quality of fit to the data

The match between observed and calculated ground motion was subjective, relying on comparisons like those in Figure 6.1-4. This can be put on a quantitative basis through a statistical goodness-of-fit measure, and provide a basis for characterizing uncertainty in the predictions of site-specific motions.

- Computational efficiency

A limitation of the DELTA model was that every earthquake calculation required considerable computer time. This limited the number of examples that could be run. Algorithms can now be developed to operate much more efficiently, allowing many more calculations.

In the next section, a review is provided of some of the most important advances in understanding earthquakes and ground motion simulation. These advances allow improvements of the DELTA model, and, in particular, overcoming the limitations noted above.

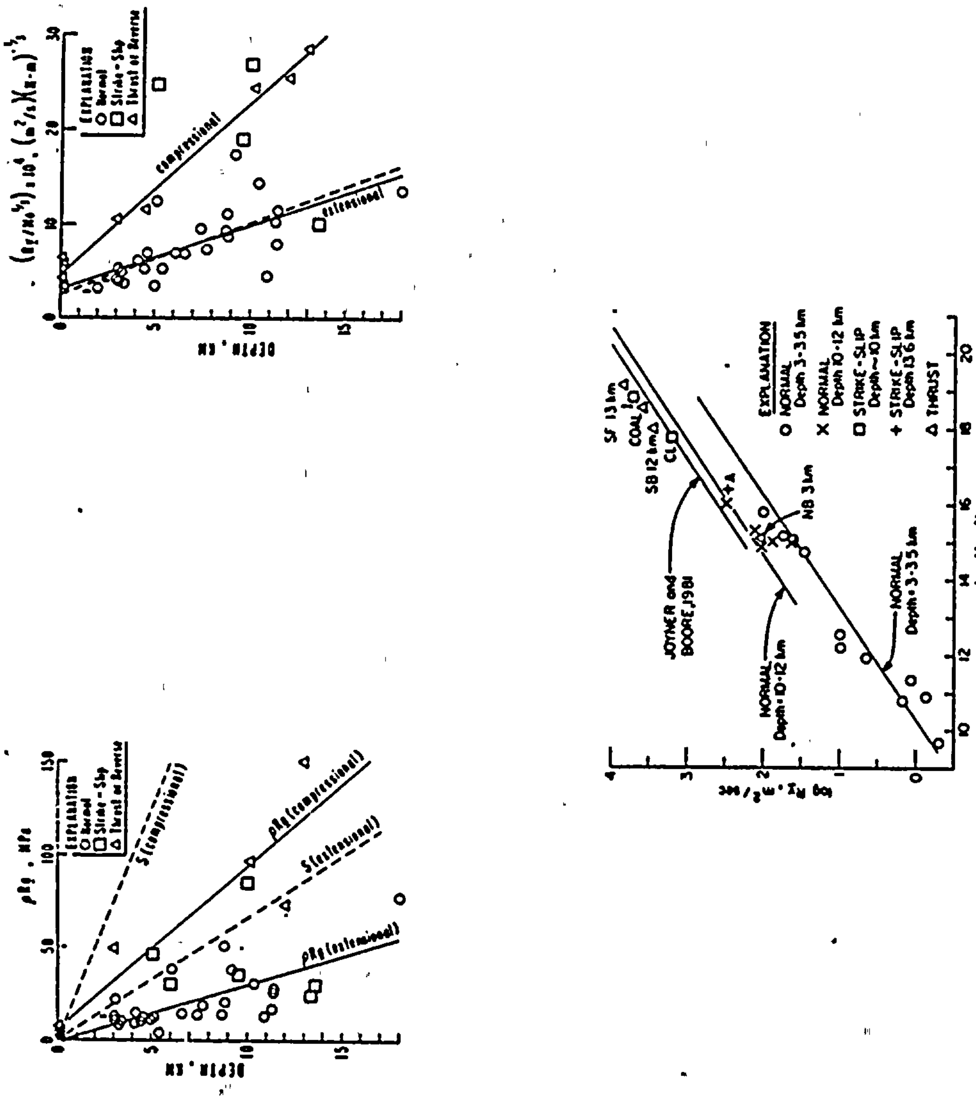


Figure 6.1-4. Results are reproduced from McGarr (1984). The upper plots show the normalized peak acceleration and velocity as a function of focal depth. The S in the acceleration plot is the crustal shear strength. The ρ is density, R is hypocentral distance and M_o is moment. The lower plot shows normalized peak velocity as a function of moment for various subsets of the data chosen according to stress state and depth. All lines on this plot have a slope of 1/3.

6.1.4 Advances in Understanding Earthquake Ground Motions

a. Wave Propagation Calculations

It is clear that much of the complexity of strong motion records is caused by the path structure. Methods for computing wave propagation in realistic geologic structures have been rapidly improved in the past several years. There are now accurate and efficient techniques for computing wave propagation in plane-layered models. Also, methods for computing waves in more realistic two- and three-dimensional structures have recently been developed.

There are two general numerical approaches for plane-layered models which have had widespread use in modeling near field records. These are the generalized ray method (Ref. 1) and the wavenumber-frequency numerical integration approach (Ref. 2), and each has some advantages. A more efficient wavenumber integration technique was recently developed by Yao and Harkrider (Ref. 3). For many cases of interest it will suffice to combine the generalized ray solution for body waves with a normal mode solution for surface waves. Numerous comparisons of synthetics computed by these various methods are given in Yao and Harkrider and Apsel and Luco (Ref. 4). Thus, it appears that wave propagation in flat-layered models is becoming better understood.

Three-dimensional features of the geology can be shown to have important effects on the ground motions at some locations (Refs. 5 and 6), and computational techniques to represent some of these effects have recently been developed. One of the most useful techniques for computing body waves in complex structures is called Glorified Optics (Ref. 7). The Glorified Optics method was extended to longer periods by Cerveny et al. (Ref. 8), who call this technique the Gaussian beam method. Both the Gaussian beam and WKBJ (Ref. 9) method are particular solutions of Maslov asymptotic theory. The Gaussian beam method has attracted much interest and is being rapidly improved (Refs. 10 and 11). Another useful

technique for complex structures is the finite difference method. For example, Vidale et al. (Ref. 12) uses a new technique based on a fourth-order finite difference code and a complex line-to-shear dislocation mapping to compute the response in a basin.

b. Scattering

Wave scattering by heterogeneities along the travel path has been recognized as an important factor influencing high frequency ground motions. A straightforward example of scattering effects was obtained by McLaughlin et al. (Ref. 13) who fielded a small array near a large (M_L 5.6) nuclear explosion at the Nevada Test Site. The data indicate transition to an irregular heterogeneous medium for wavelengths shorter than about 1 km. These data appear to be somewhat more coherent than small array data from earthquakes, at least in terms of the one quantity (PGA) for which comparisons can be made. For example, Smith et al. (Ref. 14) show that the El Centro differential array data from the 1979 Imperial Valley earthquake show a PGA variation of a factor of 1.2 (one standard deviation), while McCann and Boore (Ref. 15) found yet larger variations (factor of 1.3) in data from nearby stations recording the 1971 San Fernando earthquake. The PGA variations in the Nevada Test Site data is about a factor of 1.1. Much of the difference is probably due to the explosion source being simpler than an earthquake source.

There is a large and increasing literature devoted to the development of models for representing wave scattering. The usual approach is to represent the earth by a random, inhomogeneous medium. The data are then used to determine the statistical properties of this medium. Methods of this type have been applied to many regions including Kanto, Japan (Ref. 16), the Kuril (Ref. 17), Montana (Ref. 18), the Hindu-Kush (Ref. 19), the central U.S. (Ref. 20) and along the Imperial Fault (Ref. 21). The theory is presented in terms of operators which can, with some effort, be included in the earthquake simulation model. For example, Sato (Ref. 22) develops a model for synthesizing three-component

mean power spectral densities for P and S coda waves due to single scattering by distributed random inhomogeneities.

c. Faulting - Asperities and Barriers

A much improved understanding of the earthquake faulting process has emerged in recent years. The analysis of faulting is no longer restricted to uniform slip or stress drop over the entire fault plane, but now considers heterogeneous distribution of asperities and barriers. An asperity is a region of concentrated energy production, perhaps because it is under higher stress than surrounding regions. A barrier is a region that does not break during the main event, perhaps because it has unusually high fracture strength. Actual earthquakes probably include both asperities and barriers. This general picture of earthquake faulting has good theoretical support since detailed calculations of faulting with inhomogeneous prestress and fault strength (Ref. 23) result in slip distributions like those expected for a fault plane with asperities and barriers.

The asperity/barrier model assumes that the stress state and fracture strength vary over the fault plane. The intensity of the seismic radiation would be expected to vary the same way. Indeed, as will be discussed later, kinematic models inferred from the long period (> 0.5 seconds) ground motions have slip distributions consistent with this view; generally indicating that the long period energy production is dominated by localized regions of the fault surface. A key issue for estimating the high frequency ground motion for postulated earthquakes is whether the same is true for the high frequency energy production, or if this is distributed more uniformly over the fault plane. The dependence of high frequency energy production on depth is understood rather well, as will be discussed. Much less is known about the lateral distribution, but the detailed modeling intended should provide the information needed.

d. Radiation Energy Dependence on Fracture Strength and Depth

Theoretical considerations lead to the conclusion that ground motion energy production should be a strong function of stress state, which is generally a linear function of depth, at least to the base of the seismogenic zone. The geologic arguments for the dependence of shear resistance on depth have been summarized by Sibson (Ref. 24). McGarr (Ref. 25) presents data that strongly support this conclusion. The results of this study are summarized in Figure 6.1-4. The data were limited to recordings at small hypocentral distances, so the path effect is essentially limited to geometrical spreading (scaling by R). The free surface effects were also removed (essentially multiplication by two). Care was taken to measure the peak amplitude of a particular pulse consistently seen in all data from a particular earthquake (this was not necessarily the peak motion on every trace).

As is seen in Figure 6.1-4, the data span about 10 orders of magnitude in moment. They lead to a number of important conclusions about earthquake ground motion, including:

- Peak acceleration is essentially independent of event moment or magnitude.

- Focal depth has a first order effect on peak motions. In fact, the motions increase linearly with depth, as expected from increasing fracture strength due to increasing lithostatic pressure. This conclusion is best supported for the extensional stress regime (normal faulting) where there is a large data set. The data are rather sparse for strike-slip and reverse faulting events.

e. Fault Inhomogeneity from Long Period Data

The depth dependence of rupture production and other key characteristics

of the earthquake faulting process can be determined by modeling the long period data in detail. This has now been done for a number of large earthquakes, including the 1971 San Fernando (Ref. 26), 1979 Imperial Valley (Refs. 27 and 28), the 1979 Coyote Lake (Ref. 29), the 1978 Santa Barbara (Ref. 30), and the 1968 Borrego Mountain earthquake (Ref. 31). The ground motions from some well-instrumented aftershocks have also been carefully modeled, for example, by Cohn et al. (Ref. 32) and Lui and Helmberger (Ref. 6).

The best understood earthquake is probably the 1979 Imperial Valley earthquake, which has been carefully studied by many seismologists. The best models fit the long period strong motion data and far-field data rather well. This is indicated in Figure 6.1-5 from Hartzell and Helmberger (Ref. 28). The main conclusion is that a uniform rupture model on a rectangular fault plane does not explain the data. The preferred fault model has slip concentrated below 5 km (in the basement material). Laterally, there appear to be two localized areas of large dislocations. The average rupture velocity is 2.5-2.7 km/sec, which is 0.8-0.9 times the basement shear wave velocity. The estimated stress drop for the entire fault plane is only 5-10 bars, but the stress drop for the localized sources is about 200 bars.

The most complex event studied at this level of detail is the 1971 San Fernando earthquake, and there have been many attempts to infer the detailed nature of the rupture of this event from the ground motion data. Nearly all agree that it included at least two distinct rupture episodes. Most investigators represent this with a connected fault including two segments at different dip angles. However, Heaton (Ref. 26) found that the strong ground motions and teleseismic data could be better explained with a model that includes two separate and nearly parallel thrust fault events. It is difficult to resolve this or indeed to determine any of the characteristics of this complex source with high confidence because ground motions were recorded at only two stations (Pacoima Dam and Holiday Inn) within 10 km of the source.

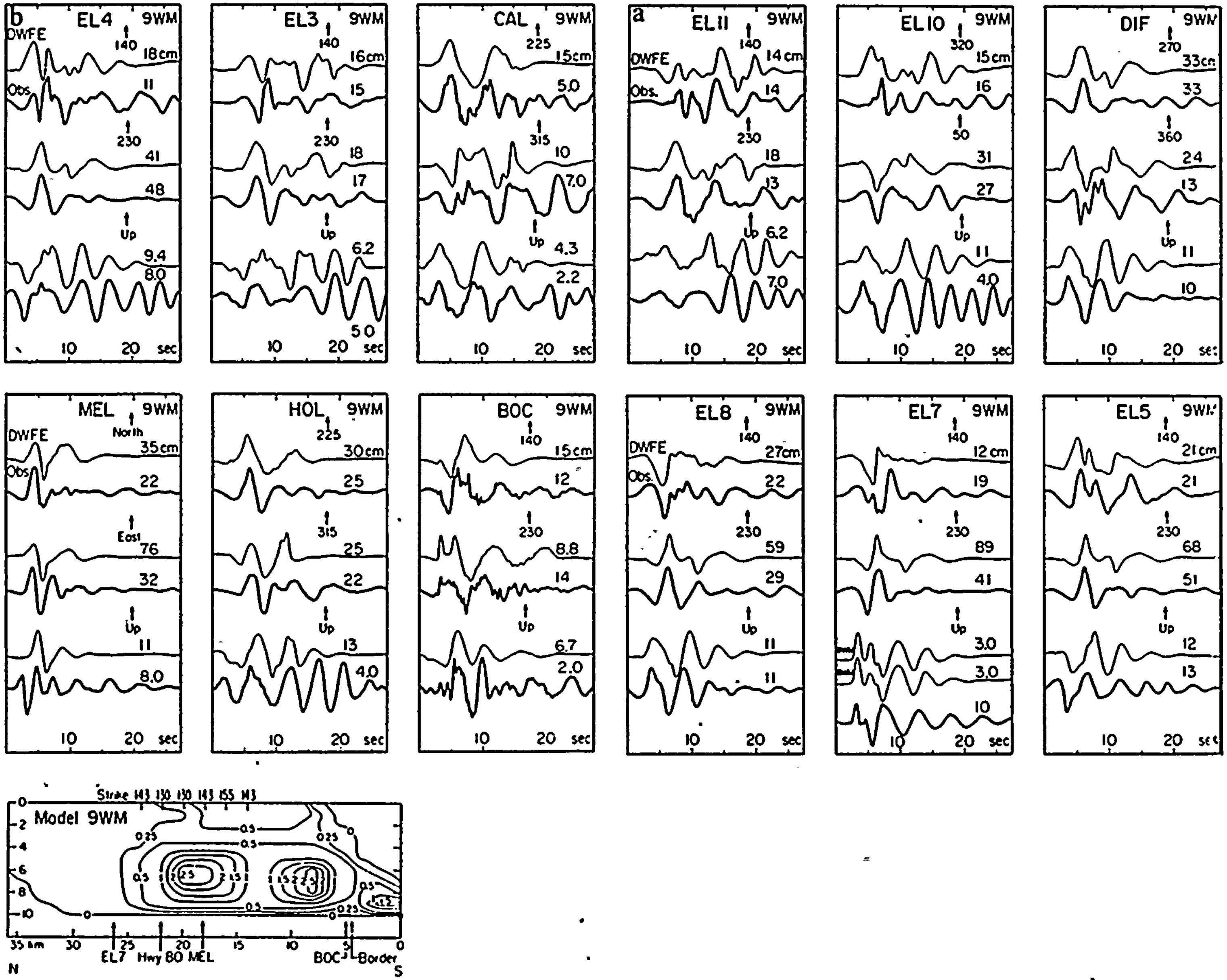


Figure 6.1-5. The fault model for the 1979 Imperial Valley earthquake is shown in terms of contoured dislocaton in meters. The observed and computed displacements are compared for twelve stations. The EL are El Centro array stations; DIF, El Centro differential array; MEL, Meloland Overpass; BOC, Bonds Corner; CAL, Calexico; HOL, Holtville. (Reproduced from Hartzell and Helmberger, 1982)

6.2 PROGRAM DESCRIPTION

A numerical model will be used to represent earthquake ground motion data and extend these data into the site-specific regime. It appears that the capability is now available to adequately deal with all the demands of such an approach. The remaining challenge is to assemble the various elements into a complete package, fit the model to the data, and apply it to estimated site-specific motions. The credibility of the results is not expected to depend on any particular theoretical aspect of the model. Rather, it will depend on how well the model represents the available data and on the extent to which events near Diablo Canyon may be different from events within current experience.

This section describes the program developed to achieve the established objectives. This program involves four major tasks:

- Formulate and develop the computational methods
- Fit the model to earthquake data
- Estimate the prediction uncertainty
- Compute estimated motions at the Diablo Canyon Power Plant site

In the remainder of this section, the effort required under each of these tasks is described. A summary description is then provided of the program in terms of the main sub-tasks.

6.2.1 Formulate and Develop the Computational Methods

This task is to assemble the computational tools necessary to simulate earthquake ground motions. The model must represent the production of energy on the fault and the propagation of seismic waves from the fault to the receiver. It must be flexible and capable of representing the key parameters that control earthquake ground motion. These include:

- Fault geometry
- Stress orientation
- Depth
- Direction of rupture
- Stress drop
- Rupture velocity
- Inhomogeneous fault propagation and energy production
- Travel path characteristics:
  - Velocity-depth profile
  - Q
  - Heterogeneous earth structure
  - Local site conditions

The DELTA model was capable of representing most of these parameters, and can be extended in a straightforward manner to give a satisfactory representation of the others. In Section 6.1.4, the technology available for this was reviewed. The major extensions of the model are to:

- Allow the slip velocity to vary over the fault plane
- Add an element to represent scattering in the wave propagation

Another major improvement on the DELTA model will be to introduce more efficient algorithms for computing the Green's functions and convolving them with the slip histories on the fault plane. First, the time for the Green's function calculations can be reduced by an order of magnitude; in fact, by much more than that for most cases of interest. Even more important, methods

will be developed for interpolating Green's functions in areas of the fault plane where they are slowly varying. This allows the time convolutions on the fault plane to be performed accurately and efficiently.

A key addition to the modeling capability is to be the development of a goodness-of-fit criterion to quantitatively characterize the agreement between model simulations and data. Several ways of doing this will be implemented. An elementary goodness-of-fit measure would be to compute the mean and standard deviation of G_1 computed from:

$$G_1^2 = \frac{1}{n} \sum_n (\log a_o - \log a_m)^2 \qquad (6.2\text{-}1)$$

where:

> a_m and a_o are the PGA for the model and observed data at each of the n stations

This is a mean square residual measure which is entirely analogous to quantities used to judge the success of regression fits to the empirical data.

While the G_1 is a useful quantity, it seems better to use a goodness-of-fit measure that includes broader band spectral information. Smoothed response spectra like those shown in Figure 6.1-3 provide a way to represent that information. For example, a G_2 can be computed by replacing the peak acceleration difference in Equation 6.2-1 with a measure of the area between the model and observed response spectra. That is, compute G_2 from:

$$G_2^2 = \frac{1}{n} \sum_n A^2$$

$$A = \sum_p W_p \cdot |\log R_m - \log R_o| \cdot \Delta\log f \qquad (6.2\text{-}2)$$

where:

> R_m and R_o are the model and observed response spectra sampled at m even steps in log frequency

The W_p are weights that could be selected to emphasize the fit at the frequencies (10-25 Hz) of primary interest. This measure is a quantification of the subjective criterion used to judge the DELTA model fit to the data.

A more severe basis for judging the model fit to the data is a measure based on Fourier spectra. As for the response spectra, it seems reasonable to base the measure on the area between smoothed model and observed spectra on a log-log plot. This can be done with whole record spectra, or with spectra computed for time windows chosen to isolate the peak arrivals. In most cases, these would be windows around the P wave on the verticals and around the S wave on the horizontals.

These suggested goodness-of-fit measures are all easy to implement and calculate, and there is no obstacle to calculating several measures at once. Each says something slightly different about the model fit to the data. The purpose is to obtain a statistical measure that provides a compact and easily understood quantification of the fit to the data. A secondary goal is to allow the model fit to the data to be directly compared with that from more familiar regression model fits to the data.

6.2.2 Fit the Model to Earthquake Data

The objective of this task is to parameterize earthquake ground motion data within the context of a physical model for simulating these ground motions. Obviously, success will depend on the size and quality of the data set used for the normalization. Thus, the first task is to select the earthquakes to be used.

The most relevant earthquakes are large strike-slip and reverse faulting events occuring in tectonic settings in some way similar to that of the Diablo Canyon site. The earthquakes selected should have a reasonably large set of strong motion records. Also, all else being equal, the bias is toward events that have been studied previously.

There are at least five large strike-slip and reverse faulting earthquakes in California that have been modeled in some detail for frequencies of less than 2 Hz. These are:

1. 1968 Borrego Mountain (M_L 6.4, strike-slip)

2. 1971 San Fernando (M_S 6.4, reverse)

3. 1978 Santa Barbara (M_L 5.1, reverse)

4. 1979 Coyote Lake (M_L 5.9, strike-slip)

5. 1979 Imperial Valley (M_S 6.9, strike-slip)

The DELTA model was normalized (in the sense described in Section 6.1.3) to Items 2 and 5, and to four additional earthquakes:

6. 1933 Long Beach (M_S 6.3, strike-slip)

7. 1940 Imperial Valley (M_S 7.2, strike-slip)

8. 1966 Parkfield (M_S 6.4, strike-slip)

9. 1976 Parkfield (M_L 4.9, strike-slip)

Two important earthquakes have recently occurred that are now being intensively studied:

10. 1983 Coalinga (M_L 6.5, reverse)

11. 1984 Morgan Hill (M_S 6.1, strike-slip)

A reasonable set to be emphasized in the model normalization includes Items 2, 3, 4, 5, 10, and 11. These six earthquakes include three of each type and

collectively provide a substantial fraction of the total strong motion data from strike-slip and reverse faulting events. Of these, by far the most difficult to model is the 1971 San Fernando earthquake, and several other events can be done with the same effort required for it. Of course, other events can be substituted or added, depending on the resources available.

Once the earthquake simulation model has been assembled and the events to be studied selected, the parameters of the model can be determined by fitting the data. This involves several steps:

- Fix as many parameters as possible with long period data

  Long period (>0.5 seconds) data are plentiful and the path effects reasonably well-understood. These data fix the fault properties (geometry, orientation, rupture velocity, and fault heterogeneity) on a scale of a few kilometers.

- Determine the path effects at high frequency

  It is very important to avoid confusing source and path effects in the large earthquake data. But small event data (e.g., aftershocks) allow the path effects to be isolated. They can then be represented empirically (using small event recordings) or with a model which reproduces the main features of the empirical data.

- Fit the model to high-frequency data ($\geq$25 Hz)

  This key step has not yet been done at the necessary level of detail, but the technology to do so is available.

The process of fitting the high frequency data with a model is basically an inversion problem. After fixing the low frequency characteristics of the model, what needs to be determined is the distribution of high frequency sources which best fits the observed data. The DELTA model assumed a uniform

production of energy (at all frequencies) over the fault plane. Models that include a linear increase of energy production with increasing depth are expected to provide a better fit to the data (they certainly do at the longer periods). This must be demonstrated.

The sources of high frequency energy can be thought of as asperities on the fault plane. After introducing depth dependence, the next step is to determine the distribution of these asperities. Some formal inversion of the data [e.g., by the isochronic procedure (Ref. 33)] can be employed. However, an approach of fitting the data that allows many earthquake-specific parameters must be avoided, unless these earthquake-specific parameters can reasonably be specified for postulated earthquakes at the Diablo Canyon site. Rather, more general characteristics will be determined of earthquakes that also can be expected to characterize earthquakes at Diablo Canyon. Thus, the emphasis will be on whether shallow strike-slip and reverse faulting earthquakes are characterized by high frequency radiation that tends to be distributed uniformly along the lateral extent of the fault plane, or whether it tends to be dominated by relatively few large asperities.

6.2.3 Estimate the Prediction Uncertainty

It is important that careful quantification be made of the uncertainty in ground motion predictions made by the model. The goodness-of-fit measure (Section 6.2.1) provides a statistical description of how well earthquake data are fit by the model (e.g., in terms of the mean and standard deviation of the ratio of observed and computed ground motions). Quantification must also be made of the sensitivity of the model to variations in the input parameters.

The objective will be to obtain a model with relatively few earthquake-specific source parameters; there is doubtless some tradeoff between the goodness-of-fit and the number of earthquake-specific parameters. This tradeoff will be explored, but the general view is that the most useful site-specific predictions will be obtained with models with relatively few earthquake-specific parameters. A detailed knowledge of the model sensitivity to parameter variations is very important for developing such models.

Another key part of this task will be to determine the range of earthquake characteristics that are consistent with the relevant ground motion data. A large body of data will be modeled, and the earthquakes studied will presumably be different in various aspects. Since the earthquakes studied will be chosen because they are, in some sense, representative of the Diablo Canyon site, these differences are indicative of the range of characteristics that might be encountered at Diablo Canyon.

Site-specific estimates of ground motion for a postulated earthquake should be expressed as a range of plausible motions. The expressed range should include effects resulting from alternate configurations for the detailed source representation and unexplainable characteristics generally classified as data scatter. The range of predictions should be characterized in terms of their probability of occurrence, given the conditions specified for the postulated earthquake. That is, the most probable or median levels of motion should be determined, and the level of motion characterized as the median plus one standard deviation should be determined so as to envelope 84 percent of the plausible cases.

Methods for obtaining these site-specific estimates can be tested by predicting the motions recorded at selected sites. Comparisons between predicted and recorded levels of motion can serve to verify the procedures used for establishing the median and the 84th percentile estimates.

6.2.4 Compute Estimated Motions at the DCPP Site

Path characteristics can have an important effect on earthquake ground motions. There are some ground motion data from stations on the site. These include information about site-specific travel path characteristics and will be studied to estimate such characteristics. Also, the geologic data must be examined for evidence of any special feature that could influence the ground motions.

Work done in other parts of the overall Program will lead to specification of

the general characteristics of postulated earthquakes at the site. These general characteristics must be interpreted within the parameterization of the model. This will result in a range of plausible parameters for the postulated earthquakes. Model calculations then provide a range of site-specific models. The uncertainty in the ground motion predictions will be quantified by combining the uncertainty associated with the model misfit to the data with the uncertainty introduced by the inability to confidently fix the input parameters of the model. The sensitivity studies performed in the second task are very important for the latter.

The ground motion data must be presented in a form suitable for the soil-structure interaction analysis. These estimates will be in the form of a range of site-specific time histories. The angle of incidence will be specified throughout the time history.

6.2.5 Summary of Research Tasks

a. Task I - Formulate and Develop the Computational Model

(1) Develop criteria for goodness-of-fit with recorded motions

The criteria are to provide quantitative measures of the agreement between the recorded and computed ground motions at relevant frequencies. The statistics should be in a form suitable for comparison with the statistics characterizing the fit obtained with more familiar regression models.

(2) Develop module for characterizing the wave transmission

This module must compute realistic path Green's functions. The computed path effects must be consistent with empirical observations of path effects (where they can be isolated from source effects).

(3) Develop module for representing the fault process and for convolving the path and source functions to compute seismograms.

The representation must be flexible and capable of representing inhomogeneous faulting.

(4) Expedite the computational methods

Fast and efficient algorithms must be used. For most calculations, approximations can be introduced that vastly reduce the cost without severely compromising the accuracy, but this tradeoff must be explored and understood.

b. <u>Task II - Fit the Model to Earthquake Data</u>

(1) Select earthquakes to be modeled and prepare data for analysis

The emphasis is on strike-slip and reverse faulting events in California. These provide most of the relevant strong motion data for empirically-based ground motion estimates.

(2) Establish site-specific wave propagation

Data from other events (mainly aftershocks) indicate site-specific wave propagation characteristics. These must be examined to avoid confusing path and source effects, and also to improve the quantification of the path effects that do occur.

(3) Constrain the earthquake with long.period data (>0.5 seconds)

Teleseismic and strong motion displacement data allow many of the gross fault properties (geometry, orientation, rupture velocity, and fault inhomogeneity) to be determined on a scale of a few kilometers. Reasonable models have already been determined for most

of the events of interest, so it is only necessary to check these models and make appropriate alterations.

(4) Fit the model to empirical strong motion data to 25 Hz

Beginning with the model determined in sub-task (3) above, the model features controlling the high frequency radiation must be adjusted to fit the data. The key issues have to do with the distribution of regions of high frequency radiation. The extremes are a roughly uniform distribution over the fault plane and concentration at a relatively small number of asperities.

c. <u>Task III - Estimate the Prediction Uncertainty</u>

(1) Establish generic source characteristics

Based on the source properties determined from Task 2, general features of earthquake sources will be established. Teleseismic recordings of very large earthquakes will be used to confirm the source trends with increasing magnitude.

(2) Determine the prediction uncertainty

The numerical model will be used to predict the ground motion recorded for several earthquakes using generic representations of the source. That is, recorded earthquakes will be modeled using methods to be applied at the Diablo Canyon site, and variances with the recorded data will be used to provide the measure for prediction uncertainty. The prediction uncertainty will be expressed as a statistical distribution about the median prediction of response spectrum.

d. Task IV - Compute Estimated Motions at the Diablo Canyon Power Plant Site

(1) Establish site-specific conditions

Review the geologic data and, especially, recordings from seismometers at the site to understand site-specific conditions that control the ground motions.

(2) Determine the range of motions for postulated earthquakes

Given a description of the general characteristics of earthquakes postulated for the Hosgri Fault or other nearby faults, compute the ground motions at the site. Vary the model over the range of plausible parameters for these postulated events and compute the associated motions.

(3) Provide a statistical estimate of uncertainty in the ground motion estimates

The prediction uncertainty (Task III) provides one component of the uncertainty. Another component must be determined from the range of motions in Task IV.B, and the two must then be combined.

(4) Provide input for soil-structure analysis

The ground motion data must be presented in a form suitable for use in the soil-structure interaction analysis. In particular, estimates of the angle of incidence and spatial coherence of the wave field must be provided.

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7. SOIL-STRUCTURE INTERACTION

7.1 OBJECTIVE

This section describes the study of seismic soil-structure interaction (SSI) to be conducted for the Diablo Canyon plant structures. The objective is to examine the effect of dynamic coupling between the plant structures and the supporting rock medium on the structural base motions associated with the free-field seismic ground motion at the site. The study will utilize the free-field ground motions indicated by the earthquake ground motion studies for the site described in Sections 5 and 6. The SSI analyses to be performed will generate the structural base motions and in-structure response motions to be used for developing the plant fragility curves and for performing deterministic evaluations as necessary.

Seismic SSI analysis techniques have advanced rapidly since the plant was designed. Three-dimensional (3-D) SSI analyses, including consideration of interaction of multiple structures and different types of seismic wave incidence characteristics, which were not feasible during the design of the plant, have now become technically feasible through the recent development of several 3-D SSI analysis computer codes. Although limitations still exist for any individual analysis technique, the effect of these limitations can be evaluated through the use of different analysis techniques and the reconciliation of results with each other. The current study on the SSI effect will employ these new SSI analysis techniques and will include the following elements in the analysis approach:

- o Three-dimensional soil-structure interaction analysis methods will be employed
- o All components of free-field ground motions at the site will be considered in the evaluation of seismic response
- o Consideration will be given to the effects of variations in seismic

wave incidence characteristics including inclined body waves and surface waves

- If necessary, consideration will be given to the effects of inelastic response of the plant structures under the strong earthquake ground motions

- Recorded earthquake data at the Diablo Canyon plant site will be utilized, to the extent practicable, to assist in calibrating the low amplitude dynamic characteristics of the SSI dynamic models

7.2 ANALYTICAL APPROACH

Phenomenologically, the seismic soil-structure interaction effect can be separated into two physical effects acting simultaneously: the so-called kinematic interaction effect and the inertial interaction effect. The former results from diffractions and reflections of impinging (incident) seismic waves in the foundation medium, i.e., seismic wave scattering, due to the presence of structural foundations, without regard to the inertial properties of the structures. The latter results from the dynamic response of a coupled dynamic system formed by coupling the dynamic characteristics (i.e., the inertial properties) of the structures with those of the foundation medium, i.e., the foundation impedances. By separating the SSI effects into these two physical phenomena, the analysis of SSI effects can also be methodologically separated into two phases: the analysis of kinematic interaction and the analysis of inertial interaction. The kinematic interaction analysis generates seismic motions at the structural bases from the free-field ground motions; these are then used as the input motions to the SSI dynamic model for the analysis of inertial interaction.

By definition, the kinematic interaction is affected not only by the structural base geometry and configuration, but also by the free-field incident seismic wave compositions (shear and/or compression body waves, and/or surface waves) and wave incident characteristics (i.e., wave incident

angle as a function of wave types and frequencies). For a structure with a rigid base, the result of kinematic interaction for a specific seismic wave incident specification will, in general, produce three translational components and three rotational components of seismic input motion at the structural base from kinematic interaction. For a consistent analysis, the effects of these six component input motions at the structural base should be considered for the inertial interaction analysis.

The inertial interaction is, by definition, affected only by the contrast of the inertial properties of the structures relative to those of the foundation medium. Thus, for a structure supported on a relatively hard rock foundation, the foundation impedances will be high and the effects of inertial interaction will be relatively small. The inertial interaction response will approach the response of a fixed-base structure as the foundation medium becomes more rigid. On the other hand, if the structure is supported on a relatively soft soil foundation, the effects of inertial interaction will be more significant, and the inertial interaction response will approach the response of a rigid body on a flexible foundation as the foundation medium becomes softer.

Since the Diablo Canyon plant is founded on a rock site, the foundation impedances are expected to be relatively high. Thus, it might be expected that the effects of inertial interaction would be relatively small at this site, although they may still be significant enough to warrant consideration.

The state-of-the-art for analyzing the seismic SSI effect basically follows the substructure approach or the direct approach. In the substructure approach, the analysis of kinematic interaction and that of inertial interaction are separated into two successive analysis steps. The kinematic interaction is analyzed, then the result is fed into an SSI dynamic model as the input motion for the subsequent inertial interaction analysis. The SSI model adopted in this approach is formed by coupling the dynamic model of the structure with the foundation model represented by the foundation impedances associated with the structural base motion degrees-of-freedom. The foundation impedances are usually derived by assuming that the structural base is rigid

and the foundation medium is a uniform or horizontally-layered elastic or viscoelastic half-space continuum. Thus, this approach is sometimes referred to as the half-space approach. The CLASSI computer program (Ref. 1) is a typical example which implements the half-space approach of SSI analysis methodology.

In the direct approach, the analyses of kinematic interaction and inertial interaction are generally combined into one integrated analysis step. The analytical SSI model used in this approach is formed by combining the dynamic models, represented usually by finite elements, for both the structure and a finite portion of the foundation medium into an integrated SSI system. The free-field seismic ground motion is used directly as the input motion for the SSI analysis, and the analysis procedure combines the result of kinematic interaction with that of inertial interaction internally giving the final SSI response as the direct output. Due to its extensive use of finite element models, the direct approach is also often referred to as the finite element approach. The recently developed 3-D SSI analysis computer program SASSI (Ref. 2) is an example which implements the finite element approach of SSI analysis methodology.

Either the half-space approach using, for example, the computer program CLASSI, or the finite element approach using, for example, the computer program SASSI, can be adopted for a 3-D SSI analysis for the Diablo Canyon plant. However, each analysis approach has its limitations because of the specific analytical assumptions used in formulating the SSI solution, and the specific numerical technique adopted in the analysis computer code. For example, the half-space approach utilizing the CLASSI computer code has the limitations that the structural base is considered rigid and the foundation medium is approximated by a uniform or horizontally-layered elastic or viscoelastic half-space continuum. Thus, the effect of structural embedment, basemat flexibility, and foundation material inhomogeneity cannot be addressed directly by this technique. On the other hand, the structural embedment, basemat flexibility, and material inhomogeneity in the foundation medium can be included in the finite element approach utilizing the SASSI computer code.

However, due to the enormous size of the SSI model that usually results from the use of 3-D finite-element representation for the foundation medium, the degree of refinement in the structural model that can be used for the finite element approach is usually cruder than that for the half-space approach. Furthermore, because of the extensive calculational effort, the analysis by the finite element approach is usually limited to a frequency range lower than what can be accommodated by the half-space approach. Consequently, in order to compensate for the limitations in each analysis approach, the current study will employ both the half-space approach and the finite element approach for the SSI analysis of the Diablo Canyon plant. This will not only increase the reliability of the analysis result, but will also allow an investigation of the sensitivity of SSI response to the limitations of each analysis approach. For the current study, the CLASSI computer code will be adopted for the half-space approach and the SASSI computer code will be adopted for the finite element approach.

7.2.1 CLASSI Computer Program

CLASSI (Continuum Linear Analysis for Soil-Structure Interaction) is a linear 3-D seismic SSI analysis program developed by Luco and Wong (Ref. 1) at the University of California, San Diego.

a. Program Theory

The analysis method used in CLASSI is based on the substructuring technique which separates the analysis of kinematic interaction from that of inertial interaction in two successive analysis steps. Considering a typical structure on a rigid foundation supported on a soil medium as shown in Figure 7.2-1, the substructuring technique applied to this soil-structure system is schematically shown in Figure 7.2-2.

The analysis of kinematic interaction as shown in block I of Figure 7.2-2, is handled by first deriving the so-called seismic wave scattering matrix, which is then used to transform a given free-field

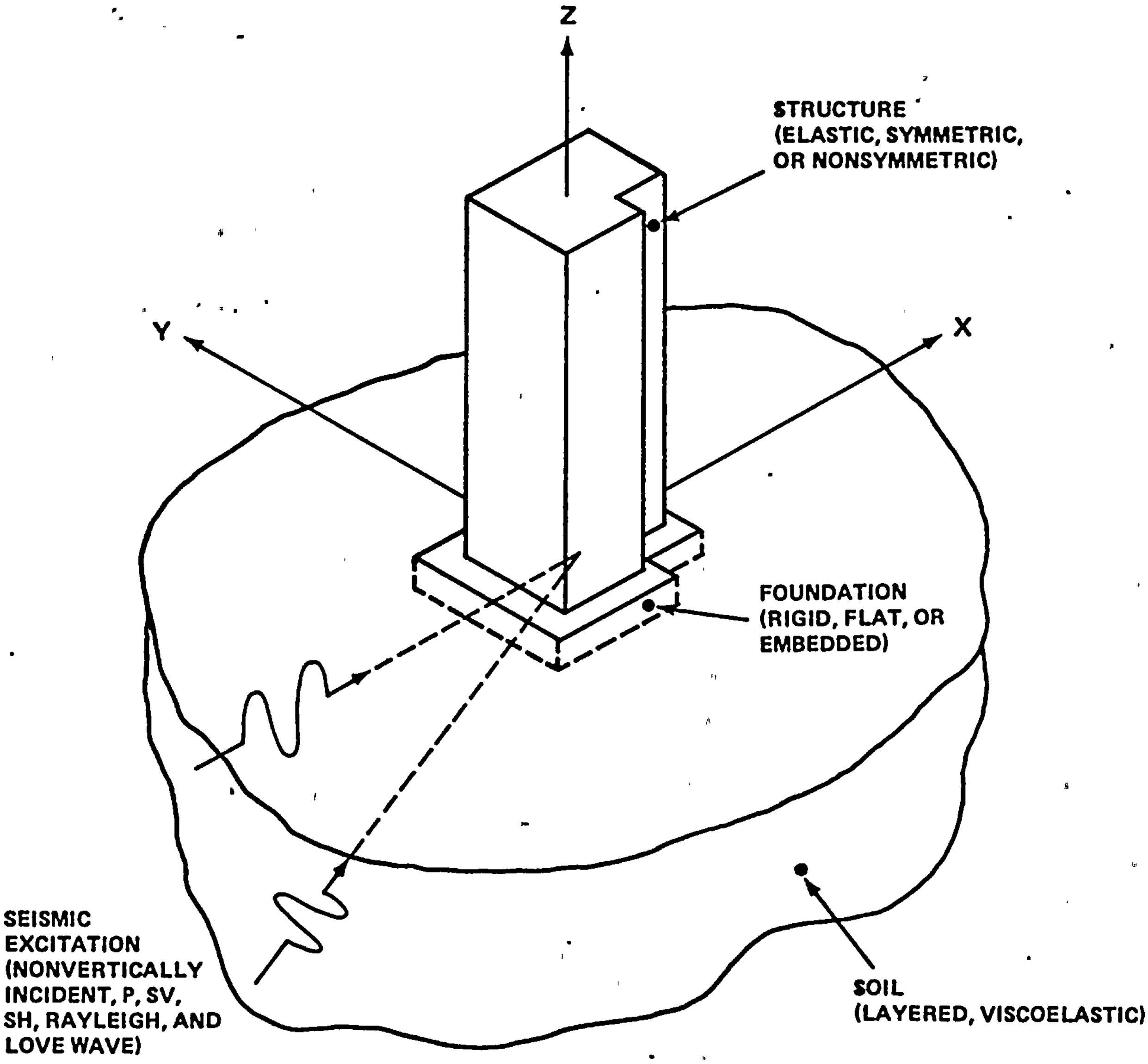

Figure 7.2-1 DESCRIPTION OF THE SOIL-STRUCTURE SYSTEM

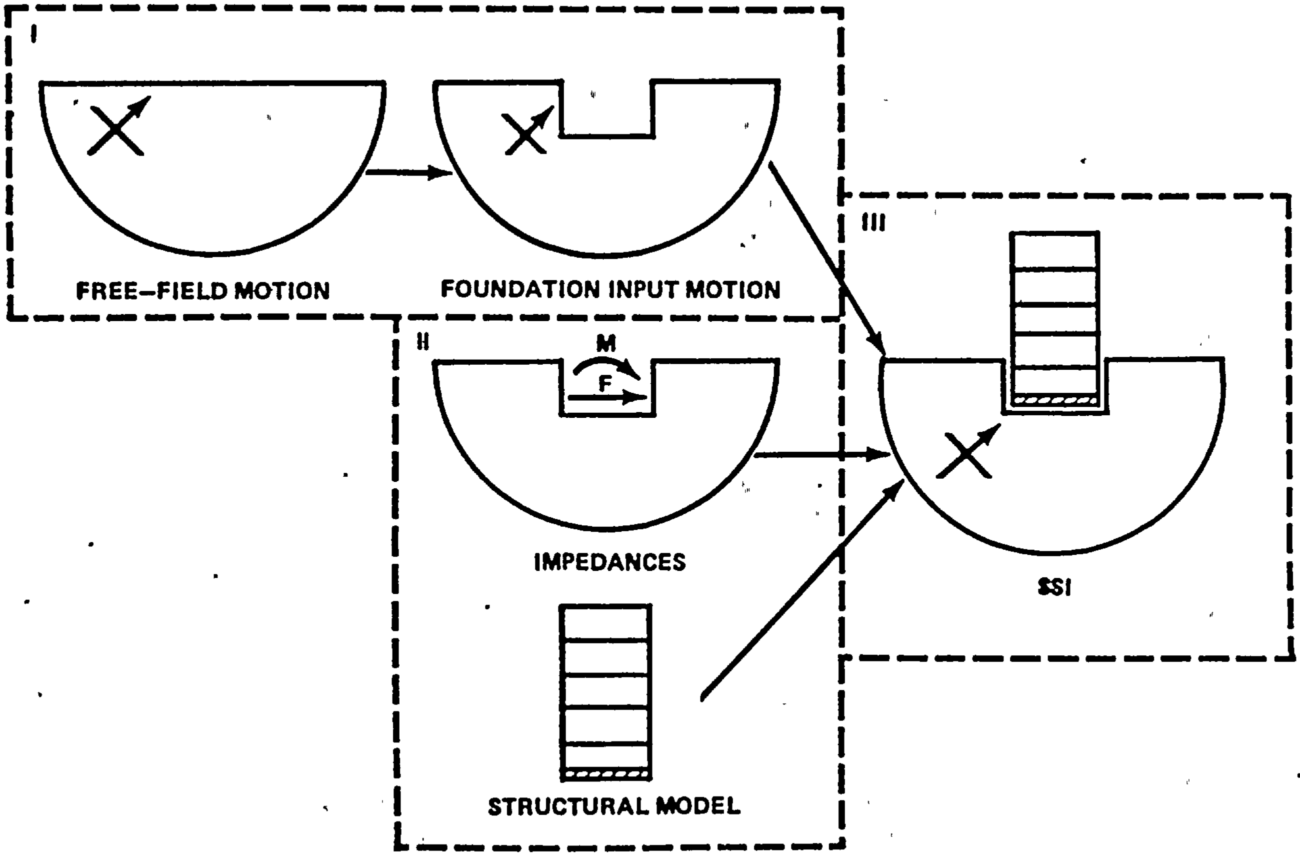

Figure 7.2 - 2 CLASSI SUBSTRUCTURING TECHNIQUE

seismic ground wave field into a set of seismic motions associated with the structural base motion degrees-of-freedom. The analysis of inertial interaction is handled by first deriving the foundation impedance matrix using an integral equation method and Green's functions of a continuum half-space (Ref. 3). The foundation impedances are then combined with the fixed-base structural impedances to form the SSI system, as shown in block II of Figure 7.2-2. Finally, the interaction response is calculated as shown in block III of Figure 7.2-2 by subjecting the SSI system to the motions at the structure base resulting from the kinematic interaction from block I as the input seismic excitation. For the case of multiple structures interacting through the foundation soil, the above procedure is extended in a generalized sense as detailed in Ref. 1.

b. Program Description

CLASSI is a linear 3-D computer program for seismic SSI analysis using the half-space approach. The program solves the SSI problem in the frequency domain using the Fast Fourier Transforms technique. CLASSI is comprised of program modules developed to solve the SSI problem in separate steps; the results of individual steps by different modules are combined in the final interaction analysis module to satisfy the interaction conditions at the structural base.

c. Program Capabilities and Limitations

CLASSI has the following capabilities and limitations:

- The foundation medium can be modeled as an elastic or viscoelastic, uniform or horizontally-layered, half-space.

- Free-field seismic ground motions can be specified as a seismic wave field composed of arbitrary incidence angles of incoming P, SV, or SH body waves, or Rayleigh and Love surface waves, or any combination thereof.

- The structural base must be rigid and flat but can be of any arbitrary planar shape; multiple structural bases can be accommodated.

- The effects of embedment and structure-to-structure interaction with different embedment depths can only be approximately evaluated using embedment foundation impedance modification factors.

- The analysis procedure utilizes the frequency domain solution method. Therefore, nonlinear analyses cannot be directly performed.

- The fixed-base modal properties of structures need be extracted using other programs before they are used as input to CLASSI. Either finite element models or generalized stick models can be used as structural models.

7.2.2 SASSI Computer Program

SASSI (System for Analysis of Soil-Structure Interaction) is a computer program for dynamic analyses of SSI systems using the finite element approach. The program was developed by Lysmer and his research group at the University of California, Berkeley (Ref. 2).

a. Program Theory

The computer program SASSI uses the so-called flexible volume method to formulate the soil-structure interaction problem in the frequency domain using the complex response technique. By the flexible volume method, the complete soil-structure system, as shown schematically in Figure 7.2-3(a), is partitioned into the foundation and the structure as shown in Figures 7.2-3(b) and (c), respectively. In this partitioning, the structure consists of the superstructure and the basement substracting the excavated soil. The soil to be excavated is retained with the foundation model, making the foundation model free of excavation pits. This enables the calculation of foundation impedances associated with any

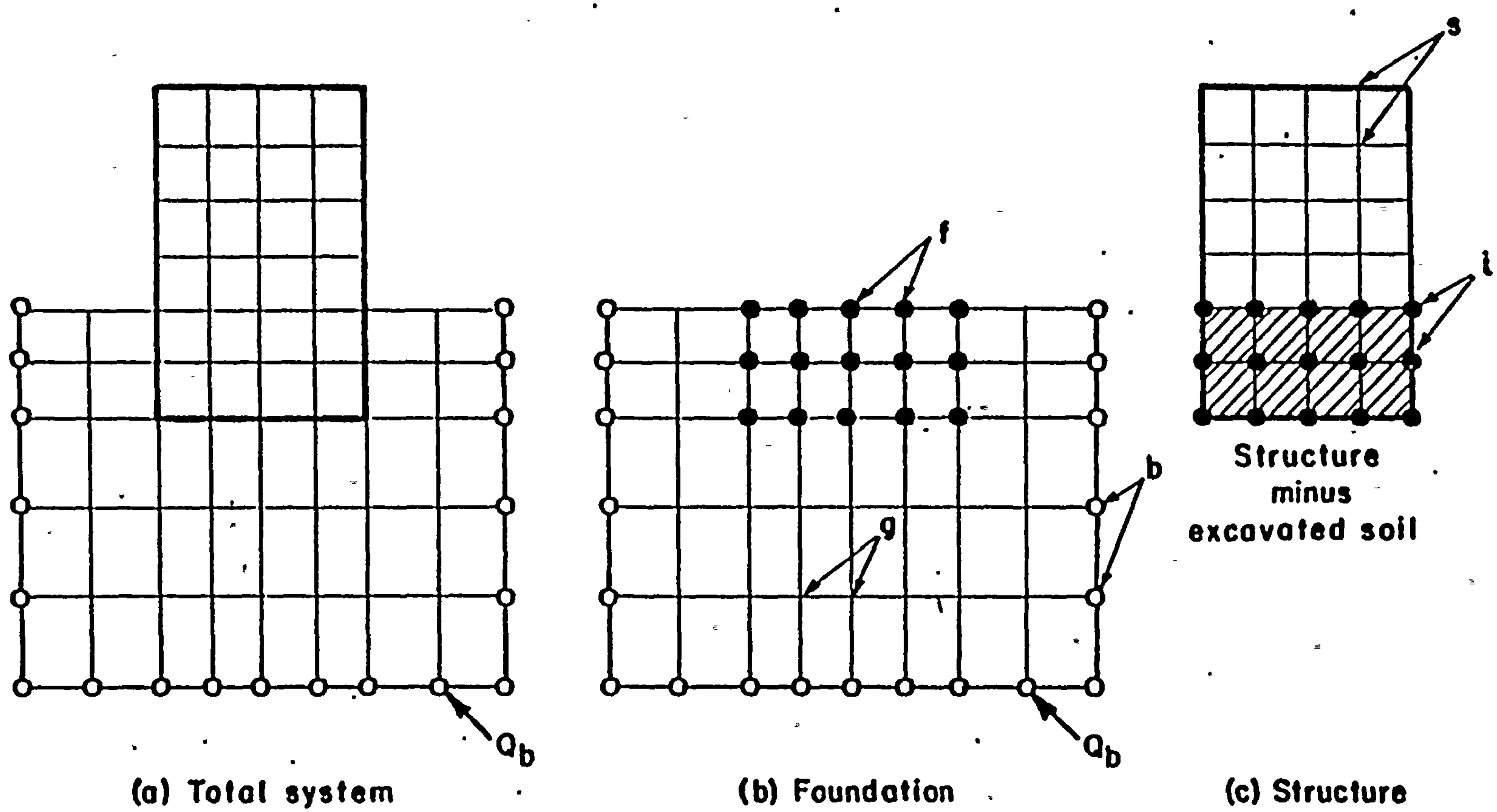

Figure 7.2-3 SASSI Flexible Volume Method

node in the foundation using the Green's function for a half-space continuum. Because of the way the excavated soil is partitioned, the interaction between the structure and the foundation thus takes place at all basement nodes, i.e., the flexible volume. The equations of motion for the combined SSI model are formulated by combining the equations of motion for the structural subsystem with those of the foundation soil subsystem in the frequency domain.

By this formulation, the solution of the soil-structure interaction problem reduces to the following three steps:

- Solve the site response problem to determine the free-field motions for the interaction nodes within the flexible volume based on a specified free-field ground motion wave field. The free-field ground motion can be specified as a seismic wave field composed of arbitrary incidence angle of incoming P, SV, or SH body waves, and Rayleigh and Love surface waves, or any combination thereof.

- Compute the foundation impedance matrix which represents the dynamic stiffnesses and damping coefficients of the foundation at the interaction nodes in the flexible volume using the method in Ref. 4.

- Solve the interaction problem to determine the SSI responses. This involves forming the load vector and the complex stiffness matrix for the SSI system by coupling the foundation impedance matrix with the complex stiffness matrix of the structures, and then solving the equations of motion for the SSI response.

b. Program Description

SASSI is a finite element program for dynamic analyses of SSI systems subjected to seismic and/or external forcing excitations. The program uses the Fast Fourier Transform technique to solve the 2- and 3-D SSI

problems in the frequency domain. SASSI is a linear analysis program although approximate nonlinear analysis can be performed using the equivalent linear method.

SASSI is comprised of program modules developed to provide flexibility for practical applications. The arrangement of these modules permits users to execute parts of the program when changes occur in input parameters such as the input motion, seismic wave environment, dynamic external force, and superstructural properties. SASSI can be used to compute structural transfer functions, response time histories, response spectra, and stresses and strains in structural and soil elements.

c. Program Capabilities and Limitations

The SASSI program has the following capabilities and limitations:

- o The site can be modeled with semi-infinite elastic or viscoelastic horizontal layers on a rigid base or elastic half-space. Soil material inhomogeneity can be accommodated within the finite element soil model.
- o The flexibility of the basemat can be included in the model.
- o Material damping can be assigned differently for different soil elements using the complex modulus approach; this leads to effectively frequency-independent damping ratios for each soil element.
- o Arbitrary incidence angles of P, SV, or SH body waves, and Rayleigh and Love surface waves, can be specified for the free-field seismic wave environment.
- o The dynamic external force can be specified as input excitation.

- o The effect of structural embedment on the SSI response can be directly considered.

- o The effect of structure-to-structure interaction with different embedment depths can be evaluated.

7.3 PROGRAM DESCRIPTION

In order to implement the analytical approach outlined in Section 7.2, a six-task program plan is envisaged:

a. Task 1 - Assemblage and review of the existing foundation rock configuration and properties.

b. Task 2 - Review of the results of the earthquake ground motion studies and development of free-field input motions for the SSI analyses.

c. Task 3 - Development of 3-D SSI analytical models using both the half-space approach and the finite element approach.

d. Task 4 - Analyses of appropriate earthquake accelerograms recorded at the plant site and in the plant structures, and correlation of analytical results with recorded data.

e. Task 5 - Parametric studies for investigating the sensitivity of SSI responses to variations in system parameters in order to evaluate the effects of uncertainties.

f. Task 6 - SSI response analyses to generate the structural base motions and in-structure response motions, as necessary.

This program will be modified, however, as determined appropriate in the light of the results obtained from the various studies in the LTSP. A general description of each of the above tasks is presented in the following subsections.

7.3.1 Foundation Rock Configuration and Properties

The Diablo Canyon plant is founded on rock. The existing site rock boring data and data from the geophysical and geotechnical investigation reports will be assembled and reviewed. The results of this review will be used to determine appropriate values and associated uncertainties in the geophysical and geotechnical properties to be used for constructing the SSI models and for SSI response analyses. The review of data will cover the following information:

a. The ground surface topography.

b. The foundation rock stratification and layering orientation and material homogeneity.

c. The geophysical data such as the field-measured shear and compression wave velocities.

d. Available geotechnical data concerning such rock characteristics as the dynamic shear modulus, Poisson's ratio, material density, and material damping, as well as possible variations of these properties with dynamic strains, and uncertainties associated with the available data.

During the review of rock data, an evaluation will be made to determine the adequacy of the existing data base so that the confidence level of the rock properties determined from the data base can be assessed.

7.3.2 Free-field Input Motion

In this task, a review will be made of the results of the earthquake ground motion studies for the Diablo Canyon plant site (described in Sections 5 and 6) to determine the appropriate free-field seismic input motions for the SSI analyses. The ground motion information to be reviewed includes:

a. The site-specific free-field ground response spectra and the location of the motion definition.

b. The ensemble of real and/or synthetic ground motion time histories associated with the site-specific spectra.

c. The free-field seismic wave incidence characteristics (incidence angles and wave compositions) and their relationship with seismic source locations.

If the required free-field input motion time histories are not readily available from the earthquake ground motion studies, synthetic earthquake ground motion time histories, which are compatible with the site-specific response spectra and other relevant ground motion parameters such as the duration of strong shaking, and the response spectrum intensity, will be developed for use as the input for SSI analyses. If consideration of nonlinear response is required, an appropriate set of real earthquake ground motion time histories will be identified for use as the input for SSI analyses.

7.3.3 SSI Analytical Models

Based on the as-built structural configuration of DCPP and the foundation rock profile and properties determined from the review described in Section 7.3.1, suitable 3-D analytical models for the power block structures and the rock foundation will be developed. If appropriate, the analytical models for all four structures of the power block, i.e. the containment structures for both units, the auxiliary building, and the turbine building, will be combined with the analytical model for the rock foundation to form an integrated 3-D SSI analytical model.

7.3.3.1 3-D Structural Models

A review will be made of the as-built structural configuration and the existing structural models for the power block structures. Suitable 3-D

dynamic models for each of these structures, to be used for coupling with the foundation model, will be developed separately. These 3-D structural models will be in the form of generalized 3-D lumped-mass-beam-stick models. As-built structural and equipment masses will be lumped at the floor locations. The generalized stiffnesses of beam elements in the stick models will be developed considering realistic stiffness distribution of major structural elements. The effect of floor flexibilities will be considered in developing the stick models. Three-dimensional finite element structural models will be utilized as necessary for a more realistic representation of the structural stiffness distribution, from which the generalized stiffnesses of the 3-D beam-stick models can be deduced. An adequate number of lumped masses and dynamic-degrees-of-freedom will be used for the structural models so that the modal properties of the fixed-base structural modes within the frequency range of interest will be adequately represented. Damping ratios for the fixed-base structural model will be selected such that they are consistent with the level of structural response expected from the SSI analysis.

7.3.3.2 3-D Foundation Models

Three-dimensional foundation models for the power block structures will be developed using both the half-space and finite element approaches. For the model using the half-space approach, the structural base for individual structures will be assumed to be rigid. Six dynamic-degrees-of-freedom, i.e., three translations and three rotations, will be used for each structurally separate basemat. The seismic wave scattering matrix which represents the kinematic interaction effect, and the foundation impedance matrix which represents the inertial interaction effect, will be developed considering the presence of all four power block structures. Thus, the resulting matrices represent not only the SSI effect of individual structures, but also the effect due to the through-rock, structure-to-structure interaction. The CLASSI computer program, described in Section 7.2.1, which is capable of treating 3-D interaction, multiple structures, and different types of free-field seismic wave environment, will be used for the development of the half-space foundation model.

For the foundation model using the finite element approach, the structural embedment, basemat flexibilities and possibly foundation rock material inhomogeneity will be included in the finite element foundation model. All four structures in the power block will be coupled with the finite element foundation model to form an integrated 3-D finite element SSI model. The finite element mesh for the rock foundation will be selected to accommodate the significant frequency seismic wave components of interest in the free-field ground motion. The model will be developed utilizing the SASSI computer code described in Section 7.2.2, which is capable of treating 3-D interaction, structural embedment, near-field foundation material inhomogeneity, multiple structures as well as different types of free-field seismic wave environment.

7.3.4 Correlation with Recorded Data

Data analyses will be performed of selected earthquake accelerograms recorded at the Diablo Canyon site and in the plant structures. Transfer functions from the free-field recording station to the instrumented locations in the power block structures, and between paired recording stations in the structures, will be computed from the recorded data. The processed data will be used to correlate with the analytical SSI response for checking the following:

a. The SSI effect for the power block structures.

b. The validity of the analytical techniques for low amplitude responses.

c. The low amplitude dynamic characteristics of the plant structure-foundation system.

The recent earthquakes for which recorded data are available at the Diablo Canyon Plant are: (1) Point Sal earthquake of May 28, 1980 ($M_L = 4.6$); (2) Coalinga earthquake of May 2, 1983 ($M_L = 6.5$); and (3) Santa Maria offshore earthquake of June 20, 1984 ($M_L = 4.3$). The recorded data for

these earthquakes will be analyzed using current accelerogram processing techniques. Due to the low intensity levels (maximum accelerations recorded were about or below 0.01g), the useful frequency range of recorded data will be evaluated and determined when these data are processed. The processed data in the useful frequency range will be utilized, to the extent practicable, for correlating the low amplitude dynamic response characteristics of the analytical SSI models.

7.3.4.1 Recording Instrumentation Locations

The strong motion instrumentation at Diablo Canyon Plant consists of a basic system and a supplemental seismic system. The basic system consists of three triaxial force-balance accelerometers. The supplemental seismic system consists of 61 force-balance accelerometers, and has an automatic gain-ranging feature, enabling the system to record small accelerations at a high gain, thus allowing recording of low intensity ground motions (Ref. 5). Due to the automatic gain-ranging feature of the supplemental seismic system, most of the data recorded at the site for small magnitude earthquakes are from this system.

The locations of sensors of the supplemental seismic system are summarized as follows. There are three triaxial accelerometers located in the free-field as shown in Figure 7.3-1. There are a total of 11 triaxial accelerometers located in the containment structures of both units: three each at the basement (el. 89 feet) of each unit, three at the springline level (el. 231 feet) of the Unit 1 containment shell, and two at the operating deck (el. 140 feet) of Unit 1 containment near the steam generator compartments. Additionally, there are two biaxial horizontal accelerometers located at el. 140 feet on the operating deck of the Unit 1 containment structure and one vertical accelerometer located at el. 91 feet near the reactor of Unit 1. Three triaxial accelerometers are located in the auxiliary building at el. 100 feet: one at the west end, one at the east end, and one at the north end of the building. There are two triaxial accelerometers located at el. 85 feet in the turbine building: one at the north end and one at the south end. Additionally, one biaxial horizontal accelerometer is located on the turbine deck (el. 140 feet) near the north end of the turbine building.

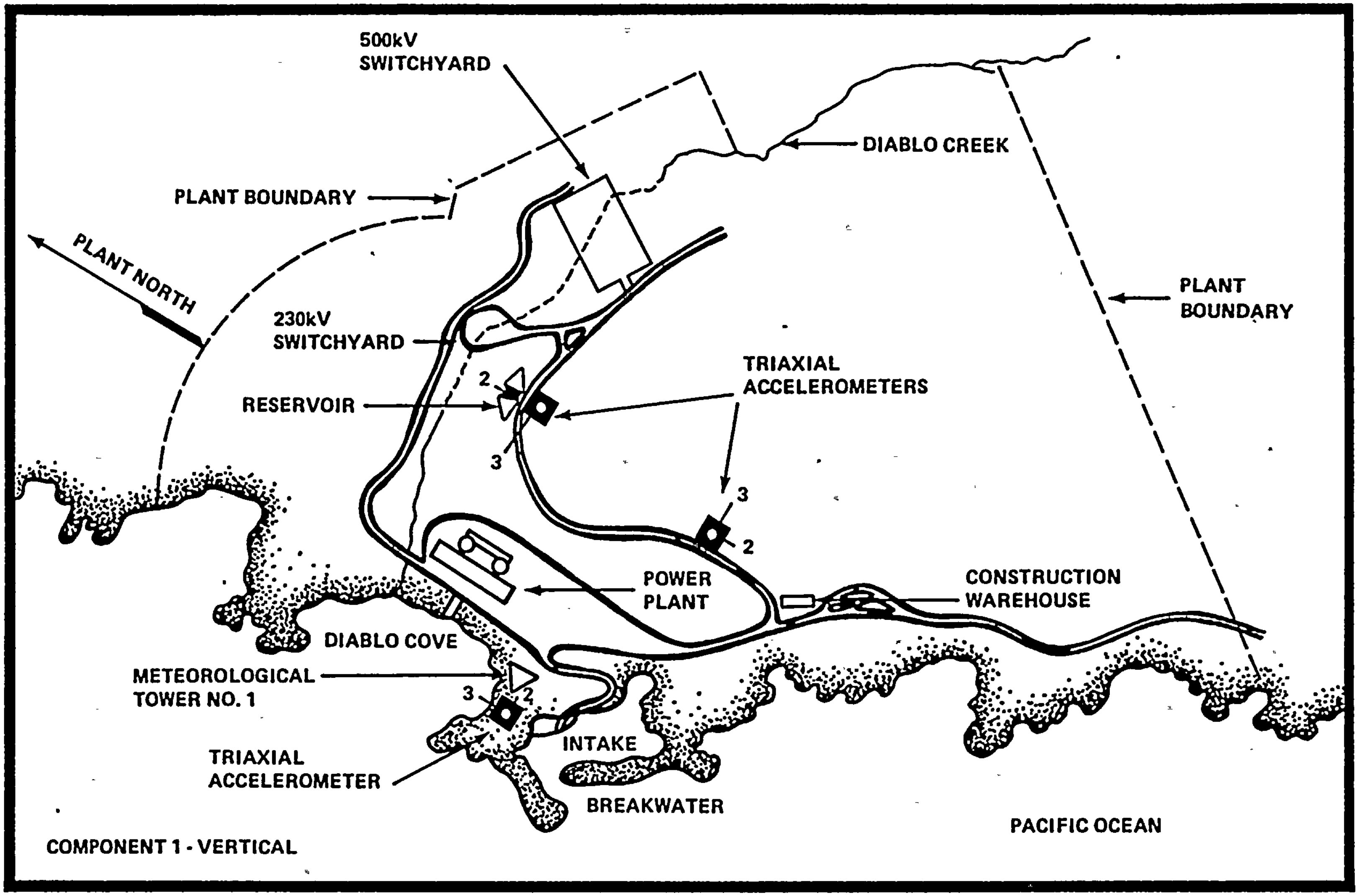

Figure 7.3-1
SUPPLEMENTAL SEISMIC INSTRUMENTATION
IN FREE FIELD
DIABLO CANYON POWER PLANT

7.3.4.2 Data Processing Technique

In processing the recorded acceleration time history data, errors related to the instrument characteristics and the digitization process will be corrected. Details of these errors have been discussed, e.g., by Trifunac et al. (Refs. 6 and 7) and recently by Sunder (Ref. 8). It has been found that the instrument error causes data inaccuracy at high frequencies, and that the digitization error causes data inaccuracy at low frequencies. Thus, in order to correct these errors, the recorded data will be filtered through a low pass filter and a high pass filter to remove the unwanted signal (noises) on high frequencies and low frequencies, respectively. The velocity and displacement of the corrected accelerogram will be computed and evaluated. Base line correction will also be performed as necessary to remove the non-zero mean and the drift in the data.

The corrected accelerograms will be analyzed and the results used to evaluate the results of the analytical SSI response. Transfer functions will also be computed from pairs of corrected accelerograms, and used to the extent practicable for evaluating the SSI effect for the power block structures using the techniques in Refs. 9 and 10.

7.3.5 <u>Parametric Studies</u>

Using the analytical SSI models developed under the task described in Section 7.3.3, benchmark solutions will be performed using the half-space and finite element SSI models. The results from both analyses will be compared. Parametric studies will be performed, as necessary, to investigate the sensitivity of analytical SSI responses to variations of input motion parameters, and variations of structural and foundation rock properties. The effect of embedment and basemat flexibility will be investigated by comparing the solutions obtained from the half-space approach and the finite element approach. If necessary, the effects of inelastic structural response will be considered by variations of structural stiffness and damping parameters derived using an equivalent linear procedure. The potential effect of

structural base uplifting under strong motions will be considered separately where necessary using a nonlinear time-history analysis technique which is capable of simulating the nonlinear base overturning moment versus rotation relationship due to base uplifting. Examples of such techniques that can be employed are given in Refs. 11 and 12. The results of parametric studies will be used for developing the range of response variations that need to be considered for the SSI response of the plant.

7.3.6 SSI Response Analyses

The preceding studies will be used to generate the structural base motions as well as the in-structure response motions for a representative SSI model with model parameters adjusted from correlation with applicable recorded data. The final evaluation will consider the effect of all components of free-field seismic ground motions. The ranges of SSI response variations deduced from the parametric studies will be used as the bases for developing the final SSI response of the Diablo Canyon power block structures.

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8. SEISMIC HAZARD ANALYSIS

8.1 INTRODUCTION

A probabilistic seismic hazard analysis is an evaluation of the frequencies of occurrence of various types of earthquake ground motion at a site, and the uncertainties in those frequencies. A guiding principle in such an analysis is to make realistic statements about the frequencies and their uncertainties. The term realistic means that potential conservatisms and unconservatisms are recognized, and accounted for, in the analysis. Thus, the analysis represents a best estimate interpretation of the probabilities associated with future occurrences of various ground motion levels. These probabilities are used to estimate the likelihood of various consequences for the structural, mechanical, and electrical systems of the nuclear plant.

For the Diablo Canyon seismic hazard analysis, special consideration will be given to tectonic interpretations in central coastal California. These interpretations are particularly important because different hypotheses have different implications on what earthquakes, and ground motions, might occur at the Diablo Canyon site. Known interpretations will be incorporated into the analysis; provisions will be made to incorporate additional information gained during the term of the project.

Some hypotheses regarding earthquake occurrences near the Diablo Canyon site may imply particularly severe ground motions at that site. Care will be taken to represent these hypotheses accurately; care will also be taken to accurately assess the probability that they will occur in nature in order that accurate assessments of frequencies of occurrence of ground motion levels can be achieved. There are three requirements of a seismic hazard analysis: (1) to properly represent levels of seismic ground motion which might occur, (2) to accurately assess their frequencies of occurrence during a facility's lifetime, and (3) to accurately assess the uncertainties in those frequencies of occurrence.

In the Diablo Canyon seismic hazard study, the analyses and assessments used will be carefully documented. In particular, subjective probability assessments will be well-documented; this will facilitate justification and review of the decisions made and positions taken in support of the seismic hazard analysis.

8.2 SOURCES OF INFORMATION

8.2.1 Geology and Tectonics

The primary source of geologic and tectonic information will be ongoing studies in geology and tectonics relevant to the Diablo Canyon site, as described in Section 3. These studies are primarily deterministic; they will be interpreted in a probabilistic way for the seismic hazard analysis. The primary information involved will be interpretation of regional tectonics, fault locations, style of faulting, rate of movement, and probability of being active. These assessments will be made not only in the plant area, but in the region of central coastal California, in order to properly interpret regional tectonics and their implication on earthquakes in the vicinity of the plant site.

8.2.2 Seismology

Ongoing deterministic studies of the maximum magnitude associated with various faults (see Section 4) will be incorporated in the seismic hazard analysis, with probabilistic interpretation. This will involve assessing distributions for the maximum magnitude earthquake expected during the lifetime of the plant, rather than the maximum possible earthquake according to a regulatory criterion.

Additional seismological information will be gathered and analyzed, in the form of historical seismicity (both preinstrumental and instrumental). Data bases from the National Oceanographic and Atmospheric Administration (NOAA), U.S. Geological Survey (USGS), California Division of Mines and Geology

(CDMG), University of California, and the California Institute of Technology will be used in compiling this data set. Historical seismicity is the basis for calibrating probability distributions on earthquake magnitude, which form the foundation of probabilistic seismic hazard analysis. Care will be taken to convert relevant historical observations to a common magnitude scale (and to interpret the implications of tectonic theories in that same scale) to ensure consistency.

8.2.3 Ground Motion

Empirical and numerical models being developed under the LTSP for Diablo Canyon (see Sections 5 and 6) will be incorporated into the seismic hazard analysis. The first of these models will yield estimates of spectral response; the second model will yield detailed estimates of ground motion under certain assumptions of source size, geometry, configuration, rupture characteristics, and attenuation properties. The first set of results, based primarily on empirical data, will be easily applied to frequency domain estimates for events characterized by earthquake magnitude and distance. The second set, based primarily on theoretical considerations, will be particularly useful for specific, well-defined source properties.

An additional type of stochastic ground motion model will be used, as necessary, to represent strong motions during earthquakes. This will adopt the work of McGuire and Hanks (Ref. 1), Hanks and McGuire (Ref. 2), and Boore (Ref. 3), as extended by Toro and McGuire (Ref. 4), to represent seismic ground motion as band-limited, finite duration, white Gaussian noise, with time-varying amplitude functions accounting for rupture directivity and distances to fault segments at sites located close to faults. These models have been shown to be accurate in representing recorded ground motions in California; their advantage in the seismic hazard analysis is that they can be applied with relative efficiency as compared to theoretical models which require explicit specification of source properties. In comparison to empirical models, the stochastic ground motion model yields duration of shaking and temporal behavior of spectral amplitudes, both important characteristics for nonlinear analysis of structures and equipment, as well as

standard spectral amplitudes. The efficient, simple calculation of these parameters for a wide range of earthquakes justifies the use of these models for seismic hazard analysis. The stochastic models used to extend the empirical and theoretical results will be compared with, and calibrated to, those models, to ensure consistency.

8.2.4 Soil-Structure Interaction

Detailed deterministic methods are being developed to estimate the effects of soil-structure interaction (SSI) at the Diablo Canyon plant as described in Section 7. These methods will consider the effects of the massive, large foundations in transforming free-field ground motion to the motion at the base of the structure.

For seismic hazard analyses, the detailed methods being developed will be generalized and simplified so that they can be easily applied for a wide-range of earthquake magnitudes, transmission path properties, and ground motion amplitudes. This generalization will be accomplished using the experience of analysts involved in the detailed SSI analysis. As an example of a simplified, approximate analysis, linear filtering of the free-field ground motion might be used to estimate the effects of large massive foundations for most free-field earthquake motions; this might be an approximate but accurate-enough solution for the majority of cases. Other, more critical, effects can be handled using more elaborate or full theoretical SSI calculations under the scenario approach to the seismic hazard analysis described below.

8.3 ANALYSIS

8.3.1 Logic Trees

The primary tool used to represent alternative scientific interpretations and possible future events will be the logic tree. This representation shows the relative interdependencies among various possible states-of-nature and conditional events, and allows a straight-forward assignment of subjective

probabilities to those states and events. An example of a logic tree showing elements in the seismic hazard analysis is shown in Figure 8.3-1. Tectonic interpretations are represented in the first node, with three possibilities shown by three links (arrows).

Subsequent nodes and links represent earthquake sizes (on a given fault), ground motion at the plant for the tectonic interpretations and earthquake magnitude leading to that node, and SSI effects for a given ground motion. The final branch represents base mat motions in terms of spectral ordinates, duration, or any other characteristic necessary for structure or equipment analysis in the plant. All links in the logic tree will have probabilities assessed, representing the likelihood that a given link represents the correct states-of-nature or the correct future event. The product of all probabilities equals the probability associated with an end branch, i.e., it is the probability that a given end branch represents the correct states-of-nature and event. In application, the link probabilities are divided into those that indicate probabilistic uncertainties or frequencies-of-occurrence, and those that represent statistical or judgmental uncertainties, because these two classes of uncertainties are handled differently in the application of the hazard analysis. This is discussed further in Section 4.1.

8.3.2 Subjective Probabilities

Proper and accurate assessments of frequencies of occurrence are critical for analyzing seismic hazard. One of the most important assessments for the Diablo Canyon analysis is the evaluation of subjective probabilities indicating the relative credibilities assigned to various interpretations of states-of-nature and future events. Examples of the interpretations for which credibilities will be required are:

- o Tectonic interpretation of central coastal California
- o Activity of faults given a tectonic interpretation

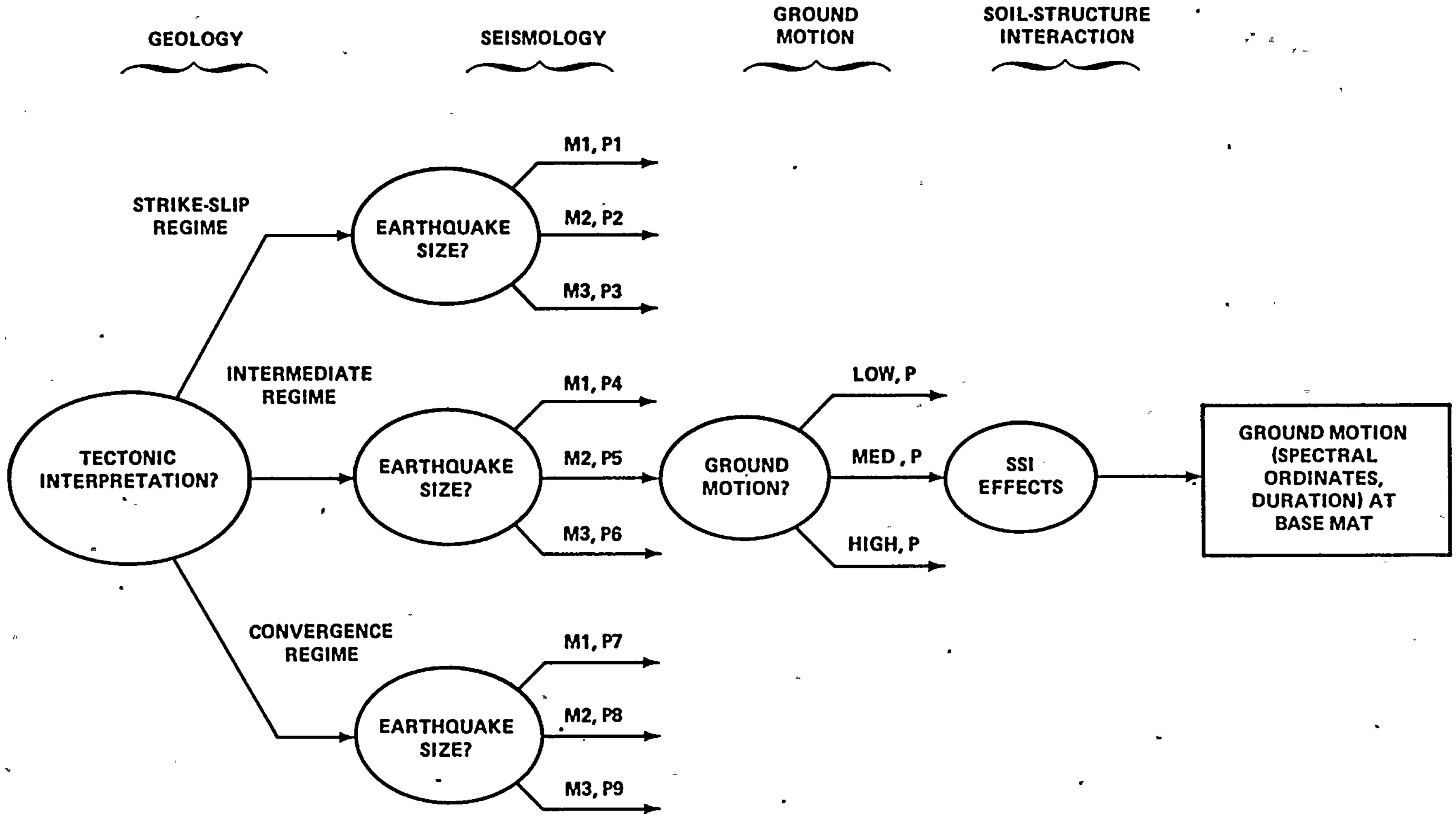

Figure 8.3-1 EXAMPLE OF ELEMENTS IN SEISMIC HAZARD ANALYSIS FOR DIABLO CANYON

- Style of faulting on a particular fault

- Largest possible magnitude on a particular fault

- Ground motion at the plant for a given seismic event

Subjective probabilities for these interpretations for each category will be assessed. In all cases, a formal structure will be used to assess and document subjective probabilities.

In some cases, it may be convenient and appropriate to use a formal Bayesian analysis to estimate the probability that a particular state-of-nature exists, given a set of observations relevant to that state. As an example, if we are interested in fault activity, and we designate the states-of-nature as S_1 (fault is active) and S_2 (fault is inactive), the posterior probability of state S_1 given observations Z is:

$$P''(S_1|Z) = \frac{P(Z|S_1)\ P'(S_1)}{P(Z|S_1)\ P'(S_1) + P(Z|S_2)\ P'(S_2)} \tag{8.3-1}$$

where:

P' indicates the prior probability on state S_1 (and likewise for S_2)

This could be assessed, for example, by looking at all similar faults, without regard to observations, and inferring the fraction that are active. The probability $P(Z|S_1)$ is the probability of observing Z given that the fault is in state S_1 (active). This may be relatively easy to assess. The Bayesian format allows observations to be properly taken into account, along with all prior assessments on states-of-nature. In particular, data from other, similar areas of coastal California can be formally taken into consideration, rather than restricting the data and analysis to the faults only under detailed study for this project.

8.3.3 Earthquake Distributions

All relevant earthquakes will be considered in the seismic hazard analysis. Seismic events will be characterized by their associated probabilities of occurrence. In many cases, the probability distribution of earthquake sizes can be obtained empirically by analysis of historical seismicity in central California. For certain important cases, such as when major seismic events occur as characteristic earthquakes, additional information will be used, e.g., the long-term fault slip rates, estimated empirically or judgmentally. Examples of applications of this type are given by Anderson (Ref. 5) and McGuire and Shedlock (Ref. 6)

8.3.4 Aggregation of Characteristics

The detailed output of the seismic hazard analysis will be a scenario representation of earthquake ground motions at the plant base mat, and associated frequencies of occurrence, and uncertainties in those frequencies. Ground motions can be characterized by spectral amplitude, duration, and even time-domain realizations, if these are important for the analysis of the structural and mechanical response.

For presentation and further analysis in the probabilistic risk assessment, these scenarios will be aggregated into a small number of representative sets with associated probabilities. The aggregation process will depend on the final characterization used to represent ground motion. A simple example of the aggregation procedure is the current seismic hazard analyses conducted for probabilistic risk assessments (PRAs), which combine all ground motions into a single category with a common frequency content and duration, and scale this representation by a single parameter, peak acceleration.

8.4 SEISMIC HAZARD CHARACTERIZATION

8.4.1 Scenario Representations

The fundamental representation of seismic hazard at Diablo Canyon will be made

using scenarios descriptive of the ground motion expected at the plant under the condition that a certain tectonic condition, fault condition, event magnitude, ground motion, and SSI effect take place. One scenario represents one final branch in the logic tree (refer to Figure 8.3-1). Attached to each scenario is an annual frequency of occurrence, representing the annual frequency with which that event takes place, and produces the calculated ground motion at the plant. This frequency represents the integration of inherent (irreducible) uncertainties represented in the event tree. Attached to each scenario is a probability of its being the correct representation of seismic hazard. In this format, the annual frequency represents uncertainty in future occurrences, conditional on a set of physical interpretations and probabilities attached to sets of scenarios representing subjective or professional uncertainties on those interpretations.

The hazard representation can be conveniently aggregated in this format. For example, if the characteristics critical for determining structure and equipment damage are spectral amplitude, frequency content, and duration, the scenario ground motions could be divided into three groups:

- Frequency content for M=5.5, duration of 5 seconds

- Frequency content for M=6.5, duration of 10 seconds

- Frequency content for M=7.5, duration of 15 seconds

Separating the amplitudes into 10 intervals would imply 30 categories of ground motions for analysis. Alternatively, a frequency-of-exceedance representation could be used for each category.

An advantage of the scenario representation is that critical ground motions which might occur under the hypothesized tectonic scenarios are represented with their appropriate probabilities. In the aggregation process, special conditions associated with these ground motions can be represented in as accurate a detail as is warranted. In an extreme case, for example involving

particular phasing of seismic waves which might imply that a structure in its nonlinear behavior tunes in to changing frequency content of the ground motion and thus is severly damaged, the ground motion can be represented by several time-domain sample functions. These can be treated separately in the fragility analysis, and incorporated into the PRA with the appropriate annual frequency of occurrence and subjective probability.

8.4.2 Integrated Hazard Curves

The scenario representation discussed above will be aggregated to reduce the number of alternative ground motions to be analyzed in the fragility analysis. It is also possible to present integrated hazard curves, e.g., for peak acceleration, without designating the other characteristics of ground motions necessary for fragility analyses. These integrated hazard curves can be used for comparison to other studies. This illustrates the advantage of the logic tree scenario representation of seismic hazard: details of ground motion characteristics, and their probabilities and frequencies, can be correctly represented in as detailed a fashion as is required by structural analysis, but broader, less sophisticated characterizations (including the traditional annual-frequency-versus-peak-acceleration curves) can easily be derived for comparative purposes.

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9. FRAGILITY ANALYSIS

9.1 INTRODUCTION

The purpose of a seismic fragility analysis is to determine the probability of failure of structures and equipment for various levels of earthquake ground motion. Since there is no direct observational data from seismic-induced failures of nuclear power plants, the capacity of the structures and equipment at DCPP must be developed from analysis, static and dynamic testing, and engineering judgment based on the performance of similar structures and components during earthquakes. This capacity of structures and equipment is conveniently expressed in terms of an earthquake parameter denoting its potential for causing damage, such as the motion at the base of the structure or the peak foundation acceleration (PFA). It is advantageous to use a cumulative distribution function which expresses this PFA capacity as a function of probability of failure or failure fraction which ranges from zero, representing no chance of failure, to one, representing certain failures. This cumulative distribution function is referred to as a fragility curve. Fragility curves will be used as input to the Probabilistic Risk Assessment (PRA) described in Section 10. Preliminary fragility curves for the structures and equipment will be developed early in the PRA and final curves will be developed incorporating the refined information being generated by ongoing activities in the LTSP.

9.2 DETERMINATION OF STRUCTURAL AND EQUIPMENT CAPACITY

The approach taken in the seismic fragility analysis for determining PFA capacities for structures and equipment is to first determine the median factor of safety against failure and its statistical variability for the governing earthquake. From this factor of safety and associated variability, the median PFA capacity and its variability are determined.

The factor of safety of a structure or equipment is defined as the resistance

capacity at failure divided by the response produced by the governing earthquake. Several parameters are involved in determining both the structural response and the structural strength, and each such parameter, in turn, has a median factor of safety and variability associated with it. The overall factor of safety is the product of the factors of safety for each parameter. The median of the overall factor of safety is the product of the median factors of safety of all the parameters. The variability of the individual parameters also combine to determine the variability of the overall factor of safety.

The parameters influencing the factor of safety on structural capacity to withstand seismic-induced vibration include the actual strength of the equipment or structure compared to that obtained from the design stress level and the inelastic energy absorption capacity (ductility) of a structure or its ability to carry load beyond yield. The variability in computed structural response for a given peak foundation acceleration is made up of many factors. Some of the more significant factors include variability in: (1) the design response spectra compared to the median-centered spectra for the site, (2) energy dissipation (damping), (3) structural modeling, (4) method of analysis, (5) combination of modes, (6) combination of earthquake components, and (7) soil-structure interaction.

Equipment located inside a building acts as a secondary system and requires the previously mentioned structural response factors together with a similar set of equipment response factors that are specific to the equipment itself. The ratio between the median value of each of these factors and the value used in the Hosgri evaluation together with the variability of each factor will be quantitatively estimated for the important structures and components. These estimates will be based on available test data for the Diablo Canyon structures and equipment, analysis, experience in the analysis of nuclear power plant components, and engineering judgment.

9.2.1 Definition of Failure

Electrical, mechanical, and electromechanical equipment and piping vital to mitigating the effects of earthquakes are considered to fail when they are no longer able to perform their required safety function.

Structures are considered to have reached their limit of functionality for the purpose of the fragility analysis when inelastic deformations of the structures under seismic load prevent the equipment attached to or contained within the structure from performing its safety function. For the containment the acceptable leakage rate will establish the functionality limit.

9.2.2 Strength

The design strength of a structure or a component is typically determined from applicable codes and standards such as the American Concrete Institute (ACI) building codes for concrete or the American Society of Mechanical Engineers (ASME) boiler and pressure vessel code for mechanical equipment. Inherent in these design codes is a factor of safety from material strength. Sometimes this factor is known reasonably accurately, such as the design allowable being one-half the minimum yield strength or some similar relationship. At other times, it is less well defined or may be a function of the geometry or other physical characteristics of the component such as for reinforced concrete shear walls.

The safety factor included in the codes for metal structures and components is usually fairly accurately known, as are relationships between minimum and mean or median strengths. For concrete structures, the factor of safety is normally less accurately known. In this case, the strength of the element is a function of the concrete strength, the amount and strength of the reinforcing steel, and the configuration of the element including the element geometry and reinforcing steel details. In establishing the strength and seismic capacity of concrete components, the results of concrete compression tests and reinforcing steel strength and elongation tests provide a valuable basis for establishing the element strength. However, the increase in concrete strength with age, together with the specific details of the element, must also be considered.

9.2.3 Ductility

In order to establish realistic seismic capacity levels for most structures and components, an assessment of the inelastic energy absorption must usually be considered. Exceptions to this are some modes involving brittle failure, functional failure, or elastic buckling. However, most failures due to seismic response involves at lease some degree of yielding. This is true of reinforced concrete as well as the somewhat more ductile metal structures and components.

Consideration of structure ductility typically predicts the ability of the structure to withstand greater seismic excitation than would be predicted using linear elastic techniques. The dissipation of inelastic energy can be adequately accounted for by the use of the ductility-modified response spectrum approach, together with a knowledge of the elastic model results and the expected ductility ratios of the critical elements of the structure or component. This approach is based on a series of nonlinear time-history analyses using single-degree-of-freedom models with various nonlinear resistance functions and levels of damping. For different levels of ductility, the reduction in seismic response for the nonlinear system compared to the equivalent elastic system reponse is calculated. This reduction has been shown to be a function of the frequency and damping of the system as well as the ductility. However, a reasonably accurate assessment of the reduction in response of a structure or component can be made provided the results of the elastic analysis are available and a realistic evaluation of the system ductility can be made.

9.2.3 System Response

A number of parameters must be evaluated when considering the expected system response near failure compared to the governing design conditions. Among these parameters are the expected earthquake characteristics for the close-in and distant events, duration of the earthquake, directional combinations, system damping, load combinations, and system modeling approaches and

assumptions. Some of the parameters may be essentially median-centered and introduce little change in the expected seismic capacity.

It is anticipated that spectra associated with various types of earthquakes will have different durations, different peak ground velocity to acceleration ratios, and possibly different vertical to horizontal directional components. In addition, it may be possible to identify the direction of the earthquake excitation so that capacities of major structures can be developed taking this into account, rather than assuming that the excitation has an equal probability of occurrence from all directions as has typically been done for east coast plants.

System damping consistent with the level of response of the structure and equipment will be used to develop the seismic fragilities. Attention must be given to the relative capacities of the equipment and the structures in which they are housed in order to assure the proper excitation of the equipment.

Load combination criteria define a large number of load combinations that must be considered in design. For the containment structure and much of the equipment contained within it, these load combinations include a combination of loss-of-coolant accident (LOCA) and governing earthquake loads. Random LOCA events have an extremely low frequency of occurrence as do seismic events such that the frequency of both events occurring simultaneously is so small that their inclusion is judged to not be important to the risk analysis results.

9.3 FRAGILITY CURVES

The fragility curves will be developed primarily from existing analysis combined with engineering judgment and supported by limited test data. Such fragility curves will contain a great deal of uncertainty, and it is imperative that this uncertainty be recognized in all subsequent analyses. Because of this uncertainty, great precision in attempting to define the shape of these curves is unwarranted. Thus, a procedure which requires a minimum

amount of information, incorporates uncertainty into the fragility curves, and easily enables the use of engineering judgment, will be utilized.

The entire fragility curve for any mode of failure and its uncertainty can be expressed in terms of the best estimate of the median foundation acceleration capacity, $\overline{A}$, times the product of random variables. Thus, the foundation acceleration, A, corresponding to failure is given by:

$$A = \overline{A} \; E_R \; E_U \tag{9.3-1}$$

where:

E_R and E_U are random variables with unit median representing the inherent randomness about the median and the uncertainty in the median value, respectively

Equation 9.3-1 enables the fragility curve and its uncertainty to be represented as shown in Figure 9.3-1 (i.e., as a set of shifted curves with attached uncertainty levels). Thus, it is assumed that all uncertainty in the fragilities can be expressed through uncertainty in the median alone.

Next, it is assumed that both E_R and E_U are lognormally distributed with logarithmic standard deviations of B_R and B_U, respectively. The advantages of this formulation are:

- o The entire fragility curve and its uncertainty can be expressed by three parameters: $\overline{A}$, B_R, and B_U. With limited data available on fragility, it is much easier to only estimate three parameters rather than the entire shape of the fragility curve and its uncertainty.

- o The formulation in Equation 9.3-1 and the lognormal distribution are very tractable mathematically.

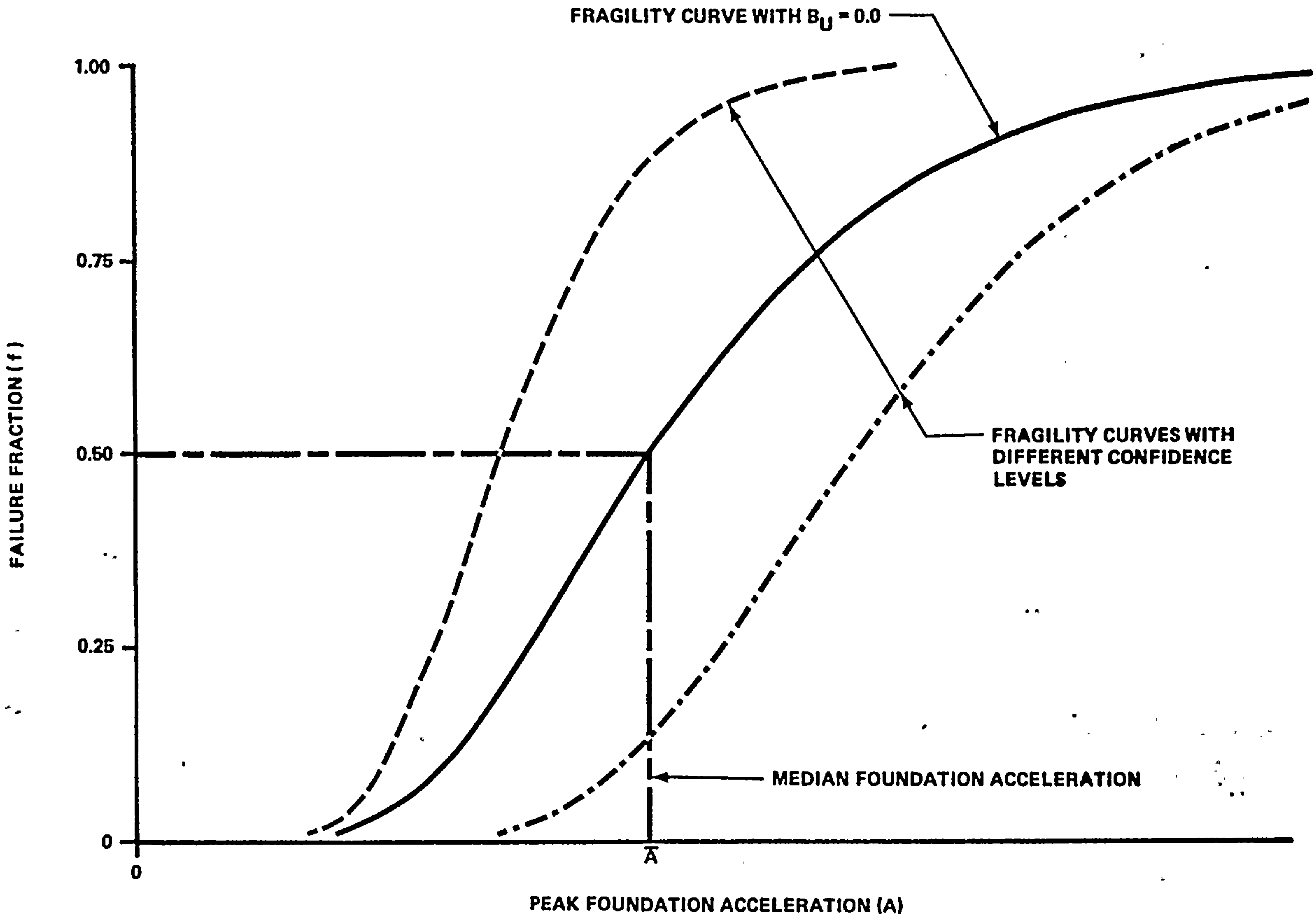


Figure 9.3-1 FRAGILITY CURVE REPRESENTATION

In this study, the guidelines used to estimate the values of B_R and B_U for each variable affecting $\overline{A}$ will be based on considering the inherent randomness, B_R, to be associated with the earthquake characteristics themselves, and B_U to be associated with other lack of knowledge. Thus, such variability as results from earthquake response spectra shapes and amplification, earthquake duration, number and phasing of peak excitation cycles, together with their contributions to structure ductility and response characteristics, is attributed to randomness. In general, it is not considered possible to significantly reduce randomness by additional analysis or test based on state-of-the-art techniques. Uncertainty, on the other hand, is considered to result primarily from analytical modeling assumptions and other lack of knowledge concerning variables such as material strength, and damping which could, in many cases, be reduced by additional study or test.

The lognormal distribution can be justified as a reasonable distribution since the statistical variation of many material properties and seismic response variables may reasonably be represented by this distribution. In addition, the central limit theorem states that a distribution consisting of products and quotients of distribution of several variables tends to be lognormal even if the individual distributions are not lognormal. Use of this distribution for estimating failure fractions on the order of one percent or greater is considered to be quite reasonable. Lower fraction estimates which are associated with the extreme tails of the distributions must be considered less accurate.

9.4 REVERIFICATION AND FINAL FRAGILITIES

The fragility curves as discussed above may require revision to incorporate the results of several ongoing studies. The areas where more recent information may be generated will include the geotechnical and soil-structure interaction investigations which are addressed in other sections of this Program Plan.

Additional reverification may be desirable depending on the contribution of

seismic to overall plant risk. Based on the initial fragilities, controlling structures and equipment can be identified. This will not be accomplished by simply ranking the seismic capacities. Instead, the dominant contributors to seismic risk will be determined from preliminary analyses of the plant damage states. From these analyses, the dominant structure or component fragilities will be determined and, depending on their contribution to overall plant risk, further sensitivity studies or deterministic reverification investigations may be performed.

Normally, in the course of establishing seismic failure capacities, engineering judgement is necessary and various assumptions are required. In many instances, it may be shown that the overall effects on the seismic contributions to the plant damage states are not materially changed for various bounding assumptions. For those fragilities where this is the case, it is often more efficient to perform these types of sensitivity studies compared to more detailed investigations to refine the assumptions.

In those areas where it is determined that the overall seismic risk is sensitive to certain assumptions, or where further benchmark analysis is considered necessary, additional deterministic analysis may be performed. These areas may possibly include development of additional ductility modified response spectra, nonlinear static load distributions for selected structures, nonlinear dynamic analyses of selected structures or equipment, and fragility testing of equipment prototypes with functional modes of failure which were qualified by test. Whether these or other reverification investigations are required will be determined after the development of the initial fragilities and completion of the sensitivity studies as discussed above.

10. PROBABILISTIC RISK ASSESSMENT

10.1 BACKGROUND

The fourth element of the DCPP License Condition requires that:

> PG&E shall assess the significance of conclusions drawn from the seismic reevaluation studies in Elements 1, 2, and 3, utilizing a probabilistic risk analysis and deterministic studies, as necessary....

This section describes the performance of a full-scope Level 1 probabilistic risk assessment (PRA). The seismic work to be performed in the PRA will utilize updated seismic information and techniques to assess the seismic risk at Diablo Canyon. Extending the scope from a seismic risk assessment to a full-scope risk assessment places the seismic risk in perspective with the total risk from all other contributors.

10.2 OBJECTIVES

The purpose of the Diablo Canyon Probabilistic Risk Assessment (DCPRA) is to satisfy the requirements of the license condition by quantitatively estimating the Level 1 risk from operating the DCPP. This will be done by quantifying the total and seismic risk. The quantification will develop probability curves on the frequency of occurrence of different plant damage states and the probability curve for the frequency of occurrence of core melt resulting from the summation of the plant damage states. The risk information is to be presented in such a way as to enable backtracking from core damage to contributing sequences, systems, components, causes, and basic event data.

PGandE is fully aware of the need to thoroughly document the DCPRA results. The approach to documentation of the DCPRA will permit an in-depth technical review of the results, conclusions, and methodology by peers and experts in relevant disciplines.

10.3 SCOPE

The DCPRA will be a full-scope Level 1 PRA. In general, the methods adopted in the DCPRA will conform to the guidance given for the performance of a PRA in the "ANS/IEEE PRA Procedures Guide" (Ref. 1) and the "National Reliability Evaluation Program (NREP) Procedures Guide" (Ref. 2). The results from the proposed DCPRA will meet the requirements for results in the NREP Procedures Guide. The procedures guides give various options for performing specific parts of a PRA.

The term full-scope is taken to mean: (1) the risk due to all causes, including internal and external events; (2) quantification of the frequencies of occurrence of core damage, including all the contributing elements, such as specific plant damage states, accident sequences, systems and component failures, specific causes, and basic event and cause data; and (3) a quantification of uncertainty. Another important quality of a full-scope risk assessment is the detailed modeling of dependent events and recovery actions. The treatment of dependencies includes systems and human interactions, location dependencies, and intersystem dependencies. Recovery actions include the probability of recovery from loss of electric power and operator response as a function of different accident sequences.

The DCPRA will be at least equivalent to the seismic risk analyses performed as part of previous PRAs. The DCPRA will provide a logical framework for putting into perspective the actual risk from seismic events at the DCPP site. That is, it will display all the contributors to risk, including seismic. The result will be a quantitative basis for ranking the importance of safety issues at the DCPP.

The seismic analysis in the DCPRA will be keyed to the results that evolve from the studies described in other sections of this Program Plan. For example, as significant results from the geology/seismology studies become available, they will be used in the probabilistic seismic hazard analysis (described in Section 8) to generate modifications to the seismic hazard

analysis and curves as applicable. This, in turn, may necessitate generating revised plant seismic fragility curves to augment the initial fragility curves developed on the basis of the available qualification analysis of plant structures, equipment, and other components. This procedure is discussed in Section 9 of the Program Plan. These integrated results are then input into the DCPRA seismic models of the plant to determine the contribution of seismic risk that is added to the risk from the other contributors.

10.4 APPROACH

PGandE will provide management oversight of the prime investigator and will be extensively involved in the DCPRA. Throughout the study, PGandE will provide information about the plant's design, as well as plant maintenance and operations procedures. In addition, PGandE will review key products of the PRA at various stages of the project to ensure that the plant model is accurately portrayed. Further, they will participate in analytical segments of the study to gain hands-on experience.

The DCPRA will be accomplished in three phases. Phase I is the planning stage, including this section of the Program Plan. Phase II will accomplish plant familiarization and preliminary analysis leading to qualitative judgments about sources of risk and a good basis for focusing attention on analyses to be performed in the following phase. Phase III will be the full scope analysis and risk quantification, producing the DCPRA documentation. These phases are discussed further in Section 10.6.

10.5 DCPRA INTEGRATED RISK MODEL OVERVIEW

This section will summarize the technical approach to be employed in the development of a risk model uniquely appropriate for Diablo Canyon. The basic concepts and definitions of PRA are presented first, followed by a description of the architecture of a general plant risk model.

10.5.1 Risk Model Structure

a. Qualitative Description of DCPRA Risk Model

A PRA is basically a listing and analysis of scenarios, and a full-scope PRA can contain literally billions of scenarios depending on how finely the scenarios are described. Modeling and quantifying all these event tree paths incorporated into a plant risk model is a cumbersome task requiring a carefully structured approach. To enumerate these possible scenarios requires detailed modeling of the plant, its systems, its components, and their interdependencies, as seen in Figure 10.5-1. Physical and human interactions within the plant that can affect the frequency of occurrence of an accident scenario must also be included.

Event frequencies and their associated uncertainties are quantified using historical evidence in both nuclear and nonnuclear experience when applicable. The plant model contains all the systems reliability aspects, including the engineered safety features of the containment, in order to define the possible conditions within containment if the scenarios were to occur.

b. Logical Structure of a Risk Model

The first step in the development of a risk model is to identify initiating events that may, depending on the response of the plant, lead to core damage. These are identified using several independent approaches, including a master logic diagram (another form of a fault tree), failure modes and effects analysis of plant systems, and cross-checks against reactor-operating experience and events identified in other PRAs.

Once the initiating events are identified, scenarios or accident sequences that could result are identified using a plant event tree, which is actually a network of event tree modules. The top events of

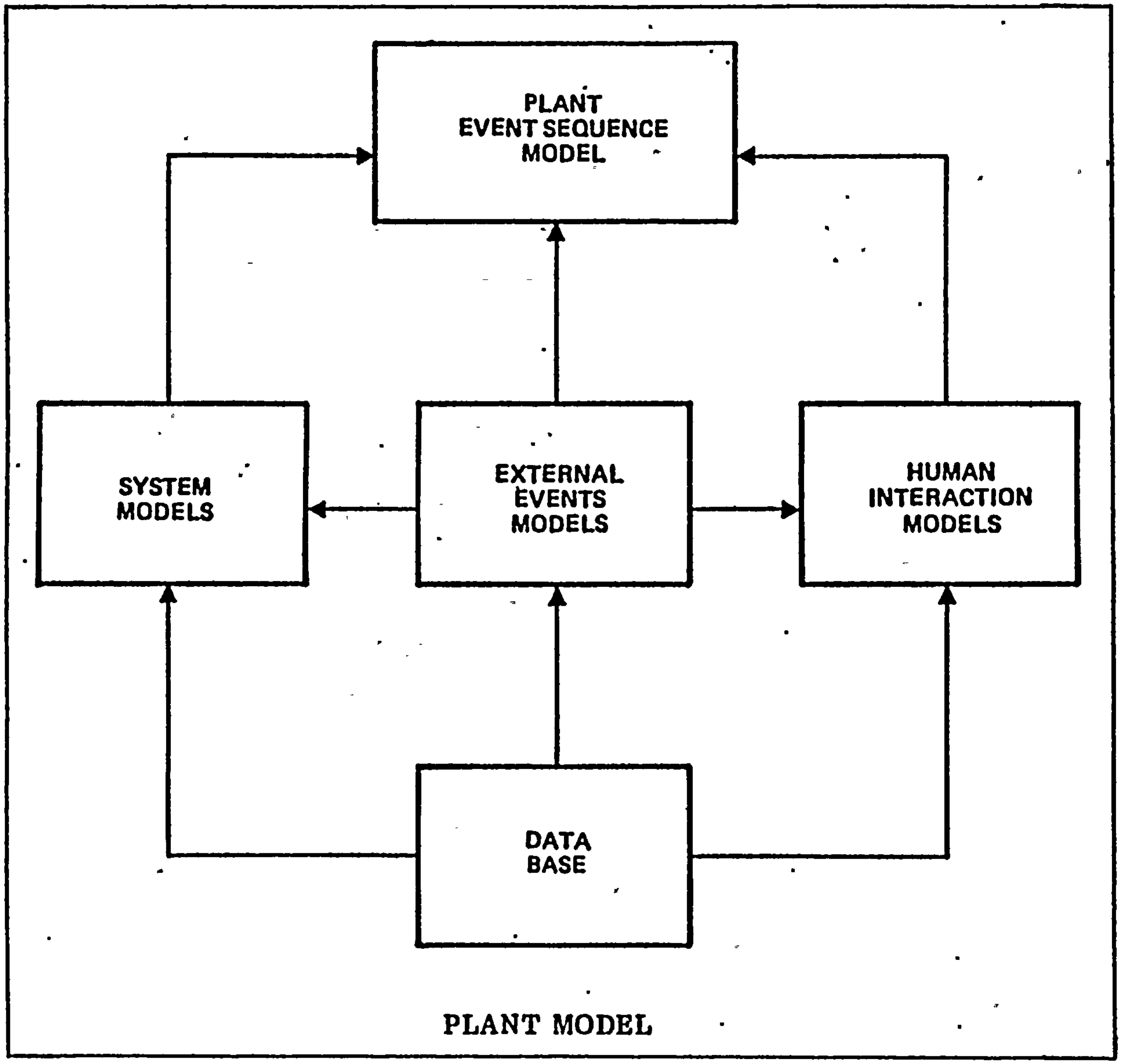


FIGURE 10.5-1 BLOCK DIAGRAM STRUCTURE OF A FULL-SCOPE LEVEL 1 RISK MODEL

each event tree represent the responses of the various plant systems so that each path through the tree represents an event sequence. In this way, the event tree embodies all possible success/failure combinations of the plant systems. At the end of each sequence, the plant either is in a stable, recovered condition or has suffered some core damage. A set of plant states y_j is defined, and each path through the tree is assigned to one of these states. This provides the basis for the standard form of defining event sequences in the risk model, as is illustrated in Figure 10.5-2.

c. Matrix Formulation of a Risk Model

The key idea in the matrix formulation of the risk, which is illustrated in Figure 10.5-3, is that the event trees may be considered equivalent to transition matrices: the trees define the likelihood of moving from each initiating event to various output states.

In the plant event trees, the input states are the initiating events, i, and the output states are the plant states, y_j. From the event tree, the number m_{ij}, representing the conditional frequency of being in plant state y_j, given that initiating event i has occurred, can be calculated. The trees can then be represented by a matrix M composed of these m_{ij}. Because the plant event tree is very large, it is actually comprised of a set of connected event trees. To determine the unconditional frequencies associated with the various states, an initiating event vector ϕ^I_I must be introduced. The symbol ϕ^I is a row vector whose entries ϕ^i denote the frequency of occurrence of each initiating event i.

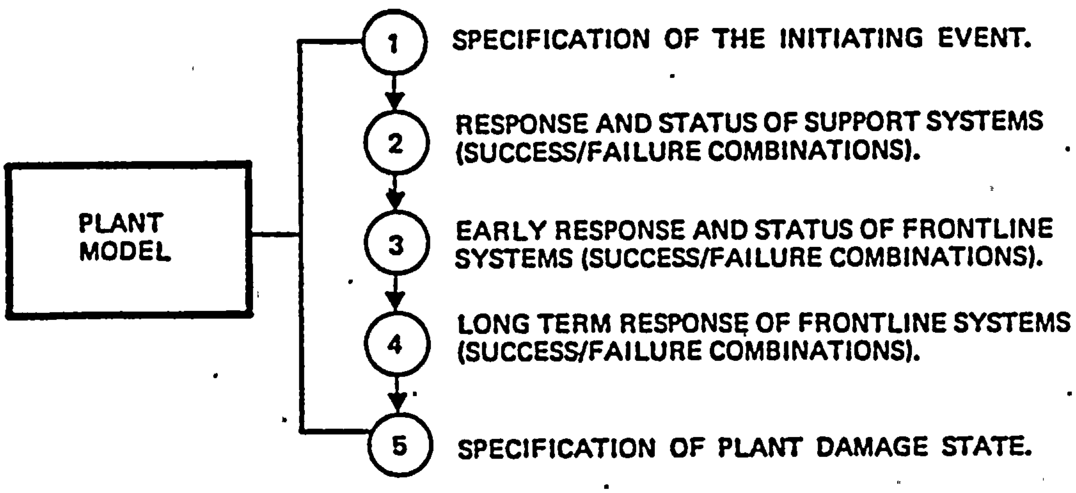
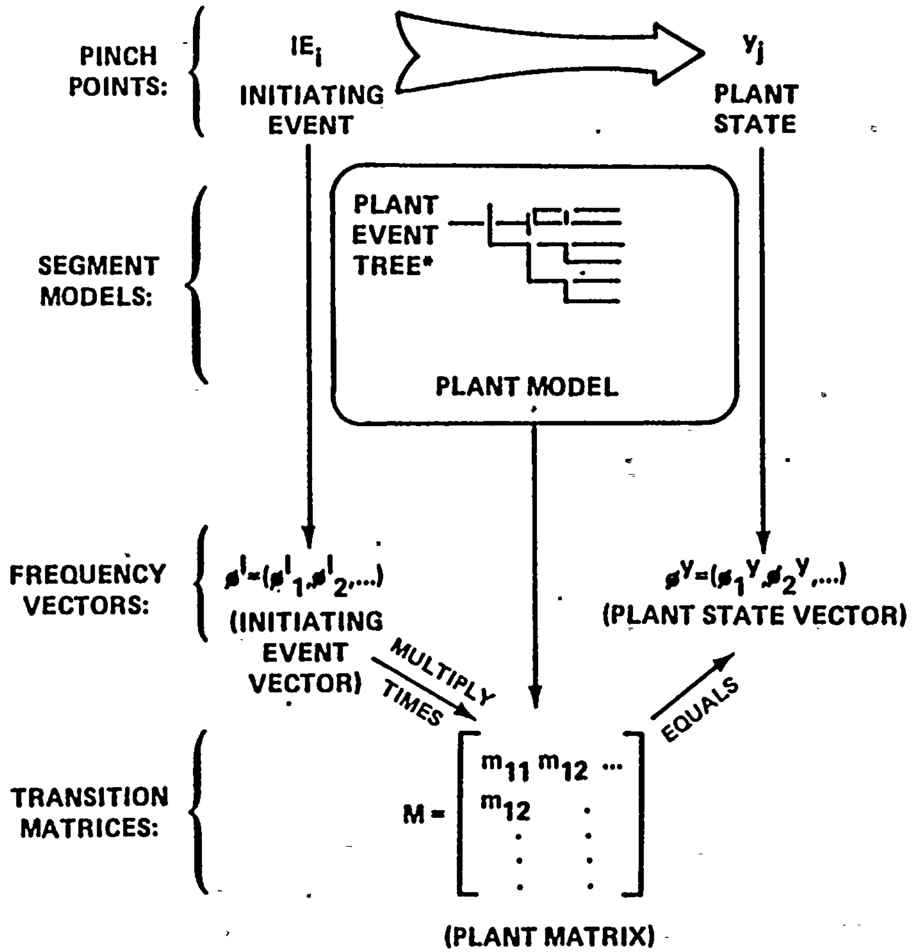


FIGURE 10.5-2 STANDARD FORM OF ACCIDENT SEQUENCES IN A RISK MODEL



ASSEMBLY PROCESS:

$\phi^Y = \phi^I M$

*THE PLANT EVENT TREE, WHICH IS VERY LARGE, MAY BE SUBDIVIDED INTO SEVERAL EVENT TREE MODULES TO FACILITATE PRESENTATION AND QUANTIFICATION.

Figure 10.5-3 OVERALL VIEW OF THE PRA ASSEMBLY PROCESS SHOWING RELATIONSHIPS OF EVENT TREES, FREQUENCY VECTORS, AND THE MATRIX

These frequencies can be quantified with the aid of a thought experiment in which clones of identical plants are imagined to undergo the various initiating events and the number of occurrences of such events per plant year are counted. When multiplied by the plant matrix M, the result is the plant state vector ϕ^y whose elements ϕ^{y_j} denote the (unconditional) frequency of occurrence of plant state y_j.

This assembly process can be summarized as follows:

$$\phi^y = \phi^I M \text{ (frequencies of the plant damage states)} \qquad (10.5\text{-}1)$$

Figure 10.5-3 summarizes the relationship between the event tree model and the matrix approach which forms the basis of the assembly equation.

d. Decomposition of Risk and Cause Tables

If the initiating event vector ϕ^I is written as a diagonal matrix:

$$\phi_D^I = \begin{bmatrix} \phi_1^I & & & 0 \\ & \phi_2^I & & \\ & & \ddots & \\ 0 & & & \phi_N^I \end{bmatrix} \qquad (10.5\text{-}2)$$

the i,jth element of the product matrix $\phi_D^I M$ is the frequency of occurrence of the jth plant state resulting from the ith initiating event. Comparison of this i,jth element of $\phi_D^I M$ with the jth element of ϕ^y gives the fraction of the total frequency of the jth plant state attributable to the ith initiating event. The vector ϕ^y is actually the column sum of this product matrix.

The overall logic of the risk decomposition is shown in Figure 10.5-4. The steps below matrix operation $\phi_D^I M$ are performed with the aid of a computer program which traces through the event sequence logic to identify paths between the initiating events and plant damage states that make major risk contributions.

10.5.2 DCPRA Plant Model

Plant model development involves event sequence analysis, systems analysis, data analysis, human actions analysis, accident sequence quantification, seismic analysis, spatial interactions analysis, and analyses of other external events. These topics are discussed below, with particular emphasis on seismic analysis.

a. Event Sequence Analysis

The technical approach to event sequence analysis is embodied in five basic work elements:

- o Definition and categorization of initiating events
- o Construction of event sequence diagrams
- o Analysis of dependent failures
- o Construction and modularization of event trees
- o Definition and assignment of plant damage states

The key output of these work elements is a model of the accident sequences to be quantified.

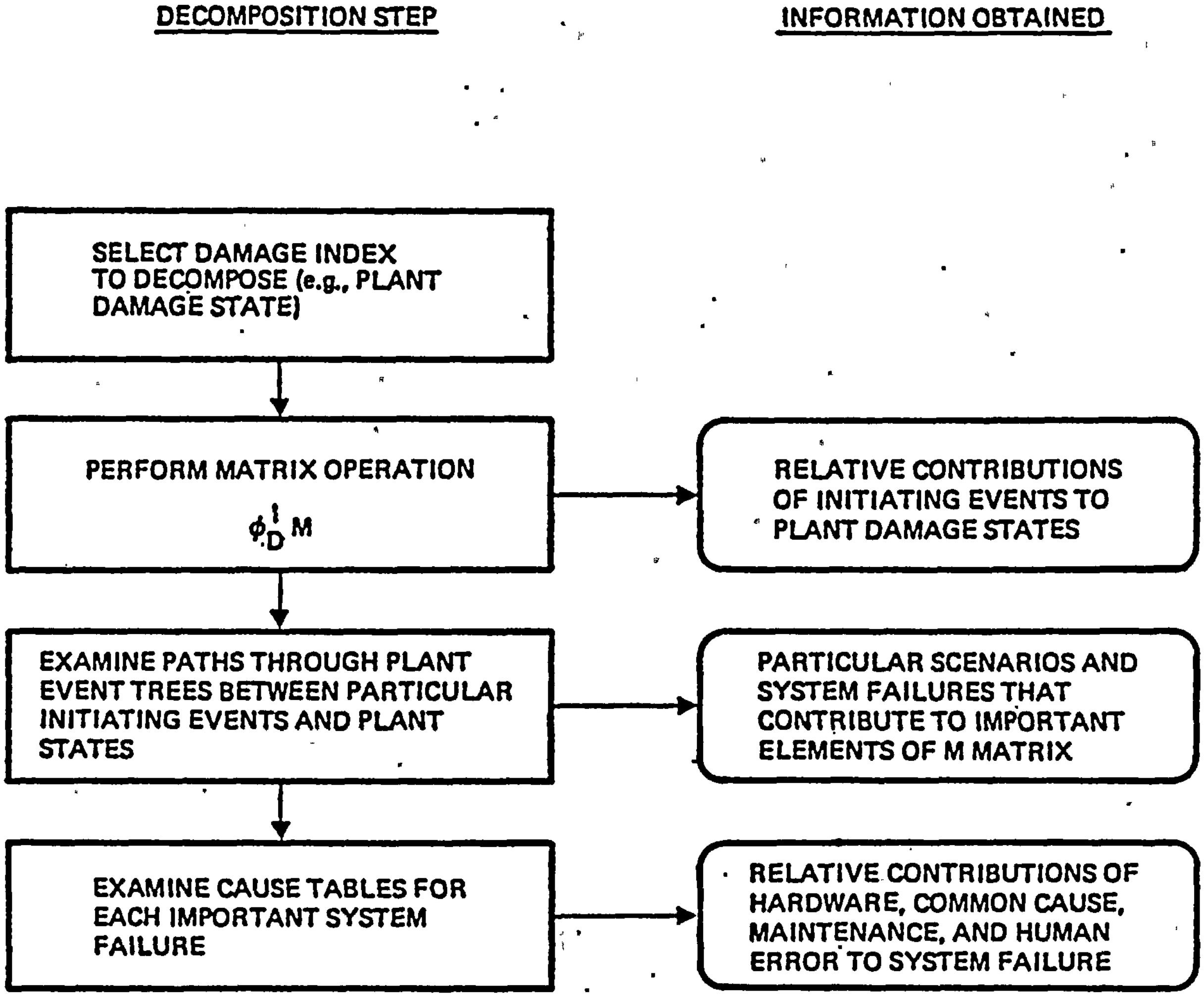


FIGURE 10.5-4 PROGRESSIVE STEPS IN RISK DECOMPOSITION

- Definition and Categorization of Initiating Events

An initiating event is defined as an occurrence, usually a system malfunction, that causes an identifiable departure from steady state operation and eventually perturbs the reactor coolant or reactivity systems. Such events have the potential to start sequences of events that could, depending on the response of plant systems, lead to core damage.

The initiating event list is developed in top-down fashion by structuring a master logic diagram to define a functional set of initiating event categories. These categories form a complete set in the sense that any event that leads to core damage must cause an event in at least one of these categories. Some common cause initiating events (e.g., earthquakes) can cause more than one initiating event and can also disable plant equipment useful in controlling the ensuing sequence of events. Four sources of common cause initiating events will be evaluated: (1) severe environmental events (such as fires, floods, earthquakes, and wind); (2) hazardous activities in the vicinity of the plant (such as aircraft patterns and transportation or storage of dangerous materials); (3) dependencies between systems or components; and (4) human actions that could potentially fail mitigating systems.

- Construction of Event Sequence Diagrams

Historically, the construction of event trees for use in accident sequence quantification has been carried out in two steps. The first step is the construction of a functional event tree that expresses the response of the plant to initiating events in terms of basic safety functions. The second step is the development of a system-oriented event tree that reflects the response of the actual systems that provide the basic safety functions as well as certain types of dependencies. The transition between these two steps is not an easy task and often entails the need to make numerous assumptions that are often poorly documented.

An intermediate step enhances the quality and documentation of the event sequence model. This step is the construction of event sequence diagrams (ESDs) as precursors to the event trees. ESDs focus on the plant and system responses to initiating events and are, therefore, fundamental to accident sequence development. One particularly attractive aspect of ESDs is their ability to document the assumptions used in an event tree analysis. In addition to documenting the expected plant response to each initiating event, ESDs also delineate the operator/system interactions that must be analyzed. The ESDs therefore help to: (1) disseminate information to all project participants about how the plant has been assumed to respond to initiating events, and (2) document which systems and actions must be analyzed.

o Analysis of Dependent Failures

Although ESDs display certain types of system dependencies and interactions that directly follow from the plant dynamics and control, additional analysis of dependent failures is necessary before converting ESDs into final event trees. Hence, a dependent failure analysis must be completed before the event trees are constructed. Although analysis of dependent failures is performed in several PRA tasks, the event sequence analysis is the focal point for the analysis of functional and shared equipment intersystem dependencies, and it also analyzes the physical and human interactions that give rise to common cause initiating events and intersystem dependencies.

The process of identifying the intersystem functional and shared equipment dependencies to be modeled in the event trees entails obtaining an intimate understanding of the plant systems, their interfaces, and their capabilities and limitations in relation to the accident environments to which they are exposed. To facilitate the documentation of dependencies and the necessary review by knowledgeable plant personnel, dependence matrices are prepared.

o Construction and Modularization of Event Trees

The number of dependencies to be modeled in a given event tree is often quite large in practice. If a single event tree were constructed that explicitly modeled all these dependencies as well as the information embodied in the ESDs, the resulting tree would be unmanageably large. To circumvent this problem without the need to oversimplify the logic with ultraconservative assumptions, a modular approach has been adopted based on separate analyses of relatively small event tree modules. The results of the event tree module analyses can then be linked together.

The extent of modularization necessary to adequately model dependencies is dependent on plant design. In general, modern commercial plants that are designed to stringent separation criteria tend to require higher degrees of event tree modularization than older plants.

o Definition and Assignment of Plant Damage States

The final element of the event sequence analysis task is the assignment of plant damage states as the endpoints of sequences in the plant model. Thousands, perhaps millions, of event sequences will be modeled and eventually quantified in the DCPRA. Each sequence will be associated with one of the plant damage states.

b. <u>System Analysis</u>

The principal objective of the system analysis task is to determine the frequencies of failure of those systems necessary to prevent or mitigate core damage for each plant initiating event. This task is divided into three major work elements:

- o Determining the plant systems to be analyzed

- o Collecting system information

- o Developing and quantifying the system logic models

- Determination of Systems to be Analyzed

  Early in the study, the key plant systems are identified based on the event sequence analysis and a review of the plant. The systems to be included are updated, if necessary, as the study progresses. The event tree analysis uses the data and descriptions generated by the system analyses.

- Collecting System Information

  System configurations and plant procedures that affect system operation need to be translated into a system logic model for analytical purposes. The interpretations and assumptions necessary to perform this step must be reviewed with personnel familiar with the plant and system configuration and operation. The documents used in developing each system information base include the following:

  - Safety Analysis Reports
  - Operator training documents
  - Test Procedures
  - System Operating Procedures
  - Emergency Operating Procedures
  - Drawings and plant designs
  - Electrical load lists
  - Direct communications with plant staff

- Technical Specifications

- System Logic Model Development and Quantification

  The boundary conditions for each system analysis are defined and documented based on the success criteria and the system description. These boundary conditions specify the assumptions used and define the scope of the analysis effort. The top event (or events) for each system analysis is based on the event tree success criteria and boundary conditions. A system model is defined for each event tree top event, and Boolean logic equations are derived from this model for the quantification of the system failure frequency. The system logic models are analyzed both qualitatively and quantitatively to determine the effects on the system failure frequency due to each of the following types of factors:

  - Component hardware failures
  - Testing and inspection
  - Maintenance
  - Human interaction
  - External events
  - Common cause failures
  - Combinations of causes
  - Other causes not explicitly defined

The results of these three tasks will be well-documented.

c. Data Analysis

The objective of the data analysis task is to provide a set of failure rates and initiating event frequencies that are consistent with the overall approach to the system and event sequence analyses. PRA data requirements fall into the following five categories:

- o Component failure rate data
- o Component test and maintenance data
- o Common cause failure data
- o Human error rates
- o Initiating event frequencies

Information on the frequencies of basic events, such as component failure rates or initiating event frequencies, can come in a variety of forms ranging from judgment to the historical records of equipment failures and event occurrences in nuclear and nonnuclear industries (generic data), including the operating data in the plant being studied (plant-specific data). The data analyst combines all relevant information in a consistent manner to generate a state-of-knowledge distribution for the frequency of each event.

The method used to develop the data base for the DCPRA applies the principles of Bayesian analysis. This methodology is an advanced version of the techniques that have been applied in several recently completed and continuing PRA studies. It provides a logical framework for the state-of-knowledge approach to data assimilation and for the quantification of the uncertainty associated with the data.

A detailed, computerized generic data base has already been compiled for

use in risk assessment and availability studies. Any further data collection includes extensive documentation on the sources and rationale behind the information used and, therefore, provides a firm basis for future extension of the data base.

d. Plant Model Analyses of Dependent Failures

The design criteria and operating practices for nuclear power plants use redundant and diverse systems to provide plant safety. Consequently, it is necessary to postulate a sequence of multiple failures of systems, components, and human actions in order for a serious accident to occur. Various physical and human interactions result in dependent failures in the postulated accident chain and must be taken into account to achieve a realistic perspective of accident probabilities. It is clear that an understanding of the nature, causes, and effects of dependent failures is essential to performing credible safety assessments.

In view of the different types of dependent failures, the variety of physical and human interactions that cause them, and the multifaceted needs of PRA, there is no single approach or method of dependent failure analysis. The available, useful methods of dependent failure analysis have been categorized as (1) explicit, (2) parametric, and (3) computer-aided (Ref. 3). The applicability of the dependent failure analysis methods to the various tasks of risk assessment and to the various classes of dependent failures is presented in Table 10-1. Because of the diversity of tasks and classes, there is no single method or category of methods that covers all the important aspects of dependent failures.

As can be seen from the table, the major thrust of dependent failure analysis is focused in the event sequence and systems analysis tasks.

In the former task, the master logic diagram method and a specialized failure-modes-and-effects-analysis procedure are applied to identify

TABLE 10-1 COVERAGE OF DEPENDENT FAILURE TYPES OF DCPRA ANALYSIS TASKS

Dependent Failure Type	Subtypes	DCPRA Plant Analysis Tasks					
		Event Sequence Analysis	Systems Analysis	Data Analysis	Spatial Interactions	External Events Analysis	Human Actions Analysis
1. Common Cause Initiating Event	1A Physical Interaction	X*	X				
	1B Human Interaction	X	X	X		X	X
2. Intersystem Dependency	2A Functional Dependency	X	X				
	2B Shared Equipment	X	X				
	2C Physical Interaction		X		X	X	
	2D Human Interaction		X			X	X
3. Intercomponent (system) Dependency	3A Functional Dependency		X				
	3B Shared Equipment		X				
	3C Physical Interaction		X	X	X	X	
	3D Human Interaction		X	X		X	X

*X = contributing analyses; X = principal analyses.

common cause initiating events. In this task as well, functional and shared equipment dependencies among systems (types 2A and 2B) are modeled explicitly in the event tree logic.

The systems analysis task gets involved with the analysis of all types of dependent failures, principally because this is the task in which the plant is conceptually disassembled and reconstructed to facilitate risk quantification, and to acquire an intimate knowledge of how the plant is designed, operated, and maintained. The methods employed in the task include explicit modeling and an advanced version of the beta factor method, which provides a means of incorporating all relevant experience with common cause failures into the analysis. All remaining tasks draw heavily from the systems analysis task in their analysis of dependent failures.

In the data analysis task, evidence relative to initiating events and common cause failures is used to quantify the frequency of initiating events, to explicitly model common cause failures, and to develop beta factors in support of systems and event sequence analysis.

The event sequence and systems analysis tasks provide a thorough coverage of interactions between physically-connected and functionally-related systems. These basic tasks also address interactions between nonconnected and nonfunctionally-related systems; however, the information normally processed in these tasks provides a limited ability to incorporate all possible interactions in this category. To address this gap, a special task is performed to address spatial interactions between and among all systems. This task includes the use of a separate plant model that explicitly models all localized interactions and the performance of an in-depth physical inspection of the plant layout. This task provides comprehensive coverage of all physical interactions, including those in categories 1A, 2C, and 3C, and enables a more comprehensive treatment of external events.

Among the dependent failures that are explicitly modeled are the so-called external events, which comprise a major segment of the possible causes of physical interactions leading to multiple failures. Although the methods used are largely specialized to the particular events in question, which include seismic events, fires, floods, missiles, hazardous chemicals, and others, the same general procedure is followed in each. This procedure, which evolved from an early probabilistic analyses of seismic events (Ref. 4), includes the identification of sources, a quantification of frequency of occurrence as a function of severity level, an assessment of impact on plant systems and structures, and the integration with the overall risk model.

e. Spatial Interaction Analysis

An important element in the analysis of many events is the physical proximity of vital equipment to the location of the event. It is necessary to establish the locations of critical equipment, piping, and cables to assess the probability of this equipment being damaged by each individual type of hazard and to determine whether the failure of one component could cause other equipment failures. A cross-reference between critical plant components and their locations is, therefore, necessary.

A listing of key equipment, piping, and cable runs is required, identifying the rooms or spaces in which they are located or through which they pass. With this information, a fault tree code or other analytical tool will be used to help analyze the importance of these locations based on the potential for initiation of accident scenarios, the potential for damage to safeguard equipment in each location, possible system interactions, and the probability of significant events taking place in each location. The more important locations will be analyzed in greater detail in the earthquake, fire, and flood external event analyses.

f. Human Actions Analysis

The objective of the human actions analysis task is to enhance the completeness of the event sequence model with respect to both favorable and unfavorable operator actions. Human actions that affect the plant at or below the systems level (such as test and maintenance interactions) are handled in the system analysis task previously described. The types of operator actions analyzed in the human actions task are as follows:

- Actions that cause initiating events
- Actions that lead to the recovery of a failed system
- Errors of omission and commission in following a procedure after an initiating event
- Actions based on misinterpretations about the condition of the plant and the status of the plant systems
- Human-induced common cause failures affecting more than one system in any of the event trees

The plant model developed in the event sequence analysis task, with only minimal consideration of operator actions, provides the underlying structure for the human actions analysis. A point estimate quantification of that model yields a list of dominant initiating events and accident sequences. In addition to these sequences, which all involve core damage, the successfully terminated sequences resulting from the dominant initiating events are also considered. This set of sequences is the basic input to the operator response model.

For each of the identified sequences, the response of the plant and its instrumentation is determined and characterized. Based on this information and the human reliability handbook (Ref. 5), an operator

response model is developed. First, a small set of possibly perceived plant states is determined. Based on reactor operating experience and relevant human performance data, the probability of the operator perceiving the plant to be in each of the above states is then estimated. At a minimum, at least one recovery action and one compounding action are modeled for each significant sequence.

g. External Events Analysis

Occurrences external to the plant's mechanical and electrical systems can cause initiating events as well as degrade systems' performance. The external events typically considered in a PRA are earthquakes, wind and tornadoes, tsunamis, internal and external flooding, aircraft accidents, hazardous chemicals and gas releases, fires, and turbine missiles. Plants typically are designed to function through severe levels of these hazards. The range of events can, at extremely low frequencies of occurrence, be hypothesized to extend beyond those used for the plant design basis. PRA has developed a methodology to deal with these rare events.

At the present time, two approaches can be taken in analyzing external events--general and detailed. Before considering a detailed analysis for an external event, it is highly desirable to determine from a general or more simplified analysis if the events can have a significant contribution to risk. A general analysis might show events whereby the largest magnitude or severity that can be postulated is less than the plant design basis. Such events can be eliminated from further consideration.

On the other hand, the events might be larger than the plant can withstand, but their estimated frequencies are so low that, even if initiators and systems failures were assumed to occur with certainty (probability = 1.0), the frequency of core melt and plant states would be far less than that calculated for other external and internal events in

the project. Such events can also be eliminated. There are, however, some external events for which there has been an expressed interest by utilities and the NRC for having a relatively detailed analysis performed even in cases when the event frequencies appear to be insignificant. These events are earthquakes and fires.

The approach taken to obtain a more detailed examination is comprised of the following major steps:

- Hazard assessment
- Structure/component fragility assessment
- Development of plant response logic
- Determination of plant states and core melt frequencies
- Combining plant state frequencies with those of other internal and external initiators

10.5.3 Seismic Analysis

As seen in Figure 10.5-5, a detailed seismic risk analysis consists of five main steps:

- Seismicity hazard analysis
- Fragility analysis
- Plant logic analysis
- Initial assembly
- Final assembly

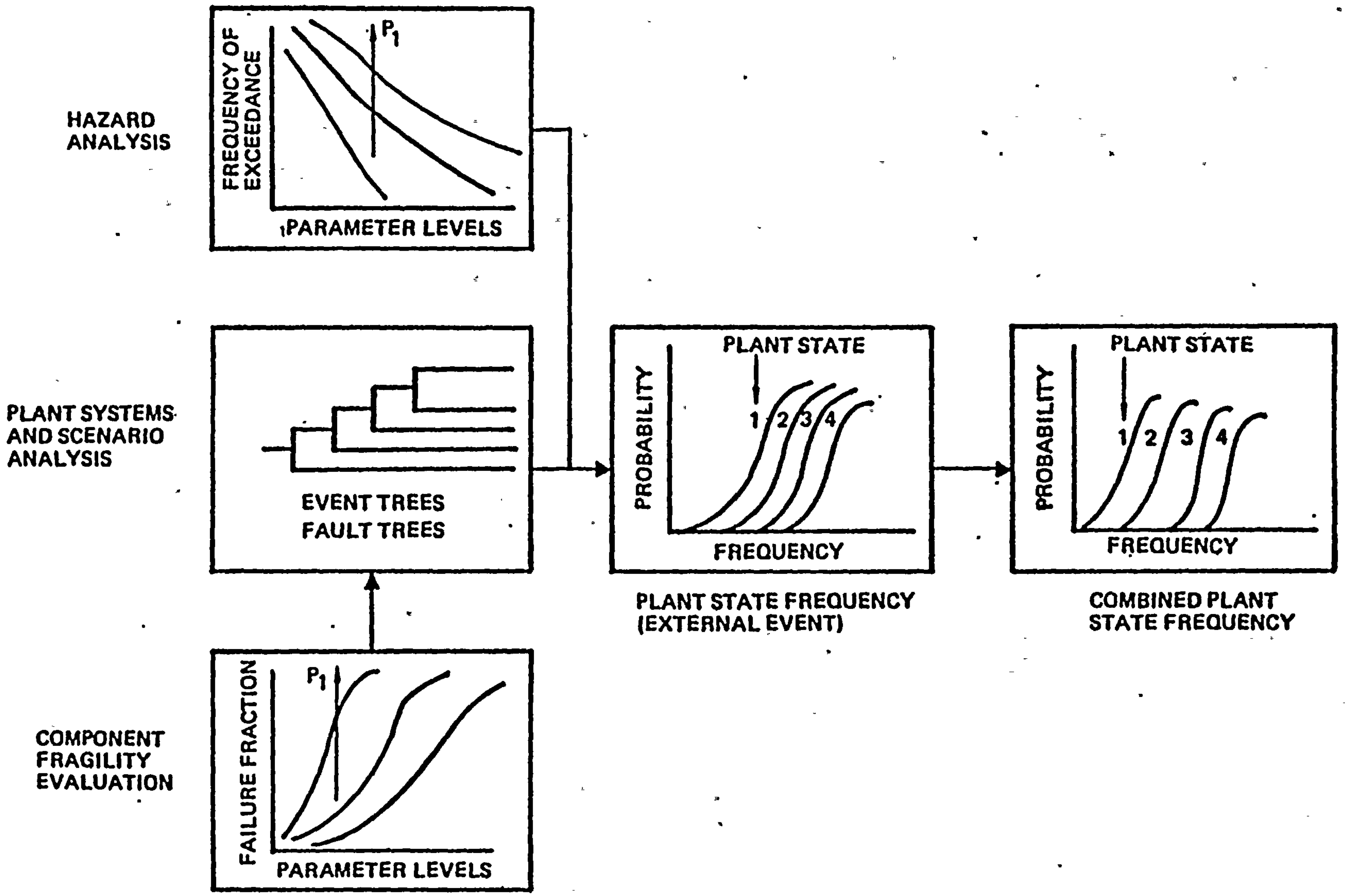


FIGURE 10.5-5 EXTERNAL EVENT ANALYSIS AND INTEGRATION WITH OTHER INITIATORS

a. Seismic Hazard Analysis

The seismic hazard analysis presents the likelihood of various ground motion levels in terms of their annual exceedance frequencies, i.e., the frequency of exceeding various amplitudes. Multiple curves reflect the uncertainty in the seismicity and result from the variations in each of the parameters that form the basis of the curves. A treatment of the technology is given in Section 8.

b. Fragility Analysis

The seismic fragility analysis provides a set of fragility curves that defines the fraction of failure of structures, equipment, and components corresponding to a specific earthquake parameter, such as the peak base motion acceleration. The description of this analysis is given in Section 9 of the Program Plan.

c. Plant Logic Analysis

It is necessary to determine from the fragility analysis if predicted seismic events are large enough to possibly cause failure of plant components that would initiate an accident scenario. Such initiators determine the event trees that are used to evaluate the effects of other equipment and structure failures. The event trees for internal event analysis are also used to describe the plant response to seismic failures, but they must be modified to reflect other components that could fail from earthquakes. These event trees then closely model the scenarios initiated by earthquakes and also reflect the unavailabilities from nonseismic causes, such as random failures, testing, or maintenance. These other causes can, therefore, be included in the seismic analysis.

The main event trees and the auxiliary trees that reflect support system functions common to multiple trees are modified as applicable to include

[illegible]

[illegible]

[illegible]

the possibility of seismic failures of passive components, such as key tanks, piping, cable trays, and structures, that could result in the disabling of a mitigating system. In complimentary fashion, the plant analysis identifies the components (and hence, the structures) for which fragility analyses are needed.

d. Initial Assembly

The initial assembly and quantification process uses mean values of seismicity frequencies at discrete acceleration levels and mean values of seismic fragilities for components that initiate accident scenarios, to calculate point estimates of initiating event frequencies using the fragilities of the components that make up each top event on the event tree. The seismic and nonseismic unavailabilities of each top event are also calculated. Using these as input, the plant damage state frequencies are obtained for each of the scenarios reflected in the applicable event tree.

e. Final Assembly

To accomplish the final assembly, the frequencies of the seismic-initiated plant damage states are first compared with plant damage state frequencies from other initiating events. For each plant damage state for which a seismic-initiated event is a major contributor, a Boolean expression is developed. These expressions include possible seismic and nonseismic unavailabilities of mitigating plant systems.

Using these Boolean expressions and the full families of component fragility curves, as well as failure probabilities from the nonseismic contributors to unavailability, the plant level fragility curves are determined by a convolution process. The process convolves the resulting family of plant level curves with the full family of seismicity curves. The process thereby accounts for uncertainties and calculates the probability distributions of plant damage state frequencies. The [illegible] [illegible]

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resultant seismic-initiated plant damage state frequencies are then added to those from the other initiators.

10.5.4 Design and Construction Errors

A survey will be made of the literature that has been generated on the subject of design and construction errors, the papers recently written on the subject, and the progress that may have been made by Lawrence Livermore Laboratory in its early program on the subject sponsored by the NRC. The earlier methodology for quantifying design and construction errors in industry PRAs will be augmented with information derived from the survey. Past PRAs will be reviewed to explicitly extract coverage of design and construction errors embedded in existing analyses.

10.5.5 Plant Damage State Definitions

For a Level 1 PRA, it is possible to distinguish two end states--success and core damage. Past experience with full-scope PRAs has shown that there is a close correlation between certain features of an accident scenario and potential accident consequences. A few parameters of an accident scenario can be used effectively to define a matrix of plant damage states in such a way that it is possible to distinguish those plant damage states that are likely to have low consequences from those that can have high consequences. For a given design, these plant damage state parameters are normally the following:

- RCS pressure at vessel melt-through
- Quantity of water in the containment
- Success or failure of containment isolation
- Success or failure of containment heat removal and fussion product scrubbing functions

o Size of containment bypass

A matrix of plant damage states and their associated success criteria is defined specific to the plant design. Each end state on the Level 1 plant model is then assigned to one of the plant damage states so that the frequency of each plant damage state can be quantified. This will permit an important qualitative judgment with respect to the composite frequency of high consequence and low consequence scenarios.

10.6 SCOPE OF WORK

10.6.1 Overview

This section describes the task-by-task work breakdown structure for the DCPRA. The DCPRA will be performed in three phases:

a. Phase I - Program Planning

   This Program Plan has been developed in Phase I to describe the proposed program for completing a Level 1 PRA during Phases II and III.

b. Phase II - Preliminary Scoping Assessment

   The PRA team will construct the nucleus of a PRA model after an accelerated process of plant and systems familiarization. This will provide an early identification of important initiating events and scenarios, plant systems and equipment, and plant damage states. The process provides a solid basis for subsequent analysis and quickly focuses on the unique factors of the plant and supporting analyses and data. This process will permit careful refinement of the schedule and work scope for Phase III.

[illegible] will be performed [illegible] will be made of the [illegible] that was gained as a result [illegible]

This phase will be [illegible] during which [illegible] and initiating event [illegible] alternative systems [illegible] a small [illegible] of those [illegible] used for [illegible]

[illegible] for [illegible] as a long [illegible] events will be [illegible] as [illegible]

[illegible] to delineate how [illegible] the [illegible]

[illegible]

[illegible]

c. Phase III - Full Assessment

A comprehensive undertaking of the specific tasks required for the full-scope Level 1 PRA will be performed. Full use will be made of the knowledge, information, and insight into DCPP that was gained as a result of the Phase II effort.

10.6.2 Phase II

The initial activity in this phase will be plant familiarization during which information will be gathered about the plant. A failure and initiating event data base will be initiated for use in the DCPRA. A qualitative systems summary analysis will be accomplished, a small representative set of important initiating events will be identified, and the top events that will be used for all event trees will be selected.

A support systems model that provides for dependency consideration among support systems and among events on the front line event trees will be generated. Support system states will be defined and will serve as end points in this tree.

A general transient event sequence diagram will be developed to delineate how the plant will respond to specific initiating evens and to confirm the success criteria for the model. An event tree will be generated to reflect, through the top events, the way in which the frontline systems perform and interact to reflect all possible plant responses to each initiating event.

A preliminary seismic analysis will be performed in which the preliminary seismic hazard and fragility analyses results are utilized. The support and frontline event trees will be modified to reflect all components indicated by these analyses that could fail. Other external events will be preliminarily evaluated to determine if they warrant an in-depth analysis in Phase III.

A preliminary evaluation of the containment and primary coolant systems will define plant damage state definitions suitable for the ... event tree scenarios will be assigned to one of these

... findings at the ... of Phase II a determination ... of focus and the efforts ... in Phase III ... scope.

The preliminary work accomplished in Phase II, focusing ... having importance. The final list of initiating events ... data collection and analysis will be completed and ... generated for use in the plant analysis. Event ... trees will be developed to enable analysis of all ... events, boundary conditions, and success criteria ... analysis, modeling, and quantifications, will be

... analyses, human error analyses will ... operator actions and errors, the ...

... analysis will be ... analyses ...

be made in order to define plant damage state definitions suitable for the analysis. All frontline event tree scenarios will be assigned to one of these plant damage states.

Finally, using qualitative findings at the end of Phase II, a determination will be made of the areas of focus and the efforts required in Phase III to accomplish the Phase III scope.

Phase III will extend the preliminary work accomplished in Phase II, focusing on areas identified as having importance. The final list of initating events will be determined. The data collection and analysis will be completed and a plant-specific data base generated for use in the plant analysis. Event sequence diagrams and event trees will be developed to enable analysis of all initiating events. Top events, boundary conditions, and success criteria for systems, and the systems analyses, modeling, and quantifications, will be accomplished.

For these systems and event sequence analyses, human action analyses will be performed to include maintenance, testing, operator actions and errors, and recovery action in critical scenarios.

A spatial interaction analysis will be performed to establish the locations of critical equipment, piping, and cables and to consider the spatial interactions that might take place at these locations. Cross-references will be developed between the locations of plant components needed to mitigate each scenario and the locations that are affected by the scenario.

A more refined seismic analysis will be performed in this phase to include updated seismic hazard and fragility analyses and more advanced event trees. The impact of earthquake effects, including those caused by tsunamis, will be evaluated. Consideration will also be given to seismic-initiated fires and flooding in the plant.

A detailed internal plant fire analysis will be performed, analyzing possible

fires in critical areas of the plant, their potential growth and suppression, the possible resulting damage to equipment, and the consequences of such damage.

Internal floods in the plant, the potential damage that could result, the important flood-initiated scenarios, and the flooding contributions to plant damage state frequencies will be analyzed. Other external events will be accomplished by a bounding analysis in order to show that the results are insignificant compared to the frequencies of scenarios from other initiating events that go to the same plant damage state, or to show that a more detailed analysis is necessary. Among these other external events will be toxic and explosive gases from transportation accidents, wind and tornadoes, aircraft accidents, turbine missiles, and external flooding. Design and construction errors will also be evaluated.

The results from the various PRA tasks will be combined. Uncertainties are an integral part of the risk assessment process. The quantification of uncertainties will be propagated through the foregoing analysis. When combined, Level 1 PRA results will be available in terms of the probabilities of frequencies of the various plant damage states and total core melt frequency.

Important accident sequences, system failures, component failures, and human errors that contribute to the core damage frequency will be identified. The contribution of each initiator, accident sequence, frontline or support system, or major cutset to the core damage frequency will be presented.

The DCPRA analysis will be documented to provide a scrutable, coherent, and comprehensive account of the risk analysis.

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