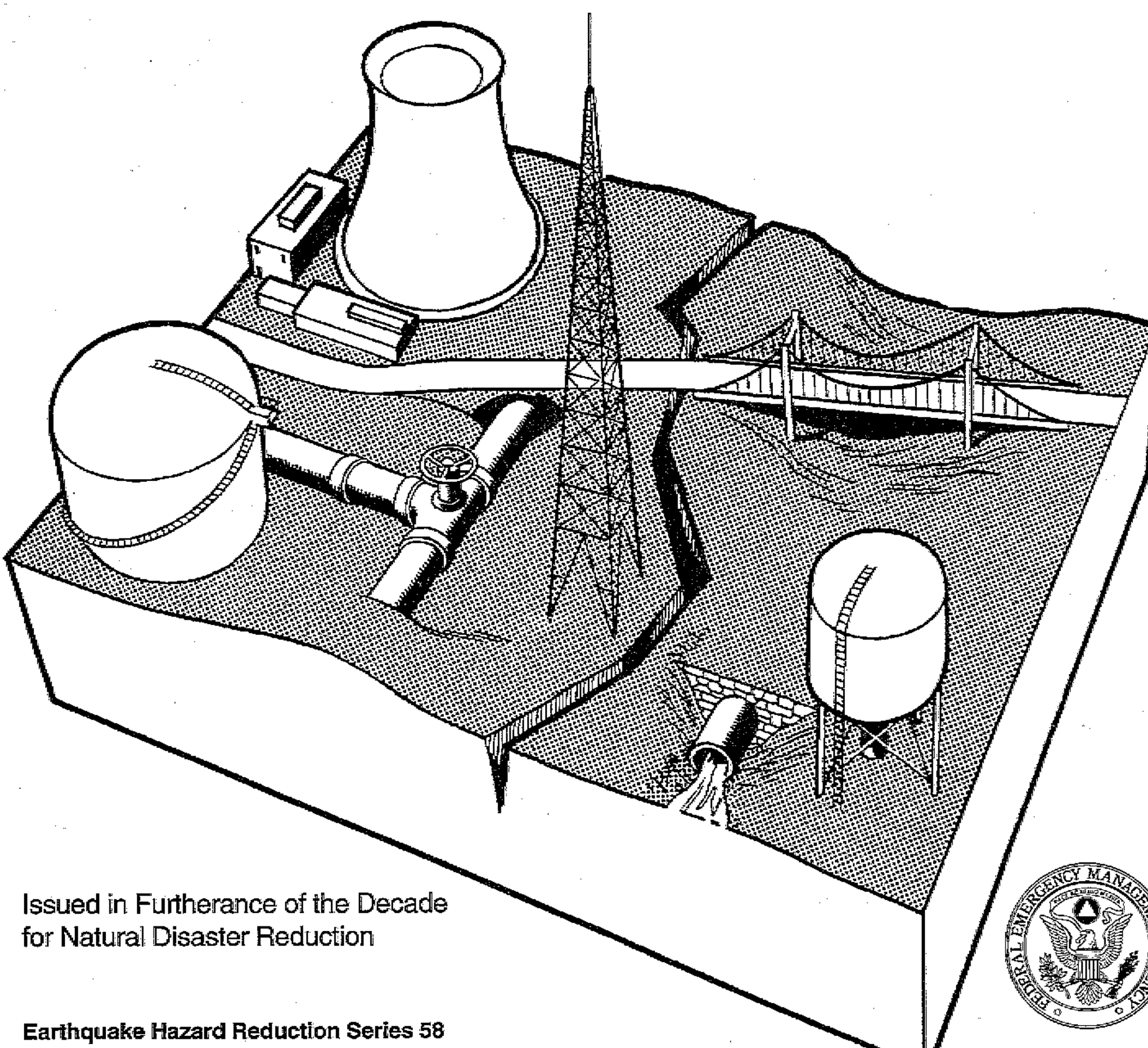
Federal Emergency Management Agency FEMA 224 / September 1991

Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous United States



Issued in Furtherance of the Decade for Natural Disaster Reduction

Earthquake Hazard Reduction Series 58

ATC-25
Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous United States

by
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Washington, D.C.

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Preface

In September 1988 Applied Technology Council (ATC) was awarded a contract by the Federal Emergency Management Agency to assess the seismic vulnerability and impact of disruption of lifeline systems nationwide. The purpose of the project is to develop a better understanding of the impact of disruption of lifelines from earthquakes and to assist in the identification and prioritization of hazard mitigation measures and policies. In addition, FEMA plans to utilize results from the project to promote national awareness of the importance of protecting lifeline systems from earthquakes, and assuring reliability and continued serviceability of lifelines.

The project is being conducted in several phases. Phase I, reported on herein, provides a national overview of lifeline seismic vulnerability and impact of disruption. Lifelines considered include electric systems, water systems, transportation systems, gas and liquid fuel supply systems, and emergency service facilities. The vulnerability estimates and impacts developed are presented in terms of estimated direct damage losses and indirect economic losses. These losses are considered to *represent a first approximation* because of the assumptions and methodology utilized, because several lifelines are not included, and because, in some case, the available lifeline inventory data lack critical capacity information.

Phase II, reported on in the ATC-25-1 Report, provides a practical model methodology for the detailed assessment of seismic vulnerability and impact of disruption of water transmission and distribution systems. Subsequent phases to develop model methodologies for the seismic assessment of other lifeline systems are also planned.

EQE Inc., a structural and earthquake engineering firm with experience in the seismic evaluation of lifeline systems, served as the project subcontractor and prepared this report. The research and engineering work was performed by Charles Scawthorn, Principal-in-Charge, Mahmoud Khater, Principal Research Engineer, and other EQE staff. Marvin Feldman of Resource Decisions served as consultant on the indirect economic loss methodology and data.

The ATC-25 Expert Technical Advisory Group (ETAG), comprised primarily of individuals drawn from the technical committees of the American Society of Civil Engineers (ASCE) Technical Council for Lifeline Earthquake Engineering (TCLEE), provided overall review and guidance for the project. Members were: Lloyd Cluff, James D. Cooper, Holly Cornell, John W. Foss, James H. Gates, Neal Hardman, Jeremy Isenberg, Anne S. Kiremidjian, Le Val Lund, Peter McDonough, Dennis K. Ostrom, Gerard Pardoen (ATC Board Representative), Michael Reichle, Anshel J. Schiff, J. Carl Stepp, and Domenic Zigant. The affiliations and addresses of these individuals are provided in Appendix A.

Applied Technology Council gratefully acknowledges the valuable assistance, support and cooperation provided by Kenneth Sullivan, FEMA Project Officer, and Arthur J. Zeizel and Kupussammy Thirumalai, prior Project Officers.

Christopher Rojahn
Executive Director

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Executive Summary

1. Introduction

Lifeline is an earthquake engineering term denoting those systems necessary for human life and urban function, without which large urban regions cannot exist. Lifelines basically convey food, water, fuel, energy, information, and other materials necessary for human existence from the production areas to the consuming urban areas. Prolonged disruption of lifelines such as the water supply or electric power for a city or urbanized region would inevitably lead to major economic losses, deteriorated public health, and eventually population migration. Earthquakes are probably the most likely natural disaster that would lead to major lifeline disruption. With the advent of more and more advanced technology, the United States has increasingly become dependent on the reliable provision of lifeline-related commodities, such as electric power, fuel, and water. A natural question is: What is the potential for major disruption to these lifelines, especially at the regional level?

The initiation of this study by the Federal Emergency Management Agency (FEMA) is based in part on a need to better understand the impact of disruption of lifelines from earthquakes and to assist in the identification and prioritization of hazard mitigation measures and policies. In addition, the report is intended to improve national awareness of the importance of protecting lifeline systems from earthquakes, and of assuring lifeline reliability and continued serviceability.

The specific contractual requirements of this project and report are:

- To assess the extent and distribution of existing U.S. lifelines, and their associated seismic risk; and
- To identify the most critical lifelines, and develop a prioritized series of steps for reduction of lifeline seismic vulnerability, based on overall benefit.

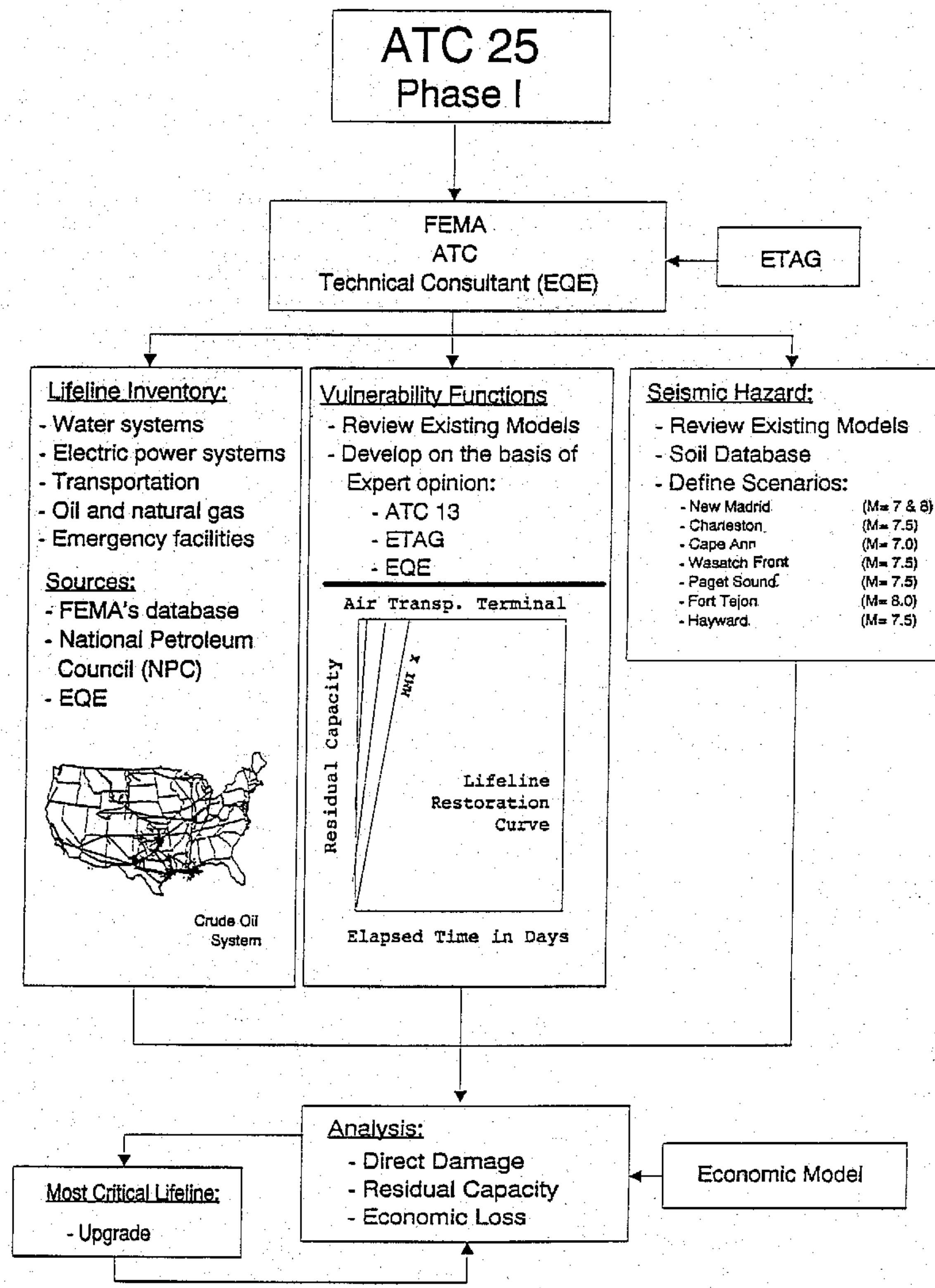
FEMA is also sponsoring a companion study to develop and demonstrate a model methodology for assessing the seismic vulnerability and impact of disruption of water transmission and distribution systems (ATC, in preparation).

In this initial study, lifelines of critical importance at the U.S. national level have been analyzed to estimate overall seismic vulnerability and to identify those lifelines having the greatest economic impact, given large, credible U. S. earthquakes. The lifelines examined include electric systems; water, gas, and oil pipelines; highways and bridges; airports; railroads; ports; and emergency service facilities. The vulnerability estimates and impacts developed are presented in terms of estimated direct damage losses and indirect economic losses. These losses are considered to *represent a first approximation* because of the assumptions and methodology utilized, because several lifelines are not included, and because, in some cases, the available lifeline inventory data lack critical capacity information.

Project Approach. As summarized in the project technical-approach flow chart (Figure 1), four basic steps were followed to estimate lifeline damage and subsequent economic disruption for given earthquake scenarios.

1. Development of a national lifeline inventory database.
2. Development of seismic vulnerability functions for each lifeline component/system,
3. Characterization and quantification of the seismic hazard nationwide, and
4. Development of direct damage estimates and indirect economic loss estimates for each scenario earthquake.

Limitations and Constraints. During development of this report and its supporting data, several problems were encountered that could not be resolved because of technical difficulties and lack of available data. For example, telecommunication systems, nuclear and fossil-fuel power plants, dams, and certain water, electric, and transportation facility types at the regional transmission level were excluded from consideration in this project because of the



Notation: ATC-13: ATC-13 Report, *Earthquake Damage Evaluation Data for California* (ATC, 1985)
ETAG: Expert Technical Advisory Group (project advisory panel)
EQE: EQE Engineering (project subcontractor)

Figure 1 *Flow chart showing main steps in project approach.*

unavailability of inventory data or the need for more in-depth studies.

Interaction effects between lifelines, secondary economic effects (the impact of a reduced capacity of one economic sector on a dependent sector), and damage resulting from landslide (due to lack of inventory data nationwide) were also not considered in developing this report. These limitations and others described in Chapters 2, 4, and 5 tend to underestimate the losses presented herein; and other factors, as described elsewhere in this report, tend to overestimate the losses. Lack of capacity information for most lifelines was also a definite limitation. In the aggregate, due primarily to the exclusion of certain systems (e.g., dams and telecommunication systems), we believe the estimates of losses presented in this report are, in fact, quite conservative.

We also emphasize that this report is a macroscopic investigation at the national level and the results should not be used for microscopic interpretations. The results, for example, are not intended to be used to evaluate any particular regional utility or lifeline, and no specific information on such specific facilities has been included.

2. National Lifeline Inventory

Development of the ATC-25 inventory, for all major lifelines in the United States, was a major task. The project scope required that lifelines be inventoried in sufficient detail for conducting lifeline seismic vulnerability assessments and impact of disruption at the national level. This in turn required that the inventory be compiled electronically in digital form and dictated that inclusion of lifelines at the transmission level, as defined below, was of primary importance.

Initially, a number of government, utility, trade and professional organizations, and individuals were contacted in an effort to identify nationwide databases, especially electronic databases. In most cases, these organizations or individuals referred the project back to FEMA, since they had either previously furnished the information to FEMA, or knew that the data had been furnished to FEMA by others. As a result, FEMA's database (FEMA, 1987) became a major source of data for several of the lifelines. A significant portion of these data consist of digitized U.S. Geological Survey (USGS) topographical maps and/or the National Atlas (Gerlach, no date), performed by the U.S. Geological Survey in support of national census requirements. With the exception of oil and gas pipeline data provided by the National Petroleum Council, the inventory data generally date from about 1966, unless later updated by FEMA. A number of other sources were employed in various ways, which are further discussed below.

The network inventory contained in the database is generally at the higher transmission levels, as opposed to lower distribution levels. That is, inventories were generally only compiled for networks at the bulk and/or regional level, as opposed to lifelines at the user-level (i.e., distribution level) *within* an area. To use an analogy, the inventory contains only the national *arterial* level, and neglects the distribution or *capillary* system. For example, all federal and state highways are inventoried (Figure 2), but county and local roads are not. The major reason for focusing on the transmission level is that at lower levels the systems only support local facilities. Thus, a disruption of a local activity could not be used to identify the overall regional importance of the lifeline. However, disruptions at the transmission level impact large regions and are therefore important for understanding the seismic vulnerability and importance of lifelines to the United States.

Inventory Overview. The inventory data (Chapter 2) have been compiled into an electronic database, which generally consists of (i) digitized location and type of facility for single-site lifeline facilities, and (ii) digitized right-of-way, and very limited information on facility attributes for network lifelines. The inventory is only a partial inventory, in that important information on a number of facility attributes (e.g., number or length of spans for highway bridges) was unavailable from FEMA.

The inventory data include information for the conterminous United States only. Lifeline data for Alaska, Hawaii, and U. S. territories, such as Puerto Rico, have been excluded because lifelines in these regions would not be affected by the scenario earthquakes (see Chapter 4) considered in this study.

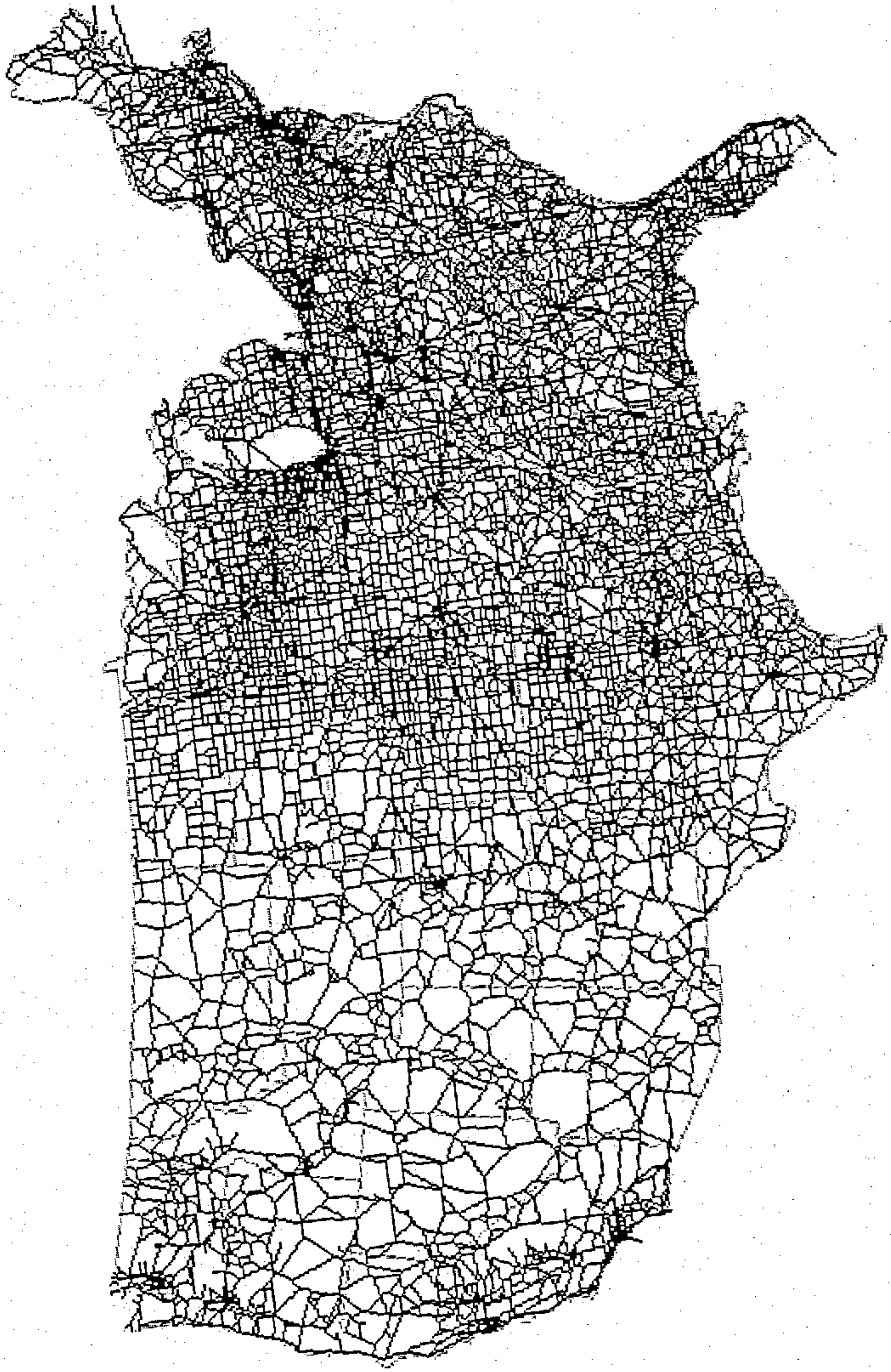


Figure 2 State and federal highways.

The specific lifelines that have been inventoried for the conterminous United States are:

Transportation

- Highways (489,892 km of highway (Figure 2); 144,785 bridges)
- Railroads (270,611 km of right-of-way)
- Airports (17,161 civil and general aviation airports)
- Ports (2,177 ports)

Energy

- Electric Power Transmission (4,551 substations; 441,981 km of transmission lines)
- Gas and Liquid Fuel Transmission (77,109 km of crude oil pipelines; 85,461 km of refined oil pipelines; 67,898 km of natural gas pipelines.)

Emergency Service Facilities

- Emergency Broadcast Facilities (29,586 stations)
- Hospitals (6,973 medical care centers)

Water Aqueducts and Supply (3,575 km of aqueduct; excludes aqueducts in Utah, which were unavailable)

An important lifeline, telecommunication systems, which would be severely impact by earthquake-induced ground shaking, was excluded because of the unavailability of data, as are certain regional transmission network facility types (e.g., railway terminals, bridges, and tunnels; certain aqueducts; major freeway/highway bridges; fossil-fuel power plants; and aqueduct pumping stations). In addition, data on nuclear reactors and dams are excluded because it was believed that such facilities should be the subject of special studies, particularly because of the existing regulations relating to seismic safety in many regions and the expected complexity of the performance and impact of these facility types. As a result, the losses provided by this study will be underestimated to the extent that these facility types are not included.

Also excluded from the inventory, but included in the analysis, are distribution systems at the local level (water, highway, and electrical systems) and police and fire stations. For these facility types, the number of facilities in each 25-km by 25-km grid cell, which is the grid size for the seismic hazard analysis, is estimated on the basis of proxy by population (see Chapter 2).

PC-Compatible Electronic Database. Because the data could also serve as a valuable framework (or starting point) for researchers who wish to investigate lifelines at the regional or local level, including applications unrelated to seismic risk, the data have been formatted for use on IBM-PC compatible microcomputers. The data are unrestricted and will be made available by ATC on 18, 1.2-megabyte, floppy diskettes, together with a simple executable computer program for reading and displaying the maps on a computer screen.

3. Lifeline Vulnerability Functions

The second step in the project was the development of lifeline vulnerability functions, which describe the expected or assumed earthquake performance characteristics of each lifeline as well as the time required to restore damaged facilities to their pre-earthquake capacity, or usability. Vulnerability functions were developed for each lifeline inventoried, for lifelines estimated by proxy, and for other important lifelines not available for inclusion in the inventory. The components of each vulnerability function and how they were developed are described in Chapter 3; the functions themselves, too lengthy to include in the main body of the report text, are provided in Appendix B.

The vulnerability functions developed for each lifeline consist of the following components:

- *General* information, which consists of (1) a *description* of the structure and its main components, (2) *typical seismic damage* in qualitative terms, and (3) *seismically resistant design* characteristics for the facility and its components in particular. This information has been included to define the assumed characteristics and expected performance of each facility and to make the functions more widely applicable (i.e., applicable for other investigations by other researchers).

- Direct damage information, which consists of (1) a description of its basis in terms of structure type and quality of construction (degree of seismic resistance), (2) default estimates of the quality of construction for present conditions and corresponding *motion-damage curves*, (3) default estimates of the quality of construction for upgraded conditions, and (4) *restoration curves*.

These functions reflect the general consensus among practicing structural engineers that, with few exceptions, only California and portions of Alaska and the Puget Sound region have had seismic requirements incorporated into the design of local facilities for any significant period of time. For all other areas of the United States, present facilities are assumed to have seismic resistance less than or equal to (depending on the specific facility) that of equivalent facilities in California NEHRP Map Area 7 (Figure 3). Three regions, representing these differences in seismic design practices, are defined for the United States:

a. California NEHRP Map Area 7, which we take to be the only region of the United States with a significant history of lifeline seismic design for great earthquakes,

b. California NEHRP Map Areas 3-6, Non-California Map Area 7 (parts of Alaska, Nevada, Idaho, Montana, and Wyoming), and Puget Sound NEHRP Map Area 5, which we take to be the only regions of the United States with a significant history of lifeline seismic design for major (as opposed to great) earthquakes, and

c. All other parts of the United States, which we assume have not had a significant history of lifeline seismic design for major earthquakes.

The two key quantitative vulnerability-function relationships developed under this project--*motion-damage curves* and *restoration curves*--define expected lifeline performance for each of these regions and form the heart of the quantitative vulnerability analysis. The curves are based on the data and methodology developed on the basis of expert opinion in the ATC-13 project (*Earthquake Damage Evaluation Data for California*, ATC 1985). Because the ATC-13 data and methodology are applicable for California structures only, however, the data were revised and reformatted to reflect differences in seismic design and construction practices nationwide and to meet the technical needs of the project. All assumptions operative in ATC-13, such as unlimited resources for repair and restoration, also apply to these results.

The *motion-damage curves* developed under this project define estimated lifeline direct damage as a function of seismic intensity (in this case, Modified Mercalli Intensity); direct damage is estimated in terms of repair costs expressed as a fraction or percentage of value. Curves are provided for each region defined above. An example set of motion-damage curves for ports/cargo handling equipment is provided in Figure 4.

The *restoration curves* developed for this project define the fraction of initial capacity of the lifeline (restored or remaining) as a function of elapsed time since the earthquake. Again curves are defined for each region. A sample set is provided in Figures 5 and 6.

4. Seismic Hazard

Seismic hazard, as used in this study, is the expectation of earthquake effects. It is usually defined in terms of ground shaking parameters (e.g., peak ground acceleration, Modified Mercalli Intensity, peak ground velocity) but, broadly speaking, can include or be defined in terms of fault rupture, ground failure (landslides, liquefaction), or other phenomena (earthquake-induced fire) resulting from an earthquake. Seismic hazard is a function of the size, or magnitude of an earthquake, distance from the earthquake, local soils, and other factors, and is independent of the buildings or other items of value that could be damaged.

The technical approach for evaluating the seismic hazard of lifeline structures in this project (see Chapter 4) involved identifying (1) the most appropriate means (parameter(s)) for describing the seismic hazard, (2) regions of high seismic activity, (3) representative potentially damaging, or catastrophic,

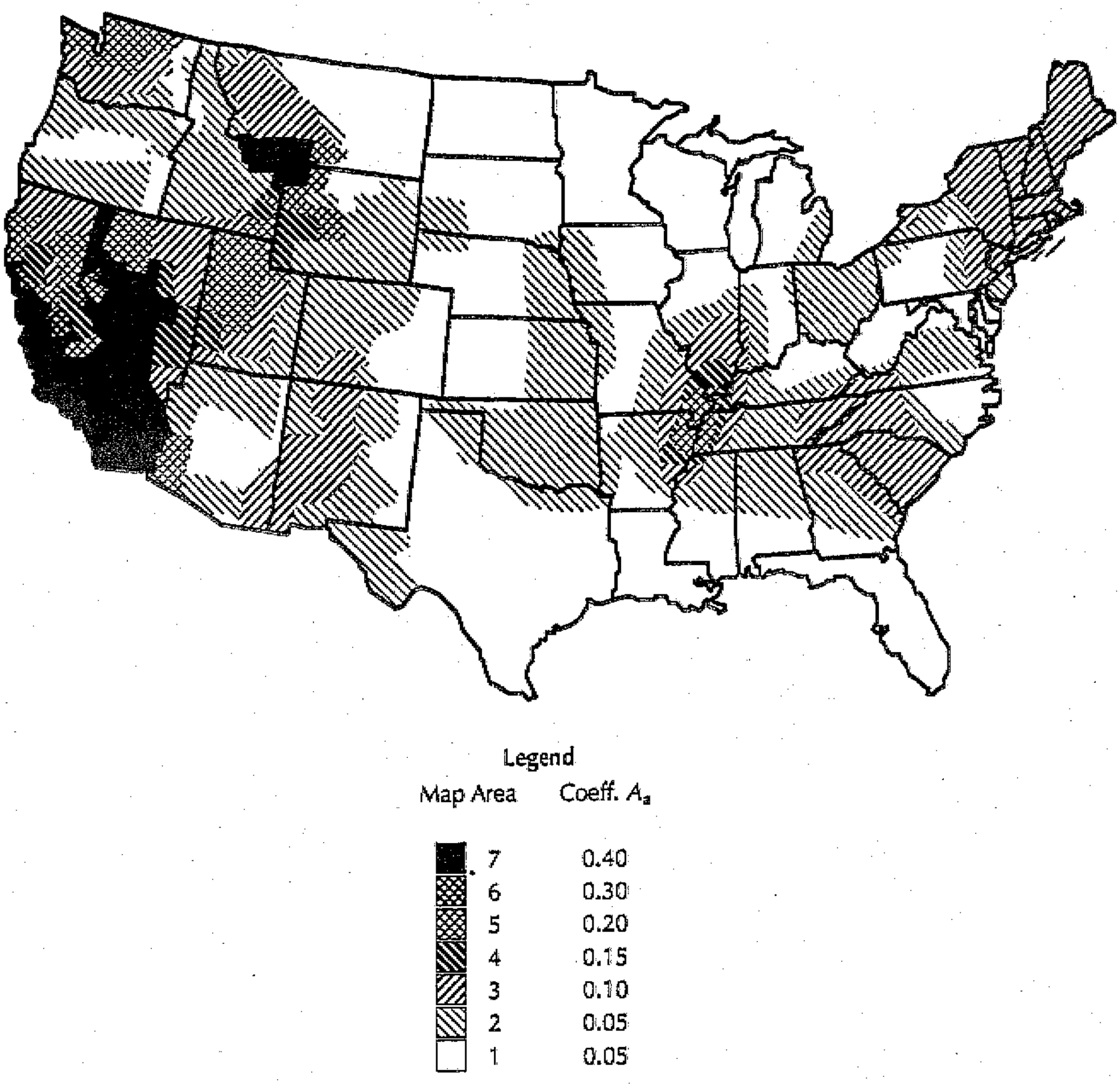


Figure 3 *NEHRP Seismic Map Areas (ATC, 1978; BSSC, 1988).*

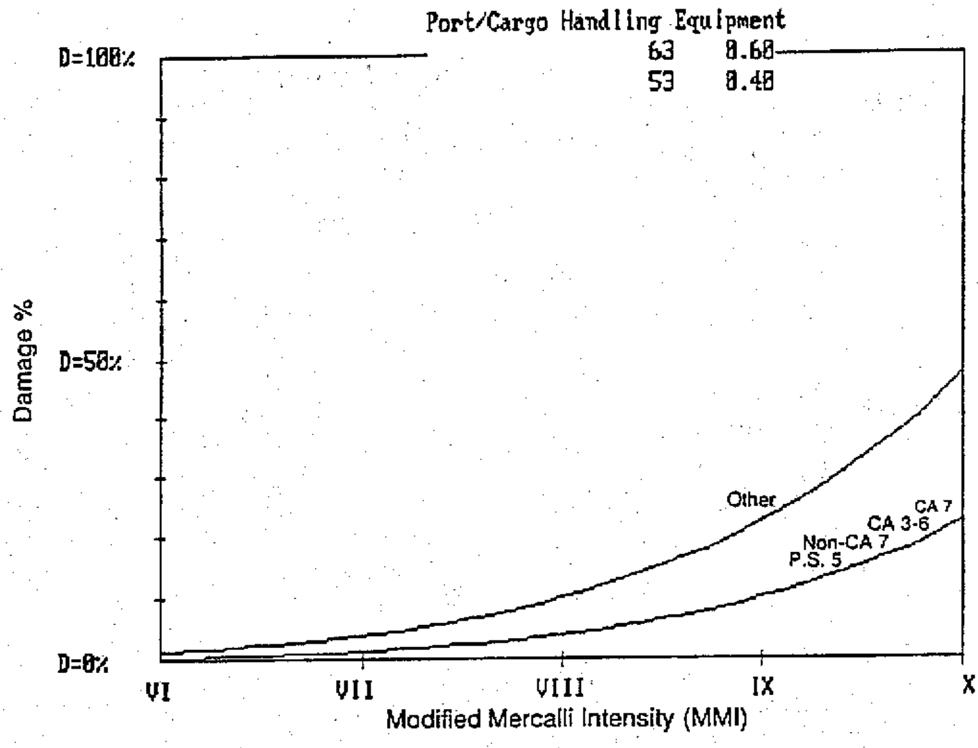


Figure 4 *Damage percent by intensity for ports/cargo handling equipment.*

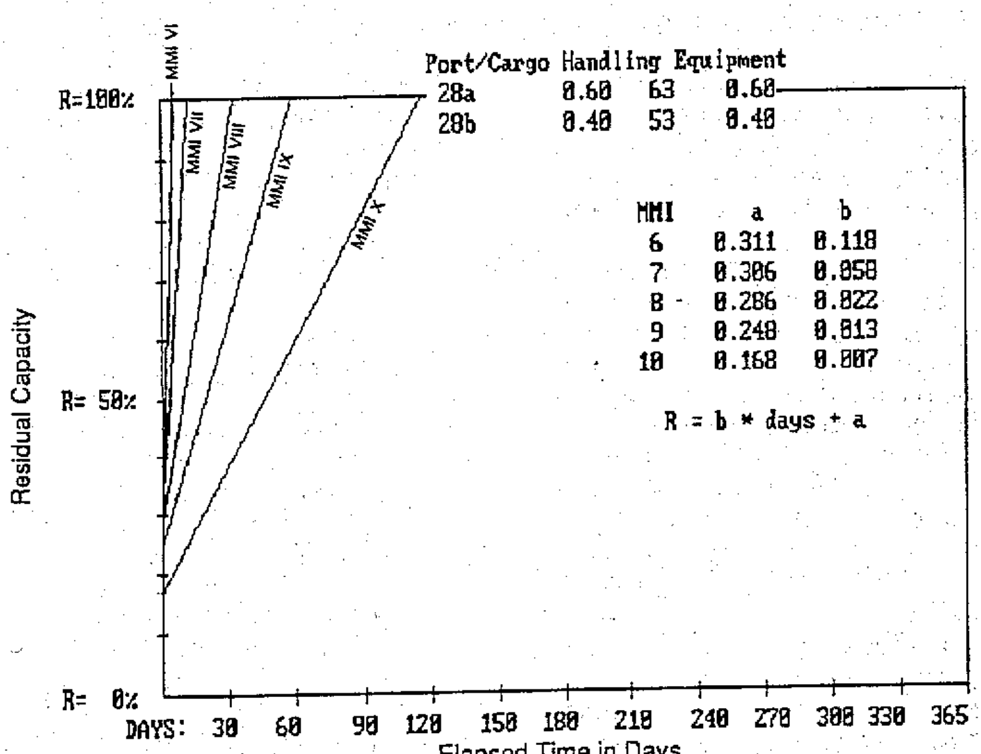


Figure 5 *Residual capacity for ports/cargo handling equipment (NEHRP Map Area: California 3-5, California 7, Non-California 7, and Puget Sound 5).*

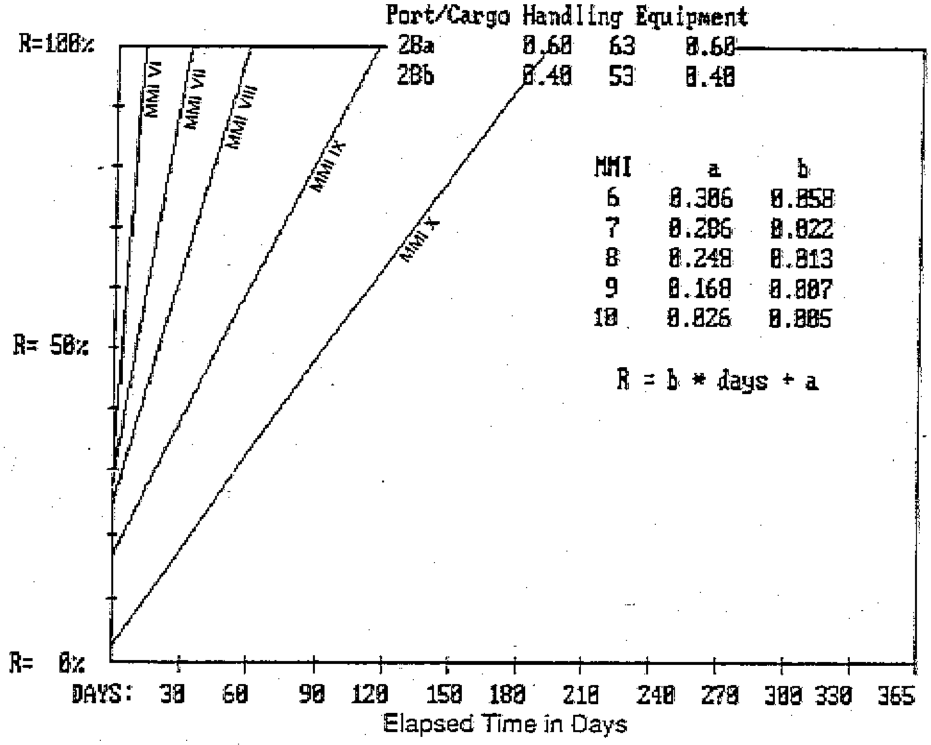


Figure 6 *Residual capacity for ports/cargo handling equipment (all other areas).*

earthquakes within each of these regions that could be used as scenario events for the investigation of lifeline loss estimation and disruption, and (4) a model for estimating the seismic hazard for each of these scenario events.

Descriptor of Seismic Hazard for this Study. Following a review of available parameters for characterizing seismic hazard, we elected to use the Modified Mercalli Intensity (MMI) Scale (Wood and Neumann, 1931), a commonly used measure of seismic intensity (effects at a particular location or site). The scale consists of 12 categories of ground motion intensity, from I (not felt, except by a few people) to XII (total damage). Structural damage generally is initiated at about MMI VI for poor structures, and about MMI VIII for good structures. MMI XI and XII are extremely rare. The MMI scale is subjective; it is dependent on personal interpretations and is affected, to some extent, by the quality of construction in the affected area. Even though it has these limitations, it is still useful as a general description of damage, especially at the regional level, and for this reason was used in this study as the descriptor of seismic hazard.

Seismicity Overview of the United States. For the purpose of characterizing seismicity in the conterminous United States, several regions may be identified (Algermissen, 1983):

1. Northeastern Region, which includes New England, New York, and part of eastern Canada;

2. Southeastern Region, including the central Appalachian seismic region activity and the area near Charleston, South Carolina;

3. Central Region, which consists of the area between the regions just described and the Rocky Mountains;

4. Western Mountain Region, which includes all remaining states except those on the Pacific coast;

5. Northwestern Region, including Washington and Oregon; and

6. California and Western Nevada.

The historical record indicates that each region appears to have significant historic precedent for a damaging earthquake of potentially catastrophic dimensions. For purposes of examining this potential, the earthquakes indicated in Table 1 are representative events for the investigation of lifeline loss estimation and disruption.

Evernden et al. (1981) estimates that these events represent almost the maximum earthquake expected in each area. Review of Algermissen et al. (1982) indicates general agreement.

Choice of a Model for Estimating the Distribution and Intensity of Shaking for Scenario Earthquakes. In order to estimate the seismic hazard (i.e., deterministic intensity) of the scenario events over the affected area associated with each event, a model of earthquake magnitude, attenuation, and local site effects is required. For the conterminous United States, two general models were considered: Evernden and Thomson (1985), and Algermissen et al. (1990).

Selection of one model over the other was difficult, but the Evernden model offered the following advantages for this study: (i) verification via comparison with historical events, (ii) incorporation of local soil effects and ready availability of a nationwide geologic database, and (iii) ready availability of closed-form attenuation relations. An important additional attribute for this project was that the Everden model would estimate the distribution and intensity of seismic shaking in terms of MMI, the shaking characterization used in the ATC-13 study and the basic parameter for the ATC-25 lifeline vulnerability functions.

Scenario Earthquakes. Based on the representative earthquakes identified in Table 1, which are considered representative of all major regions of the conterminous United States, eight scenario events were selected for this investigation. The eight events are indicated in Table 2. With the exception of the Cape Ann, Charleston, and Hayward events, all magnitudes are reflective of the representative earthquake for the region (as specified in Table 1). The scenario events for Cape Ann, Charleston, and Hayward have magnitudes one-half unit higher than the representative event. These magnitudes are interpreted as maximum credible for these locations.

Table 1 Representative Earthquakes for Lifeline Loss Estimation

Region	Event
Northeastern	Cape Ann, 1755
Southeastern	Charleston, 1886
Central	New Madrid, 1811-1812
Western Mountain	Wasatch Front, no date
Northwestern	Puget Sound, 1949
Southern California	Fort Tejon, 1857
Northern California	Hayward, 1868

The choice of a scenario event on the Hayward fault for the San Francisco Bay Area, rather than the 1906 San Francisco event, is based on the perceived high likelihood of a magnitude 7.0 event (USGS, 1990) as well as the potential for major damage and lifeline disruption, should such an event occur (CDMG, 1987). Since most lifelines approach San Francisco Bay from the east, more of them cross the Hayward Fault than cross the San Andreas Fault. So the Hayward event would appear to represent as disruptive an event, and potentially more so, than the 1906 event, which is presently perceived to be of low likelihood in the near future.

The Evernden model was employed to generate expected seismic intensity distribution in the conterminous United States for the eight scenario events. Shown in Figure 8 is an example intensity distribution for the New Madrid magnitude-8.0 scenario event.

Table 2 Scenario Earthquakes

Region	Event	Magnitude
Northeastern	Cape Ann	7
Southeastern	Charleston	7.5
Central	New Madrid	7 and 8
Western Mountain	Wasatch Front	7.5
Northwestern	Puget Sound	7.5
Southern California	Fort Tejon	8
Northern California	Hayward	7.5

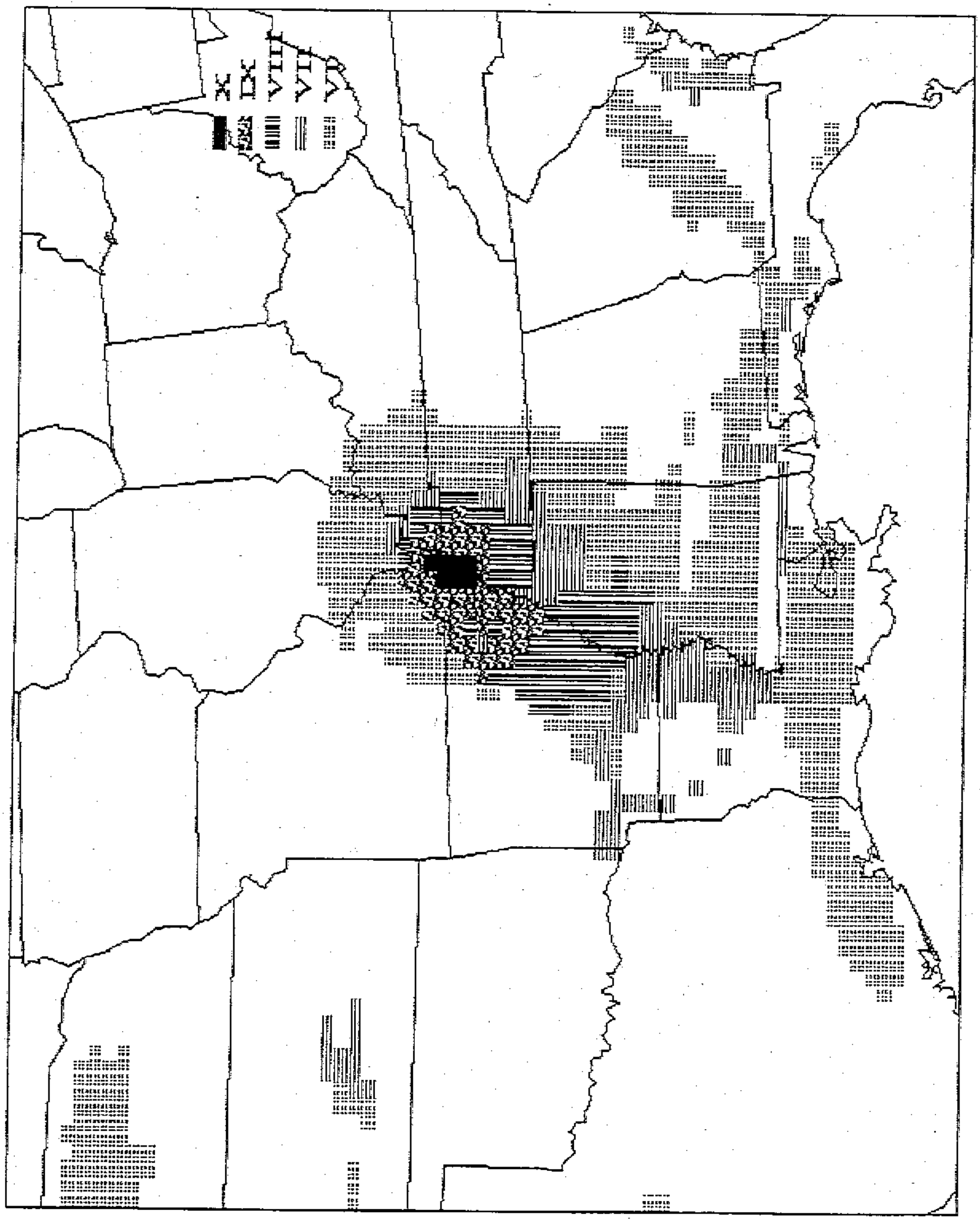


Figure 7 *Predicted intensity map for New Madrid (Magnitude 8).*

5. Estimates of Direct Damage

The analysis of seismic vulnerability of lifeline systems and the economic impact of disruption is based on an assessment of three factors:

- Seismic hazard,
- Lifeline inventory, and
- Vulnerability functions.

In this investigation these factors are used to quantify vulnerability and impact of disruption in terms of (1) direct damage and (2) economic losses resulting from direct damage and loss of function of damaged facilities. Estimates of direct damage to lifelines, expressed in terms of percent replacement value and dollar loss, are discussed in Chapter 5. Indirect economic losses are discussed in Chapter 6.

Direct damage is defined as damage resulting directly from ground shaking or other collateral loss causes such as liquefaction. For each facility, it is expressed in terms of cost of repair divided by replacement cost and varies from 0 to 1.0 (0% to 100%). In this project it is estimated using (1) estimates of ground shaking intensity provided by the seismic hazard model (from Chapter 4), (2) inventory data specifying the location and type of facilities affected (from Chapter 2), and (3) vulnerability functions that relate seismic intensity and site conditions to expected damage (from Chapter 3 and Appendix B).

The analysis approach to estimate direct damage considers both damage resulting from ground shaking as well as damage resulting from liquefaction. Damage due to other collateral loss causes, such as landslide and fire following earthquake, are not included because of the unavailability of inventory information and the lack of available models for estimating these losses nationwide.

The analysis approach for computing direct damage due to ground shaking proceeded as follows. For each earthquake scenario, MMI levels were assigned to each 25-km grid cell in the affected region, using the Everden MMI model, assigned magnitude, and assigned fault rupture location (from Chapter 4). Damage states were then estimated for each affected lifeline component in each grid cell, using the motion-damage curves provided in Appendix B. The procedure for utilizing the motion-damage curves varied slightly by facility type, depending on whether the lifeline was a site specific facility, or a regional transmission (extended) network.

Site-Specific Lifelines. Direct damage to site-specific lifelines, i.e., lifelines that consist of individual sited or point facilities (e.g., hospitals), were estimated using the methodology specified above. For airports, ports and harbors, medical care facilities (hospitals), and broadcast stations, the inventory data summarized in Chapter 2 were used to define the number and distribution of facilities. For fire and police stations, locations were assumed to be lumped at the center of the Standard Metropolitan Statistical Areas, and number of facilities affected were estimated by proxy, assuming certain established relationships between population and number of facilities.

For summary and comparative purposes, four damage states are considered in this study:

- Light damage (1-10% replacement value);
- Moderate damage (10-30% replacement value);
- Heavy damage (30-60% replacement value); and
- Major to destroyed (60-100% replacement value).

The total number of affected facilities and the percentage of facilities in each damage state are summarized for each lifeline and scenario earthquake (see Chapter 5, Tables 5-1 through 5-6). Following is a discussion of the direct damage impact on an example lifeline--ports and harbors.

Ports and Harbors. Since ports and harbors are located in the coastal regions, only those scenario earthquakes affecting these regions will negatively impact this facility type. As indicated in Table 3, the most severe damages to ports and harbors are expected for the Charleston and Puget Sound events. For example, one hundred percent, or 20 ports and harbors, in South Carolina can be expected to sustain heavy damage (30 to 60%), and 73%, or approximately

Table 3 **Damage Percent for Ports and Harbors for Selected Scenario Earthquakes (Percent of Ports and Harbors in State)**

CAPE ANN (M=7.0)

Massachusetts 34	*Connecticut* 22	*Delaware* 10	*Rhode Island* 22	*New Hampshire* 9
100%	0%	0%	86%	0%
0%	0%	0%	0%	0%
0%	0%	0%	0%	0%
0%	0%	0%	0%	0%

CHARLESTON (M=7.5)

Total Number	*South Carolina* 20	*North Carolina* 16	*Georgia* 30
Light Damage 1-10 %	0%	0%	10%
Moderate 10-30 %	0%	0%	0%
Heavy 30-60 %	100%	0%	73%
Major to Destructive 60-100 %	0%	0%	0%

	HAYWARD (M=7.5)	*FORT TEJON (M=8.0)*	*PUGET SOUND (M=7.5)*
Total Number	*California* 125	*California* 125	*Washington* 77
Light Damage 1-10 %	4%	0%	25%
Moderate 10-30 %	22%	34%	26%
Heavy 30-60 %	0%	0%	14%
Major to Destructive 60-100 %	0%	0%	0%

22 such facilities would be similarly affected in Georgia. In Washington, 14% of the ports (approximately 11) would be similarly affected. Numerous ports and harbors in these states would also sustain moderate damage (10 to 30%), as would approximately 22 such facilities in California for the Hayward magnitude-7.5 event. The primary cause of such damage, of course, is poor ground.

Extended Lifeline Networks. With the exception of pipeline systems, direct damage to extended network lifelines, such as highways, railroads and other networks at the bulk and/or regional level, was estimated using the methodology specified above. For pipelines direct damage was estimated using an analytical model that estimates the probability of breaks occurring within given lengths of pipe subjected to given earthquake shaking intensities (Khater et al., 1989).

Results are presented in terms of (1) the same four damage states used for site-specific lifelines, and (2) maps indicating the damaged portions of each extended network for the various scenario earthquakes (see Chapter 5). Example results for two extended lifeline networks follow.

Railroad System. The railroad system is a highly redundant system, and damage to the system due to the selected events was found to be relatively localized to the epicentral area. Direct damage estimates for the railroad system are based on damage curves for track/roadbed and exclude damage to related facility types not included in the project inventory--railway terminals, railway bridges and tunnels.

The direct damage data (Chapter 5, Table 5-7) suggest that the magnitude-8 New Madrid, Fort Tejon, and Hayward events would cause the most extensive damage, with 2,265 km, 872 km, and 585 km of roadbed, respectively, sustaining damage in the 30 to 100% range. Damage in the Charleston, Puget Sound, and magnitude-7.0 New Madrid events would also be severe, with 980, 650, and 640 km of roadbed, respectively, sustaining heavy damage (30-to-60 %). A map showing the distribution of damage to the railroad system for the magnitude-8 New Madrid earthquake scenario is shown in Figure 8.

Crude Oil. Direct damage to the crude oil system as a result of the magnitude-8 New Madrid event, estimated using damage curves for transmission pipelines and the special probabilistic model for pipelines, is plotted in Figure 9. This figure indicates that three pipeline sections would be damaged due to the magnitude-8.0 New Madrid event and suggests that crude oil flow to the north-central section of the United States would be disrupted. Pipelines would also be damaged as a result of the magnitude-7 New Madrid and magnitude-8 Fort Tejon earthquake scenarios.

Dollar Loss Estimates. Summaries of dollar loss estimates for direct damage to site-specific systems and extended regional lifeline networks during the eight scenario earthquakes are provided in Tables 5a and 5b. Estimated dollar losses due to direct damage to local electric, water, and highway distribution systems are provided in Table 6.

The estimates provided in Tables 5a,b and 6 are based on the available inventory data, cost per facility assumptions, and other models and assumptions described throughout the report. As a result, the accuracy of these estimates may vary from lifeline to lifeline. Estimates for electric systems, in particular, are believed to be more sensitive to the lack of capacity information than are the other lifelines.

By combining the data from Tables 5a,b and 6, we estimate the total direct damage dollar losses (in billions of U. S. dollars) for the eight scenario earthquakes as follows:

Earthquake	*Direct Dollar Loss (in Billions, 1991$)*
Cape Ann	$4.2
Charleston	$4.9
Fort Tejon	$4.9
Hayward	$4.6
New Madrid, M = 8.0	$11.8
New Madrid, M = 7.0	$3.4
Puget Sound	$4.4
Wasatch Front	$1.5

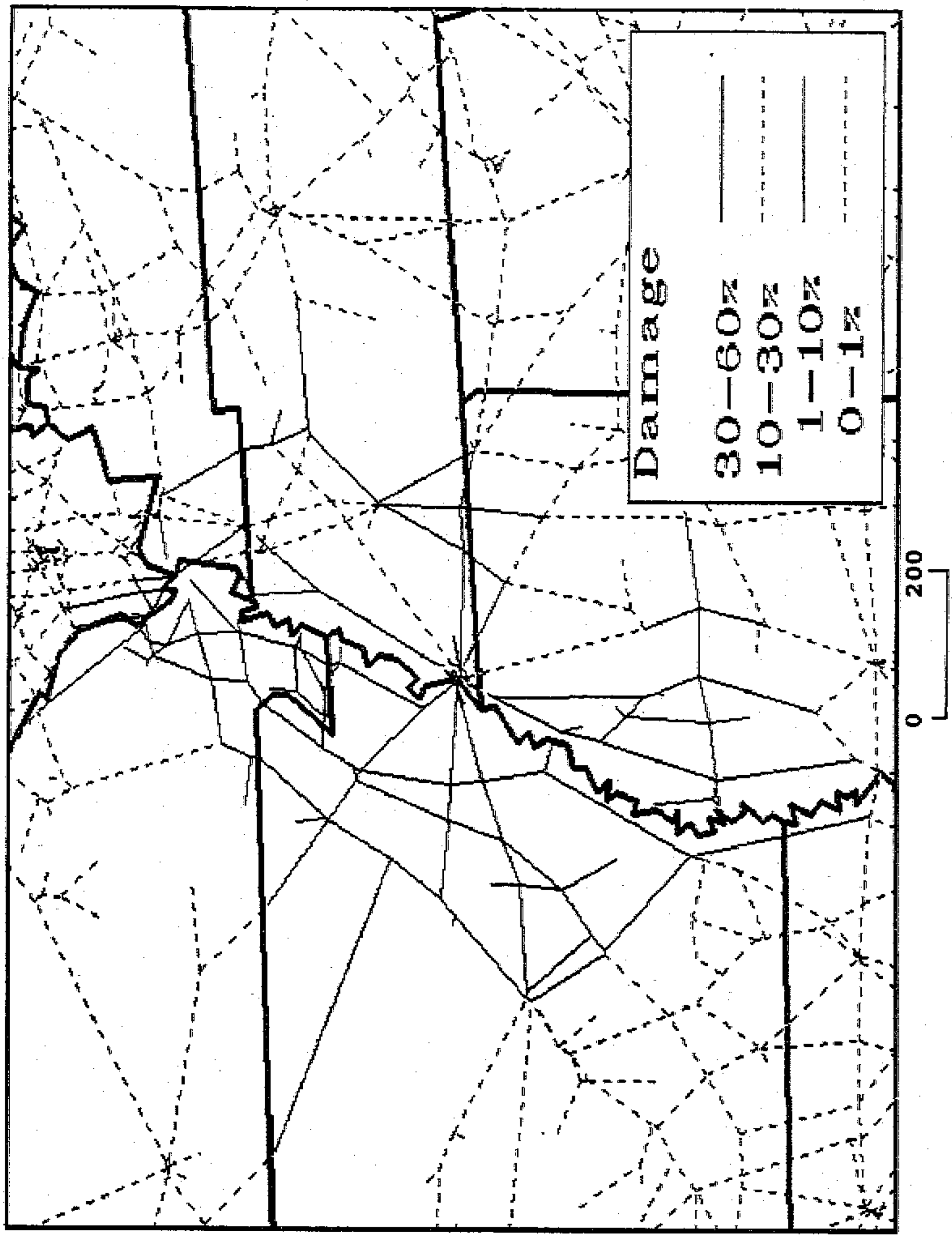


Figure 8 *Damage to railroad system following magnitude-8 New Madrid Event.*

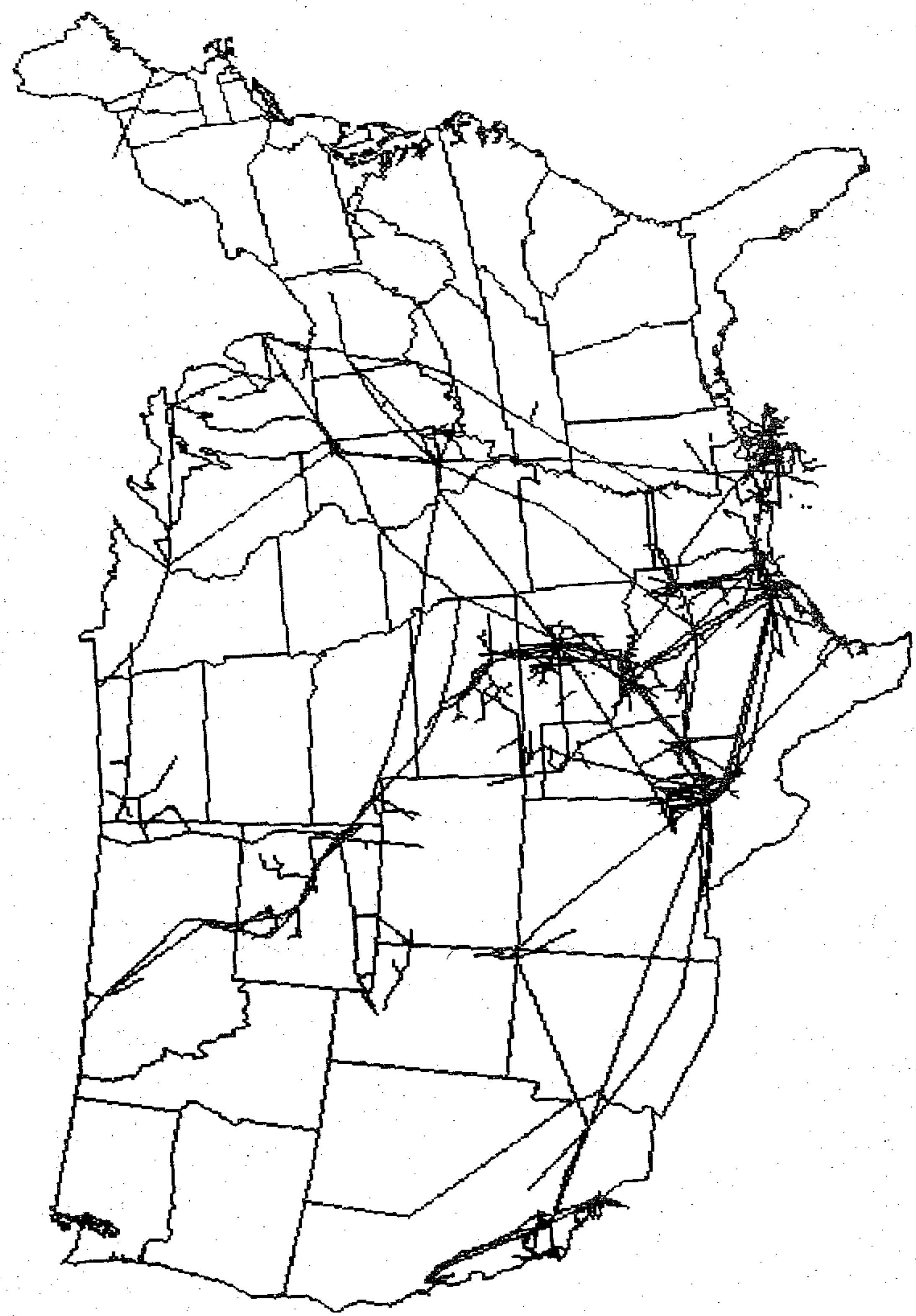


Figure 9 *Damage to crude oil system following magnitude-8 New Madrid Event. Broken pipelines are shown in red; unbroken pipelines are shown in black.*

Table 5a Direct Damage Losses to Site-Specific Lifelines ($ Millions)

Scenario Earthquake	*Airports*	*Ports*	*Hospitals*	*Broadcast Stations*	*Fire Stations*
Cape Ann	$91	$53	$490	$19	$6
Charleston	142	380	565	68	9
Fort Tejon	148	170	1,431	26	48
Hayward	37	115	1,297	17	7
New Madrid (M=8)	411	0	1,297	91	13
New Madrid (M=7)	145	0	396	34	3
Puget Sound	210	196	507	49	13
Wasatch Front	29	0	205	44	2

Table 5b Direct Damage Losses to Regional Network Lifelines ($ Millions)

Scenario Earthquake	*Highways*	*Electric*	*Railroads*	*Natural Gas*	*Refined Oil*	*Crude Oil*	*Water*
Cape Ann	$382	$1,312	$9	$0	$0	$0	$0
Charleston	773	1,264	156	0	0	0	0
Fort Tejon	470	886	158	11	0	28	140
Hayward	208	1,310	115	6	0	0	91
New Madrid (M=8)	2,216	2,786	458	56	28	47	0
New Madrid (M=7)	204	1,077	108	19	9	19	0
Puget Sound	496	1,834	96	6	0	0	18
Wasatch Front	323	90	31	6	0	0	0

Table 6 Direct Damage Losses to Local Distribution Systems

Event	*Electric $ Billion*	*Water $ Billion*	*Highways $ Billion*
Cape Ann	$0.89	$0.30	$0.60
Charleston	0.74	0.31	0.50
Fort Tejon	0.91	0.23	0.23
Hayward	0.90	0.20	0.25
New Madrid (M=8.0)	2.07	0.88	1.40
New Madrid (M=7.0)	0.65	0.28	0.44
Puget Sound	0.58	0.09	0.28
Wasatch Front	0.38	0.13	0.26

6. Estimation of Indirect Economic Effects

Earthquakes produce both direct and indirect economic effects. The direct effects, such as dollar loss due to fires and collapsed structures, are obvious and dramatic. However, the indirect effects that these disruptions have on the ability of otherwise undamaged enterprises to conduct business may be quite significant. Although the concept of seismic disturbances and their effect on lifelines has been investigated for at least two decades, there is very little literature on indirect economic losses.

This study provides a first approximation of the indirect economic effects of lifeline interruption due to earthquakes. To accomplish this the relevant literature was surveyed. Then a methodology was developed to relate lifeline interruption estimates to economic effects of lifeline interruption in each economic sector. This required a two-step process:

1. Development of estimates of interruption of lifelines as a result of direct damage

2. Development of estimates of economic loss as a result of lifeline interruption

Estimates of Lifeline Interruption. Lifeline interruption resulting from direct damage is quantified in this investigation in residual capacity plots that define percent of function restored as a function of time. The curves are estimated for each lifeline type and scenario earthquake using (1) the time-to-restoration curves discussed in Chapter 3 and provided in Appendix B, (2) estimates of ground shaking intensity provided by the seismic hazard model (from Chapter 4), and (3) inventory data specifying the location and type of facilities affected (from Chapter 2).

For site-specific systems (i.e., lifelines consisting of individual sited or point facilities, such as airports or hospitals) the time-to-restoration curves are used directly whereas for extended regional networks, special analysis procedures are used. These procedures consist of:

- connectivity analyses, and

- serviceability analyses.

Connectivity analyses measure post-earthquake completeness, "connectedness," or "cut-ness" of links and nodes in a network. Connectivity analyses ignore system capacities and seek only to determine whether, or with what probability, a path remains operational between given sources and given destinations.

Serviceability analyses seek an additional valuable item of information: If a path or paths connect selected nodes following an earthquake, what is the remaining, or residual, capacity between these nodes? The residual capacity is found mathematically by convolving lifeline element capacities with lifeline completeness.

A complete serviceability analysis of the nation's various lifeline systems, incorporating earthquake effects, was beyond the scope of this project. Additionally, capacity information was generally not available for a number of the lifelines (e.g, for the highway system, routes were available, but not number of lanes). Rather, for this project, a limited serviceability analysis has been performed, based on a set of simplifying assumptions.

The fundamental assumption has been that, on average, all links and nodes of a lifeline have equal capacities, *so that residual capacity has been determined as the ratio of the number of serviceable (i.e., surviving) links and nodes to the original number of serviceable links and nodes, for a given source/destination pair, or across some appropriate boundary*. For example, if the state of South Carolina has 100 airports, and 30 of these are determined to be unserviceable at some point in time following a major earthquake, then the air transport lifeline residual capacity is determined to be 70% of the initial capacity.

An example illustrating the residual capacity plots for one lifeline and their implication is discussed below. Included in Chapter 6 are example residual capacity plots for all lifelines considered. Appendix C contains all residual capacity plots developed under this project (for the various lifelines and scenario earthquakes).

Ports. An example residual capacity plot for South Carolina, the worst-case situation, is provided in Figure 10. In this example, the initial loss is nearly 100 percent of capacity, and full

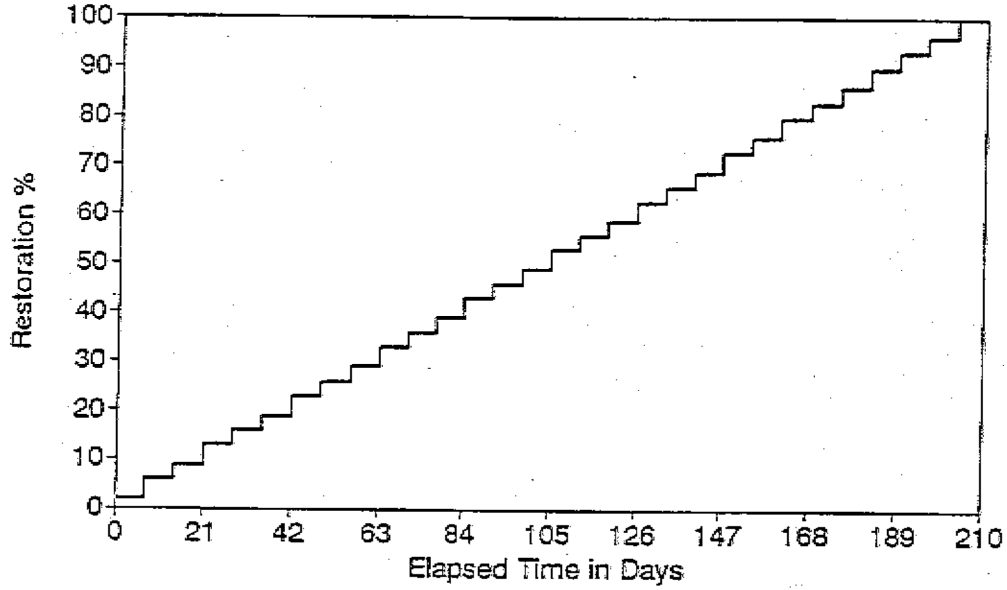


Figure 10 *Residual capacity of South Carolina ports following Charleston event (M=7.5).*

capacity is not restored until about day 200. Georgia would also experience similarly high losses due to the Charleston event. Massachusetts and Rhode Island would experience the largest losses due to the Cape Ann event.

Estimates of Indirect Economic Losses. Economic activity within each industrial sector was measured in terms of value added. Value added refers to the value of shipments (products) less the cost of materials, supplies, contract work and fuels used in the manufacture or cultivation of the product. The United States Bureau of Economic Analysis publishes annual data for value added for each industrial sector. For simplicity, data from the 99 sectors were collapsed into 36 sectors. Data for 1983 were the latest available (published by BEA, 1989), and were used in this study.

Reduction in Value Added Due to Lifeline Interruption. Table 7 presents the percent reduction in value added for each sector resulting from increasingly severe crude oil lifeline interruptions. (Similar tables are shown for all lifelines in Appendix D.) Values are shown for each decile of lifeline interruption and are assumed to pertain to *monthly* Gross National Product (GNP).

Indirect Economic Loss Results. Indirect economic losses were estimated for each lifeline system and scenario event using the residual capacity plots provided in Appendix C and the economic tables described above. The calculation procedure are described in Chapter 6.

Summaries of the total indirect economic losses resulting from damage to site-specific systems and extended regional networks, based on 1986 GNP data, are provided in Table 8. Total indirect economic losses resulting from damage to local distribution systems are presented in Table 9. We note that Table 8 contains total loss amounts expressed in terms of lower bound, upper bound, and best estimate. The lower bound represents economic loss caused by the singular lifeline system causing the greatest loss; the upper bound is the sum of losses caused by all systems; and the best estimate is the square root of the sum of the squares (SRSS) of losses

Table 7 Percent Value-Added Lost Due to Specified Percent Loss of Oil Supply Lifeline

L/L Capacity Loss-->	*U.S. Econ. Value Added (Percent)*	*10%*	*20%*	*30%*	*40%*	*50%*	*60%*	*70%*	*80%*	*90%*	*100%*
1 Livestock	0.45%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
2 Agr. Prod.	1.06%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
3 AgServ For. Fish	0.11%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
4 Mining	3.89%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
5 Construction	5.52%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
6 Food Tobacco	2.41%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
7 Textile Goods	0.37%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
8 Misc Text. Prod.	0.73%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
9 Lumber & Wood	0.52%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
10 Furniture	0.34%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
11 Pulp & Paper	0.87%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
12 Print & Publish	1.31%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
13 Chemical Drugs	1.40%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
14 Petrol. Refining	0.96%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
15 Rubber & Plastic	1.03%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
16 Leather Prods.	0.12%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
17 Glass Stone Clay	0.62%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
18 Prim. Metal Prod.	1.04%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
19 Fab. Metal Prod.	1.64%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
20 Mach. Exc. Elec.	1.56%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
21 Elec. & Electron	2.52%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
22 Transport Eq.	2.62%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
23 Instruments	0.68%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
24 Misc. Manufact.	0.69%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
25 Transp & Whse.	3.46%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
26 Utilities	5.89%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
27 Wholesale Trade	5.63%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
28 Retail Trade	5.63%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
29 F.I.R.E.	16.64%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
30 Pers./Prof. Serv.	8.03%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
31 Eating Drinking	2.12%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
32 Auto Serv.	1.09%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
33 Amuse & Rec.	0.70%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
34 Health Ed. Soc.	6.30%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
35 Govt & Govt Ind.	11.79%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
36 Households	0.25%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
TOTAL	100.00%	3.25% Avg.	9.74% Avg.	16.23% Avg.	22.72% Avg.	29.21% Avg.	35.70% Avg.	42.19% Avg.	48.68% Avg.	55.18% Avg.	61.67% Total V.A Pct. V.A.

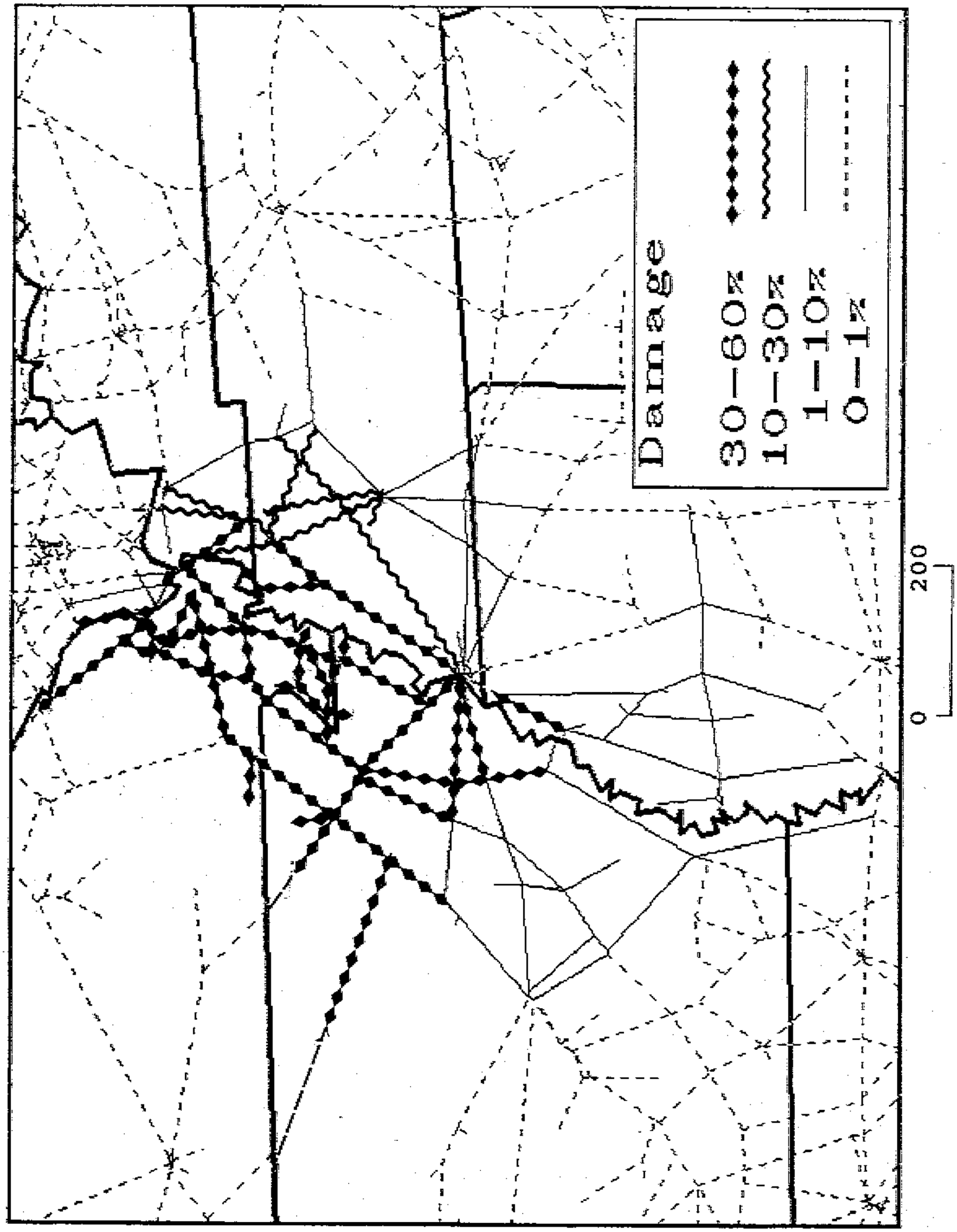


Figure 16 *Damage to railroad system following magnitude-8 New Madrid Event.*

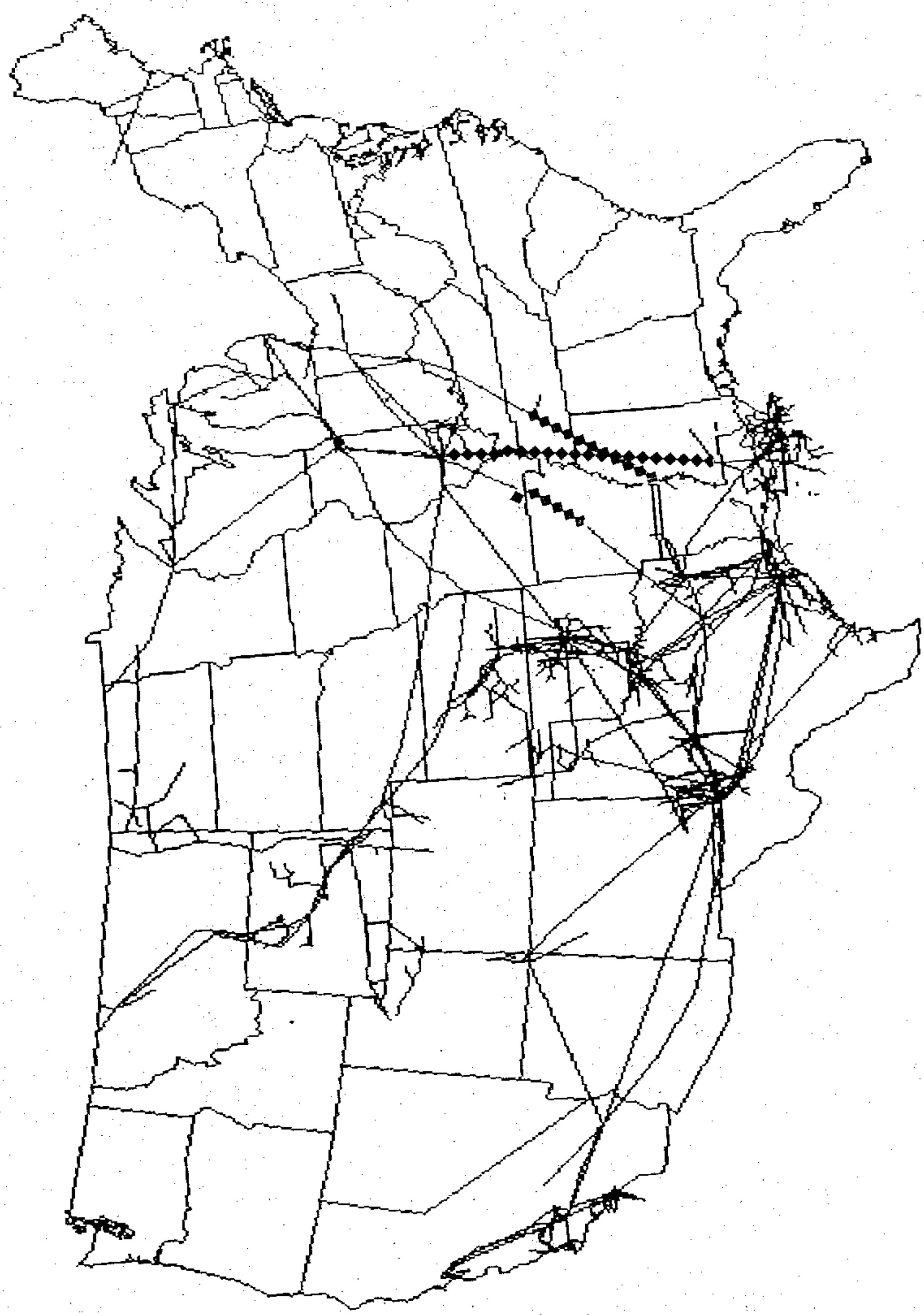


Figure 17 *Damage to crude oil system following magnitude-8 New Madrid Event. Broken pipelines are shown with solid diamonds.*

caused by each lifeline. We note also that the SRSS procedure was used to estimate total indirect economic losses resulting from damage to local distribution networks (Table 9).

By combining like system data from Tables 8 and 9 in a least squares (SRSS) fashion, we estimate the total indirect economic losses for the eight scenario earthquakes as follows:

Earthquake	*Indirect Loss (in Billions, 1991$)*
Cape Ann	$9.1
Charleston	$10.2
Fort Tejon	$11.7
Hayward	$11.1
New Madrid, M = 8.0	$14.6
New Madrid, M = 7.0	$4.9
Puget Sound	$6.1
Wasatch Front	$3.9

Bar charts showing the indirect losses caused by transmission lines (upper bound data) by state for each scenario earthquake were also developed. An example plot for the magnitude-8 New Madrid scenario event is provided in Figure 11. We note that estimates of indirect economic losses for each state are sensitive to the assumed location of the source zone for large-magnitude events (e.g., had the assumed source zone for the magnitude-8 New Madrid event been located further north, estimates of direct damage in Missouri would have been substantially larger).

The data provided in Figure 11 suggests Mississippi and Arkansas would experience the highest indirect losses due to the magnitude-8.0 New Madrid event. Similar plots for the other scenario earthquakes (Chapter 6) indicate that: Massachusetts would experience the highest indirect losses due to the Cape Ann event with the electric system contributing the highest portion; and South Carolina, Utah, Washington, Northern and Southern California would experience the highest indirect losses due to the Charleston, Utah, Seattle, Hayward, and Fort Tejon events, respectively. The electric system contributes the highest indirect losses, among all systems, for most of the events.

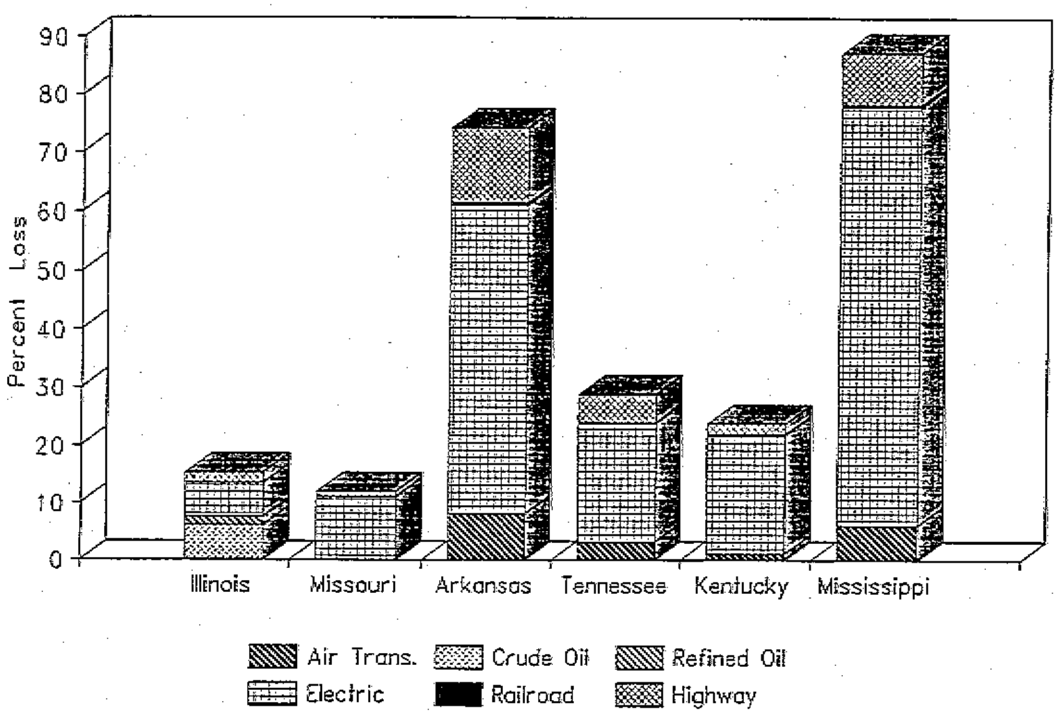


Figure 11 *Percent indirect economic loss by state (monthly GNP) resulting from damage to various lifelines, New Madrid event (M=8.0). Note that the relatively low losses for Missouri reflect the assumed location of the scenario earthquake source zone and the estimated distribution of intensity (see Figure 7).*

7. Combined Economic Losses, Deaths and Injuries

Human Death and Injury. It is generally felt that lifeline performance and continuity of operation is vital to human survival in the modern, urban, world. Most observers believe that damage to lifelines would result in human death and injury. Analogous to direct damage to property and indirect economic losses, human death and injury resulting from lifeline damage can be categorized as follows:

1. Human death and injury caused by lifeline functional curtailment, where persons suffer as a result of deprivation of vital services; and

2. Human death and injury resulting from direct damage to lifelines (e.g., occupant injuries resulting from the collapse of an air terminal building).

Casualties Due to Lifeline Functional Curtailment. Without the benefit of hard data it is difficult to estimate with high confidence the number of casualties that will result from curtailment of lifeline function. Our preliminary assessment is that human death and injury due to functional curtailment of lifelines can generally be expected to be very low. This is a fundamental assumption of this study, and will probably cause some debate. Each lifeline was considered, and this conclusion was found to hold, based on the following assumptions: (1) most vital installations that normally require a lifeline service have back-up emergency supplies, and (2) most lifelines have considerable elasticity in demand, and the level of service necessary for life maintenance is very low. Examples follow:

- Electricity. Persons can survive without power, even in the Northeast in the winter. Most hospitals and similar installations have emergency generators. Those that lack emergency generators can transfer patients to other sites.

- Water. Water for human survival is very minimal. Humans can survive without water for 48 or more hours, and water for human survival can be imported if necessary.

- Gas and Liquid Fuels. Gas and liquid fuel systems are probably the most critical of all lifelines, yet capacity is very elastic, and only short-term shortages are expected. Fuel for heating in the Northeast in the winter can be conserved if necessary by clustering people in school gymnasia, national guard armories, and so on.

- Rail, Air, and Highway Transportation. Transportation lifelines are highly redundant and thus very elastic; emergency food and medicines would be expected to be deliverable regardless of earthquake damage.

Casualties Resulting From Lifeline Direct Damage. Casualties can result from direct damage, especially catastrophic collapse, of lifeline components. Although few deaths occurred directly as a result of lifeline damage in U. S. earthquakes prior to 1989, life-loss due to lifeline failure was tragically demonstrated during the October 17, 1989, Loma Prieta, California, earthquake. Approximately two thirds of the 62 deaths from this earthquake resulted from the failure of a lifeline component--partial collapse of the Cypress structure, a double-decked highway viaduct in Oakland approximately 100 km from the earthquake source zone.

Although it can be argued that the deaths and injuries caused by lifeline failure in the Loma Prieta earthquake were the exception, not the rule, the vulnerability functions developed for this project suggest that substantial life-loss from lifeline component failure should be anticipated. Lifeline failures that could cause substantial life loss or injury include bridge failure, railroad derailment, and pipeline failure.

Unfortunately, data necessary for estimating life loss associated with these component failures are not readily available, precluding development of reliable casualty estimation methodology and data for lifeline structures.

Combined Direct and Indirect Economic Losses. Summaries of total dollar losses from direct damage and indirect economic losses are combined and summarized for each scenario earthquake and lifeline in Table 10. The total

Table 10 Total Direct Plus Indirect Dollar Losses for Each Scenario Earthquake and Lifeline (Billions of Dollars)

Scenario	*Electric*	*Highways*	*Water*	*Medical Care*	*Ports*	*Railroads*	*Airport*	*Natural Gas*	*Crude Oil*	*Refined Oil*	*Broadcasting Stations*	*Fire Stations*	*Total*
Cape Ann	$11.24	$2.06	$0.91	$0.49	$0.50	$0.03	$0.58	$0.00	$0.00	$0.00	$0.02	$0.01	$13.25
Charleston	$10.82	$2.05	$0.94	$0.57	$5.30	$0.18	$0.59	$0.00	$0.00	$0.00	$0.07	$0.01	$15.11
Fort Tejon	$9.66	$5.18	$5.27	$1.43	$2.65	$0.41	$1.57	$1.68	$4.38	$0.00	$0.03	$0.05	$16.58
Hayward	$12.21	$2.52	$4.38	$1.30	$1.46	$0.22	$0.44	$0.09	$0.00	$0.00	$0.02	$0.01	$15.66
New Madrid 8	$15.68	$13.19	$2.68	$1.30	$0.00	$0.71	$1.22	$0.34	$0.46	$0.23	$0.09	$0.01	$26.37
New Madrid 7	$5.17	$4.12	$0.85	$0.40	$0.00	$0.15	$0.31	$0.18	$0.13	$0.16	$0.03	$0.00	$8.29
Puget Sound	$8.29	$1.95	$0.90	$0.51	$0.73	$0.21	$0.62	$0.21	$0.00	$0.00	$0.05	$0.01	$10.48
Wasatch Front	$2.21	$3.85	$0.40	$0.20	$0.00	$0.05	$0.11	$0.04	$0.00	$0.00	$0.04	$0.00	$5.41

losses for each scenario earthquake are as follows:

Earthquake	*Direct Plus Indirect Losses (in Billions, 1991$)*
Cape Ann	$13.3
Charleston	$15.1
Fort Tejon	$16.6
Hayward	$15.7
New Madrid, M = 8.0	$26.4
New Madrid, M = 7.0	$8.3
Puget Sound	$10.5
Wasatch Front	$5.4

8. Hazard Mitigation of Critical Lifelines

Identification of Critical Lifelines. Based on the combined direct and indirect economic losses presented above and with due consideration of the assumptions and limitations expressed throughout this report, we offer the following relative ranking of the criticality of different lifelines in terms of the estimated impact of damage and disruption:

Rank	Lifeline	Event/Location
1.	Electric System	New Madrid (M=8.0)
		Hayward
		Cape Ann, Charleston, Fort Tejon
2.	Highways	New Madrid (M=8.0)
		Fort Tejon
		Hayward, New Madrid (M=7.0)
3.	Water System*	Fort Tejon
4.	Ports	Charleston
5.	Crude Oil	Fort Tejon

*The ranking for the water system may be underestimated because critical components such as pumping stations and dams were not included in the study.

Measures for Reducing Vulnerability of Lifeline Systems. The seismic vulnerability of lifeline systems, from the point of view of fulfilling function, can be reduced through three primary approaches:

1. Damage reduction measures. In this approach reliability of function is enhanced by reducing damage. This approach may take the form of :
   - Strengthening a building, bracing equipment, or performing other corrective retrofit measures to mitigate shaking effects;
   - Densifying the soil beneath a structure, or placing a structure on piles, or using other techniques to mitigate hazardous geotechnical conditions, e.g., liquefaction potential,
   - Other component improvements, depending on the component and potential earthquake impacts, e.g., replacement of vulnerable systems/components with new systems/components that will provide improved seismic resistance.
2. Provision for system redundancy. In this approach, reliability of function is enhanced by providing additional and alternative links (e.g., new highways, pipelines, other transmission or distribution links). Because earthquake damage is fundamentally a random phenomena, addition of system links will tend to increase system reliability.
3. Operational improvements. In this approach reliability of function is enhanced by providing emergency response planning and the capability to rapidly and effectively repair damage, redirect functions, or otherwise mitigate earthquake damage impacts on system operations and thereby re-establish system function.

Of these measures, the most common are component strengthening/retrofit measures, which are discussed at length in Appendix B of this report. The proposed measures (Appendix B) include generic solutions, such as designing structures to meet current seismic design or retrofit standards of the local community, or anchoring equipment. In addition, there are numerous specific measures that relate to unique systems or components within each lifeline. Special attention should be directed to those systems and conditions that are of greatest concern, such as porcelain components in electric substations.

Following are recommended steps when implementing a program to reduce seismic hazards of existing lifelines:

1. Review existing descriptions of seismic performance and rehabilitation measures for the lifeline(s) of concern, i.e., familiarize yourself and your organization with the overall problem. Sources include Appendix B and Chapter 10 (References) of this report.

2. Conduct an investigation of the seismic vulnerability and impact of disruption for the lifeline(s) and region(s) of concern. Lifeline seismic evaluation methodologies and other potential resources for this purpose have been developed by the ASCE Technical Council for Lifeline Earthquake Engineering (see references, Chapter 10), the Applied Technology Council (ATC, in preparation) and others.

3. Focus first on the most vulnerable lifelines, components, and conditions (e.g., liquefaction or landslide potential). Vulnerable components include:

   For electric systems:
   - Substations
   - Power stations

   For water systems:
   - Pumping stations
   - Tanks and reservoirs
   - Treatment plants
   - Transmissions aqueducts

   For highway systems
   - Bridges
   - Tunnels
   - Roadbeds

   For water transportation systems:
   - Port/cargo handling equipment
   - Inland waterways

   For gas and liquid fuels:
   - Distribution storage tanks
   - Transmission pipelines
   - Compressor, metering and pressure reduction stations

4. Conduct cost-benefit studies to determine the most cost effective measures. We note that, in some cases, retrofit measures may not be very cost effective. In regions where the return period for large earthquakes is quite long, for example, replacement over the life cycle of the facility or component may be a reasonable approach.

5. Implement the selected hazard reduction measures.

9. Recommendations for Further Work

The ATC-25 project has raised a number of questions and indicated areas in which knowledge is inadequate or nonexistent with respect to the impact of lifeline disruption due to earthquake. Following are recommendations for further research and other efforts. This list is not meant to be all inclusive but rather an overview of some of the more important issues that should be pursued.

Lifeline Inventory. Organizations such as the Federal Emergency Management Agency, Department of Transportation, and American Society of Civil Engineers Technical Council of Lifeline Earthquake Engineering are encouraged to build on the work performed in this project, develop standards for complete lifeline inventories, and coordinate the acquisition of the needed additional and updated data from various lifeline owners.

Lifeline Component Vulnerability. We recommend a major effort to acquire data on lifeline seismic performance and damage, and conduct analysis towards the development of improved component vulnerability functions. This effort should also investigate lifeline recovery data, and incorporate the extensive experience realized during the 17 October 1989 Loma Prieta, California, earthquake, as well as from other damaging earthquakes.

Seismic Hazard Data. We suggest that the U. S. Geological Survey develop, or coordinate through the various states' Office of Geologists, a series of digitized soils/geologic databases.

Economic Analysis and Impacts Data and Methodology. We recommend further research, especially in economic areas such as:

- Economic impacts associated with lifeline disruption,
- Second-order economic effects (e.g., interaction between lifelines),
- Elasticities of demand, or substitution of a lesser disrupted lifeline for a more disrupted lifeline ,
- Inter-regional impacts, and
- So-called "benefits," such as increased economic activity associated with repair, or replacement of older equipment with new technology.

Lastly, we note that this study did not address environmental consequences associated with lifeline disruption, especially the potential for oil spills from broken pipelines in the nation's waterways following a New Madrid event. Investigation of this issue is critically important.

1. Introduction

1.1 Background and Purpose

Lifeline is an earthquake engineering term denoting those systems necessary for human life and urban function, without which large urban regions cannot exist. Lifelines basically convey food, water, fuel, energy, information, and other materials necessary for human existence from the production areas to the consuming urban areas. Prolonged disruption of lifelines such as the water supply or electric power for a city or urbanized region would inevitably lead to major economic losses, deteriorated public health, and eventually population migration. Earthquakes are probably the most likely natural disaster that would lead to major lifeline disruption. With the advent of more and more advanced technology, the United States has increasingly become dependent on the reliable provision of lifeline-related commodities, such as electric power, fuel, and water. A natural question is: What is the potential for major disruption to these lifelines, especially at the regional level?

The initiation of this study by the Federal Emergency Management Agency (FEMA) is based in part on a need to better understand the impact of disruption of lifelines from earthquakes and to assist in the identification and prioritization of hazard mitigation measures and policies. In addition, the report is intended to improve national awareness of the importance of protecting lifeline systems from earthquakes, and of assuring lifeline reliability and continued serviceability.

The specific contractual requirements of this project and report are:

- To assess the extent and distribution of existing U.S. lifelines, and their associated seismic risk; and
- To identify the most critical lifelines, and develop a prioritized series of steps for reduction of lifeline seismic vulnerability, based on overall benefit.

FEMA is also sponsoring a companion study to develop and demonstrate a model methodology for assessing the seismic vulnerability and impact of disruption of water transmission and distribution systems (ATC, in preparation).

In this study, lifelines of critical importance at the U.S. national level have been analyzed to estimate overall seismic vulnerability and to identify those lifelines having the greatest economic impact, given large, credible U. S. earthquakes. The lifelines examined include electric systems; water, gas, and oil pipelines; highways and bridges; airports; railroads; ports; and emergency service facilities. The vulnerability estimates and impacts developed are presented in terms of estimated direct damage losses and indirect economic losses. These losses are considered to *represent a first approximation* because of the assumptions and methodology utilized, because several lifelines are not included, and because, in some cases, the available lifeline inventory data lack critical capacity information.

1.2 Importance of the Lifeline Earthquake Risk Problem

The critical importance and earthquake vulnerability of lifelines were probably first strongly emphasized in the earthquake and ensuing fires in San Francisco in 1906. The disaster in San Francisco, which was the worst urban fire in history to that time, and which continues today to be the worst earthquake disaster in U.S. history, was in large part attributable to the failure of several lifelines, including:

- Breakage of gas distribution and service lines, leading to numerous outbreaks of fire.
- Damage to fire stations, resulting in inoperable apparatus and injured fire fighters. The single worst example of this was the fatal injury of San Francisco Fire Chief Dennis Sullivan, effectively "decapitating" the fire department at the worst possible moment.
- Worst of all, literally hundreds of breaks to the water distribution system within San

Francisco, resulting in total loss of water for fire-fighting purposes.

After that disaster and in recognition of the absolute necessity of water following an earthquake, the San Francisco Fire Department built and today still operates the Auxiliary Water Supply System (AWSS), a unique high-pressure water system separate and redundant from the domestic drinking water supply.

Following 1906, major earthquakes in the U.S. and elsewhere continued to illustrate the prime importance of lifelines in earthquakes. In the 1933 Long Beach Earthquake, for example, numerous authorities at the time cited the prompt shutdown of the municipally operated gas system with the prevention of major fires (e.g., NBFU, 1933; Smethurst, 1933; Binder, 1952):

> Instructions had been issued and signs had been posted near the control valves of the gas and light public utility control stations to the effect that, in the event of an earthquake, these switches must be pulled or valves closed, and this was the reason that the gas lights were shut off in less than four minutes after the earthquake had occurred (Smethurst, 1933).
>
> Broken gas services and devices caused 7 of the 19 fires reported in Long Beach during the night of 10 March 1933. Prompt closing of valves, together with a major break in a high pressure main, undoubtedly prevented fires in numerous locations in the business district. Preparedness for disturbance is of very great importance in connection with gas service (NBFU, 1933).

The 1971 San Fernando Earthquake illustrated more than any other event the essential interaction of lifelines and earthquakes. Examples of lifeline effects in that relatively modest earthquake included:

- Major damage to electrical substations, including overturning of extra high voltage (EHV) transformers;
- Literally hundreds of breaks in the water distribution system;
- Major damage to a telephone central switching office, and loss of telephone service due to this damage as well as saturation;
- Near-collapse of a major dam;
- Numerous breaks in the gas distribution system, resulting in large burning gas flares at several intersections;
- Collapse of major freeway overcrossings, resulting in fatalities and major disruption of traffic; and
- Major damage to emergency facilities, including collapse and major loss of life at a hospital, and major damage or partial collapse at several other hospitals, including very modern structures at one hospital.

Since the 1971 San Fernando Earthquake, significant research into lifelines has been conducted, too extensive to summarize herein (see the following references for major compilations: Kubo and Jennings, 1976; ASCE-TCLEE, 1977; Kubo and Shinozuka, 1981; ASCE-TCLEE, 1981; Smith, 1981; Ariman, 1983; Cooper, 1984; Scawthorn, 1985; Eguchi, 1986; BSSC, 1987). Additionally, several design guidelines have resulted from this research (ASCE-TCLEE, 1983; GLFC, 1984; ATC-6, 1981; ATC-6-2, 1983), which should result in improved future lifeline design and performance.

Based on these efforts, it is fair to say that substantial lifeline earthquake engineering knowledge, data, and experience are presently available today, for the purpose of designing or retrofitting lifelines to withstand the effects of earthquakes. However, because much of the U.S. national infrastructure was constructed prior to the research and guideline development of the 1970s and 1980s, the United States is still faced with the problem of existing lifelines that are seismically vulnerable and that, if disrupted, would result in major economic displacements, and probable environmental damage and human injury.

This last point was tragically demonstrated on October 17, 1989, when the magnitude 7.1 Loma Prieta Earthquake struck the San Francisco Bay Area, resulting in 62 deaths, more than 3,700 injuries, and leaving more than 12,000 persons homeless. Approximately two-thirds of the fatalities in this event were due to the failure of a lifeline--the collapse of the Cypress double-decked highway structure in Oakland. Lifeline damage and disruption were one of the most significant features of this earthquake, the most damaging to strike the conterminous United States since 1906. One of the world's major bridges, the San Francisco-Oakland Bay Bridge, was closed for a month due to structural failure. Power was disrupted over a widespread area, water systems failed in several communities, and other lifeline problems contributed to major disruptions.

1.3 Project Approach

This study is concerned with the seismic risk to lifelines and provides a first approximation of the indirect economic effects of lifeline interruption due to earthquakes. The analysis is first order in that uncertainties in vulnerability functions, seismic hazard, and all other factors were not considered. The overall objective of the study is to quantify the extent and distribution of lifelines in the lower 48 States, to identify the most critical lifelines in terms of their vulnerability and impact on the national economy, and to develop a prioritized series of steps for reducing seismic risk to these lifelines.

Figure 1-1 summarizes the main steps of the approach used to develop this report. Four basic steps were followed to estimate lifeline damage and subsequent economic disruption for given earthquake scenarios.

1. Development of a national lifeline inventory database.

2. Development of seismic vulnerability functions for each lifeline system,

3. Characterization and quantification of the seismic hazard nationwide, and

4. Development of direct damage estimates and indirect economic loss estimates for the various scenario earthquakes.

1.4 Limitations and Constraints

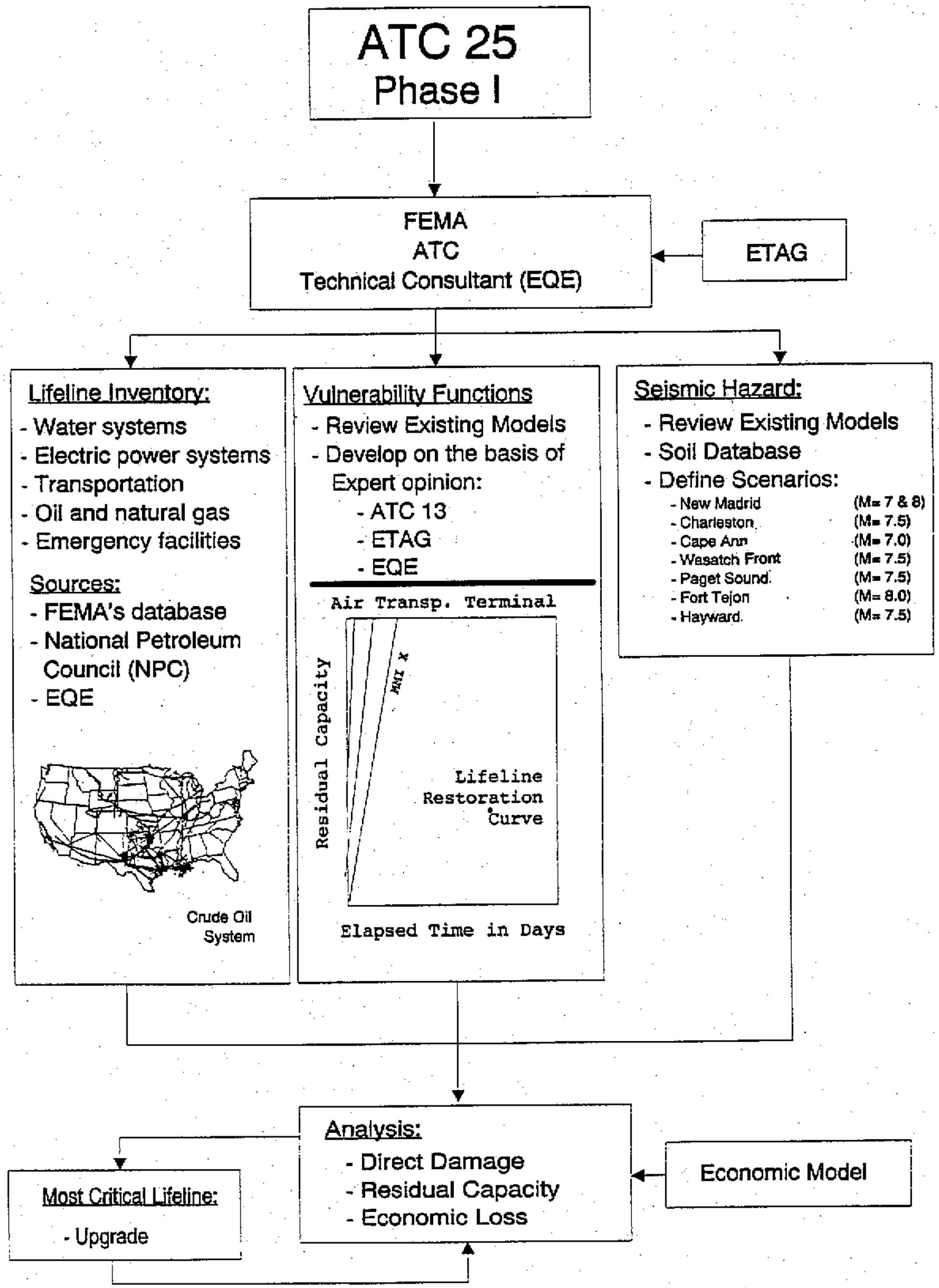
During development of this report and its supporting data, several problems were encountered that could not be resolved because of technical difficulties and lack of available data. For example, telecommunication systems, nuclear and fossil-fuel power plants, dams, and certain water, electric, and transportation facility types at the regional transmission level were excluded from consideration in this project because of the unavailability of inventory data or the need for more in-depth studies.

Interaction effects between lifelines, secondary economic effects (the impact of a reduced capacity of one economic sector on a dependent sector), and damage resulting from landslide (due to lack of inventory data nationwide) were also not considered in developing this report. These limitations and others described in Chapters 2, 4, and 5 tend to underestimate the losses presented herein; and other factors, as described elsewhere in this report, tend to overestimate the losses. Lack of capacity information for most lifelines was also a definite limitation. In the aggregate, due primarily to the exclusion of certain systems (e.g., dams and telecommunication systems), we believe the estimates of losses presented in this report are, in fact, quite conservative.

We also emphasize that this report is a macroscopic investigation at the national level and the results should not be used for microscopic interpretations. The results, for example, are not intended to be used to evaluate any particular regional utility or lifeline, and no specific information on such specific facilities has been included.

1.5 Organization of the Report

The organization and contents of this report have been dictated in large part by the project approach. Following this introduction is Chapter 2, which contains a description of the inventory data developed for and utilized in this project. Seismic vulnerability functions, in the form of damage curves and restoration curves for all lifelines considered, are developed and described in Chapter 3. In Chapter 4 we discuss the seismic hazard nationwide, identify available seismic hazard models that could have been used in the analysis stages of this project, indicate the model that was selected and describe its advantages and disadvantages, and define the eight earthquake scenarios that provide the basic framework for all damage and



Notation: ATC-13: ATC-13 Report, *Earthquake Damage Evaluation Data for California* (ATC, 1985)
ETAG: Expert Technical Advisory Group (project advisory panel)
EQE: EQE Engineering, Inc. (project subcontractor)

Figure 1-1 Flow chart showing main steps in project approach.

loss estimates presented in this report. Direct damage estimates and estimates of indirect economic loss are developed in Chapters 5 and 6. The direct damage and indirect economic loss estimates are combined, summarized, and discussed in Chapter 7. In Chapter 8 we identify the most critical lifelines, identify hazard mitigation strategies, and discuss the potential benefits of implementing such strategies.

Chapter 9 provides brief remarks about additionally needed research and other efforts. References are provided in Chapter 10. The report concludes with a series of appendices containing names and affiliations of project participants and substantial amounts of lifeline vulnerability assessment data too voluminous to include in the main body of the report.

2. National Lifeline Inventory

2.1 Introduction

Development of the ATC-25 inventory, for all major lifelines in the United States, was a major task. The project scope required that lifelines be inventoried in sufficient detail for conducting lifeline seismic vulnerability assessments and impact of disruption at the national level. This in turn required that the inventory be compiled electronically in digital form and dictated that inclusion of lifelines at the transmission level, as defined below, was of primary importance. At the same time, the level of effort that could be devoted to this task was constrained by the budget available.

Initially, a number of government, utility, trade and professional organizations, and individuals were contacted in an effort to identify nationwide databases, especially electronic databases. In most cases, these organizations or individuals referred the project back to FEMA, since they had either previously furnished the information to FEMA, or knew that the data had been furnished to FEMA by others. As a result, FEMA's database (FEMA, 1987) became a major source of data for several of the lifelines. A significant portion of these data consist of digitized U.S. Geological Survey (USGS) topographical maps and/or the National Atlas (Gerlach, no date), performed by the U.S. Geological Survey in support of national census requirements. With the exception of oil and gas pipeline data provided by the National Petroleum Council, the inventory data generally date from about 1966, unless later updated by FEMA. A number of other sources were employed in various ways, which are further discussed below.

The network inventory contained in the database is generally at the higher transmission levels, as opposed to lower distribution levels. That is, inventories were generally only compiled for networks at the bulk and/or regional level, as opposed to lifelines at the user-level (i.e., distribution level) *within* an area. To use an analogy, the inventory contains only the national *arterial* level, and neglects the distribution or *capillary* system. For example, all federal and state highways are inventoried, but county and local roads are not. The major reason for focusing on the transmission level is that at lower levels the systems only support local facilities. Thus, a disruption of a local activity could not be used to identify the overall regional importance of the lifeline. However, disruptions at the transmission level impact large regions and are therefore important for understanding the seismic vulnerability and importance of lifelines to the United States. For some lifelines, such as highways and railroads, an additional reason for focusing on the transmission level is the increasing redundancy that contributes to system reliability as one descends in the lifeline hierarchy. Lastly, even at the transmission level, the inventory effort alone is considerable.

The inventory data have been compiled into an electronic database, which generally consists of (i) digitized location and type of facility for single-site lifeline facilities, and (ii) digitized right-of-way, and very limited information on facility attributes for network lifelines. The inventory is only a partial inventory, in that important information on a number of facility attributes (e.g., number or length of spans for highway bridges) was unavailable from FEMA.

2.2 National Lifeline Inventory Data--Overview

The inventory data include information for the conterminous United States only. Lifeline data for Alaska, Hawaii, and U. S. territories, such as Puerto Rico, have been excluded because lifelines in these regions would not be affected by the scenario earthquakes (see Chapter 4) considered in this study.

The specific lifelines that have been inventoried for the conterminous United States are:

Transportation
- Highways
- Railroads
- Airports
- Ports and Harbors

Energy
- Electric Power Transmission
- Gas and Liquid Fuel Transmission Pipelines

Emergency Service Facilities
- Emergency Broadcast Facilities
- Hospitals

Water Aqueducts and Supply

An important lifeline, telecommunication systems, which would be severely impact by earthquake-induced ground shaking, was excluded because of the unavailability of data, as are certain regional distribution network facility types (e.g., railway terminals, bridges, and tunnels; certain aqueducts; major freeway/highway bridges; fossil-fuel power plants; and aqueduct pumping stations). In addition, data on nuclear reactors and dams are excluded because it was believed that such facilities should be the subject of special studies, particularly because of the existing regulations relating to seismic safety in many regions and the expected complexity of the performance and impact of these facility types. As a result, the losses provided by this study will be underestimated to the extent that these facility types are not included.

Also excluded from the inventory, but included in the analysis, are distribution systems at the local level (water, highway, and electrical systems) and police and fire stations. For these facility types, the number of facilities in each 25-km by 25-km grid cell, which is the grid size for the seismic hazard analysis (see Chapter 4), is estimated on the basis of proxy by population.

Each of the above-specified lifelines has been inventoried in terms of its nodes and/or links. Nodes are points on the lifeline, connected by links. Examples of nodes are highway intersections and electric substations. Links would be sections of highway, sections of pipeline, or electric transmission lines. Intermediate points between links have been introduced in some lifelines to provide better location information on the path of a lifeline (i.e., to capture path curvature between nodes).

The data were compiled and reduced on a graphical interactive lifelines seismic risk analysis/database management computer program named *LLEQE** (*L*ife*L*ine *E*arth*Q*uake *E*ngineering). Two operations were required: (1) reduction in the number of links by a factor of about ten to reduce the size of the database to a manageable size for analysis (i.e., minor curvatures at the local level have been eliminated), and (2) continuity corrections so that transmission lines between separately digitized sections (e.g., across state boundaries) would be continuous. The reduction effort was substantial and utilized a significant portion of the financial resources allocated to the inventory task.

The inventory was generally compiled in terms of nodes, links, and descriptive attributes, if available. These attributes are:

1. Measures of lifeline inventory, appropriate to the lifeline. These are, for example:
   - Miles of oil pipeline, by diameter;
   - Number of electric substations;
   - Miles of water pipeline; and
   - Number of emergency facilities, such as hospitals, fire stations.
2. Additionally, where available, measures of function and redundancy have been compiled on this database. For transmission line links, these include:
   - The capacity of the lifeline and/or the population served;
   - The end points of the nodes; and
   - Whether the nodes are served by other links.

Each of the inventoried lifelines, as well as those estimated by proxy, are discussed below.

2.3 Transportation Data

State and Federal Highway System. A comprehensive national digitized data set on the highway system was obtained from FEMA, as shown in Figure 2-1. The system includes state and federal highways, but excludes county and local roads. It consists of 27,761 links (about 489,892 km of highways). Right-of-way

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alignment is indicated, but capacity (i.e., number of lanes) is not.

Local Highway Distribution. Detailed highway networks at the local level were not readily available in an electronic format. Based on statistics provided by the California Department of Transportation, we have determined that there is approximately 1 mile of local roadway for every 300 persons. This would correspond to approximately 15 feet of local roadway per person.

Federal and State Highway Bridges. Figure 2-2 shows 144,785 bridges, which have been obtained from FEMA's database. Bridges included are those for state and federal highways. Number of spans and structure types were not available.

Railroad System. This system shown in Figure 2-3 consists of about 11,340 links (about 270,611 km). The railroad system was provided by FEMA in digitized form; only right-of-way was indicated.

Airports. Locations of 17,161 civil and general aviation airports were provided by FEMA, as shown in Figure 2-4.

Ports and Harbors. Location information only for about 2,177 ports was provided by FEMA, as shown in Figure 2-5.

2.4 Energy and Fuel Data

Electric Power Generation and Transmission. The electric system provided by FEMA included 230 kV and above and some 115 kV systems (Figure 2-6). The inventory contains 4,551 substations, and 27,372 links, including links used to define path curvature between nodes (about 441,981 km of transmission lines). The number of circuits, and their voltage or capacity, however, are not included in the database. While the lack of capacity information has not been a serious limitation for this study, as discussed elsewhere, we recommend that users of this inventory data seek to add capacity information before using the data to conduct regional or local studies.

Local Electrical System Distribution. Detailed electrical distribution networks at the local level were not readily available in an electronic format. It was assumed, therefore, that the person-to-unit-length ratio for electrical distribution systems was the same as that for highways. In other words, there is approximately 1 mile of electrical distribution line for every 300 persons. This would correspond to approximately 15 feet of electric line per person.

Gas and Liquid Fuel Transmission Pipelines. The National Petroleum Council (NPC, 1989) furnished relatively comprehensive national digitized data on oil and gas pipelines, including size and material of piping. Figures 2-7, 2-8, and 2-9 picture the crude oil, refined oil, and natural-gas pipelines, respectively. The crude oil system includes about 77,109 km of pipelines. The refined oil system consists of about 85,461 km of pipelines and natural gas system has about 67,898 km of pipelines. The database had been developed as part of a major study on the transportation and capacities for this important sector of the economy, and potential catastrophic disruptions (NPC 1989; it is interesting to note that earthquake was not considered as a possible source of disruption in this study).

Refineries. Figure 2-10 shows 19 refineries nationwide having capacities of 80,000 barrels or more per day (the size considered in this study). Locations of these refineries have been digitized from the National Atlas (Gerlach, no date).

2.5 Emergency Service Facility Data

Emergency Broadcast Facilities. The locations of 29,586 stations were obtained from FEMA and are shown in Figure 2-11.

Medical Care Centers. Locations of about 6,973 centers were obtained from FEMA's database and are shown in Figure 2-12. Structural types were not available.

Police and Fire Stations. Detailed information was not available for these facilities. They were estimated as follows:

Fire Stations. Detailed nationwide fire station inventory data were not readily available in an electronic format. Data for the San Francisco and Los Angeles region fire stations were available (AIRAC, 1987) and were correlated with jurisdictional population to determine a relation, which

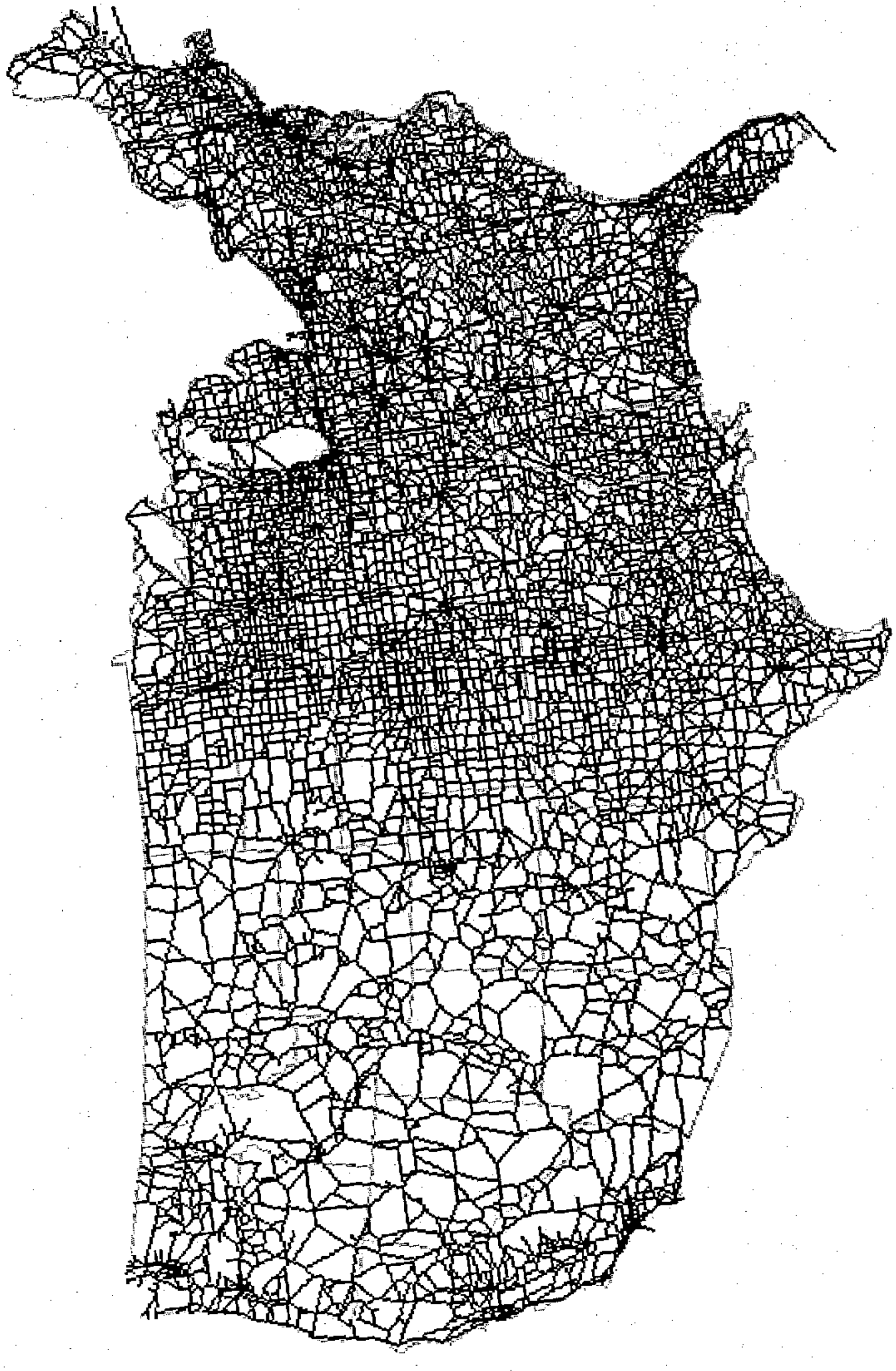


Figure 2-1 *State and federal highways.*

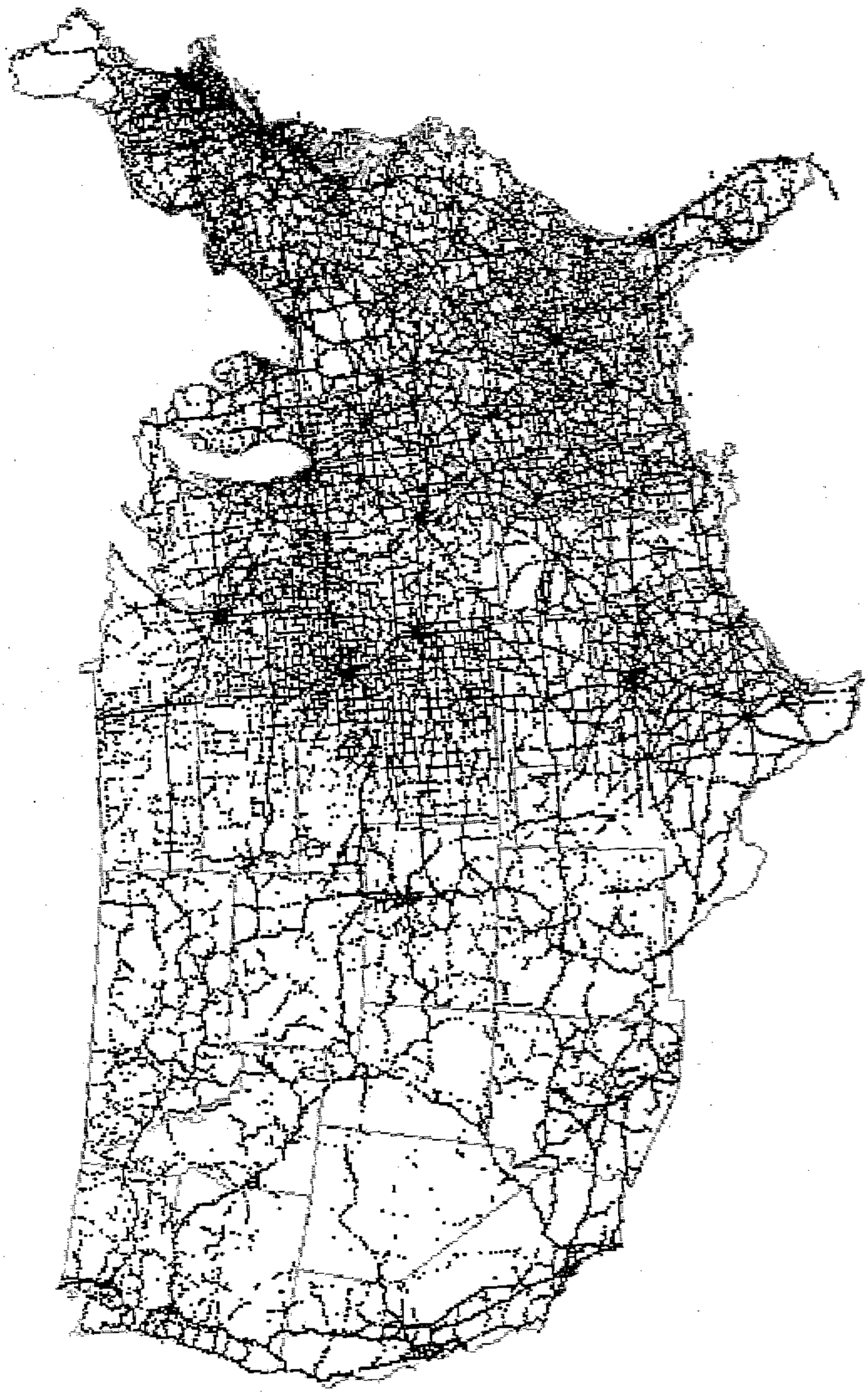


Figure 2-2 *State and federal highway bridges.*

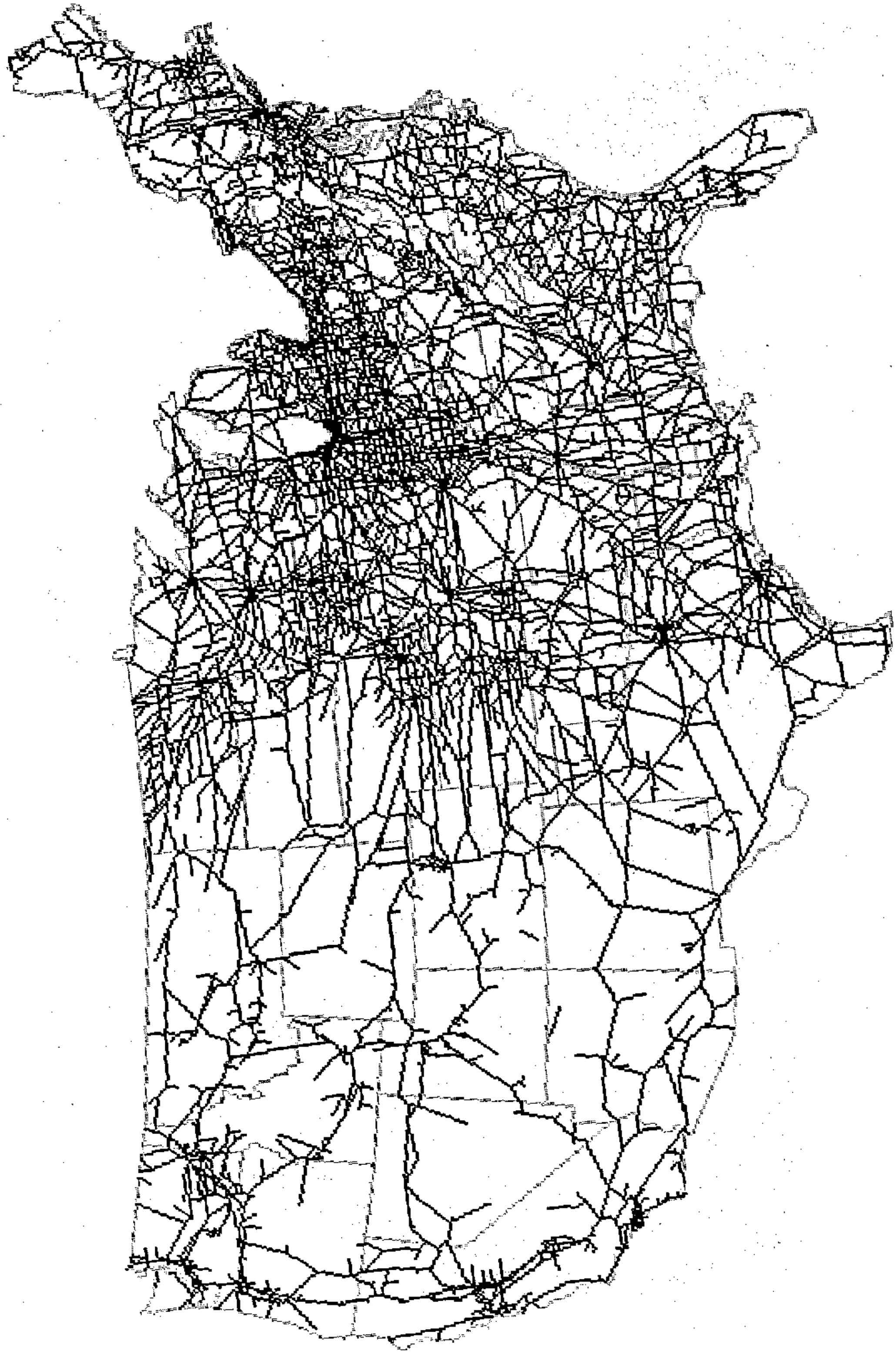


Figure 2-3 *Railroad system.*

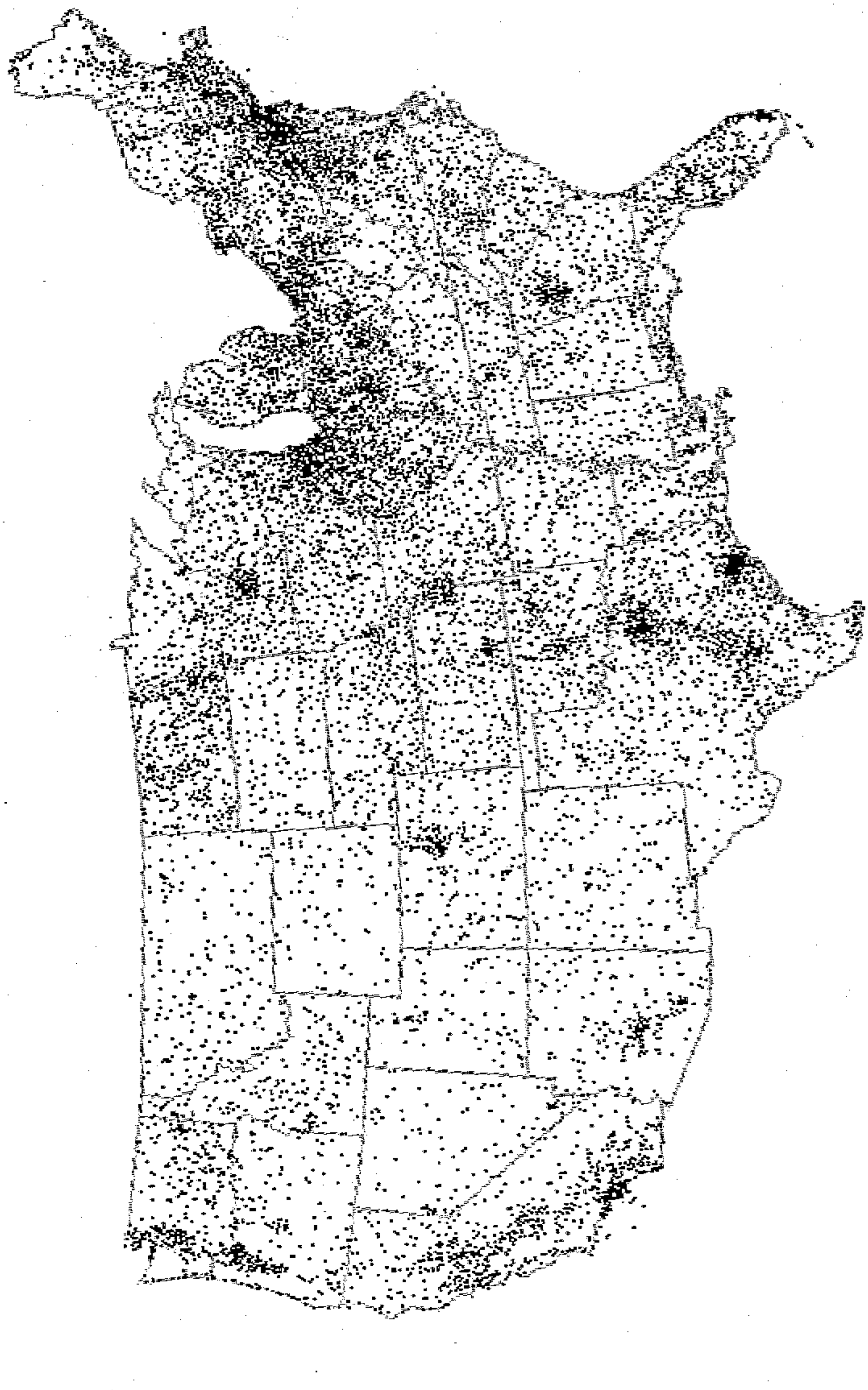


Figure 2-4 *Airports.*

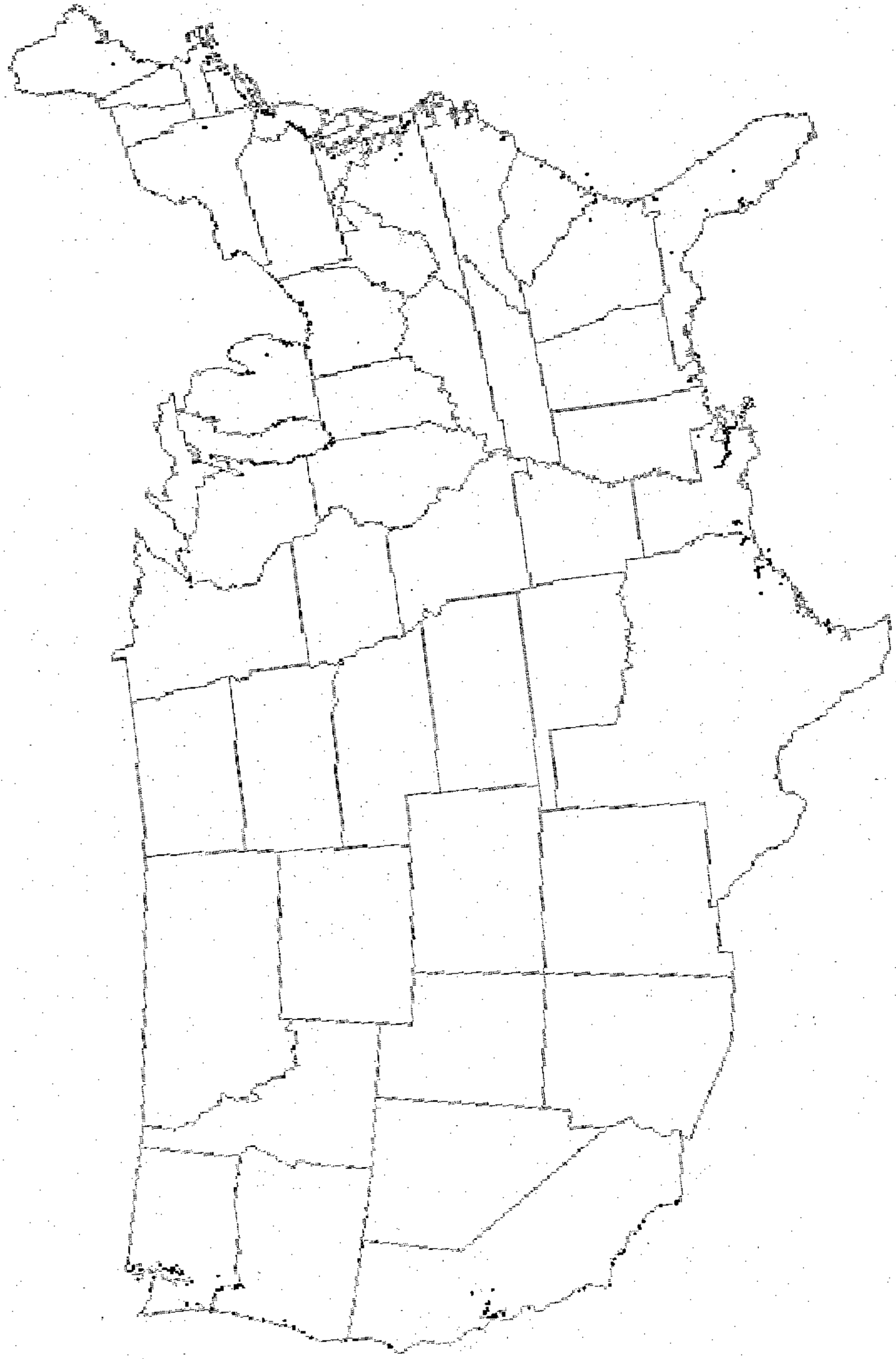


Figure 2-5 *Ports and harbors.*

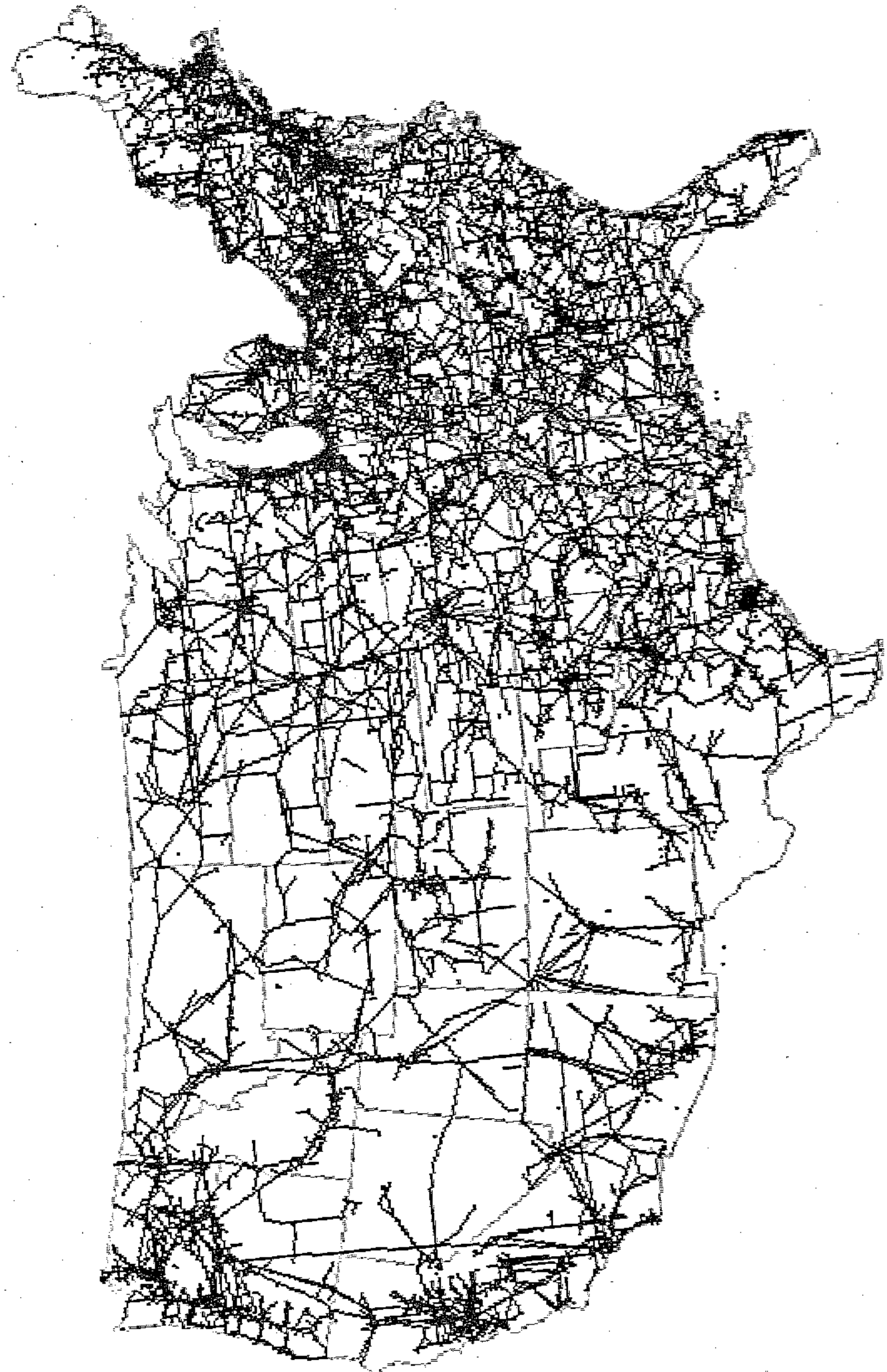


Figure 2-6 Electric transmission system.

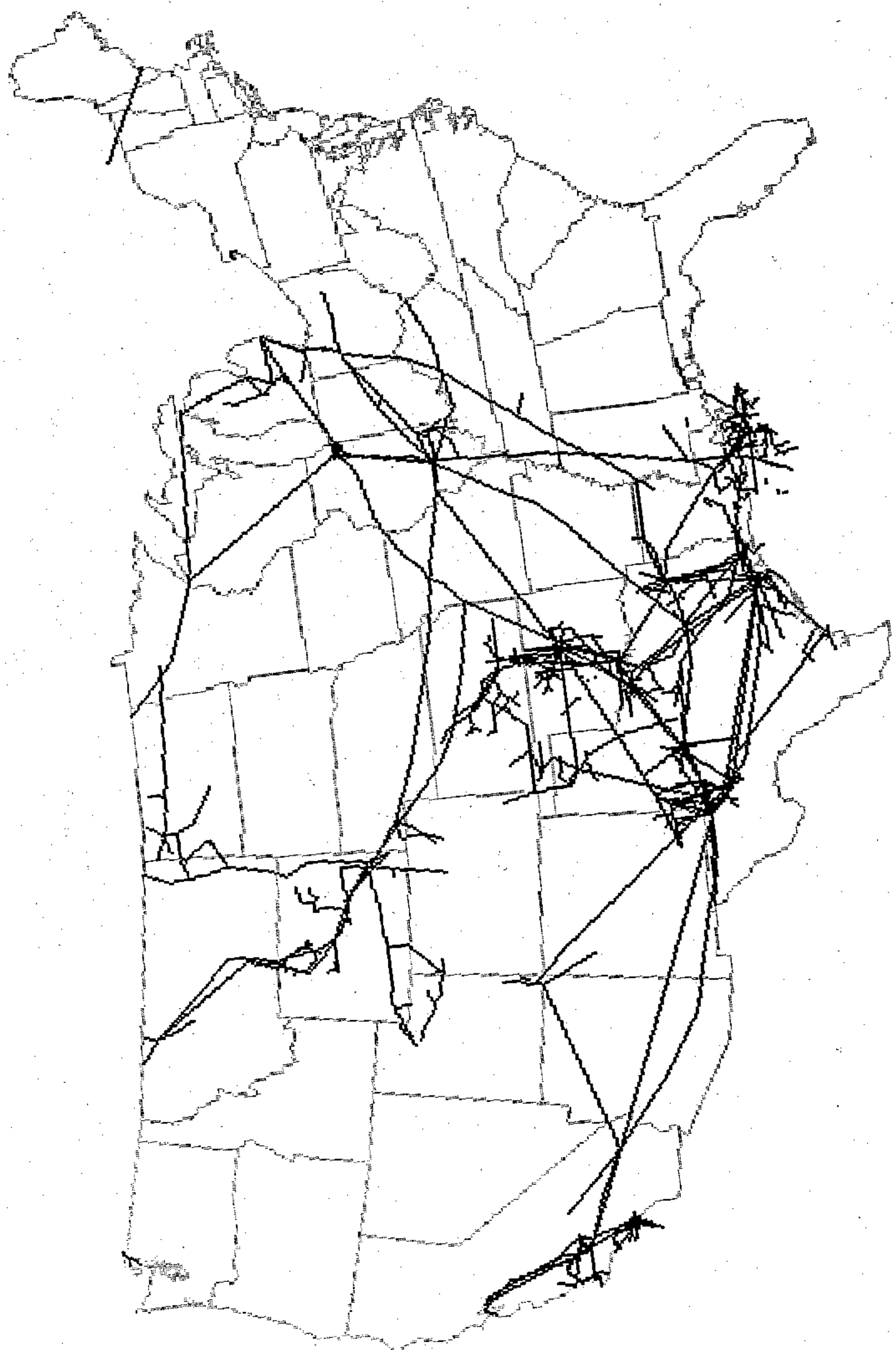


Figure 2-7 *Crude oil pipelines.*

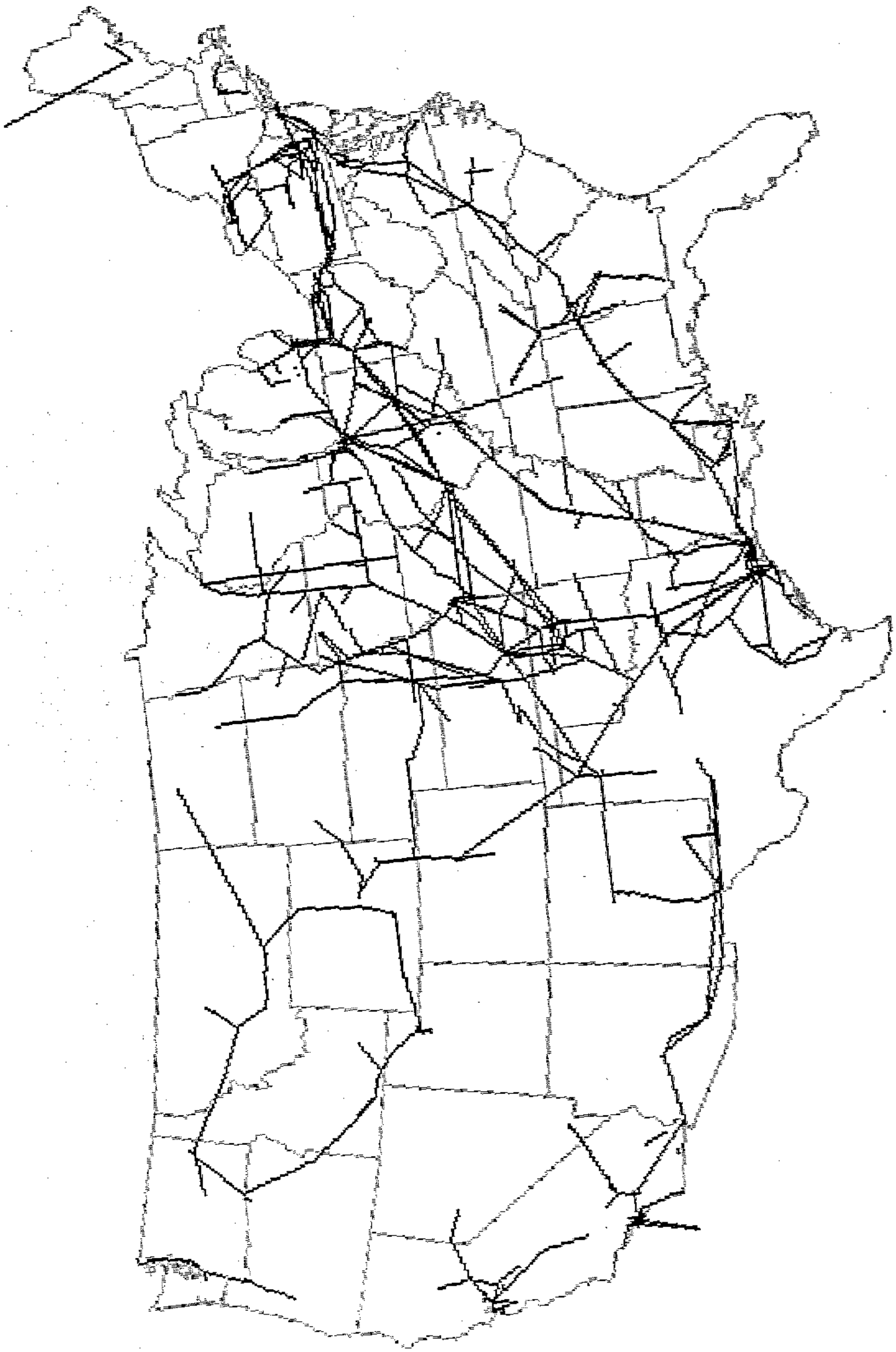


Figure 2-8 *Refined oil pipelines.*

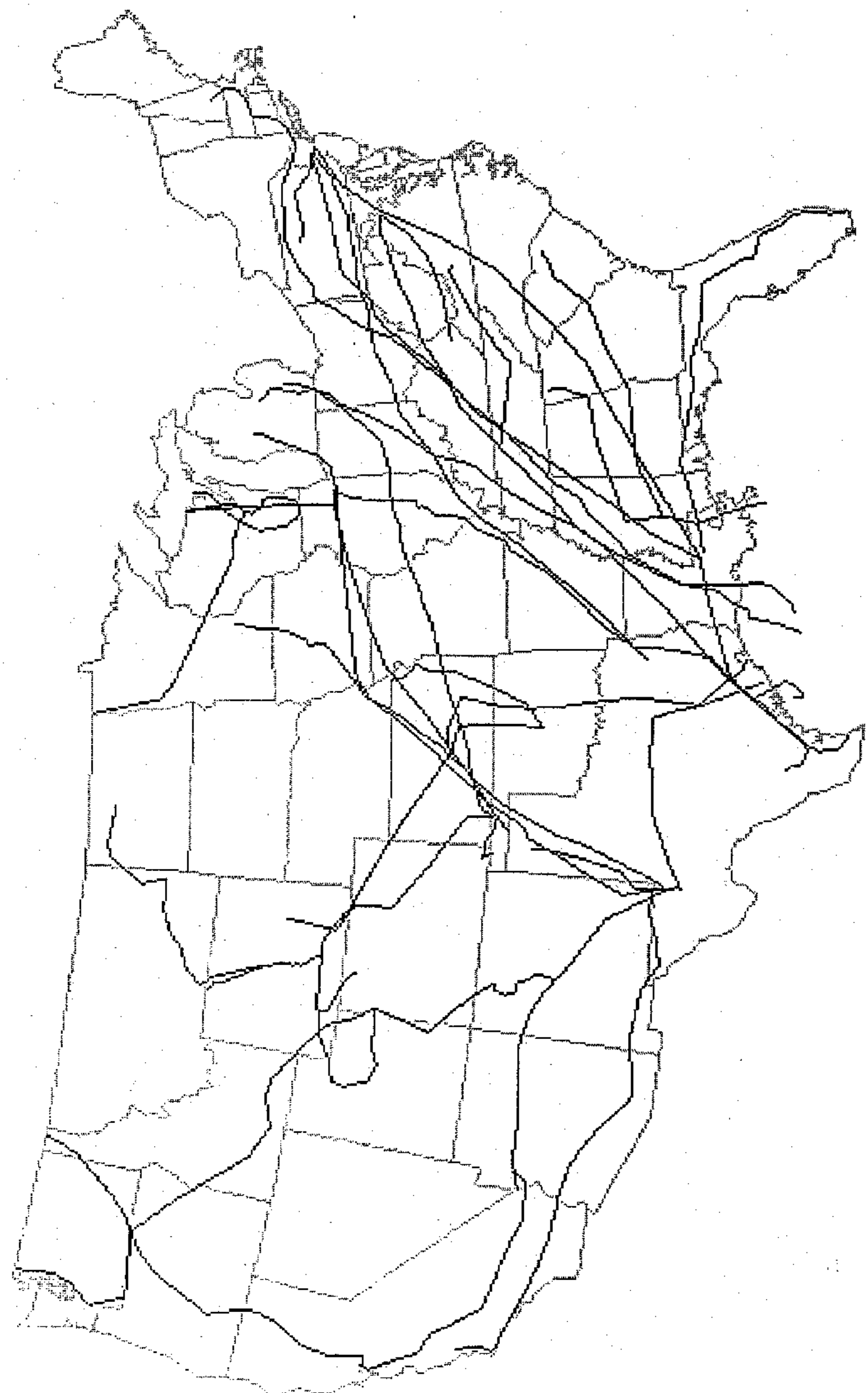


Figure 2-9 Natural gas pipelines.

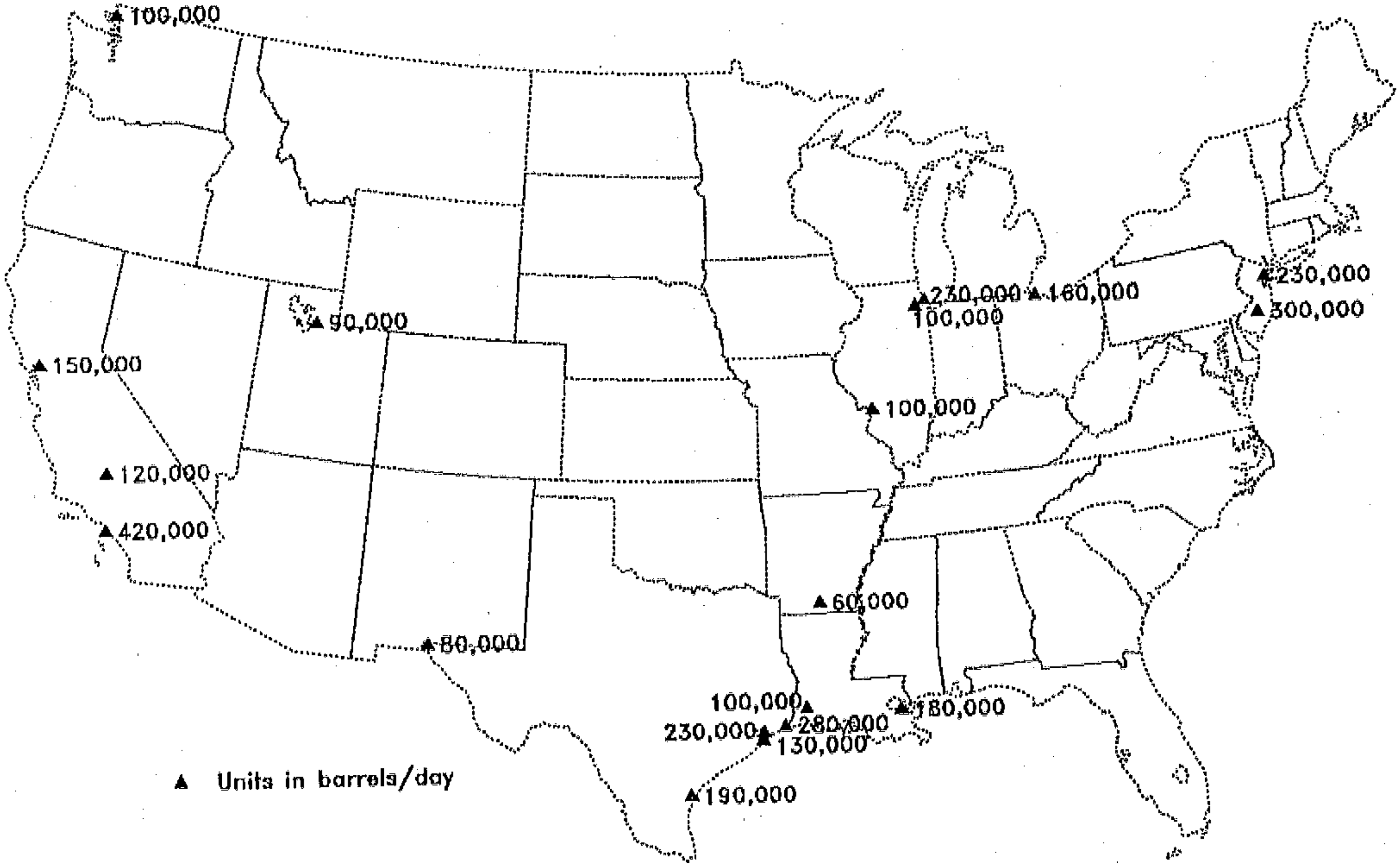


Figure 2-10 Refineries.

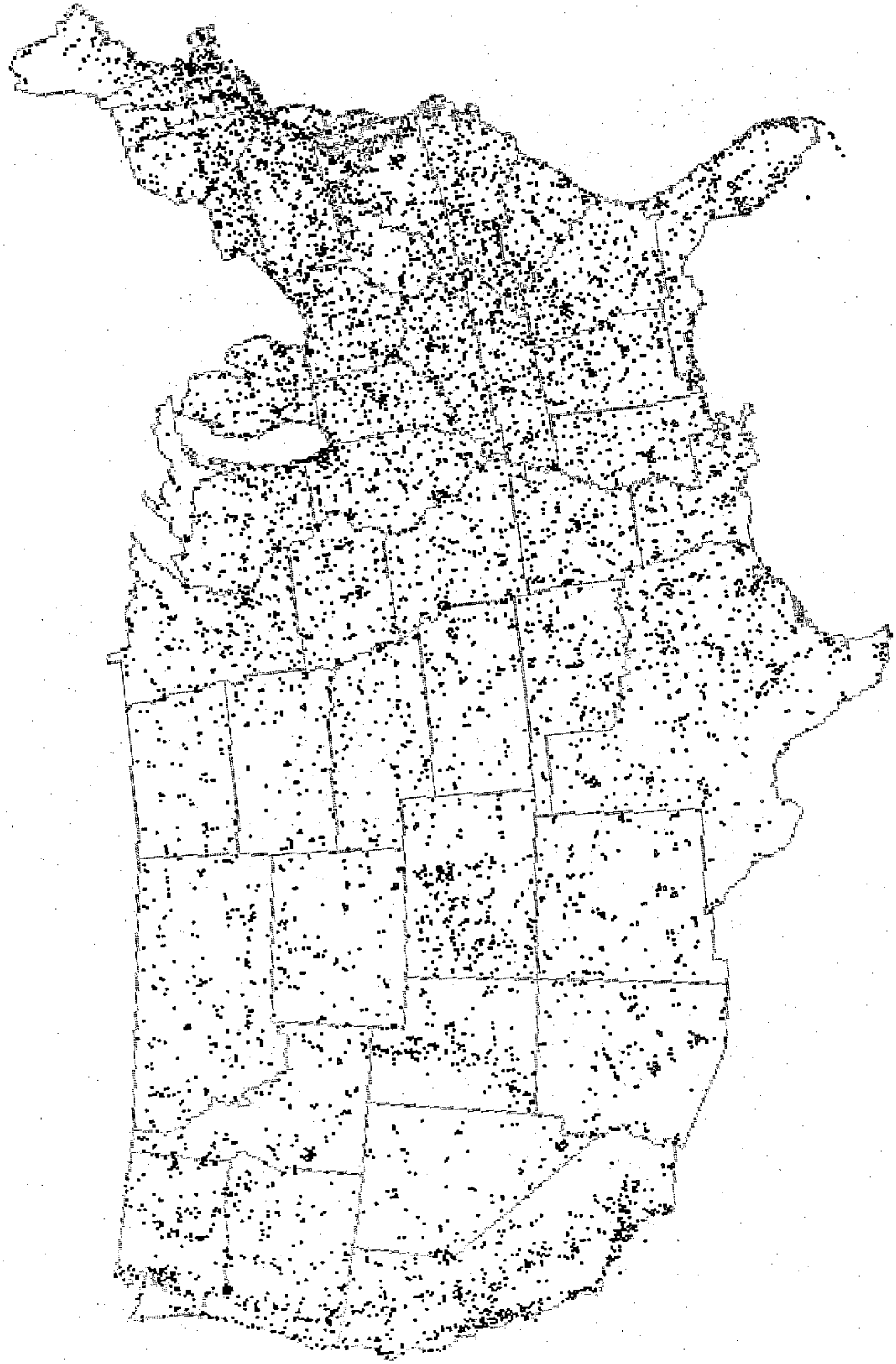


Figure 2-11 Emergency broadcast stations.

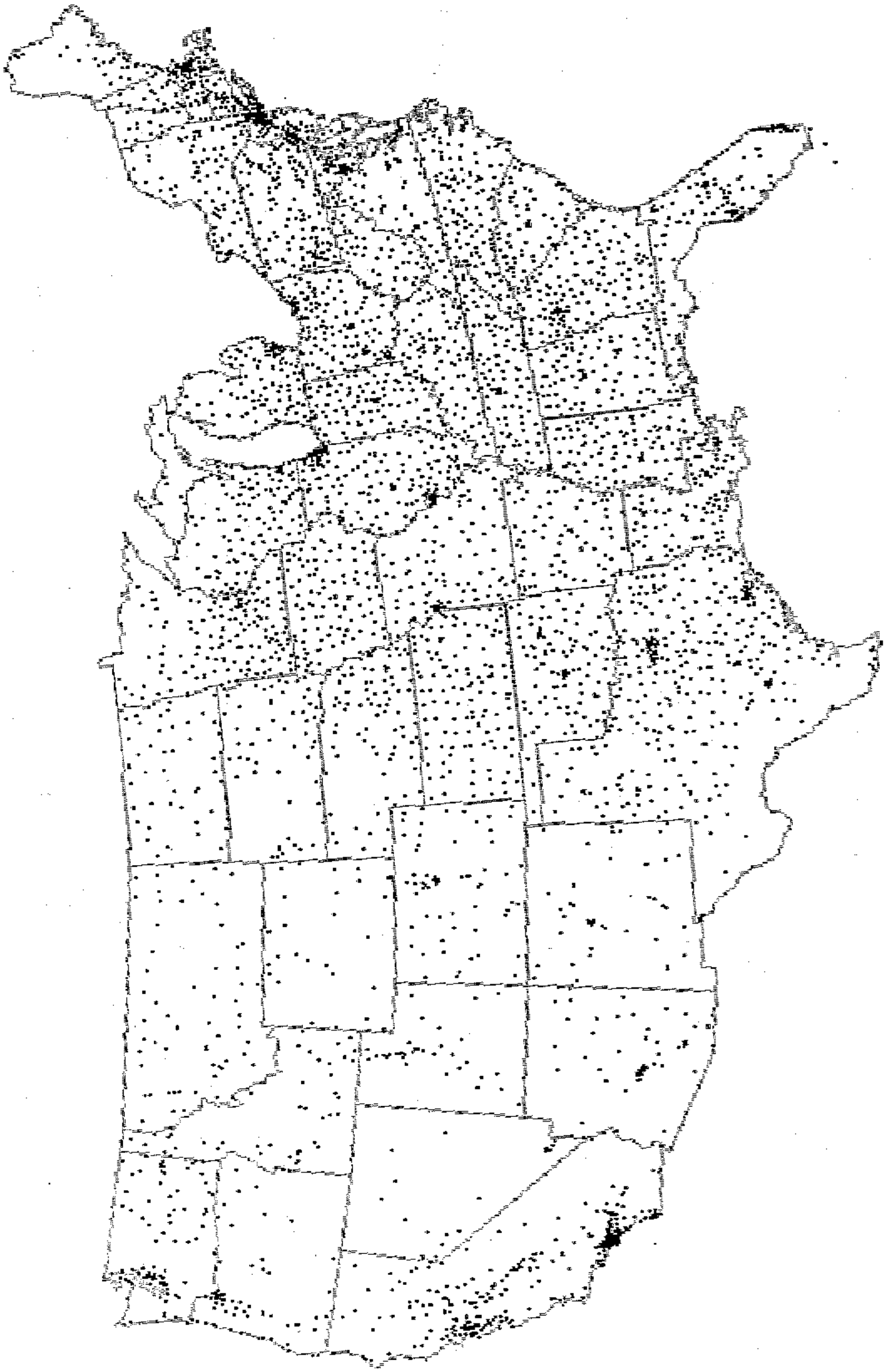


Figure 2-12 *Medical care centers.*

permits population to be used as the proxy measure of the number of fire stations. The data exhibit a trend that makes population appear to be a good basis for estimating the number of fire stations in an area. Intuition tells us that this would not be a linear function, since at the lower end of the population scale (a very small town), there would be at least one station (perhaps a volunteer unit) in most towns or areas. In rural forest areas, there may be few or no people residing in an area, but it might have several forest fire fighting crews available. A bilinear curve was deemed to be simple enough to be usable in a nationwide inventory, yet more capable of capturing the higher presence of fire stations in the less dense areas. The relationship developed is that there is one fire station per every 13,000 people in a municipality of less than 100,000 people. For municipalities of more than 100,000 people, there are 9 fire stations plus one more for every 36,000 additional people.

Police Stations. Detailed nationwide police station inventory data were not readily available in an electronic format. Data from a limited survey of municipalities with different attendant populations were obtained and correlated with the jurisdictional populations in an attempt to determine a relation, which permits population to be used as a proxy measure of the number of police stations. The data did not exhibit a strong correlation between the number of police stations and the jurisdictional population. There appears to be only one police or law enforcement station per municipality--cities with more than one police station are few, except for the largest cities. More than one police station in a municipality appears to be a relic of older days, with slower travel and communications. The data do make possible a stronger correlation to geography (such as the presence of a municipality) than directly to population, but intuition would say that the existence of law enforcement stations in rural areas, where the station size would be approximately uniform (one or two officers), would follow along population bounds. The relationship developed is that there is approximately one police station per every 60,000 people.

2.6 Water Supply Data

Water Transmission. Detailed information nationwide, on water storage, transmission, and treatment was not readily available. A variety of sources were employed to digitize reservoir locations and long-line transmission lines for large urban areas, of which only a few exceed tens of miles in length, that is, exceed our grid size (e.g., San Francisco, Los Angeles, New York). The inventory includes approximately 3,575 km of aqueduct, as shown in Figure 2-13. Excluded from the inventory are aqueducts in Utah, which were not available for inclusion in this study. It is also possible that other significant water transmission lines are inadvertently omitted from this study, as the project team had neither time nor funding to contact all potential sources of data.

Water Distribution. Detailed water distribution network inventory data were not readily available in an electronic format. Data from a survey of the largest water districts were available (AWWA report no. 20212 "1984 Water Utility Operating Data") and were used to correlate the quantity of piping with population. The data exhibit an apparent relationship between the population served by the water district and the total number of miles of piping in the distribution network. The values vary between different municipalities, apparently according to population density. New York City is one of the most densely populated municipalities in the United States, and the water distribution data reflect this. Overall, the average figure, which reflects the relationship between quantity of piping and populations for almost half the population of the United States, should be a reasonable figure to apply nationwide. The relationship we developed is that there is approximately 1 mile of distribution piping for every 330 persons. This would correspond to approximately 16 feet of distribution piping per person.

2.7 PC-Compatible Electronic Database

The data discussed above, developed as part of this project, form a very significant nationwide database on infrastructure at the regional level. Because the data could also serve as a valuable framework (or starting point) for researchers who wish to investigate lifelines at the regional

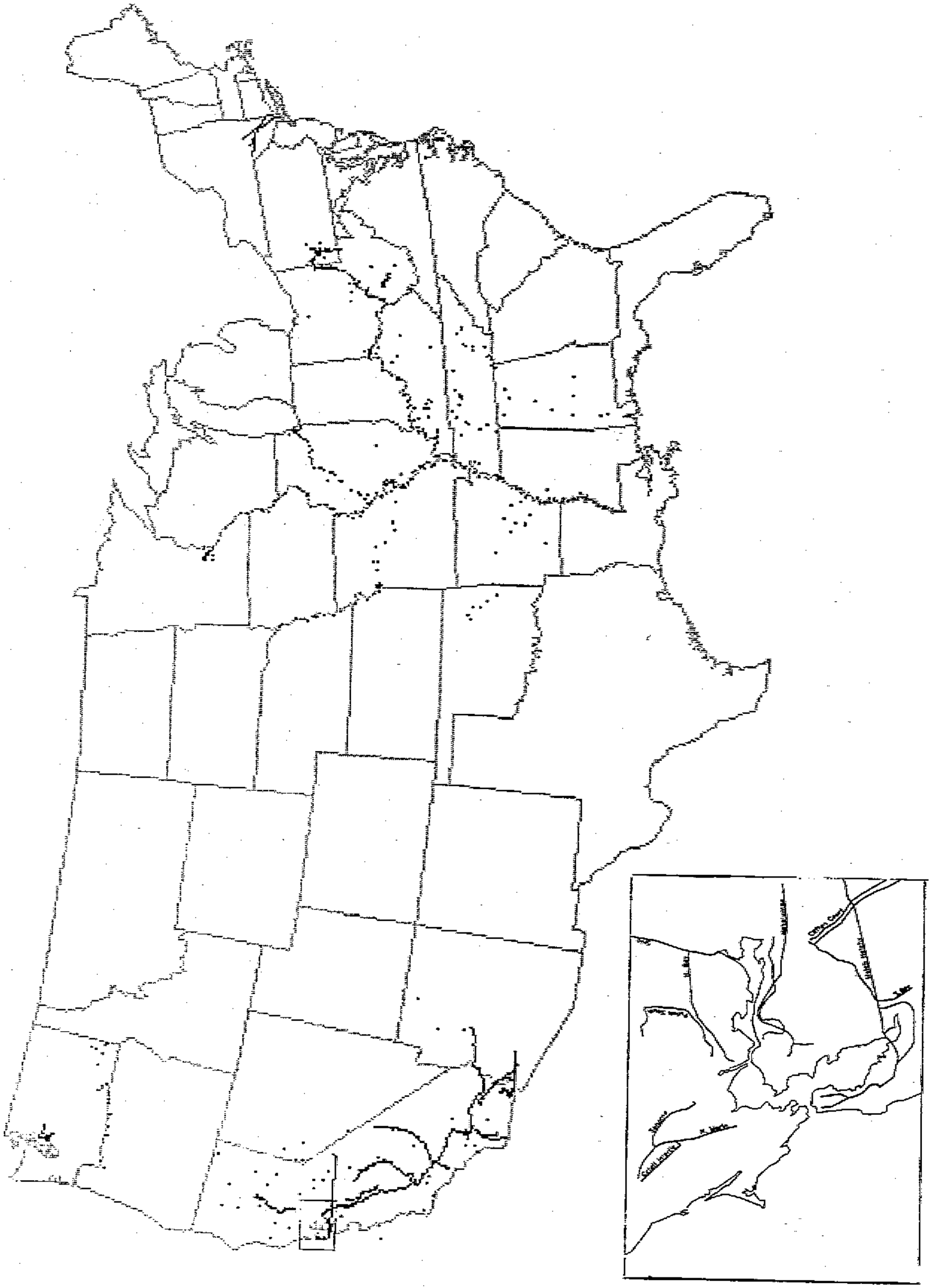


Figure 2-13 *Water aqueducts and supplies.*

or local level, including applications unrelated to seismic risk, the data have been formatted for use on IBM-PC compatible microcomputers. The data are unrestricted and will be made available by ATC on 18, 1.2-megabyte, floppy diskettes, together with a simple executable computer program for reading and displaying the maps on a computer screen. The disks contain 25 files, as shown in Table 2-1. For many of the networks, two files are presented, a .DAT file representing an ASCII file of latitude and longitude coordinates, and a .DEM file representing an x/y coordinate file for screen plotting purposes, in binary.

Table 2-1 National Lifeline Inventory Electronic Database

File No.	*File Name*	*Contents*
1.	**DEMO.EXE**	
2.	**HW.DEM**	(the highway network in x/y coordinates)
3.	**HW.DAT**	(the highway network in longitude/latitude coordinates)
4.	**RAILR.DEM**	(the railroad network in x/y coordinates)
5.	**RAILR.DAT**	(the railroad network in longitude/latitude coordinates)
6.	**ELECTRIC.DEM**	(the electric network in x/y coordinates)
7.	**ELECTRIC.DAT**	(the electric network in longitude/latitude coordinates)
8.	**CRUDE.DEM**	(the crude oil network in x/y coordinates)
9.	**CRUDE.DAT**	(the crude oil network in longitude/latitude coordinates)
10.	**REFINED.DEM**	(the refined oil network in x/y coordinates)
11.	**REFINED.DAT**	(the refined oil network in longitude/latitude coordinates)
12.	**NGAS.DEM**	(the natural gas network in x/y coordinates)
13.	**NGAS.DAT**	(the natural gas network in longitude/latitude coordinates)
14.	**BRIDGES.DEM**	(the bridges in x/y coordinates)
15.	**BRIDGES.DAT**	(the bridges in longitude/latitude coordinates)
16.	**AIRPORTS.DEM**	(the airports in x/y coordinates)
17.	**AIRPORTS.DAT**	(the airports in longitude/latitude coordinates)
18.	**PORTS.DEM**	(the ports in x/y coordinates)
19.	**PORTS.DAT**	(the ports in longitude/latitude coordinates)
20.	**BRDSTNS.DEM**	(the broadcast sta. in x/y coordinates)
21.	**BRDSTNS.DAT**	(the broadcast sta. in longitude/latitude coordinates)
22.	**MEDCARE.DEM**	(the hospitals in x/y coordinates)
23.	**MEDCARE.DAT**	(the hospitals in longitude/latitude coordinates)
24.	**WATER.DEM**	(the water system in x/y coordinates)
25.	**WATER.DAT**	(the water system in longitude/latitude coordinates)

3. Development of Lifeline Vulnerability Functions

3.1 Introduction

Vulnerability functions are used to describe the expected or assumed earthquake performance characteristics of each lifeline as well as the time required to restore damaged facilities to their pre-earthquake capacity, or usability. Functions have been developed for each lifeline inventoried for this project, or estimated by proxy (see Chapter 2). The components of each vulnerability function and how they were developed are described herein in Chapter 3. The functions themselves, too lengthy to include in this chapter, are provided in Appendix B.

The vulnerability function for each lifeline consists of the following components:

- *General* information, which consists of (1) a *description* of the structure and its main components, (2) *typical seismic damage* in qualitative terms, and (3) *seismically resistant design* characteristics for the facility and its components in particular. This information has been included to define the assumed characteristics and expected performance of each facility and to make the functions more widely applicable (i.e., applicable for other investigations by other researchers).

- *Direct damage* information, which consists of (1) a description of its basis in terms of structure type and quality of construction (degree of seismic resistance), (2) default estimates of the quality of construction for present conditions, and corresponding *motion-damage curves*, (3) default estimates of the quality of construction for upgraded conditions, and (4) *restoration curves*. As described below, these curves are based on data developed under the ATC-13 project (ATC, 1985).

In the following sections we describe the general approach and specific methodology utilized to develop the quantitative relationships for each vulnerability function (Direct Damage versus Modified Mercalli Intensity and Residual Capacity versus Modified Mercalli Intensity). Example computations are provided. In addition, a sample of a complete vulnerability function (*general information* plus *direct damage information*) is included as an illustrative example.

3.2 General Approach for Characterizing Earthquake Performance

The lifeline facility vulnerability functions used for this project are based on those developed on the basis of expert opinion in the ATC-13 project (*Earthquake Damage Evaluation Data for California*, ATC 1985). The ATC-13 direct damage data, presented in the form of Damage Probability Matrices (DPMs, Table 3-1), are applicable for Standard construction in California, as defined below, and may be modified per procedures outlined in ATC-13, which shifts the curves one-to-two intensity units down for Special construction, as defined below (i.e., -1 or -2), and one to two intensity units up for Nonstandard construction, as defined below (i.e., +1 or +2). Standard construction is defined (in ATC-13) to include all facilities except those designated as Special or Nonstandard. Special construction refers to facilities that have special earthquake damage control features. Nonstandard refers to facilities that are more susceptible to earthquake damage than those of Standard construction. Older facilities designed prior to modern design code seismic requirements or those facilities designed after the introduction of modern code seismic requirements but without their benefit can be assumed to be Nonstandard. In exceptional cases, older facilities may have had special attention paid to seismic forces and may qualify as Standard construction. While Special is defined in ATC-13 to refer to facilities that have special earthquake damage control features, in this study we take this to include, in some cases, facilities designed according to the most modern design code seismic requirements. Standard is assumed to represent existing California

Table 3-1 Typical ATC-13 Damage Probability Matrix (ATC, 1985) (Example for Liquid Storage Tanks, on ground)

Central Damage Factor	*Modified Mercalli Intensity* VI	VII	VIII	IX	X	XI	XII
0.00	94.0	2.5	0.4	***	***	***	***
0.50	6.0	92.9	30.6	2.1	***	***	***
5.00	***	4.6	69.0	94.6	25.7	2.5	0.2
20.00	***	***	***	3.3	69.3	58.1	27.4
45.00	***	***	***	***	5.0	39.1	69.4
80.00	***	***	***	***	***	0.3	3.0
100.00	***	***	***	***	***	***	***

***Very small probability

facilities (i.e., a composite of older non-seismically designed facilities, more recent facilities designed to the seismic requirements of their day, and modern facilities designed to current seismic requirements).

With regard to regional U.S. seismic design practice, the general consensus appears to be that, with few exceptions, only California and portions of Alaska and the Puget Sound region have had seismic requirements incorporated into the design of local facilities for any significant period of time. For all other areas of the United States, present facilities are assumed to have seismic resistance less than or equal to (depending on the specific facility) that of equivalent facilities in California NEHRP Map Area 7 (Figure 3-1) (ATC, 1978; BSSC, 1988). In this regard, we have broken the United States into three regions:

a. California NEHRP Map Area 7 (the general focus of ATC-13), which we take to be the only region of the United States with a significant history of lifeline seismic design for great earthquakes,

b. California NEHRP Map Areas 3-6, Non-California Map Area 7 (parts of Alaska, Nevada, Idaho, Montana, and Wyoming), and Puget Sound NEHRP Map Area 5, which we take to be the only regions of the United States with a significant history of lifeline seismic design for major (as opposed to great) earthquakes, and

c. All other parts of the United States, which we assume have not had a significant history of lifeline seismic design for major earthquakes.

As an example, examine on-ground liquid storage tanks (ATC-13 Facility Class 43, Table 3-1), for which ATC-13 indicates mean damage from ground shaking of Modified Mercalli Intensity (MMI) IX to be 4.6% of replacement value for Standard construction. If the construction is modern and judged to be Special construction, then the mean damage is indicated to be 0.5% (corresponding to MMI VII) for the same intensity of ground shaking. Alternatively, if the construction is judged to be Nonstandard (e.g., predating seismic design), then the mean damage is indicated to be 27.9% (corresponding to MMI XI) for the same intensity of ground shaking.

3.3 Method for Obtaining Lifeline Direct Damage and Residual Capacity Functions

This section presents the calculational algorithms employed in obtaining the quantitative lifeline component vulnerability functions for use in the ATC-25 project. Two vulnerability functions are determined: (1) direct damage to a lifeline component, in terms of repair costs expressed as a fraction or percentage of value, and (2) fraction of initial capacity (restored or remaining) as a function of elapsed time since the earthquake, for a given

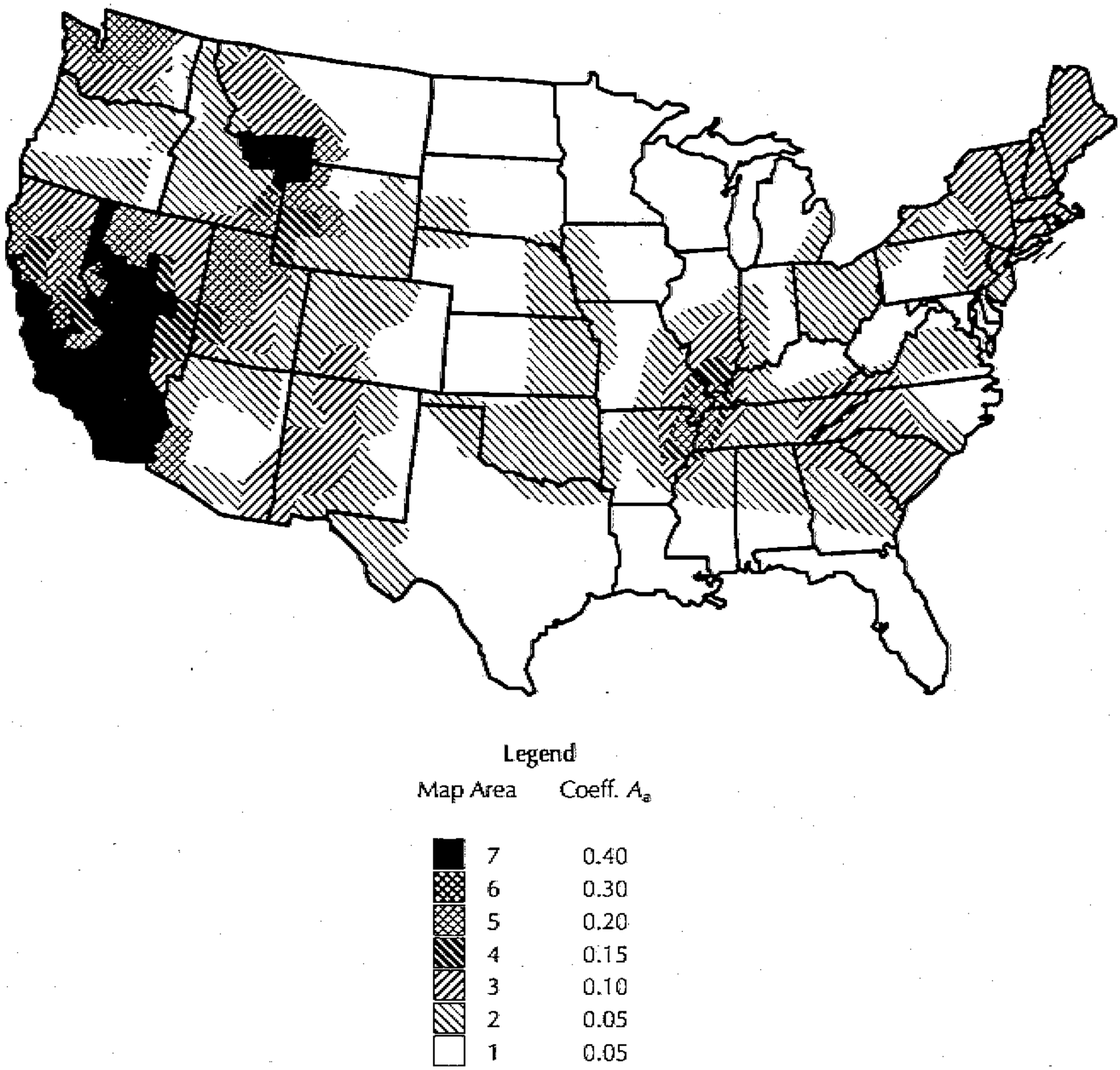


Figure 3-1 *NEHRP Seismic Map Areas (ATC, 1978; BSSC, 1988).*

MMI, herein termed restoration curves. All assumptions operative in ATC-13, such as unlimited resources for repair and restoration, apply to these results.

Three main steps are involved in obtaining the vulnerability functions for each component. Each of these steps is described below.

STEP 1

In order to obtain a continuous relation between seismic damage (DMG) and intensity (MMI), a regression of the form

$$DMG = \exp(a)\, MMI^{b} \qquad (3.1)$$

is performed on the damage data points in Appendix G of ATC-13. The regression coefficients a and b are obtained for each Facility Class (FC) corresponding to a lifeline component. A damage curve of the form shown in Figure 3-2 is thus obtained for each Facility Class in ATC-13.

STEP 2

Data on time-to-restoration for different Social Function (SF) classes, which are facility types defined in terms of the four-digit Standard Industrial Classifications of the U. S. Department of Commerce, (provided in Table 9.11 of ATC-13), are used to perform the following regression, which gives a continuous relation between the damage state and the corresponding restoration time for each social function class:

$$T_R = \exp(c)\, DMG^{d} \qquad (3.2)$$

where:

T_R	=	restoration time, in days
DMG	=	Central Damage Factor (CDF) for each damage state (DS)
c, d	=	regression coefficients

Regressions of the above form are performed for each of the social function classes using the data in ATC-13 on restoration times for 30%, 60%, and 100% restoration.

Thus,

$$T_{R=0.3} = \exp(c1)\, DMG^{d1}$$
$$T_{R=0.6} = \exp(c2)\, DMG^{d2}$$
$$T_{R=1.0} = \exp(c3)\, DMG^{d3}$$

Figure 3-3 shows the form of the regression curves we obtained.

STEP 3

The regressions obtained from the previous two steps are used to arrive at the restoration curves. The restoration curve for each lifeline component, for each intensity (MMI), is obtained by fitting a straight line through the three points corresponding to 30%, 60%, and 100% restoration time. The regression line has the following form:

$$R = f + (g)(T_R) \qquad (3.3)$$

where:

R	=	% restored
T_R	=	restoration time, in days
f, g	=	regression coefficients

The three points used to fit a straight line by the above regression are obtained in the manner described below:

For a given lifeline component, the damage corresponding to a particular MMI is assumed to have a lognormal distribution. The time to restoration is then obtained numerically as the weighted average of the restoration time (given by Equation 3.2) taken over equal intervals of the lognormal distribution of the damage. The weight factors are the areas of the equal intervals of the lognormal distribution, i. e., the probabilities of the corresponding damage. For example,

$$T_R(30\%\ R, MMI) = \sum_{i=1}^{N} \left(p_i \, x \, \exp(c1) \, x \, DMG_i(MMI)^{d1}\right) \qquad (3.4)$$

where T_R(30% R, MMI)) is the restoration time to 30% restoration for a given MMI, p_i is the probability that the damage = DMG_i, i.e., the area of the interval, i, on the lognormal distribution of the damage, and N is the number of intervals of the lognormal distribution.

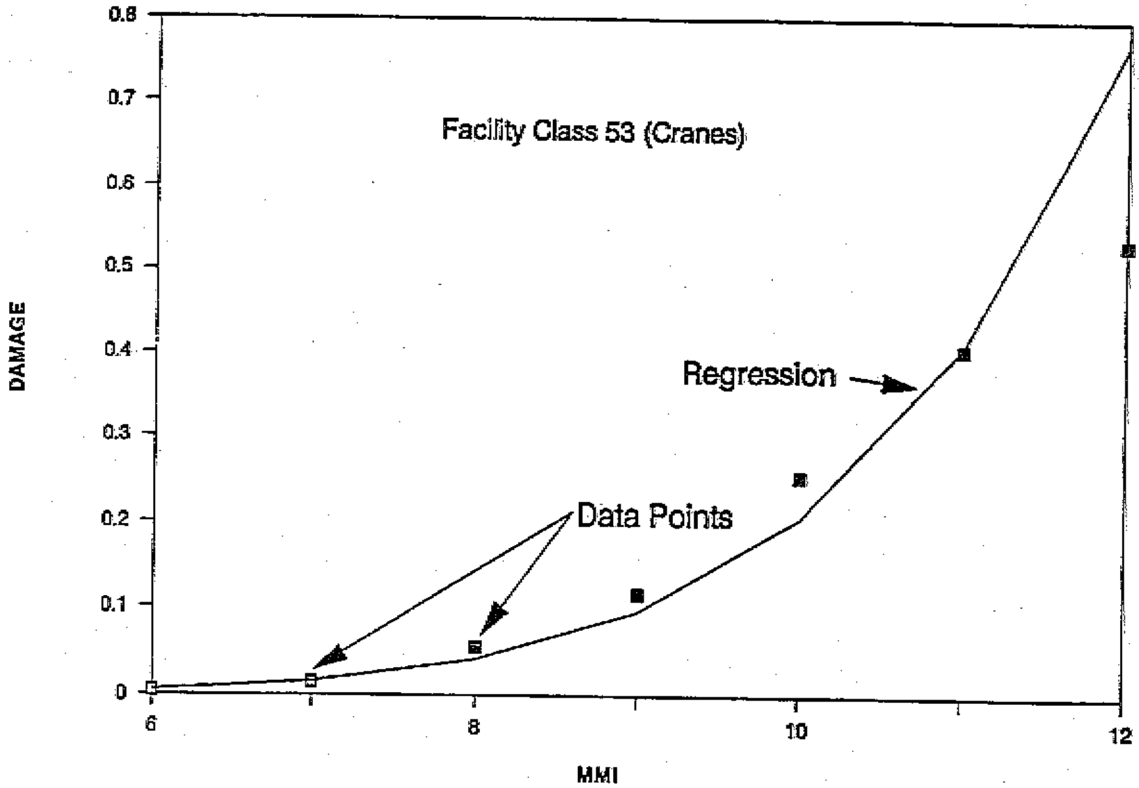


Figure 3-2 *Comparison of ATC-13 Appendix G data (Statistics of Expert Responses for Motion-Damage Relationships) versus regression curve.*

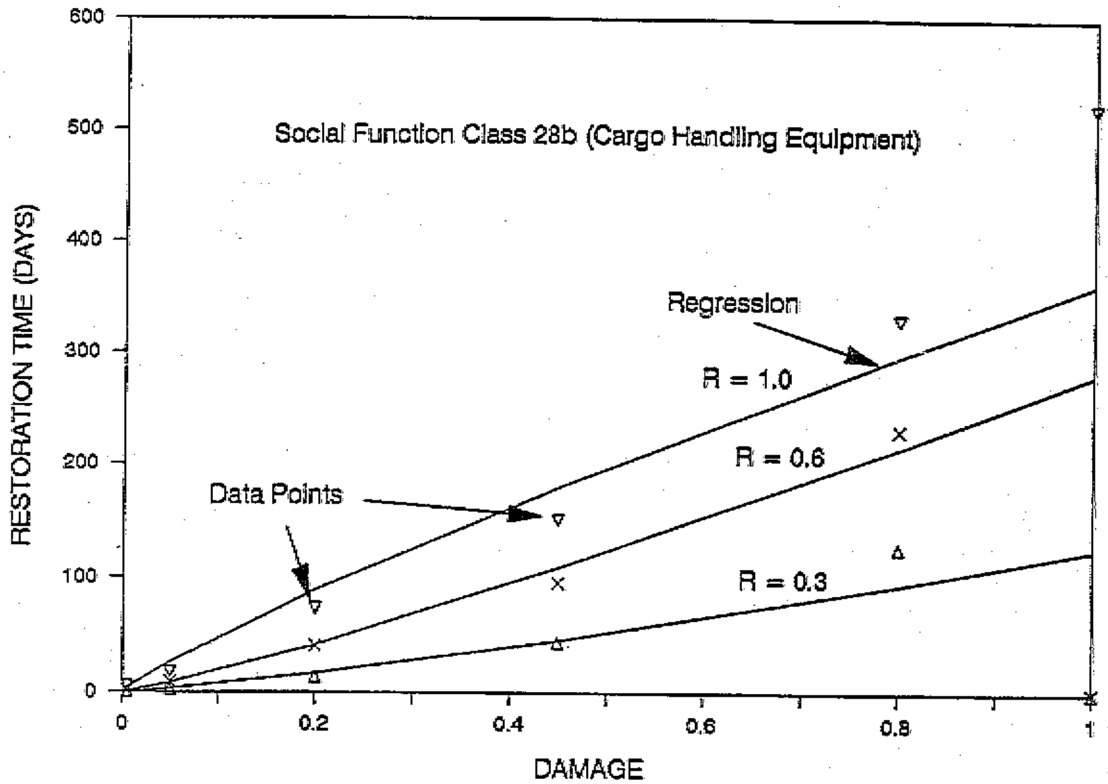


Figure 3-3 *Comparison of ATC-13 Table 9.1 data (Weighted Statistics for Loss of Function Restoration Time of Social Function Classifications) versus regression curve.*

Similar calculations are also carried out for 60% R and for 100% R.

Next, the weighted average of T_R(30%R, MMI) for the different social function classes corresponding to the lifeline component is obtained. This serves as one of the three points for fitting the restoration curve. The other two points are obtained by repeating the process for 60% and 100% restoration time. The regression line given by Equation 3.3, obtained using these three data points, is the restoration curve for the lifeline component. An example to illustrate the method of obtaining

(1) the direct damage curve and

(2) the restoration curves, for the Ports/Cargo Handling Equipment component of the Sea/Water Transportation lifeline

is provided below.

3.4 Example Direct Damage and Residual Capacity Computations

The following example illustrates the method of obtaining (1) the direct damage curve, and (2) the restoration curves, for the Ports/Cargo Handling Equipment component of the Sea/Water Transportation lifeline. Ports/Cargo Handling Equipment are typically container or general cargo cranes on piers. This component is taken to be composed of two ATC-13 Social Function Classes: 28a (Ports) and 28b (Cargo Handling Equipment), and of two Facility Classes: 63 (Waterfront Structures) and 53 (Cranes), weighted by the factors indicated in Table 3-2.

STEP 1

Regression coefficients for seismic damage are computed from Equation 3.1 for each Facility Class (FC) as follows:

Facility Class		Regression Coefficient	
Class	Factor	a	b
63	0.6	-20.0847	8.0976
53	0.4	-18.2783	7.2508

The damage regression curve obtained in this manner is illustrated in Figure 3-2 for Facility

Table 3-2 Weighting Factors Used to Determine Percent of Social Function and Facility Classes Contributing to Ports/Cargo Handling Equipment

Social Function		Facility	
Class	Factor	Class	Factor
28a	0.6	63	0.6
28b	0.4	53	0.4

Class 53 (Cranes). The values for the damage are listed below, together with the ATC-13 data (from ATC-13, Appendix G, weighted mean of best estimate of damage factor):

MMI	DMC (ATC-13)	Regr (DMC)
6	0.004	0.005
7	0.014	0.015
8	0.055	0.041
9	0.117	0.096
10	0.253	0.205
11	0.406	0.410
12	0.535	0.771

The damage curve for the component as a whole is obtained by calculating, for each MMI, the weighted average of the damage for each of the facility classes corresponding to the component.

$$\begin{aligned} DMG &= e^{a1} MMI^{b1} x \text{ factor}(1) + e^{a2} MMI^{b2} x \text{ factor}(2) \\ &= 0.101 x 0.6 + 0.096 x 0.4 \\ &= 0.099 \text{ for MMI} = \text{IX} \end{aligned}$$

STEP 2

Regression coefficients for restoration time are computed from Equation 3.2 as follows:

	Regression Coefficients			
	Social Function 28a		Social Function 28b	
Restor-ation %	c	d	c	d
30%	6.4575	2.7162	4.8240	1.2514
60%	5.4769	1.1671	5.6373	1.1880
100%	6.1996	1.0445	5.8890	0.8725

The values for the time to 30% restoration, for the Social Function Class 28b are listed below, together with the ATC-13 data from Table 9.11:

DMG	ATC-13	Regression Values
0.005	0.2	0.1643
0.05	2.3	2.93
0.2	13.3	16.61
0.45	44.4	45.82
0.8	127.0	94.14
1.0	*	125.46

*No statistics provided.

Figure 3-3 shows the curves obtained by the above regressions, as well as the ATC-13 mean data points.

STEP 3

Mean restoration times for each Facility Class (FC) are obtained from Equation 3.4 as follows:

Mean Restoration time =

$$\sum_{i=1}^{N} [p_i \exp(c) DMG_i^{d}]$$

where c and d are given above for 30%, 60%, and 100% restoration.

For MMI = XI, for example, mean restoration times are computed as follows:

	T_R=0.3	T_R=0.6	T_R=1.0
FC = 28a	79.73	93.20	211.23
FC = 28b	45.45	107.66	177.27
Mean T_R	66.02*	98.98	197.65

*e.g., Mean T_R = 79.73 x 0.6 + 45.45 x 0.4 = 66.02

(Note: P_i is 1/N where N is the number of intervals used to divide the lognormal distribution of the damage; N=100 in this example and DMG_i is the corresponding damage value for each interval, i.)

The final restoration curve for MMI = XI is the best-fit straight line using Equation 3.3 through the 3 points corresponding to restoration times 66.02, 98.98, and 197.65 days. In this case, the regression equation is as follows:

$$R = 0.026 + 0.005 (T_R)$$

Determination of these relations permits calculation of residual capacity of the lifeline as a function of time. From the above equation we see that Ports/Cargo Handling Equipment subjected to MMI XI will be restored to approximately 18% of pre-earthquake capacity after 30 days, and to 48% approximately 90 days after the earthquake.

3.5 Sample Lifeline Vulnerability Function

Following is a sample of a complete lifeline vulnerability function for ports/cargo handling equipment. Complete vulnerability functions for all lifelines are given in Appendix B.

3.5.1 Ports/Cargo Handling Equipment

1. General

Description: In general, ports/cargo handling equipment comprise buildings (predominantly warehouses), waterfront structures, cargo handling equipment, paved aprons, conveyors, scales, tanks, silos, pipelines, railroad terminals, and support services. Building type varies, with steel frame being a common construction type. Waterfront structures include quay walls, sheet-pile bulkheads, and pile-supported piers. Quay walls are essentially waterfront masonry or caisson walls with earth fills behind them. Piers are commonly wood or concrete construction and often include batter piles to resist lateral transverse loads. Cargo handling equipment for loading and unloading ships includes cranes for containers, bulk loaders for bulk goods, and pumps for fuels. Additional handling equipment is used for transporting goods throughout port areas.

Typical Seismic Damage: By far the most significant source of earthquake-induced damage to port and harbor facilities has been pore-water pressure buildup in the saturated cohesionless soils that prevail at these facilities. This pressure buildup can lead to application of excessive lateral pressures to quay walls by backfill materials, liquefaction, and massive submarine sliding. Buildings in port areas are subject to generic damage due to shaking, as well as damage caused by loss of bearing or lateral movement of foundation soils. Past earthquakes have caused substantial lateral sliding, deformation, and tilting of quay walls and sheet-pile bulkheads. Block-type quay walls are vulnerable to earthquake-induced sliding between layers of blocks. This damage has often been accompanied by extensive settlement and cracking of paved aprons. The principal failure mode of sheet-pile bulkheads has been insufficient anchor resistance, primarily because the anchors were installed at shallow depths, where backfill is most susceptible to a loss of strength due to pore-water pressure buildup and liquefaction. Insufficient distance between the anchor and the bulkhead wall can also lead to failure. Pile-supported docks typically perform well, unless soil failures such as major submarine landslides occur. In such cases, piers have undergone extensive sliding and buckling and yielding of pile supports. Batter piles have damaged pier pile caps and decking because of their large lateral stiffness. Cranes can be derailed or overturned by shaking or soil failures. Toppling cranes can damage adjacent structures or other facilities. Misaligned crane rails can damage wheel assemblies and immobilize cranes. Tanks containing fuel can rupture and spill their contents into the water, presenting fire hazards. Pipelines from storage tanks to docks can be ruptured where they cross areas of structurally poor ground in the vicinity of docks. Failure of access roads and railway tracks can severely limit port operations. Port facilities, especially on the West Coast, are also subject to tsunami hazard.

Seismically Resistant Design: At locations where earthquakes occur relatively frequently the current design practice is to use seismic factors included in local building codes for the design of port structures. However, past earthquakes have indicated that the seismic coefficients used for design are of secondary importance when compared to the potential for liquefaction of the site soil materials. Quay wall and sheet-pile bulkhead performance could be enhanced by replacing weak soils with dense soils, or designing these structures to withstand the combination of earthquake-induced dynamic water pressures and pressures due to liquefied fills. Pier behavior in earthquakes has been good primarily because they are designed for large horizontal berthing and live loads, and because they are not subject to the lateral soil pressures of the type applied to quay walls and bulkheads. However, effects on bearing capacity and lateral resistance of piles due to liquefaction and induced slope instability should also be considered.

2. Direct Damage

Basis: Damage curves for ports/cargo handling equipment in the sea/water transportation system are based on ATC-13 data for Facility Class 53, cranes, and Facility Class 63, waterfront structures. Ports/cargo handling equipment are assumed to be a combination of 60% waterfront structures and 40% cranes.

Standard construction is assumed to represent typical California ports/cargo handling equipment under present conditions (i.e., a composite of older and more modern ports/cargo handling equipment). Only minimal regional variation in construction quality is assumed, as seismic design is performed only for selected port structures, and soil performance is the most critical determinant in port performance.

Present Conditions: In the absence of data on the type of material, age, etc., the following factors were used to modify the mean curve for the two facility classes listed above, under present conditions:

	MMI Intensity Shift	
NEHRP Map Area	FC 53	FC 63
California 7	0	0
California 3-6	0	0
Non-California 7	0	0
Puget Sound 5	0	0
All other areas	+1	+1

The modified motion-damage curves for ports/cargo handling facilities are shown in Figure 3-4.

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to Social Function (SF) 28a, ports, and SF 28b, cargo handling equipment, were assumed to apply to all ports/cargo handling equipment. Ports/cargo handling facilities were assumed to be a combination of 60% ports and 40% cargo handling facilities. By combining these data with the damage curves derived using the data for FC 53 and 63, the time-to-restoration curves shown in Figures 3-5 and 3-6 were derived.

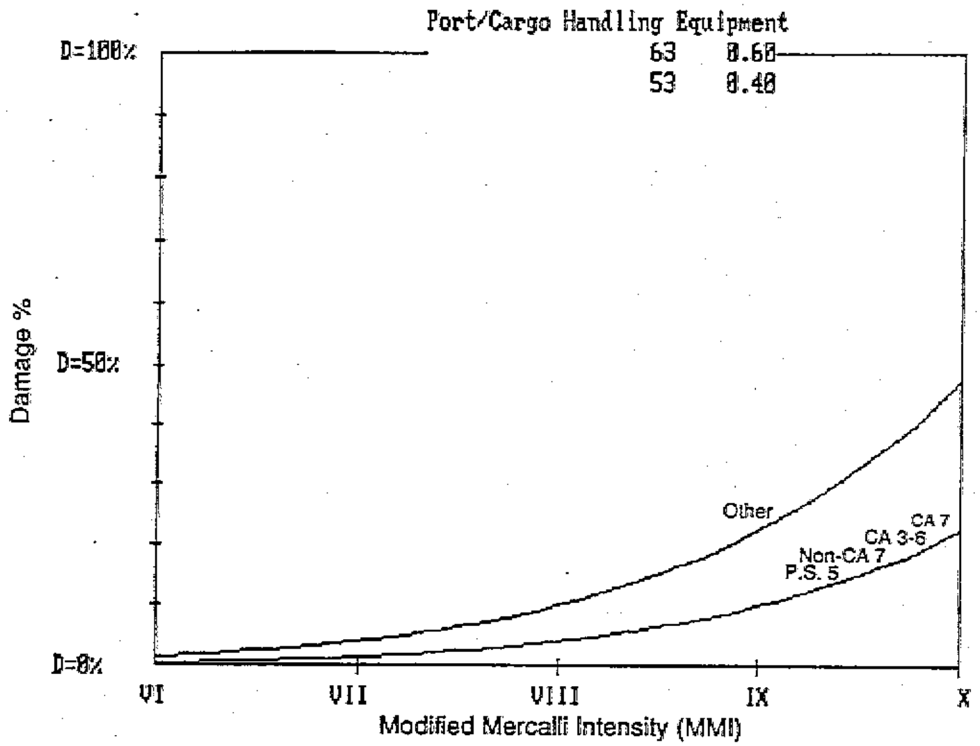


Figure 3-4 Damage percent by intensity for ports/cargo handling equipment.

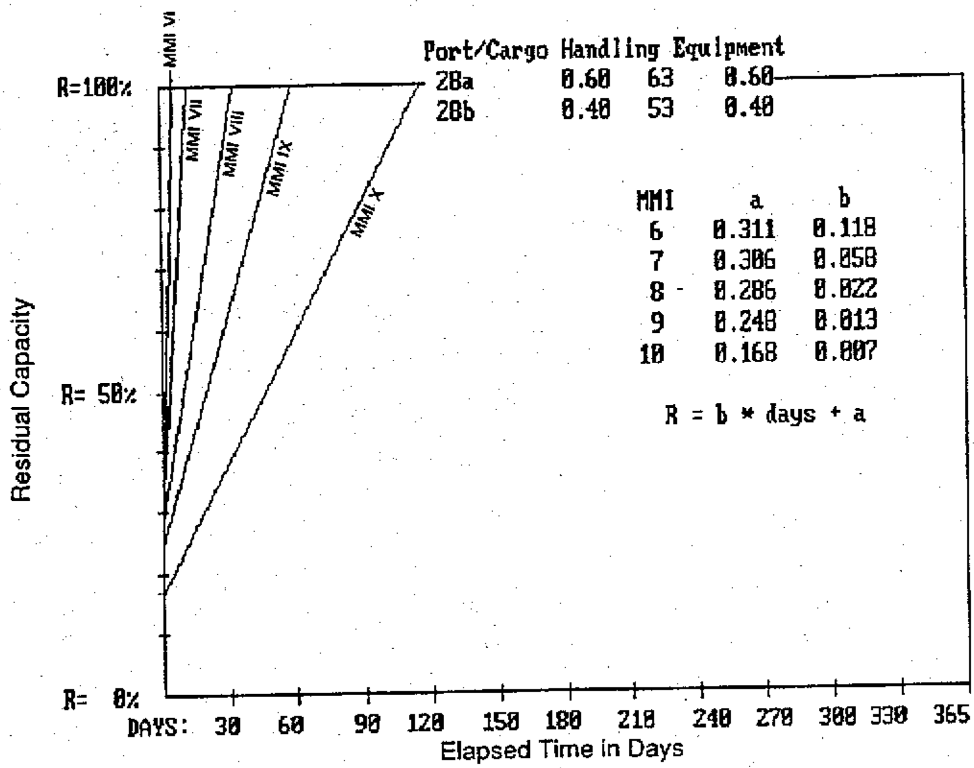


Figure 3-5 Residual capacity for ports/cargo handling equipment (NEHRP Map Area: California 3-5, California 7, Non-California 7, and Puget Sound 5).

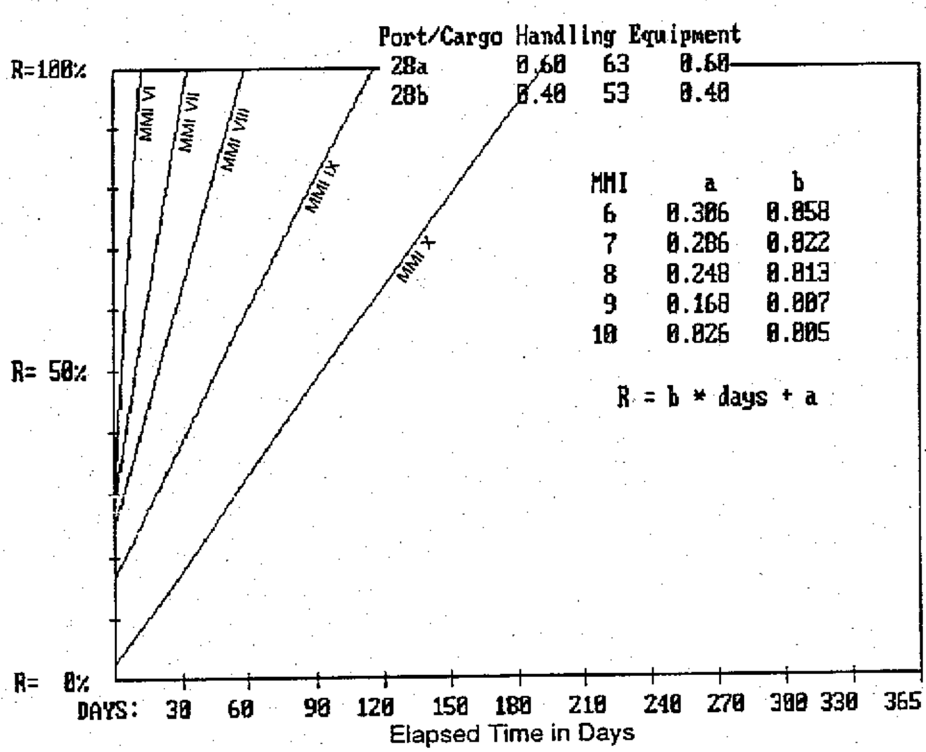


Figure 3-6 Residual capacity for ports/cargo handling equipment (all other areas).

4. Seismic Hazard

4.1 Introduction

Seismic hazard, as used in this study, is the expectation of earthquake effects. It is usually defined in terms of ground shaking parameters (e.g., peak ground acceleration, Modified Mercalli Intensity, peak ground velocity) but, broadly speaking, can include or be defined in terms of fault rupture, ground failure, or other phenomena resulting from an earthquake. Seismic hazard is a function of the size, or magnitude of an earthquake, distance from the earthquake, local soils, and other factors, and is independent of the buildings or other items of value that could be damaged. Estimation of seismic hazard can be performed on a deterministic (e.g., Evernden et al., 1981) or probabilistic (Cornell, 1968; McGuire, 1974; Scawthorn et al., 1978; Algermissen and Perkins, 1976; Algermissen, and Perkins, 1982) basis, depending on the needs of the users. In either case, the methodology follows a process beginning with the definition of seismic sources, based in part on historic seismicity.

The historical record of earthquakes in the United States is relatively short--the only data available for earthquakes prior to about 1900 are historical accounts of earthquake effects (Coffman et al., 1982), which have been used to estimate the distribution of intensities, and the locations and magnitudes of earthquakes. The record of large earthquakes in the 19th century is reasonably well documented for the eastern United States but not for other parts of the country. The large 1857 Ft. Tejon event, for example, is not well documented, when compared with the documentation for the 1886 Charleston, South Carolina event (Dutton, 1887). Instrumental data from stations in the United States were not available until after 1887 (Poppe, 1979) when the first seismograph stations in the country were established at Berkeley and Mt. Hamilton (Lick Observatory).

4.2 Magnitude and Intensity

The earthquake magnitude scale is a well-known but typically misunderstood means of describing the energy released during an earthquake. The best-known scale is that developed by C. F. Richter (Richter, 1958); and relationships between the Richter scale and other scales have been established. Magnitude scales are intended to be objective, instrumentally determined measures of the size of an earthquake, and a number of magnitude scales have been developed since Richter's (Aki and Richards, 1980). The most recent widely used scale is moment magnitude, M_W (Hanks and Kanimori, 1979). An increment in magnitude of one unit (i.e., from magnitude 5.0 to 6.0) represents an increase of approximately 32 times the amount of energy released. Unless otherwise noted, earthquake magnitude as used in this study refers to surface wave magnitude, M_S.

While *magnitude* describes the size of an earthquake, *intensity* describes its effects at a particular location or site. Intensity at a site is governed by the magnitude of an earthquake, the distance from the site to the earthquake epicenter or rupture surface, and local geologic conditions. A small or moderate earthquake may generate strong ground shaking, but the areal extent of this shaking will be substantially less than that generated by a major earthquake. The 1931 Modified Mercalli Intensity (MMI) Scale (Wood and Neumann, 1931, Table 4-1) is a commonly used measure of intensity. The scale consists of 12 categories of ground motion intensity, from I (not felt, except by a few people) to XII (total damage). Structural damage generally is initiated at about MMI VI for poor structures, and about MMI VIII for good structures. MMI XI and XII are extremely rare. The MMI scale is subjective; it is dependent on personal interpretations and is affected, to some extent, by the quality of construction in the affected area. Even though it has these limitations, it is still useful as a general description of damage, especially at the regional level, and for this reason will be used in this study, as the descriptor of seismic hazard.

4.3 Earthquake Hazards

Physical damage to structures and lifelines during and after an earthquake can be produced by ground shaking, fault rupture, landslides,

Table 4-1 Modified Mercalli Intensity Scale

I. Not felt. Marginal and long-period effects of large earthquakes.

II. Felt by persons at rest, on upper floors, or favorably placed.

III. Felt indoors. Hanging objects swing. Vibration like passing of light trucks. Duration estimated. May not be recognized as an earthquake.

IV. Hanging objects swing. Vibration like passing of heavy trucks; or sensation of a jolt like a ball striking the walls. Standing motor cars rock. Windows, dishes, doors rattle. Glasses clink. Crockery clashes. In the upper range of IV wooden walls and frames creak.

V. Felt outdoors; direction estimated. Sleepers wakened. Liquids disturbed, some spilled. Small unstable objects displaced or upset. Doors swing, close, open. Shutters, pictures move. Pendulum clocks stop, start, change rate.

VI. Felt by all. Many frightened and run outdoors. Persons walk unsteadily. Windows, dishes, glassware broken, knickknacks, books, etc., off shelves. Pictures off walls. Furniture moved or overturned. Weak plaster and masonry D cracked. Small bells ring (church, school). Trees, bushes shaken (visible, or heard to rustle).

VII. Difficult to stand. Noticed by drivers of motor cars. Hanging objects quiver. Furniture broken. Damage to masonry D, including cracks. Weak chimneys broken at roof line. Fall of plaster, loose bricks, stones, tiles, cornices (also unbraced parapets and architectural ornaments). Some cracks in masonry C. Waves on ponds; water turbid with mud. Small slides and caving in along sand or gravel banks. Large bells ring. Concrete irrigation ditches damaged.

VIII. Steering of motor cars affected. Damage to masonry C; partial collapse. Some damage to masonry B; none to masonry A. Fall of stucco and some masonry walls. Twisting, fall of chimneys, factory stacks, monuments, towers, elevated tanks. Frame houses moved on foundations if not bolted down; loose panel walls thrown out. Decayed piling broken off. Branches broken from trees. Changes in flow or temperature of springs and wells. Cracks in wet ground and on steep slopes.

IX. General panic. Masonry D destroyed; masonry B seriously damaged. (General damage to foundations.) Frame structures, if not bolted, shifted off foundations. Frames racked. Serious damage to reservoirs. Underground pipes broken. Conspicuous cracks in ground. In alluviated areas sand and mud ejected, earthquake fountains, sand craters.

X. Most masonry and frame structures destroyed with their foundations. Some well-built wooden structures and bridges destroyed. Serious damage to dams, dikes, embankments. Large landslides. Water thrown on banks to canals, rivers, lakes, etc. Sand and mud shifted horizontally on beaches and flat land. Rails bent slightly.

XI. Rails bent greatly. Underground pipelines completely out of service.

XII. Damage nearly total. Large rock masses displaced. Lines of sight and level distorted. Objects thrown into the air.

Source: Richter, C.F., 1957, *Elementary Seismology*, W. H. Freeman Co., San Francisco, Calif.

Note: To avoid ambiguity, the quality of masonry, brick, or other material is specified by the following lettering system. (This has no connection with the conventional classes A, B, and C construction.)

Masonry A. Good workmanship, mortar, and design; reinforced, especially laterally, and bound together by using steel, concrete, etc.; designed to resist lateral forces.

Masonry B. Good workmanship and mortar; reinforced, but not designed to resist lateral forces.

Masonry C. Ordinary workmanship and mortar; no extreme weaknesses, like failing to tie in at corners, but neither reinforced nor designed to resist horizontal forces.

Masonry D. Weak materials, such as adobe; poor mortar; low standards of workmanship; weak horizontally.

liquefaction, and earthquake-induced fire. Ground shaking is the primary and best-known hazard associated with earthquakes. It produces scattered but widespread damage. Ground shaking includes both horizontal and vertical motions, can last up to several minutes during major earthquakes, and can be destructive at distances of even hundreds of kilometers, depending on soil conditions. It is estimated that such shaking causes over 90% of earthquake-related damage to buildings.

Ground or fault rupture produces local concentration of structural damage. A *fault* is a fracture in the crust of the earth along which blocks have moved or been displaced in relation to each other. This displacement can be in either a horizontal, a vertical, or an oblique direction. Near fault lines, fault displacements produce forces so great that the best method of limiting damage to structures is to avoid building in areas close to ground traces of active faults.

Secondary seismic hazards are those related to soil instabilities. *Liquefaction* is the sudden loss of shear strength that can occur when saturated, soils that lack cohesion (sands and silts) are strongly and repetitively vibrated. Liquefaction typically occurs in loose sand deposits where there is subsurface groundwater above a depth of about 20 feet. Shallow groundwater and loose soil are usually localized conditions, resulting either from natural or human-made causes. As a result, site-specific data generally are necessary to accurately determine if liquefaction may occur at a location. It usually severely damages civil engineering works and low-rise buildings. Mid- and high-rise buildings in these soils will tend to have pile foundations, which mitigate the structural effects of liquefaction, or reduce liquefaction potential, but may not completely eliminate the threat.

Settlement or compaction of loose soils and poorly consolidated alluvium can occur as a result of strong seismic shaking, causing uniform or differential settlement of building foundations. Buildings supported on deep (pile) foundations are more resistant to such settlements. Substantial compaction can occur in broad flat valley areas recently depleted of groundwater.

Landslide is the downslope movement of masses of earth under the force of gravity. Earthquakes can trigger landslides in areas that are already landslide prone. Slope gradient is often a clue to stability. Landslides are most common on slopes of more than 15° and can generally be anticipated along the edges of mesas and on slopes adjacent to drainage courses.

4.4 Seismicity

Seismicity is the space-time occurrence of earthquakes. The historical seismicity of the United States is shown in Figure 4-1, which depicts the spatial distribution of earthquakes with maximum MMIs of V or greater, known to have occurred through 1976. For the purpose of characterizing seismicity in the conterminous United States, several regions may be identified (Algermissen, 1983), as shown in Figure 4-2:

1. Northeastern Region, which includes New England, New York, and part of eastern Canada;

2. Southeastern Region, including the central Appalachian seismic region activity and the area near Charleston, South Carolina;

3. Central Region, which consists of the area between the regions just described and the Rocky Mountains;

4. Western Mountain Region, which includes all remaining states except those on the Pacific coast;

5. Northwestern Region, including Washington and Oregon; and

6. California and Western Nevada.

We discuss each of these regions briefly largely using information from Algermissen (1983) and Coffman et al. (1982). These references can provide a more detailed discussion.

Northeastern Region. The Northeastern Region contains zones of relatively high seismic activity--earthquakes of at least magnitude 7.0 have occurred in New England and the St. Lawrence River Valley in Canada (Algermissen, 1983). The historic seismicity of this region is shown in Figure 4-3.

One of the largest earthquakes to have affected this area was the November 18, 1755,

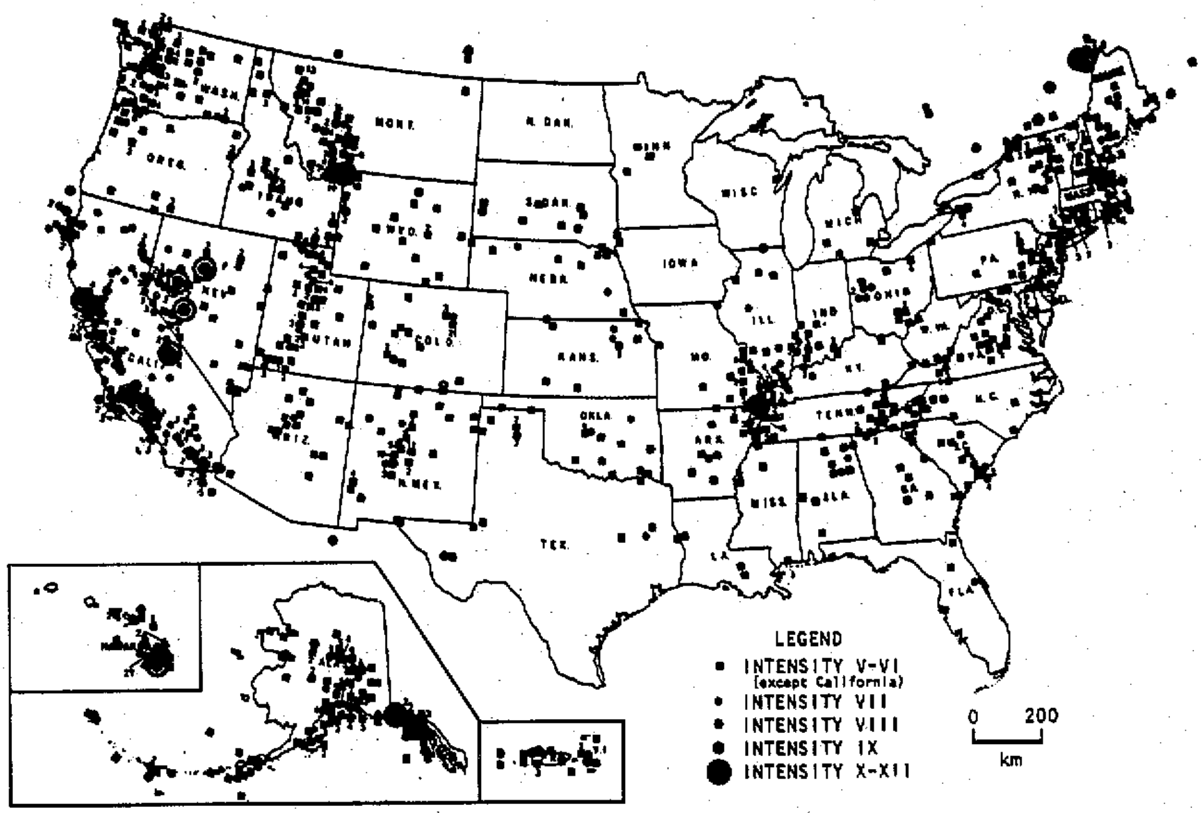


Figure 4-1 *Earthquakes with maximum Modified Mercalli Intensities of V or above in the United States and Puerto Rico through 1989 (Algermissen, 1983, with some modifications).*

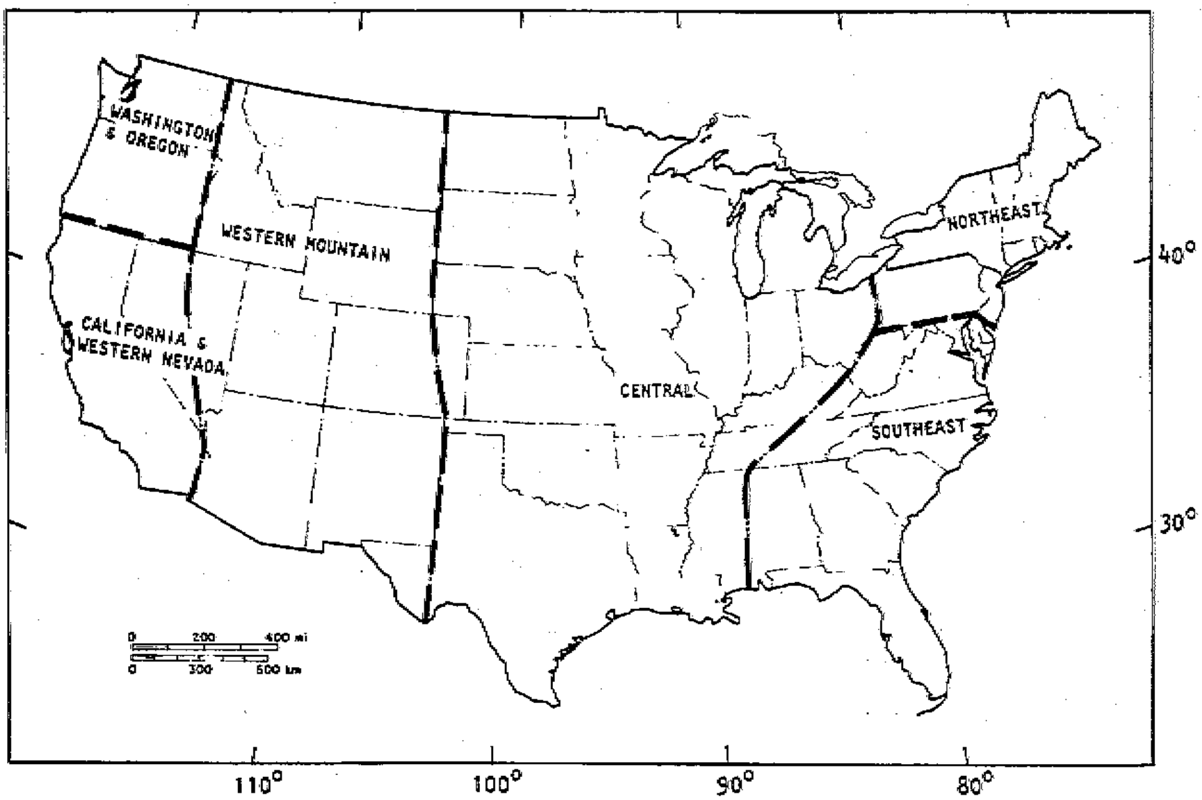


Figure 4-2 *Regional scheme used for the discussion of the seismicity of the conterminous United States.*

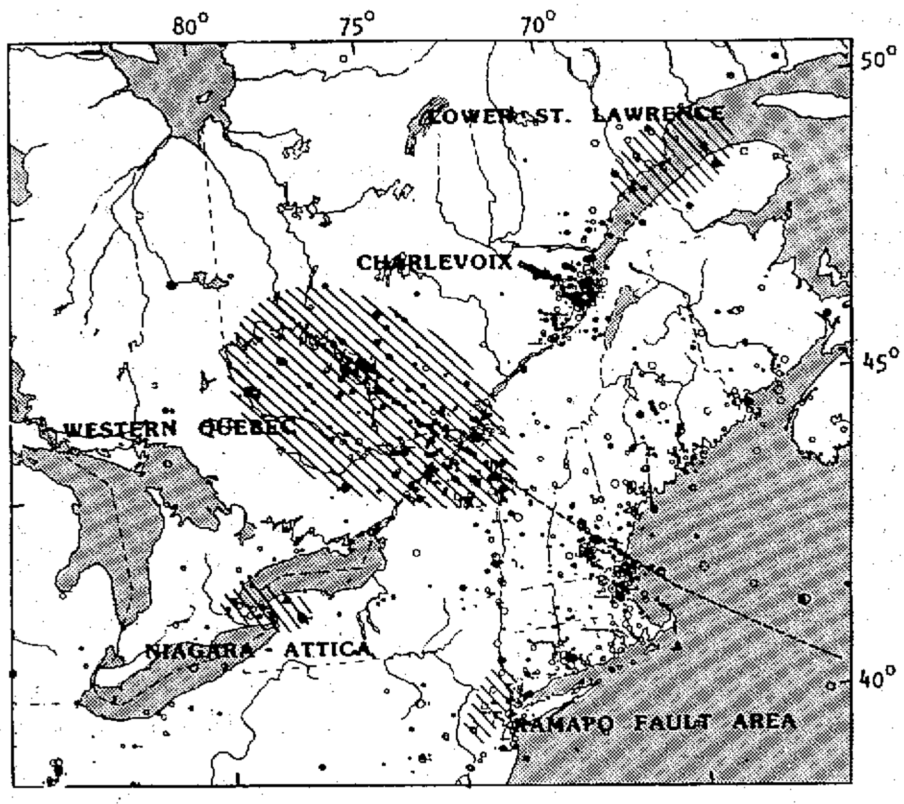


Figure 4-3 *The seismicity of the northeastern region of the United States and Eastern Canada for the period 1534-1959 (from Algermissen, 1983). The solid circles are principally instrumentally determined epicenters, while the open circles represent earthquakes located in using intensity data. The hachured and named areas represent concentrations of seismicity grouped together only for the purpose of discussion in the text. The dashed line represents the strike of the New England (Kelvin) sea mount chain offshore. Onshore, the line has been extended to show the northwest-southwest alignment of seismicity known as Boston-Ottawa trend.*

earthquake east of Cape Ann, with an epicenter located at about 42.5 N and 70.0 W, with magnitude 6.0 (magnitude and epicenter location estimated on the basis of seismic intensity data). The shock was felt from Chesapeake Bay to Annapolis River, Nova Scotia; and from Lake George, New York, to a point at sea 200 miles east of Cape Ann, an area of about 300,000 square miles.

Southeastern Region. The seismicity of this region is shown in Figure 4-4. With the exception of the Charleston, South Carolina, earthquake, this region has a moderate level of earthquake activity. The largest and by far the most destructive earthquakes in this region occurred on August 31, 1886, with their epicenter about 15 miles northwest of Charleston, South Carolina (32.9 N, 80.0 W). The first shock was at 21:51, the second about 8 minutes later. An area with a radius of 800 miles was affected; the strongly shaken portion extended to 100 miles.

The bending of rails and lateral displacement of tracks due to ground displacements were very evident in the epicentral region, though not at Charleston. There were severe bends of the track in places and sudden and sharp depressions of the roadbed. At one place, there was a sharp S-curve. At a number of locations, the effect on culverts and other structures demonstrated strong vertical force in action at the time of the earthquake. Figure 4-5 shows the effects in the epicentral area, and Figure 4-6 shows the isoseismal map for the event (Bollinger, 1977).

Central Region. Compared to the interior of other continents, the central region of North America, especially the Upper Mississippi embayment, is one of relatively frequent small-to-moderate size earthquakes and infrequent large events. In fact, three of the largest earthquakes in North American history occurred there (Hopper, 1985). These latter events occurred in 1811-1812, near the present town of New Madrid, Missouri. They were powerful enough to alter the course of the Mississippi River. Although masonry and stone structures were damaged to distances of 250 kilometers, and chimneys destroyed to distances of 400 kilometers, the sparse settlement of the area prevented grave damage. The extent and severity of ground failure and topographic effects from these shocks have not been equaled by any other earthquake in the conterminous United States.

The seismicity of this region is shown in Figure 4-7. Earthquakes of small magnitude (less than 5.0) are scattered throughout the region, and the major seismicity is associated with the rift structure identified in the New Madrid area. Since the 1811-1812 sequence, nine events of estimated magnitude greater than 5.0 have occurred through 1980, only one of which is estimated to have been greater than magnitude 6.0 (m_b 6.2, in 1895) (Algermissen, 1983).

The New Madrid Seismic Zone lies within a 40-mile-wide, 120-mile-long portion of the northern Mississippi embayment--a south-plunging trough of sedimentary rocks. The boundaries of this zone are at present somewhat uncertain. The zone may extend farther to the south than presently recognized. The epicenter pattern in the New Madrid area shows well-defined lineations: a northeast-striking zone that extends about 60 miles from near Marked Tree, Arkansas (approximately 40 miles northwest of Memphis), to near Caruthersville, Missouri; a north-northwest-striking zone from southeast of Ridgely, Tennessee, to west of New Madrid; and another northeast-striking zone extending from west of New Madrid to near Charleston, Missouri. The first zone is less active, but earthquakes along it have relatively higher magnitudes. The third zone includes frequent events of small magnitude. Note that no identifiable surface faults or offset landforms or drainage features have been identified.

Because seismic attenuation through frictional damping, or dissipation of earthquake energy with distance, is less in the eastern and central United States than in the west, earthquakes in this area have the potential or producing strong ground shaking over comparatively wide areas. The isoseismal map of the December 16, 1811, New Madrid earthquake (Nuttli, 1981) is shown in Figure 4-8. Algermissen and Hopper (1985) have developed maps of hypothetical intensities for the region, based on enveloping effects that would result from an earthquake occurring "anywhere from the northern to southern end of the seismic zone."

Western Mountain Region. Important earthquake activity in this region has occurred in

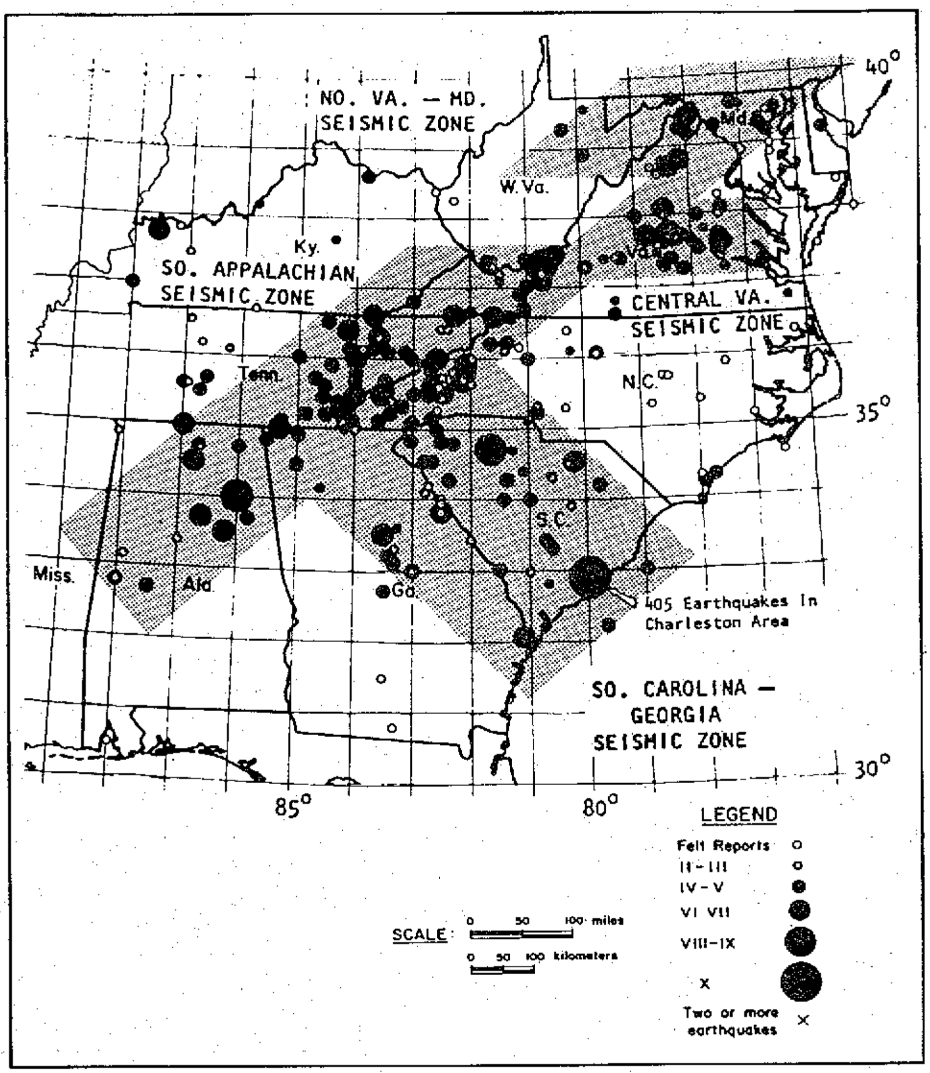


Figure 4-4 *Seismicity of the Southeastern region, 1754-1970 (from Bollinger, 1977).*

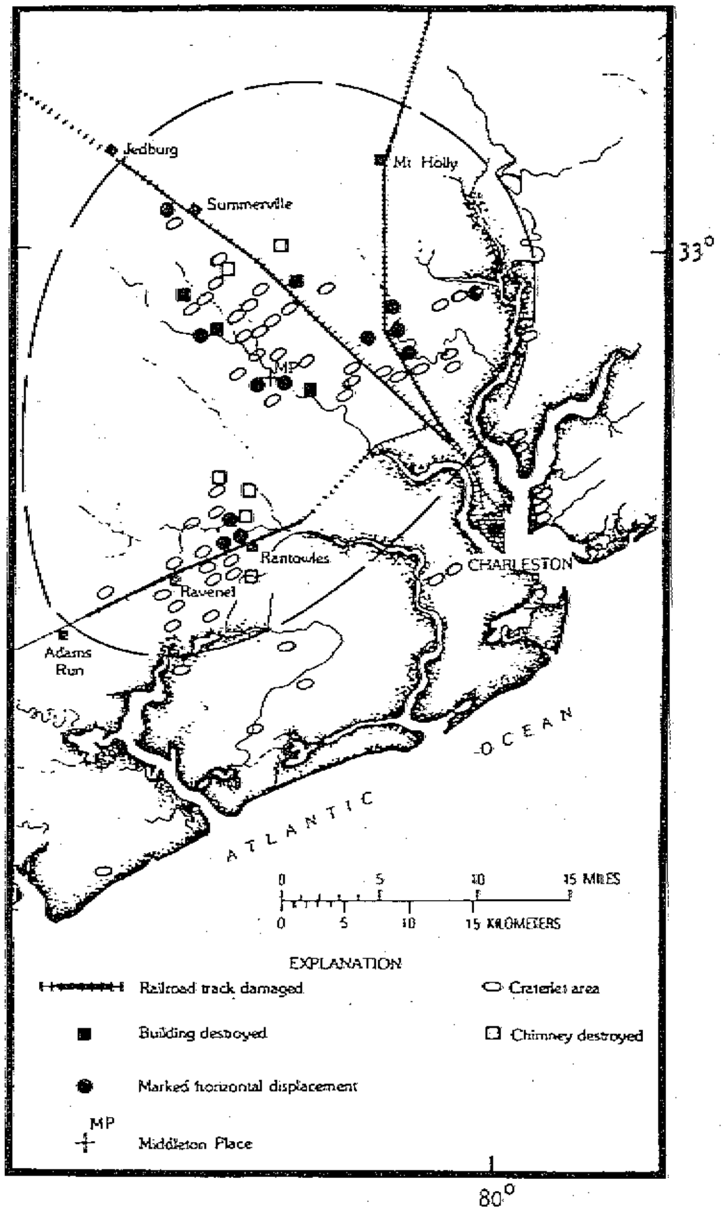
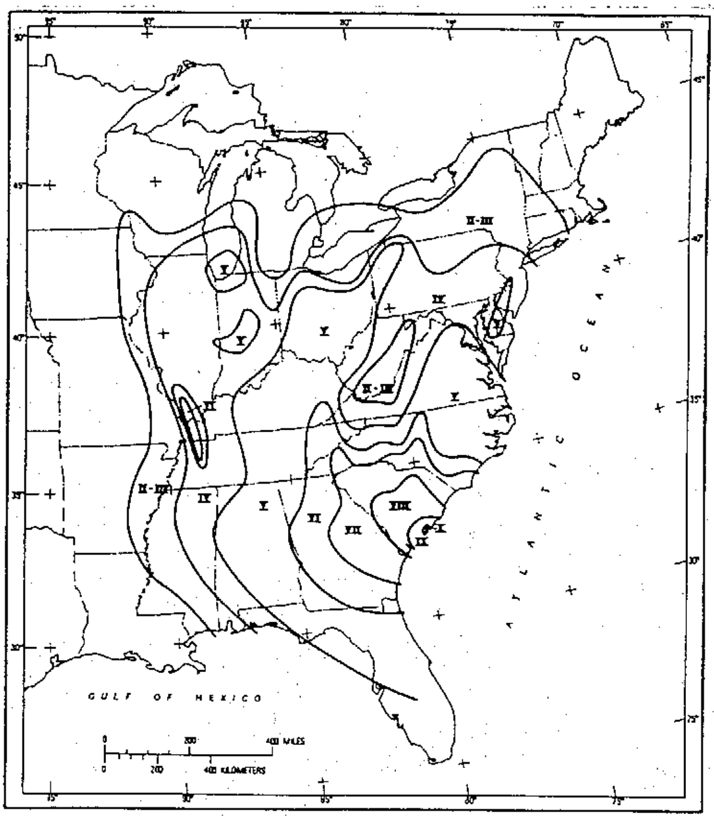
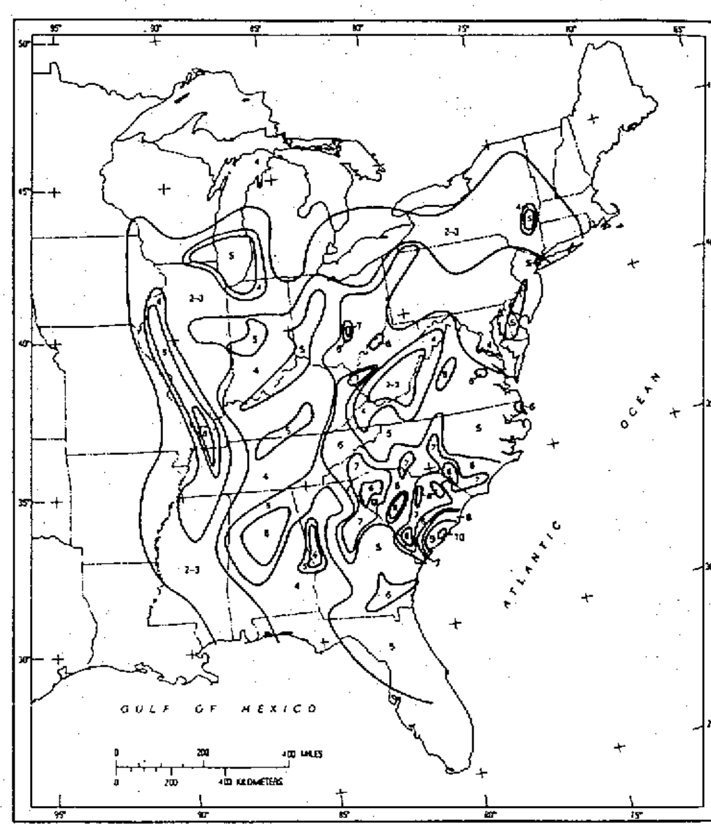


Figure 4-5 *Effects in the epicentral area of the 1886 Charleston, South Carolina, Earthquake (from Algermissen, 1983).*



a) *Broad map, based on detailed map (below)*



b) *Detailed map of seismic intensity.*

Figure 4-6 *Isoseismal map of the 1886 Charleston, South Carolina, Earthquake (from Bollinger, 1977).*

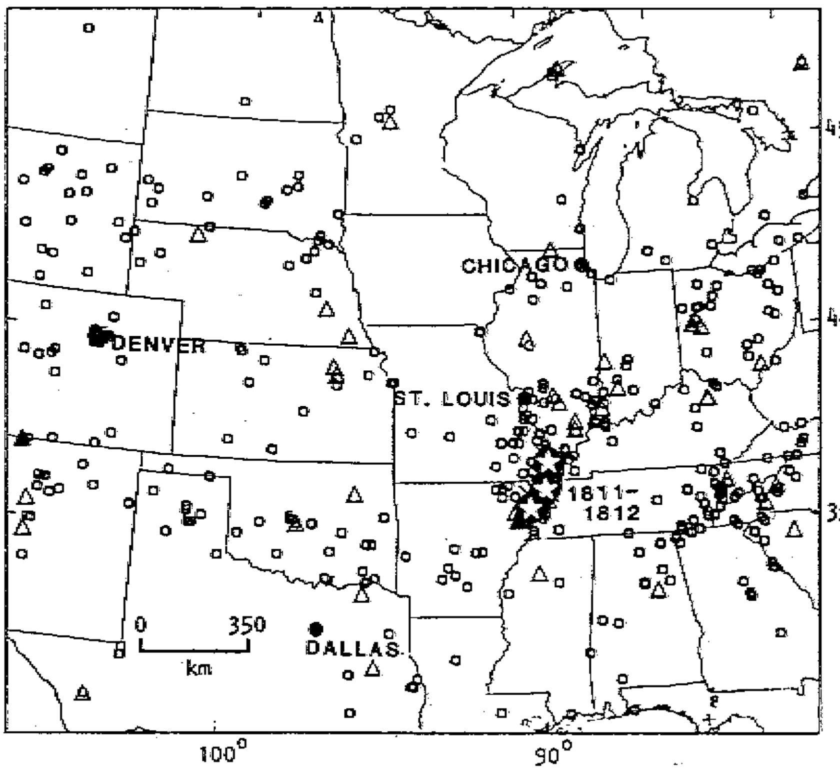


Figure 4-7 *Seismicity of the Central Region, 1811-1976. The data are taken principally from Algermissen (1983) with minor changes and additions. The stars represent earthquakes with maximum MMIs of IX or greater; triangles represent earthquakes with maximum intensities of VII-VIII; squares represent earthquakes with maximum intensities of V-VI.*

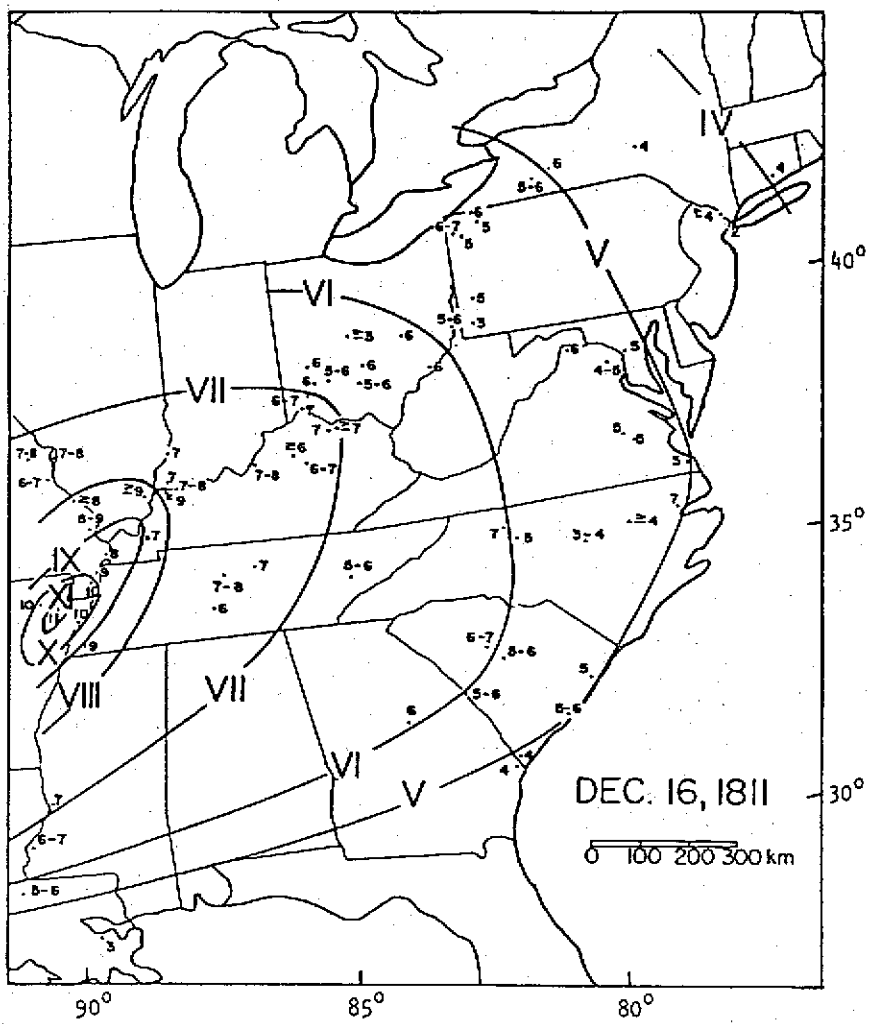


Figure 4-8 *Isoseismal map of the December 16, 1811, earthquake (from Nuttli, 1979). The Arabic numbers give the Modified Mercalli intensities at each data point.*

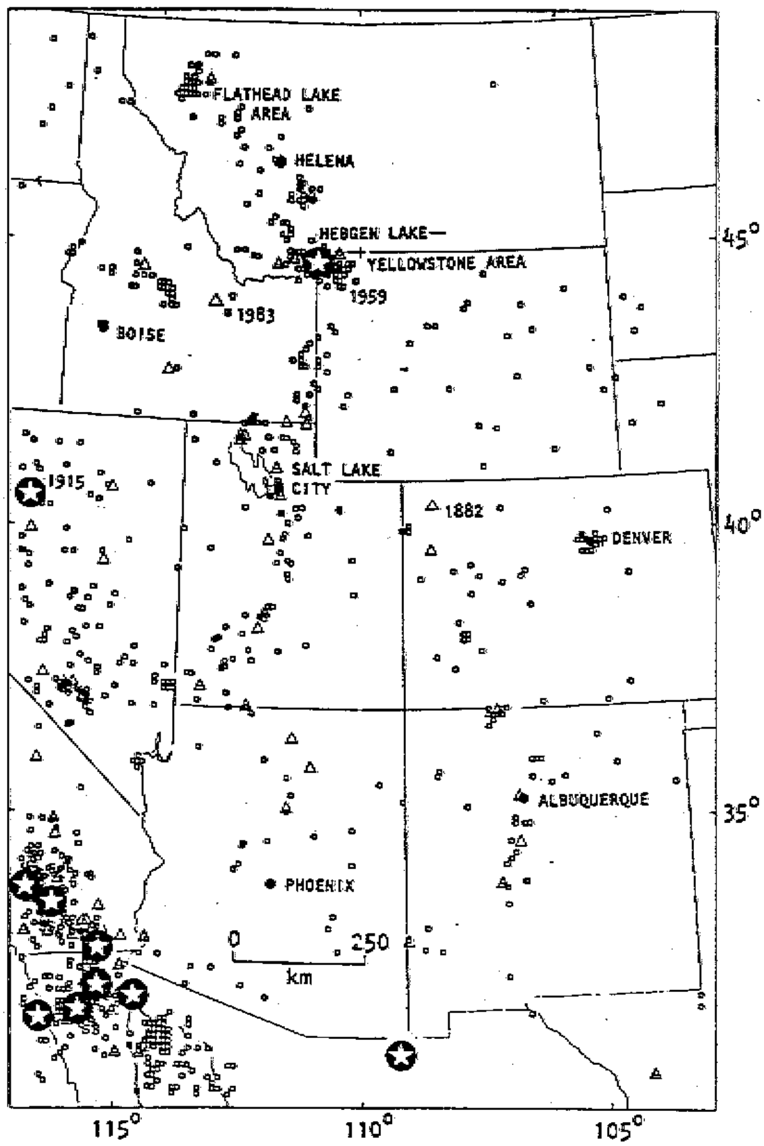


Figure 4-9 *Seismicity of the Western Mountain Region (Algermissen, 1983). Stars represent earthquakes with maximum intensities of IX or greater; triangles represent earthquakes with maximum intensities of VII-VIII; and squares represent earthquakes with maximum intensities of V-VI.*

the Yellowstone Park-Hebgen Lake area, in western Montana, in the vicinity of the Utah-Idaho border, and sporadically along the Wasatch Front, as shown in Figure 4-9. Major earthquakes occurred in Helena, Montana, in 1925 (M_s 6.7), at Hebgen Lake, Montana, in 1959 (M_s 7.1) and at Borah Peak, Idaho, in 1983 (M_s 7.3).

Probably the most serious risk in the Western Mountain Region, however, exists along the Wasatch Front region of north-central Utah. This area is dominated by the Wasatch Fault, a 220-mile-long, north-south-trending zone extending from Gunnison, Utah, in the south, to Malad City, Idaho, in the north, and directly threatening the Salt Lake City area. In this zone, young mountain blocks have been uplifted to form the prominent west-facing scarp (the Wasatch Front), which forms the eastern boundary of the Salt Lake and Utah valleys. Included in this zone is the active East Cache Fault System located on the eastern side of Cache Valley. Another related fault system of interest is the Hansel Valley Fault Zone, located north of the Great Salt Lake near the border with Idaho. It has been the most active fault in the state for larger-size events (Arabasz and Smith, 1979).

Historic records of earthquake activity in Utah date back to 1853, shortly after the region was settled permanently. Since that time, over 1,000 felt events have occurred on a regular basis. The earliest event recorded that has been estimated to have a magnitude of 6.0 or greater was the Bear Lake Valley Earthquake in 1884 (estimated magnitude 6.1). The 1909 event in Hansel Valley was assigned a maximum intensity of VIII and a magnitude of 6.0, and resulted in waves being sent over the railway causeway at the north end of the Great Salt Lake and windows being broken as far away as Salt Lake City. The largest earthquake to date in Utah, the 1934 Hansel Valley event (M_s 6.6) severely damaged brick buildings in Kosmo, produced 2-foot scarps in the ground surface, greatly altered groundwater flow patterns, and caused nonstructural damage to buildings in Salt Lake City. It occurred in a sparsely populated area, otherwise great damage could have resulted.

Historic earthquake damage to the Utah Valley area has thus far been due to local earthquakes with magnitudes of approximately 5.0 or less, with maximum intensities of about MMI VI or less. Damage has been mostly limited to cracked walls and chimneys, and broken windows. Since 1960, there has been very little notable earthquake activity in the Utah Valley. However, research has shown that many large seismic events (magnitudes 6.5 to 7.5) have taken place along the Wasatch Front during the past 10,000 years (Swan et al, 1980).

Northwestern Region. The seismicity of Washington and Oregon is shown in Figure 4-10. Most of the earthquake activity has occurred in the vicinity of Puget Sound. Although a few geologically recent faults thought to be potentially active have been located in western and central Washington, no historic seismic activity has been associated with them. Instead, most recorded seismic activity in Washington has been attributed to the subduction of the offshore Juan de Fuca crustal plate beneath the North American continental plate.

Subduction zones occur at locations where, under the influence of tectonic plate movement, one piece of the earth's crust is forced beneath another. Subduction zones have been associated with very large earthquakes including the 1985 Mexico City (M_s 8.1) and 1964 Alaska (M_s 8.3) events. Subduction zones are frequently associated with volcanic activity as well as earthquakes. The presence of the volcanically active Cascade range supports the evidence for an active Juan de Fuca subduction zone. Further supporting evidence includes the mountains on the Olympic peninsula, which appear to have been formed by debris scraped off the Juan de Fuca plate by the overriding North American plate.

Available geologic information indicates that great earthquakes, with magnitudes in excess of 8.0, have occurred on the Juan de Fuca subduction zone at least eight times in the last 5,000 years. The last such event is thought to have occurred about 300 years ago. Evidence for such an earthquake includes geologically recent submerged marsh lands and fossil forests along the Washington coastline. It is believed that portions of the Washington coast subsided by as much as 3 feet in that event.

In addition to the great earthquakes described above, extensive but more moderate seismicity

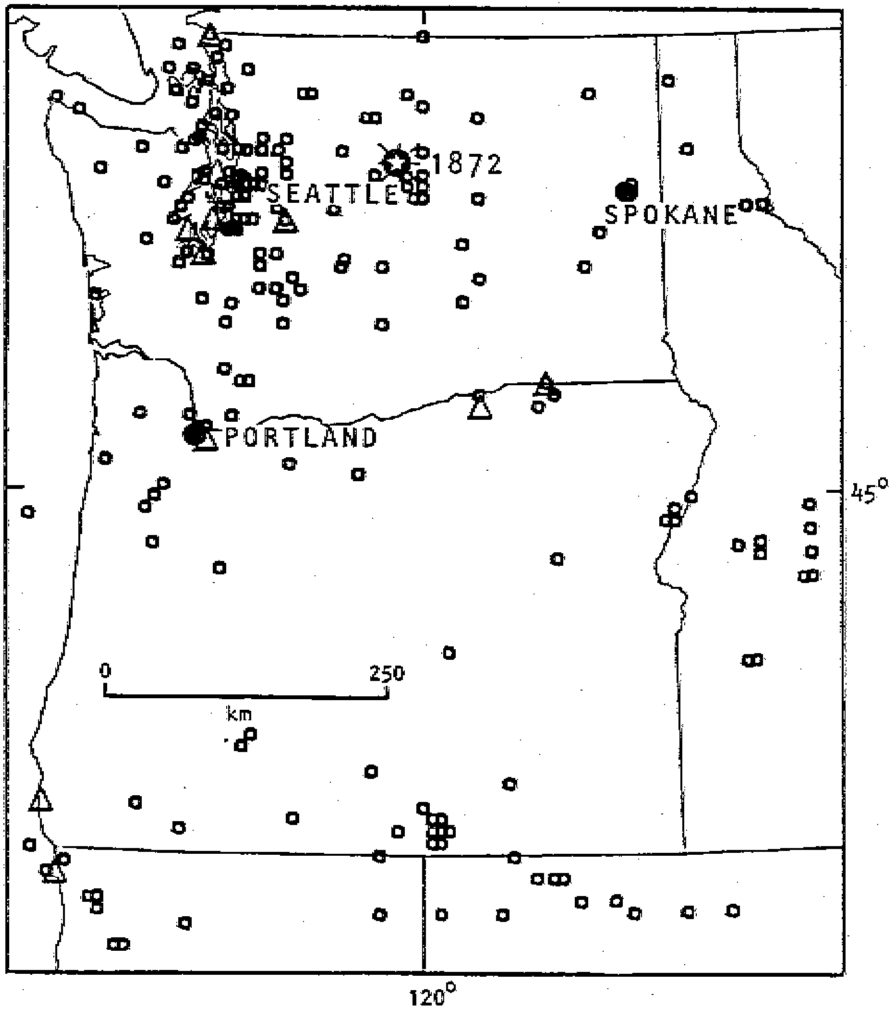


Figure 4-10 *Seismicity of Oregon and Washington, 1859-1975. The star represents an earthquake with maximum Modified Mercalli intensity of IX; triangles represent earthquakes with maximum intensities of VII-VIII; and small squares represent earthquakes with maximum intensities of V-VI (Algermissen, 1983).*

has been associated with the same subduction zone, deep beneath the Puget Sound trough between Seattle and Olympia. In this area, termed the Puget Trough Intercrustal Zone, the friction between the underlying Juan de Fuca plate and overriding North American plate has resulted in many mid-size events with occasional strong damaging shocks. Typically these events occur at depths from 20 to 30 miles below the surface and are therefore less damaging than events of similar size in California, which occur at shallower depths. Two of the largest recorded earthquakes in the Pacific Northwest have occurred in this zone. A M_S 7.1 event in 1949, located near Olympia, caused extensive damage in Seattle, Tacoma, and Olympia. A 1965 (M_S 6.5) event, centered near the Seattle-Tacoma airport, caused MMI VII and VIII damage in both Seattle and Tacoma. A mean return period of approximately 30 years has been calculated for events of this size. Great earthquakes of magnitude 7.5 or larger are believed credible.

An earthquake in the northern Cascades in 1872 had an estimated magnitude of 7.3 and a maximum intensity of MMI IX. Earthquake intensities of MMI VII were experienced on the Olympic peninsula in 1891 and again in 1904. Two moderate earthquakes in 1932 and 1945 shook the central Cascades with maximum MMI VII.

The Vancouver-Victoria area, located in the northern portion of Puget Sound, has had a relatively large number of smaller earthquakes. However, the maximum magnitudes experienced have been much lower than those in the southern portion of Puget Sound. Only three earthquakes as large as magnitude 5.5 have occurred in the Vancouver-Victoria area. The corresponding maximum intensities were on the order of MMI VII. The estimated maximum magnitude for the Vancouver-Victoria area is about 6.5.

Further north on Vancouver Island, over 200 miles from Seattle, two earthquakes of magnitudes 7.0 and 7.4 occurred in 1918 and 1946, respectively. These events produced maximum intensities of MMI VIII but did not cause significant damage in Washington.

California and Western Nevada. Earthquakes in California and Western Nevada represent a high percentage of the seismic activity of the conterminous United States. The majority of these shocks occur at relatively shallow focal depths of 10 to 15 miles and along known rupture zones or faults. Figure 4-11 shows the seismicity of this region, while Figure 4-12 shows faults with historic displacements in this region.

While this area is the most seismically active region of the conterminous United States, only three events with magnitudes greater than M_S 8.0 have occurred in historical times. Two of these events occurred on the principal fault in this area, the San Andreas, which extends over 600 miles through California, from near the Salton Sea in Southern California northwest to Cape Mendocino. The most famous of these San Andreas events was the April 18, 1906, San Francisco Earthquake (M_S 8.3), caused by a rupture of approximately 270 miles in length, from San Juan Bautista to off Cape Mendocino. Devastation was extremely widespread, with enormous losses in San Francisco caused by the ensuing conflagration (Lawson et al., 1908). The other of these events, the Ft. Tejon Earthquake, occurred on January 9, 1857, on a segment of the San Andreas Fault between Cholame and south of Cajon Pass. It may be regarded as a Southern California counterpart of the 1906 event. The isoseismal maps for these events are shown in Figure 4-13. In addition to these two great earthquakes, a number of large, potentially damaging earthquakes have occurred on the San Andreas Fault, including events in 1838, 1865, and, most recently, the October 17, 1989, Loma Prieta Earthquake (M_S 7.1). This last event resulted in very significant disruption to almost all lifelines, especially the highway and electric power networks (Khater et al., 1990).

The third of the great historic California earthquakes is the 1872 Owens Valley event, resulting from approximately 150 kilometers of faulting. The area was relatively sparsely populated but still resulted in about 10% fatalities in Lone Pine, because of the predominantly adobe construction.

Another very important fault in Northern California is the Hayward Fault, located on the eastern side of San Francisco Bay and extending approximately 55 miles from San Jose northwesterly to San Pablo (Figure 4-12). The Hayward Fault is one of the major active branches of the San Andreas Fault System, and is particularly significant because it passes

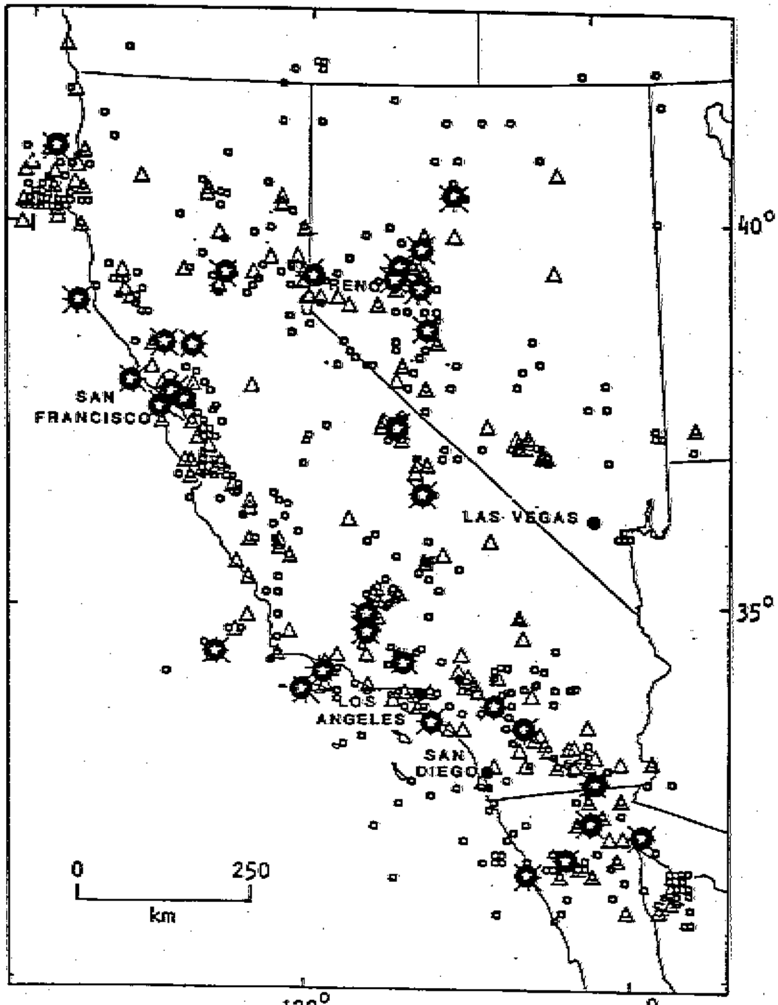


Figure 4-11 *Seismicity of Western Nevada and California, 1811-1976 (Algermissen, 1983). Stars represent earthquakes with Modified Mercalli intensities of IX or greater, triangles represent shocks with maximum intensities of VII-VIII; and small squares represent shocks with maximum intensities of VI.*

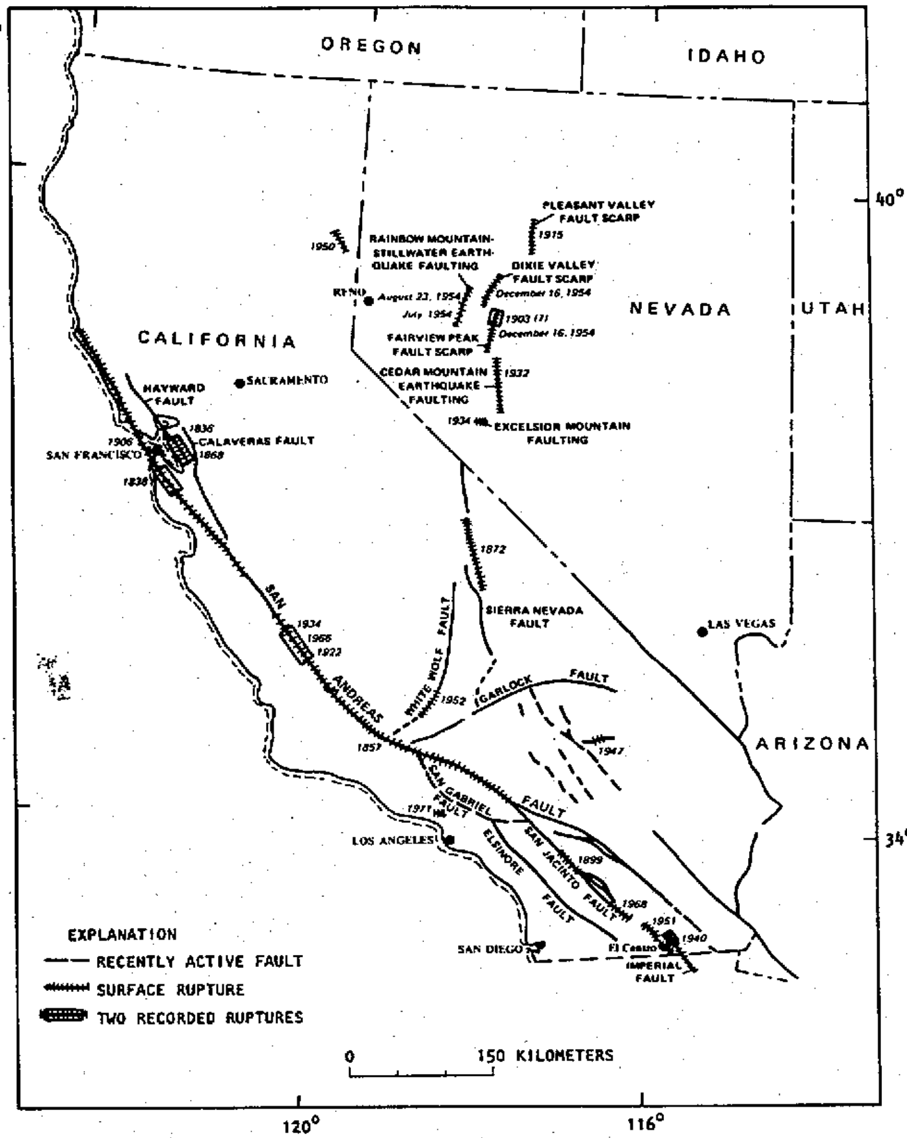


Figure 4-12 *Faults with historic displacements in California and Nevada. The year of occurrence for selected large earthquakes is shown (Algermissen, 1983).*

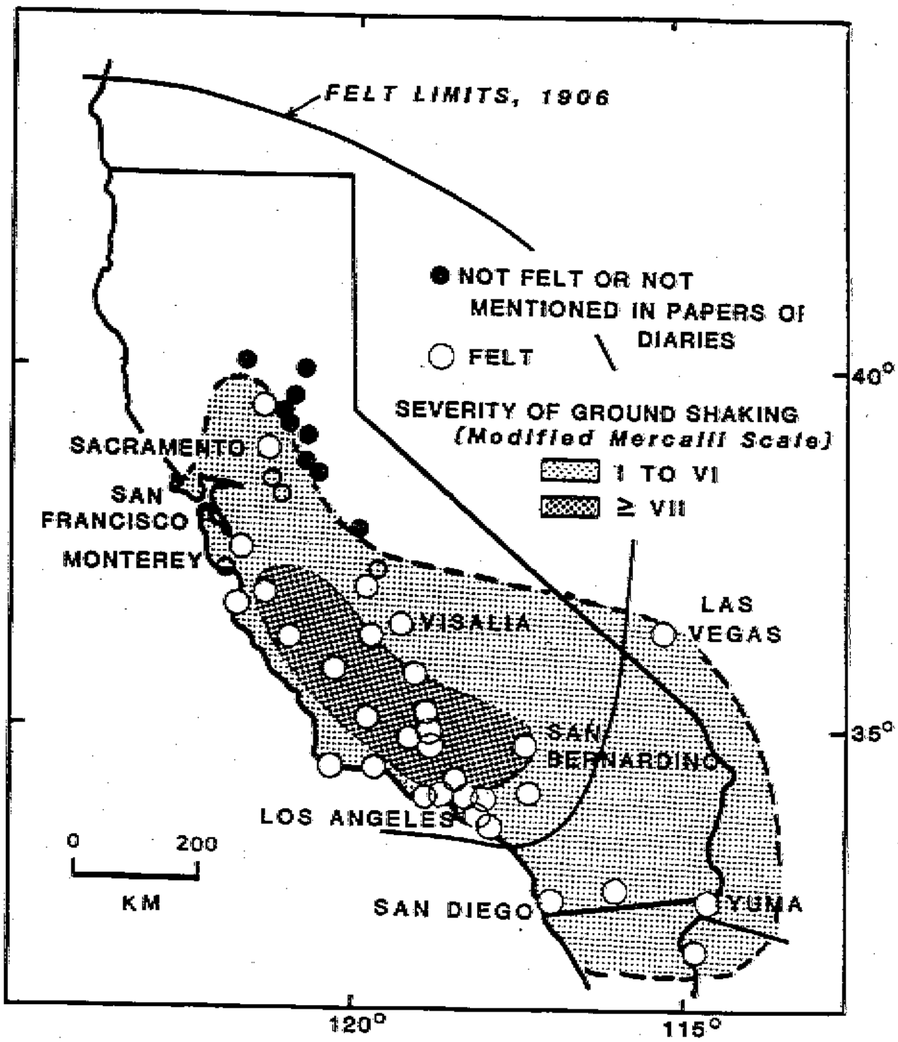


Figure 4-13 *Isoseismal map for the January 9, 1857, earthquake on the San Andreas Fault near Fort Tejon (Algermissen, 1983). Also shown, for comparison, are the felt limits for the 1906 San Francisco Earthquake.*

directly through the heavily populated cities such as Hayward, San Leandro, Oakland, and Berkeley. It was the source of the Hayward Earthquake of 1836 (estimated M_S 6.8), in which fissures opened along the fault from San Pablo to Mission San Jose, and ground shaking caused havoc in the settlements of San Jose and Monterey. In 1868 an earthquake (estimated M_S 6.8) ruptured the fault the fault for 20 miles and severely damaged every building in the village of Hayward. More recent damaging earthquakes occurred in 1915, 1933, and 1937. The Hayward Fault is believed capable of producing earthquakes as large as magnitude 7.5, and is presently judged highly likely to rupture with a magnitude of about 7.0 in the near future [United States Geological Survey (USGS), 1990]; this judgment is based, among other evidence, on the pairing of San Andreas/Hayward events in 1838/1836 and 1865/1868. A large earthquake on this fault is of potentially catastrophic proportions (Steinbrugge et al., 1987).

Similar to the Hayward Fault situation in the San Francisco Bay Area, the Los Angeles region is threatened by a number of additional faults, including the Newport-Inglewood, Santa-Monica Raymond, Elsinore, Norwalk, and other faults and fault zones. Significant events have included the 1933 Long Beach event (M_S 6.3) on the Newport-Inglewood Fault (NBFU, 1933; Binder, 1952), the 1971 San Fernando event (M_S 6.4, San Fernando Fault), and the 1987 Whittier (M_S 5.9) event.

Other significant events in California have included the 1940 El Centro (M_S 7.1), the 1952 Kern County (M_S 7.7), and the 1983 Coalinga (M_S 6.5) events.

4.5 Regional Representative Earthquakes

Based on the foregoing review of conterminous U.S. regional seismicity, each region appears to have significant historic precedent for a damaging earthquake of potentially catastrophic dimensions. For purposes of examining this potential, the earthquakes indicated in Table 4-2 are representative events for the investigation of lifeline loss estimation and disruption.

Evernden et al. (1981) estimates that these events represent almost the maximum earthquake expected in each area. Review of Algermissen et al. (1982) indicates general agreement.

Table 4-2 Representative Earthquakes for Lifeline Loss Estimation

Region	*Event*
Northeastern	Cape Ann, 1755
Southeastern	Charleston, 1886
Central	New Madrid, 1811-1812
Western Mountain	Wasatch Front, no date
Northwestern	Puget Sound, 1949
Southern California	Fort Tejon, 1857
Northern California	Hayward, 1868

4.6 Estimation of Seismic Intensities and Choice of Scenario Earthquakes for this Project

Choice of a Model. In order to estimate the seismic hazard (i.e., deterministic intensity) of the scenario events over the affected area associated with each event, a model of earthquake magnitude, attenuation, and local site effects is required. For the conterminous United States, two general models were considered: Evernden and Thomson (1985), and Algermissen et al. (1990).

Both models are applicable for the entire conterminous United States, and each offers many advantages but addresses two fundamentally different users. The Algermissen model is oriented toward probabilistic mapping of seismic hazard, while the Evernden model is oriented toward exploration of the effects of deterministic events. Both models were considered for use in this investigation. Selection of one over the other was difficult, but the Evernden model offered the following advantages for this study: (i) verification via comparison with historical events, (ii) incorporation of local soil effects and ready availability of a nationwide geologic database, and (iii) ready availability of closed-form attenuation relations. While determination of seismic intensities is fundamental to the results of this investigation, the choice of one of these models over the other was not felt to be crucial to this study, because (i) the primary purpose of this study is not the investigation of seismic hazards in the conterminous United States, or comparison of these two models, but rather the performance of selected lifelines; and (ii) both models probably provide similar results in the mean (it should be noted, however, that the two models have not been systematically compared, to the author's knowledge).

Use of the Evernden Model. Attenuation of ground motion away from the epicenter has been estimated by employing Evernden's model (Evernden et al., 1981). The model contains several parameters whose evaluations are based on empirical data. Only three factors in the model are regionally dependent: the local attenuation factor, the length of rupture, and a parameter related to depth of earthquake focus. The local attenuation factor changes significantly across different regions. Its value is about 1.75 in coastal California, 1.5 in eastern California and the Mountain States, 1.25 in the area of the Gulf and Atlantic Coastal plains including the Mississippi Embayment, and 1.0 in the rest of the eastern United States. Rupture length and energy released are related by an empirical relation, which leads to the observation that all major earthquakes of the Eastern United States have fault lengths of 10-to-40 kilometers maximum. With the local attenuation factor and rupture length established, peak intensity at the epicenter serves to establish the depth of focus.

The geological map of the United States published in the *National Atlas of the United States of America* (Gerlich, no date) was used for the complementary geologic base, digitized on a 25- by 25-kilometer grid.

As noted by Evernden et al. (1981), digitization at this resolution generally results in saturated poor ground not constituting the dominant ground condition in any particular grid element. Therefore, the resulting intensities should generally be interpreted as those on bedrock, per Evernden. This study generally concurs with this point, noting however that even the 25- by 25-kilometer digitization captures poor ground conditions in certain important locations, especially in the Mississippi Valley and along the eastern seaboard. As a generalization, intensities estimated by the Evernden model can be considered to provide lower bounds on site intensities.

Table 4-3 Geologic and Ground Condition Units, Conterminous United States (per Evernden et al., 1981)

Units of Geologic Map	*Ground Condition Unit*	*Relative Intensity*
Sedimentary rocks		
Quaternary	A	0.00
Upper Tertiary	B	-1.00
Lower Tertiary	C	-1.50
Cretaceous	D	-2.00
Jurassic and Triassic	E	-2.25
Upper Paleozoic	F	-2.50
Middle Paleozoic	G	-2.75
Lower Paleozoic	H	-2.75
Younger Precambrian	I	-2.75
Older Precambrian	J	-3.00
Volcanic rocks		
Quaternary and Tertiary volcanic rocks	K	-3.00
Intrusive rocks		
All ages	L	-3.00

Table 4-3 indicates the ground condition unit and relative intensity that correspond to the geologic units of the geologic map. Figure 4-14 shows the conterminous United States mapped in terms of these seismic units.

Scenario Earthquakes. Based on the earthquakes discussed above, representative of all major regions of the conterminous United States, eight scenario events were selected for this investigation. The eight events are indicated in Table 4-4. With the exception of the Cape Ann, Charleston, and Hayward events, all magnitudes are reflective of the representative earthquake for the region (as specified in Table 4-2). The scenario events for Cape Ann, Charleston, and Hayward have magnitudes one-half unit higher than the representative event. These magnitudes are interpreted as maximum credible for these locations.

The choice of a scenario event on the Hayward fault for the San Francisco Bay Area, rather than the 1906 San Francisco event, is based on the perceived high likelihood of a magnitude 7.0 event (USGS, 1990) as well as the potential for major damage and lifeline disruption, should such an event occur (CDMG, 1987). Since most lifelines approach San Francisco Bay from the east, more of them cross the Hayward Fault than cross the San Andreas Fault. So the

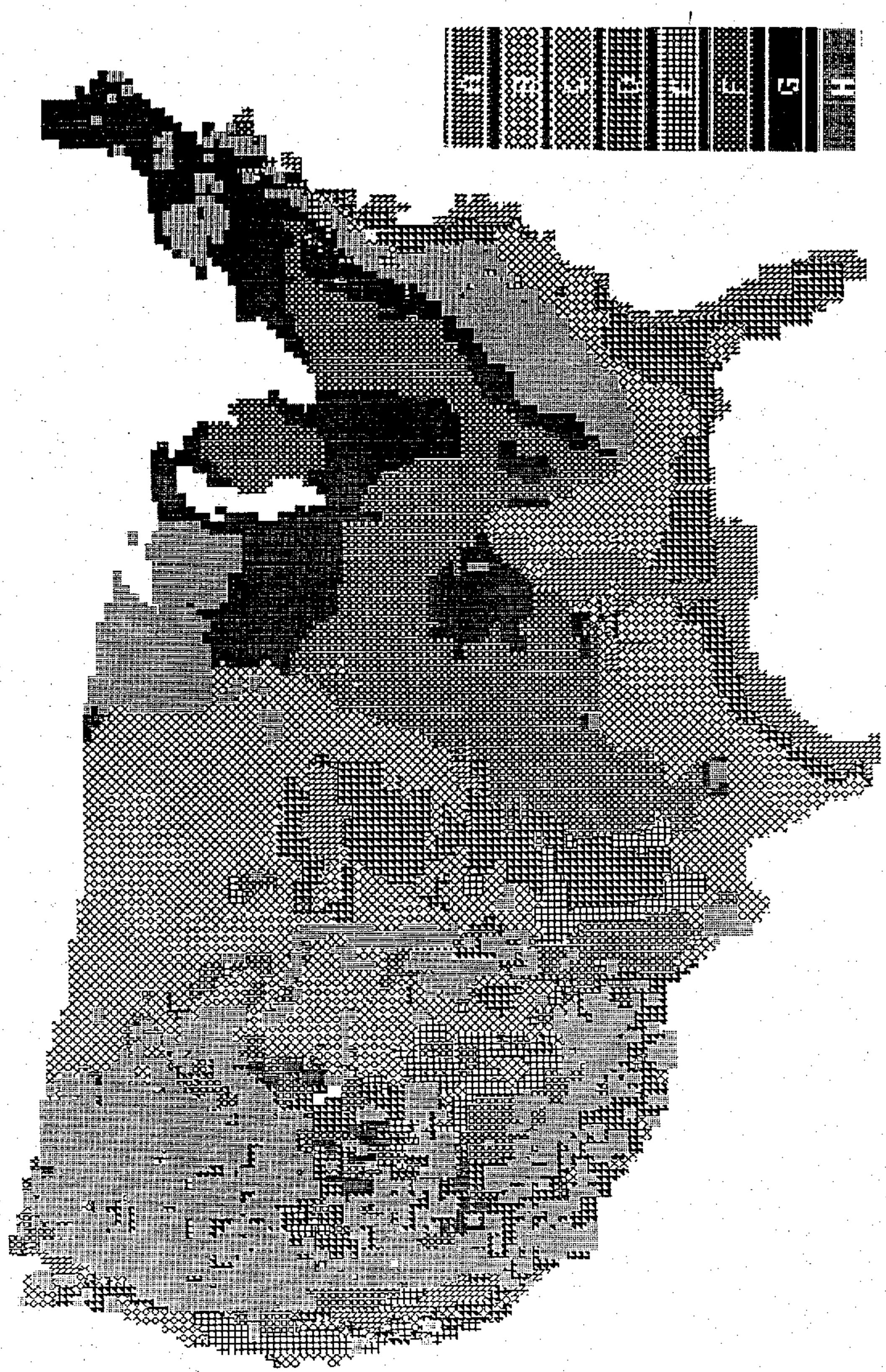


Figure 4-14 *Map of conterminous United States showing ground condition units from Evernden et al. (1981). See Table 4-3 for explanation of units.*

Table 4-4 Scenario Earthquakes

Region	*Event*	*Magnitude*
Northeastern	Cape Ann	7
Southeastern	Charleston	7.5
Central	New Madrid	7 and 8
Western Mountain	Wasatch Front	7.5
Northwestern	Puget Sound	7.5
Southern California	Fort Tejon	8
Northern California	Hayward	7.5

Hayward event would appear to represent as disruptive an event, and potentially more so, than the 1906 event, which is presently perceived to be of low likelihood in the near future.

Intensity Distributions. The Evernden model was employed to generate expected seismic intensity distribution in the conterminous United States for the eight scenario events. These intensity distributions are presented in Figures 4-15 through 4-22.

The intensity patterns for these events are seen to be basically circular, centered at the earthquake's epicenter. Deviations from the circular shape are due to local geologic conditions. Comparison of estimated intensities with historic event isoseismals indicates general agreement, though historical events are in some cases smaller than the scenario event.

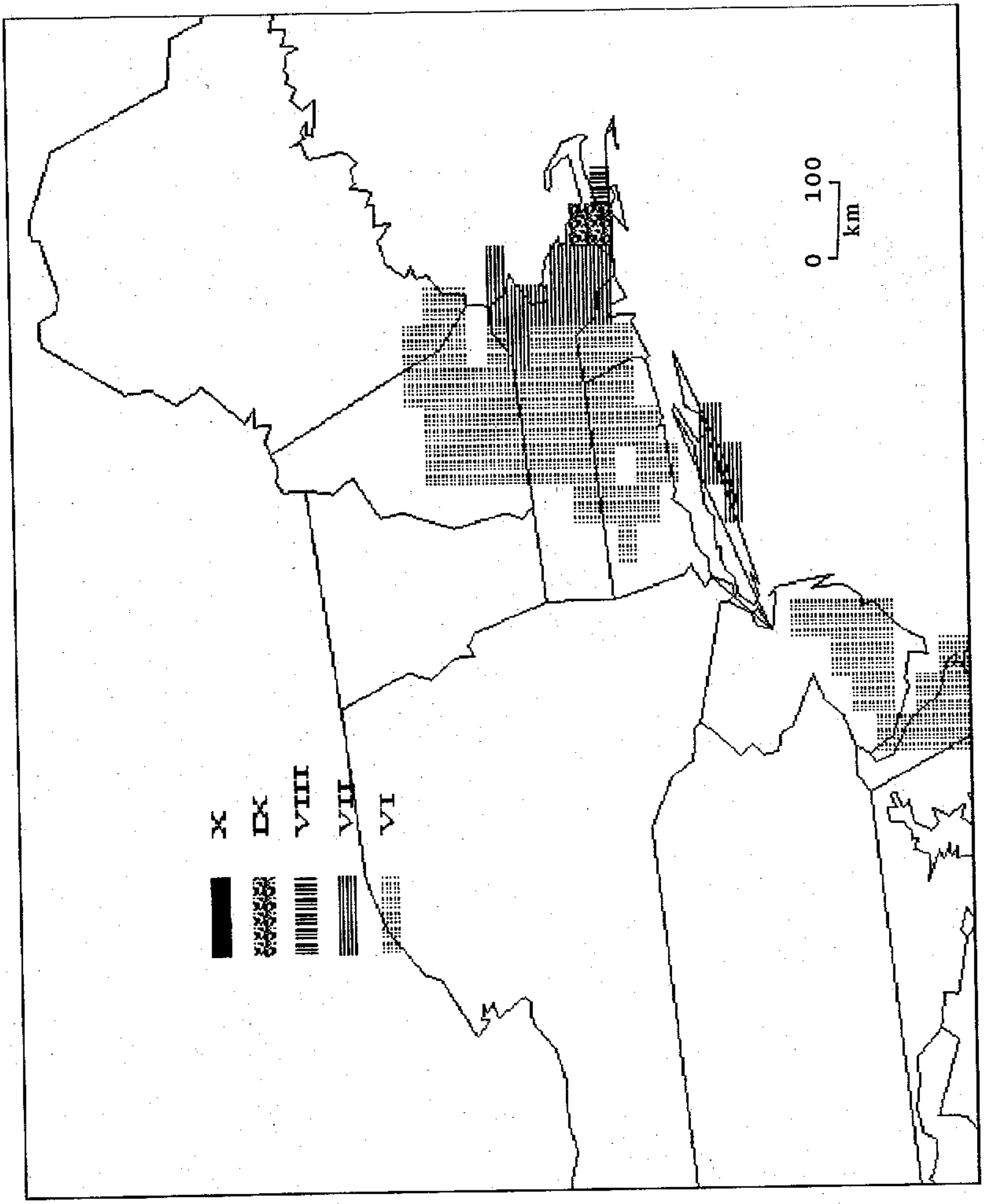


Figure 4-15 *Predicted intensity map for Cape Ann (Magnitude 7).*

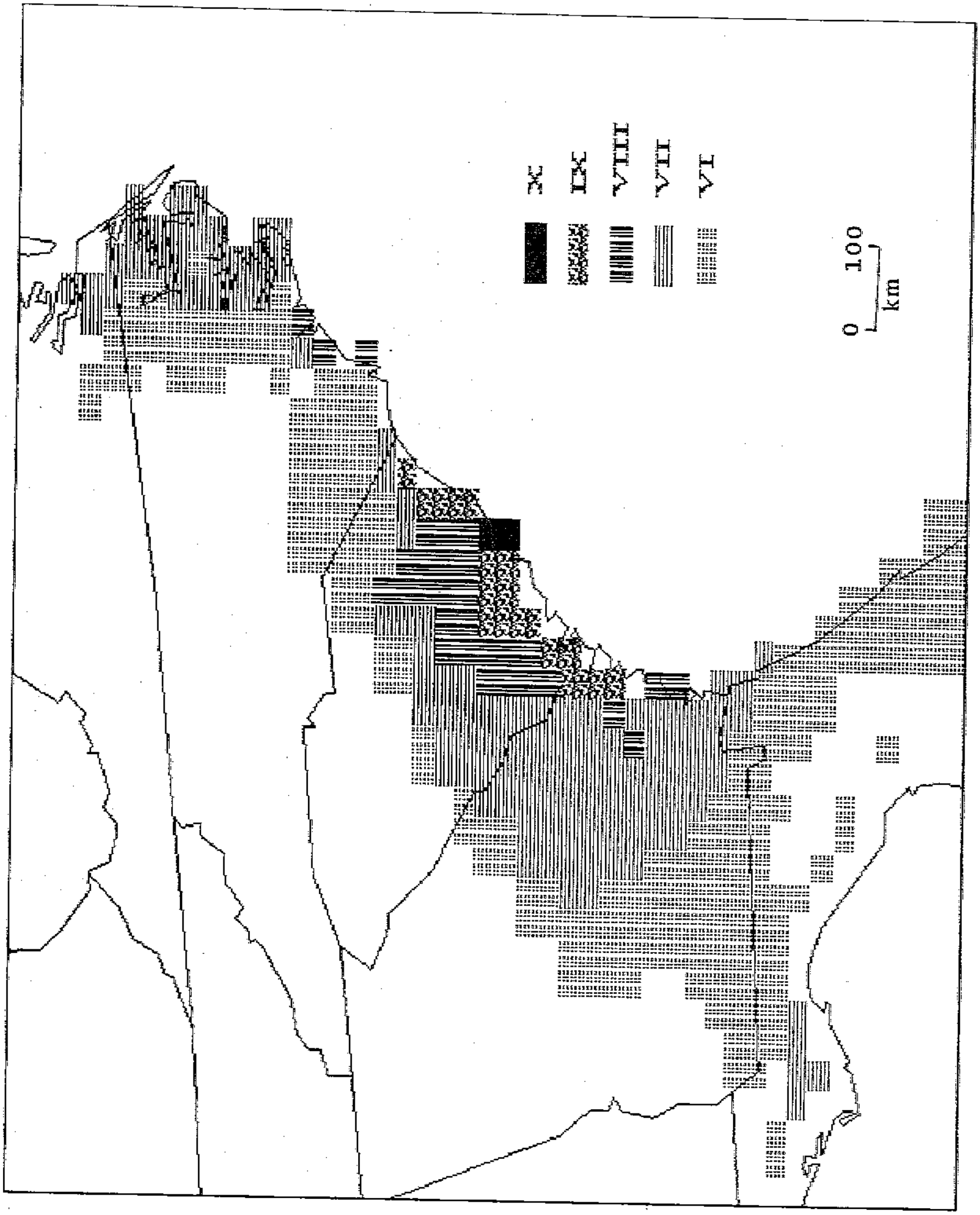


Figure 4-16 Predicted intensity map for Charleston (Magnitude 7.5).

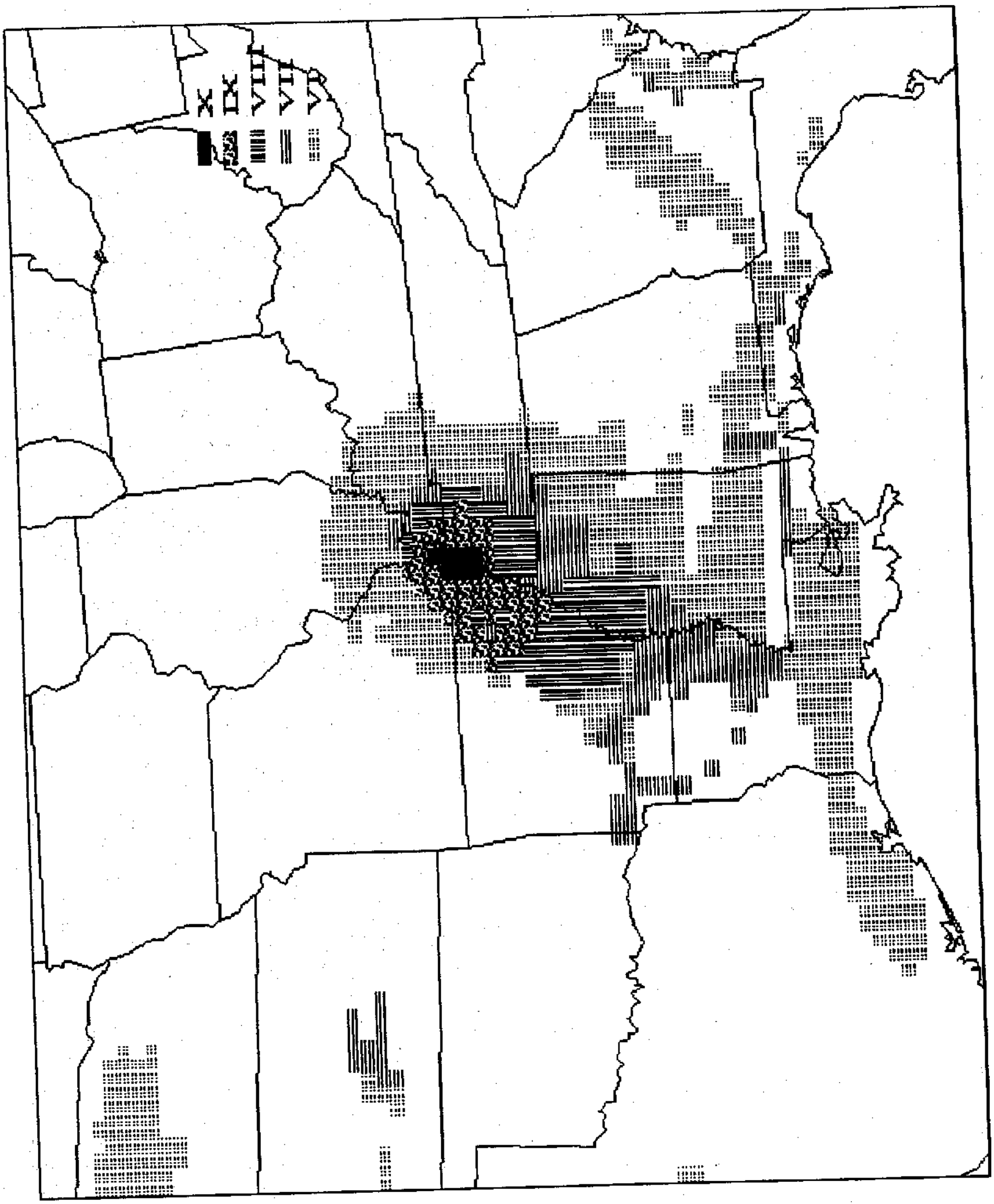


Figure 4-17 *Predicted intensity map for New Madrid (Magnitude 8).*

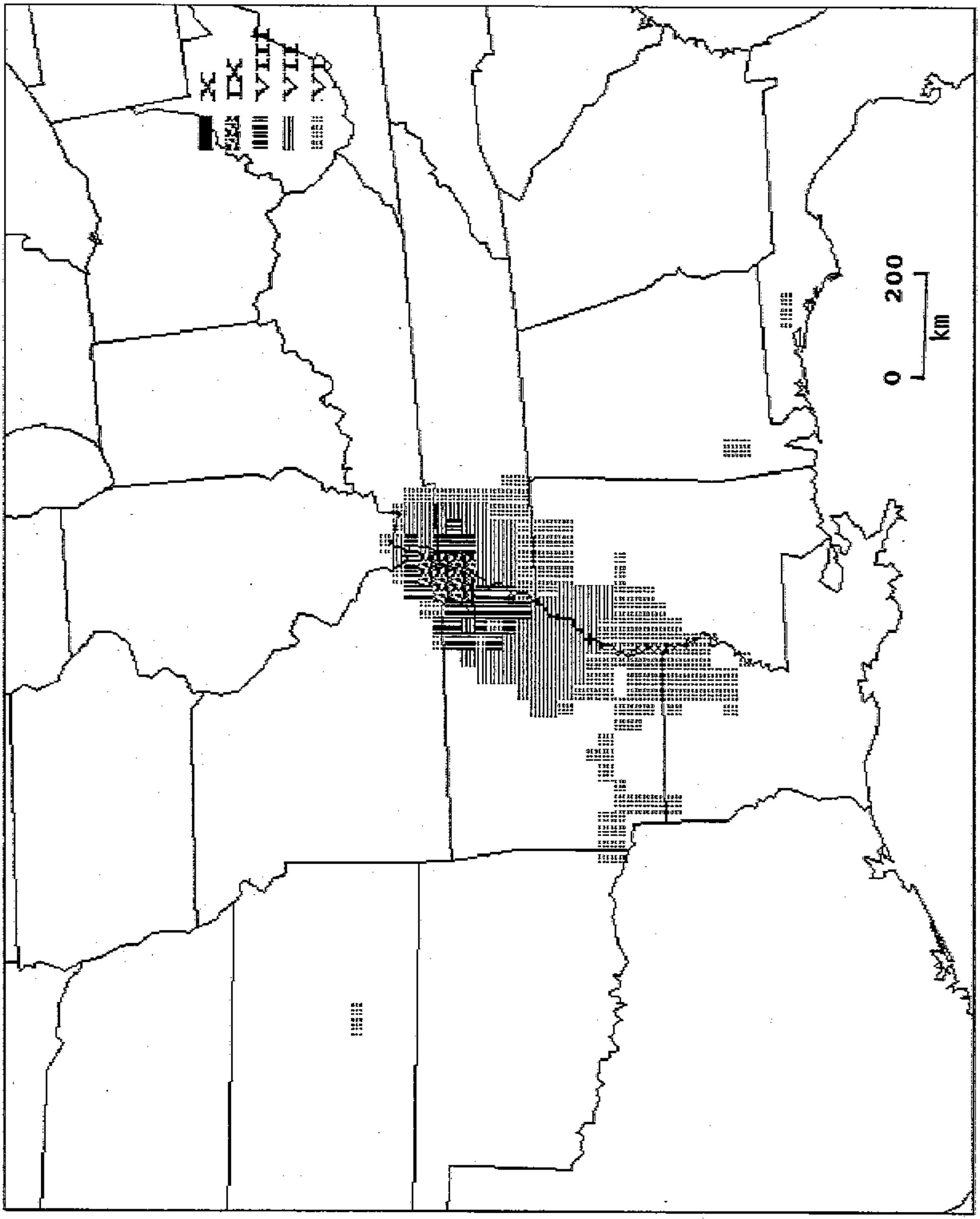


Figure 4-18 Predicted intensity map for New Madrid (Magnitude 7).

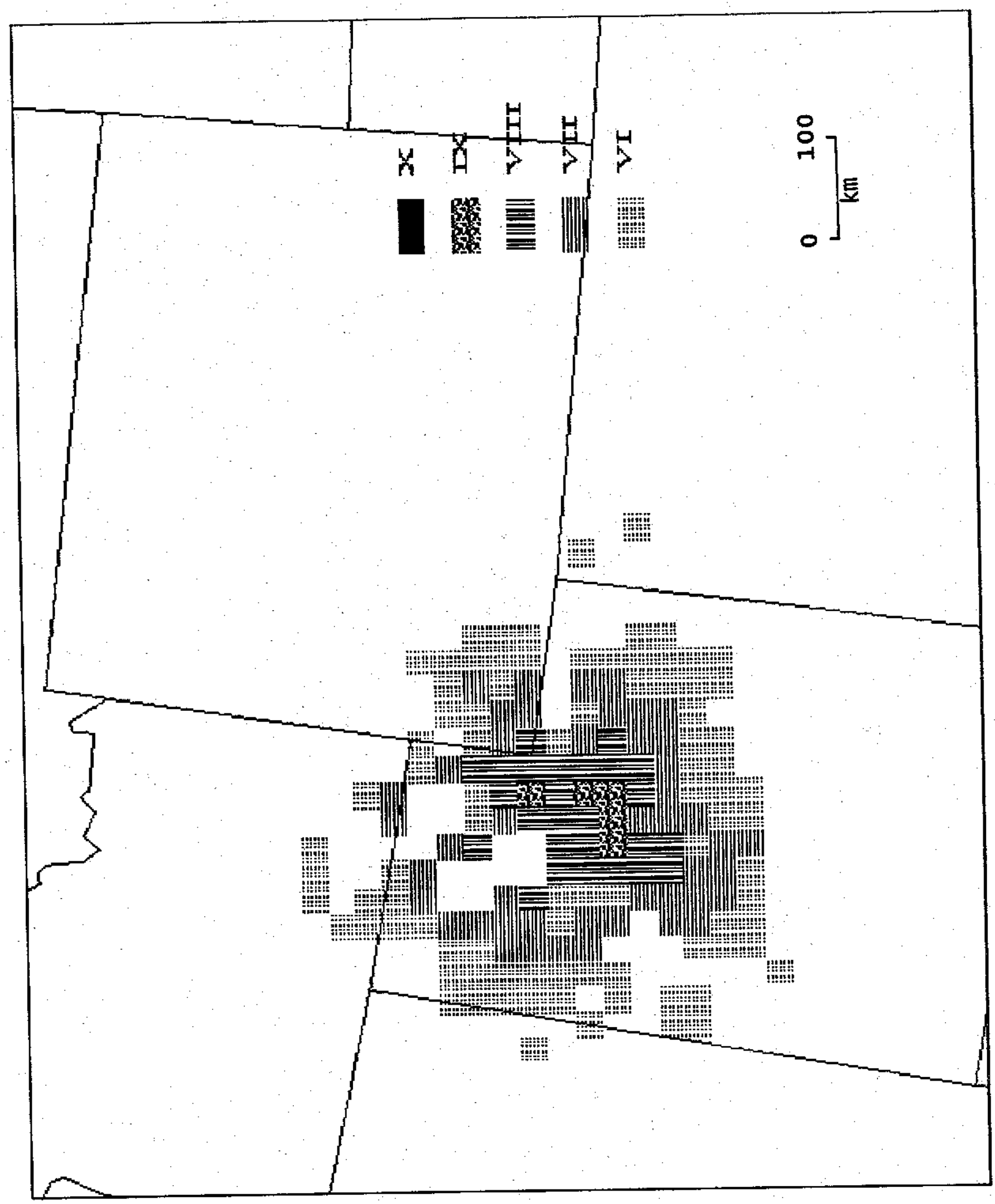


Figure 4-19 Predicted intensity map for Wasatch Front (Magnitude 7.5).

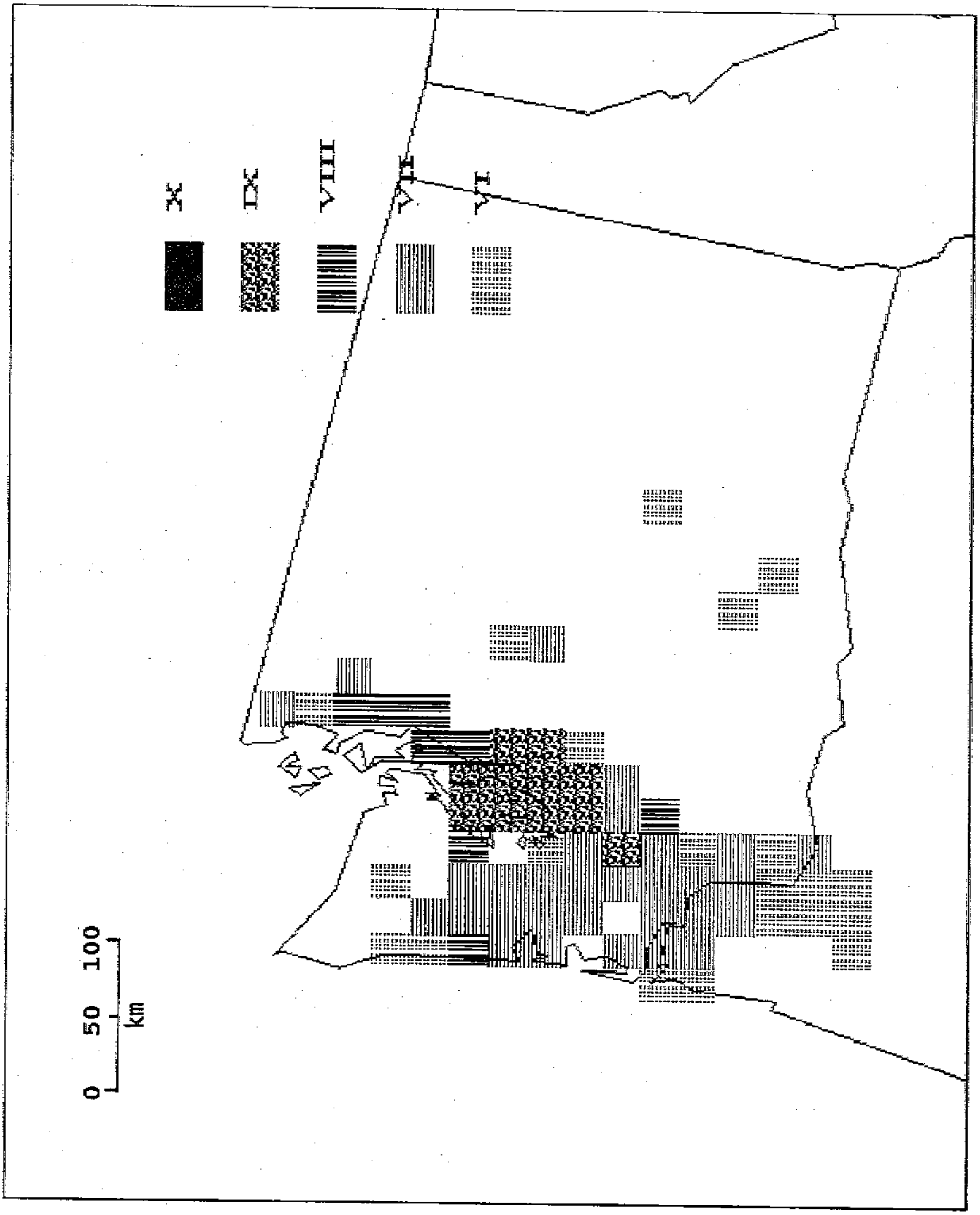


Figure 4-20 *Predicted intensity map for Puget Sound (Magnitude 7.5).*

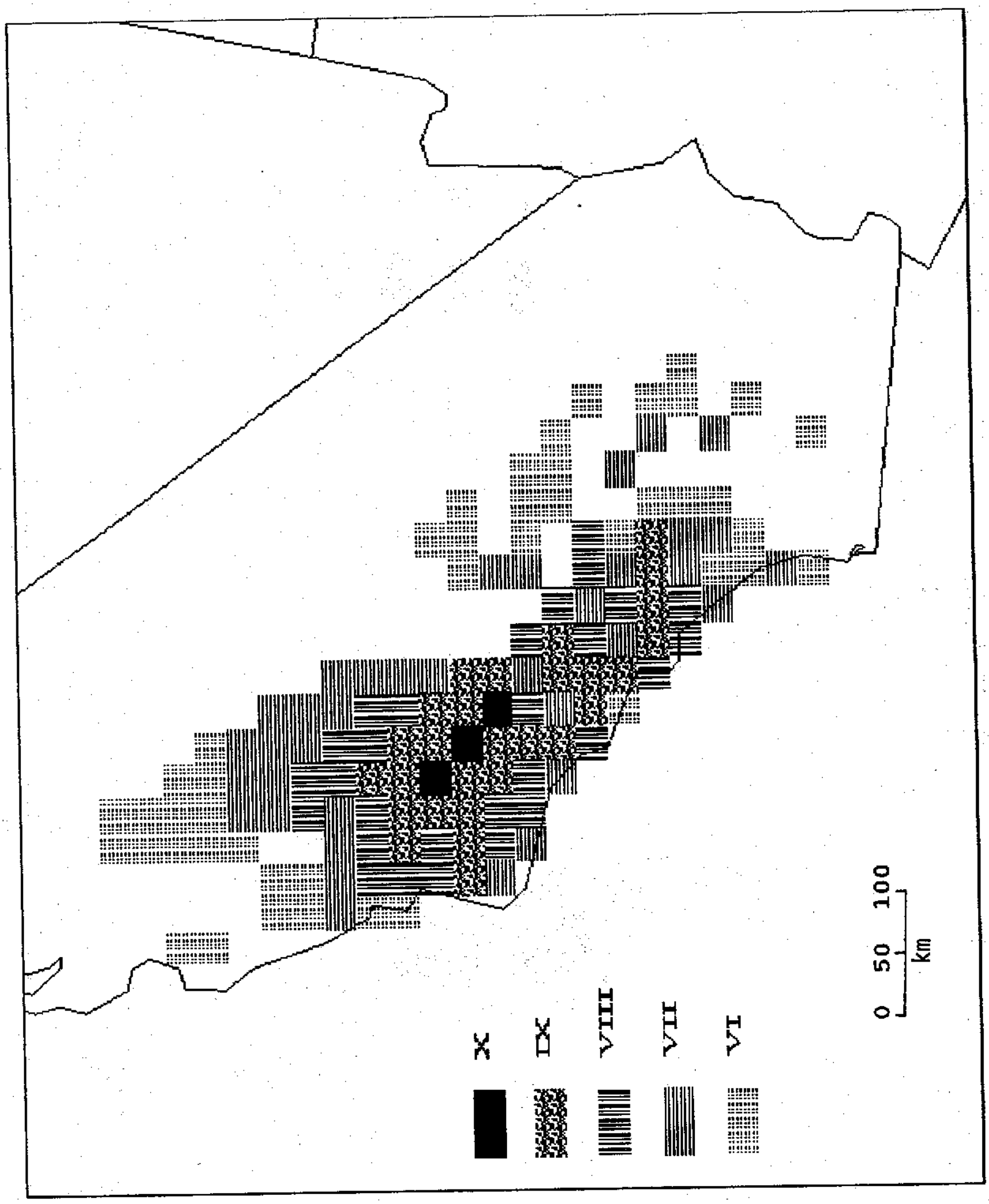


Figure 4-21 *Predicted intensity map for Fort Tejon (Magnitude 8).*

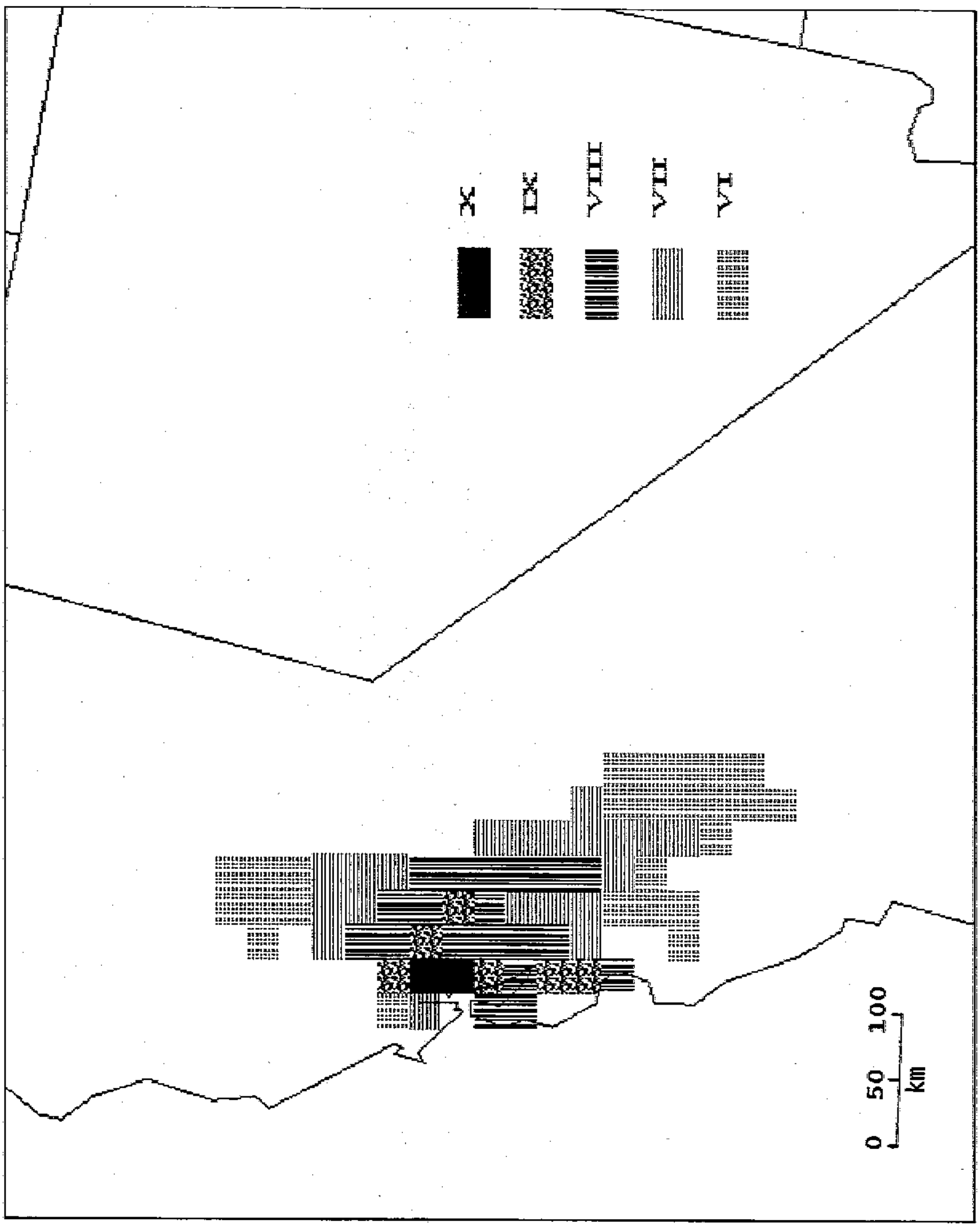


Figure 4-22 *Predicted intensity map for Hayward Fault (Magnitude 7.5).*

5. Estimates of Direct Damage

5.1 Introduction

The analysis of seismic vulnerability of lifeline systems and the economic impact of disruption is based on an assessment of three factors:

- Seismic hazard,
- Lifeline inventory, and
- Vulnerability functions.

In this investigation these factors are used to quantify vulnerability and impact of disruption in terms of (1) direct damage and (2) economic losses resulting from direct damage and loss of function of damaged facilities. Estimates of direct damage to lifelines, expressed in terms of percent replacement value and dollar loss, are discussed in this chapter. Indirect economic losses are discussed in Chapter 6.

Direct damage is defined as damage resulting directly from ground shaking or other collateral loss causes such as liquefaction. For each facility, it is expressed in terms of cost of repair divided by replacement cost and varies from 0 to 1.0 (0% to 100%). In this project it is estimated using (1) estimates of ground shaking intensity provided by the seismic hazard model (from Chapter 4), (2) inventory data specifying the location and type of facilities affected (from Chapter 2), and (3) vulnerability functions that relate seismic intensity and site conditions to expected damage (from Appendix B).

5.2 General Analytical Approach for Estimating Direct Damage

The earthquake survival of lifelines depends on their seismic performance characteristics. As described in Chapter 3 and summarized in Appendix B, the seismic performance of lifeline components has been characterized in this study using data developed from the database of expert opinion elicited in the ATC-13 project (ATC, 1985). This expert opinion was based in part on observations of lifeline components performance in previous earthquakes as well as estimates of expected performance based on knowledge of seismic design procedures and criteria. Thus, component vulnerability data for this study is essentially empirically based, rather than resulting from detailed analyses of each lifeline component.

The analysis approach to estimate direct damage considers both damage resulting from ground shaking as well as damage resulting from liquefaction. Damage due to other collateral loss causes, such as landslide and fire following earthquake, are not included because of the unavailability of inventory information and the lack of available models for estimating these losses nationwide.

The analysis approach for computing direct damage due to ground shaking proceeded as follows. For each earthquake scenario, MMI levels were assigned to each 25-km grid cell in the affected region, using the Everden MMI model, assigned magnitude, and assigned fault rupture location (from Chapter 4). Damage states were then estimated for each affected lifeline component (node or link) in each grid cell, using the motion-damage curves provided in Appendix B. As described in the following sections, the procedure for utilizing the motion-damage curves varied slightly by facility type, depending on whether the lifeline was a site specific facility, or a regional transmission (extended) network.

Damage due to liquefaction was estimated using a two-step method, also taken from ATC-13 (ATC, 1985). First, the probability of ground failure in each grid cell was calculated on the basis of the soil condition and associated liquefaction probability assessments provided in Table 8.4 of the ATC-13 report (p. 230). Only one soil unit (as defined by Everden) was assumed to be liquefiable: Unit A, which was assumed to be alluvium with water table less than 3-meters deep. Direct damage due to liquefaction in each Unit A grid cell was then estimated as follows:

$$DMG(PG) = DMG(S) \, x \, p(GF) \, x \, 5 \quad \text{(for surface facilities)} \qquad (5.1)$$

and

$$DMG(PG) = DMG(S) \times p(GFI) \times 10 \quad \text{(for buried facilities)} \qquad (5.2)$$

where:

DMG(S) = Mean damage caused by shaking

DMG(PG) = Mean damage caused by poor ground

p(GFI) = Probability of a given ground failure intensity, taken directly, noncumulatively, from Table 8.4 (ATC-13) for a given shaking intensity

After damages due to ground shaking and liquefaction were established for each facility in each affected grid cell, the total direct damage for each facility was calculated. As suggested in ATC-13, the total direct damage, DMG(T), was simply the sum of damage due to shaking plus damage due to liquefaction, with the sum always equal to or less than 1.0 (100 %):

$$DMG(T) = DMG(S) + DMG(PG) \qquad (5.3)$$

Cautionary Note Regarding Analysis Approach. In the scenario earthquakes it is assumed that the damage factor is uniquely related to the MMI zone in the manner prescribed in ATC-13 (ATC, 1985). There may be one or more MMI zones within each 25 km grid cell, depending on spatial attenuation. In either case, lifeline damage is assumed to be uniform within each MMI zone. Experts who supplied data to the ATC-13 project may question application of their opinions to cases where lifeline damage does not occur uniformly within a grid cell or MMI zone. In the ATC-13 Questionnaire, on which the damage factors and loss of function statistics are based, the damage factor is defined as damage due to ground shaking only (see ATC-13, p. 175). This approach probably led ATC-13 experts to provide an adequate picture of lifeline damage in many cases. For example, damage to pipelines in southern San Fernando Valley as a result of the 1971 earthquake was primarily due to ground shaking, and was geographically distributed in a way that it is reasonable to speak of average damage within a given MMI zone. Damage to pipelines in northern San Fernando Valley was more closely spaced and more severe due to ground rupture and to other significant ground distortions associated with nearby fault movement; at least some experts who provided opinions probably considered the fact that higher MMI is associated with such effects and incorporated it in their response despite instructions to consider only ground shaking. In this case, also, it is reasonable to speak of average damage. Thus, damage due to ground distortion can, at least in some cases, also be presented as uniform or average throughout a given MMI zone. Damage statistics prepared in this way are best applied in situations where not only the hazard (ground shaking and ground distortions) but also the structures of interest (pipelines, highway bridges, electrical substations) are distributed somewhat uniformly. It is significant that most of the pipeline damage statistics from San Fernando and from other earthquakes are derived from distribution and transmission networks, which are relatively dense within the MMI zones considered. The conditions that shaped ATC-13 expert opinion are most nearly approximated in such cases (for example, a dense network of transmission and distribution pipelines); it is reasonable to use ATC-13 damage factors for these situations.

However, to the extent that structures occur sparsely in a grid cell or MMI zone, conditions differ from those on which many expert opinions are based. This is because fewer lifeline components will be damaged at all if there are fewer components to coincide with damaging ground conditions. In the extreme case of a single lifeline structure in a 25-km grid cell, it may be misleading to apply statistics derived from regions with a dense array of structures. In at least some regions of the scenario earthquakes, there appear to be only a few lifeline components passing through the MMI zones or 25-km grid cells. In instances where trunk and transmission lines are sparse in a MMI zone or grid cell, application of ATC-13 statistics may be misleading because structure and hazard coincide much less frequently than is assumed. This possibility introduces an additional type of uncertainty that affects the average damage factors used in this study.

The foregoing discussion is based on intuition, not on rigorous analytical modeling. However, if this discussion is valid, the effect of applying

ATC-13 statistics in this study may result in overestimates of damage.

5.3 Direct Damage Estimates for Site-Specific Lifelines

Direct damage to site-specific lifelines, i.e., lifelines that consist of individual sited or point facilities (e.g., hospitals), were estimated using the methodology specified above. For airports, ports and harbors, medical care facilities (hospitals), and broadcast stations, the inventory data summarized in Chapter 2 were used to define the number and distribution of facilities. For fire and police stations, locations were assumed to be lumped at the center of the Standard Metropolitan Statistical Areas, and number of facilities affected were estimated by proxy, assuming the previously established relationships between population and number of facilities.

For summary and comparative purposes, four damage states are considered in this study:

- Light damage (1-10% replacement value);
- Moderate damage (10-30% replacement value);
- Heavy damage (30-60% replacement value); and
- Major to destroyed (60-100% replacement value).

The total number of affected facilities and the percentage of facilities in each damage state are summarized for each scenario earthquake in Tables 5-1 through 5-6. Following is a discussion of the direct damage impact on each site-specific lifeline considered.

5.3.1 Airports

Direct damage summaries for civil and general aviation airports for the various scenario earthquakes (Tables 5-1a and 5-1b) indicate that damage to terminals is expected to be particularly high in the magnitude-8.0 New Madrid and Puget Sound earthquake scenarios. For example, for the New Madrid magnitude-8.0 event, 13% of the airports in Arkansas (23 in total), 6% of the airports in Missouri (25 in total), and 2% in Tennessee (4 in total) would sustain major to destructive damage (60 to 100%) (Table 5-1a). The Puget Sound magnitude-7.5 scenario event would seriously affect an even larger number of airport terminals, with 12% or approximately 43 airports expected to sustain damage in this same range (60 to 100%). In the case of the Cape Ann and Charleston events, direct damage to terminals is also significant. Direct damage to runways (Table 5-1b), on the other hand, is relatively low for most scenario events; if damage does occur, it is usually less than 30%.

The reason for the relatively high impact on airports in the Puget Sound event is assumed to be due to the high concentration of airports near the source zone and poor ground, i.e., liquefiable sites. For the New Madrid event, the cause appears to be due to a combination of poor ground, low ground-motion attenuation with distance, and lack of seismically resistant design construction features.

5.3.2 Ports and Harbors

Since ports and harbors are located in the coastal regions, only those scenario earthquakes affecting these regions will negatively impact this facility type. As indicated in Table 5-2, the most severe damages to ports and harbors are expected for the Charleston and Puget Sound events. For example, one hundred percent, or 20 ports and harbors, in South Carolina can be expected to sustain heavy damage (30 to 60%), and 73%, or approximately 22 such facilities would be similarly affected in Georgia. In Washington, 14% of the ports (approximately 11) would be similarly affected. Numerous ports and harbors in these states would also sustain moderate damage (10 to 30%), as would approximately 22 such facilities in California for the Hayward magnitude-7.5 event. The primary cause of such damage, of course, is poor ground.

5.3.3 Medical Care Facilities

Direct damage summaries for medical care facilities (hospitals) for the various scenario earthquakes (Table 5-3) suggest that damage to this facility type will be relatively high for the Puget Sound, Charleston, New Madrid, Fort Tejon, and Hayward scenario events. For example, damage data for the Puget Sound and Charleston events indicate that 15% of the hospitals in Washington (15 in total) and 13% of

Table 5-1a Damage Percent for Air Transportation Terminals for Each Scenario Earthquake (Percent of Airports in State)

	NEW MADRID (M=8.0)					
Total Number	Illinois 547	Missouri 425	Arkansas 177	Tennessee 196	Kentucky 149	Mississippi 193
Light Damage 1-10 %	11%	5%	17%	18%	26%	64%
Moderate 10-30 %	< 1%	0%	21%	13%	3%	19%
Heavy 30-60 %	0%	0%	5%	0%	0%	0%
Major to Destructive 60-100 %	0%	6%	13%	2%	0%	0%

	CHARLESTON (M=7.5)		
Total Number	South Carolina 147	North Carolina 309	Georgia 343
Light Damage 1-10 %	33%	24%	28%
Moderate 10-30 %	20%	1%	1%
Heavy 30-60 %	0%	0%	0%
Major to Destructive 60-100 %	4%	0%	2%

	CAPE ANN (M=7.0)				
Total Number	Massachusetts 149	Connecticut 115	Delaware 37	Rhode Island 55	New Hampshire 63
Light Damage 1-10 %	77%	57%	65%	55%	56%
Moderate 10-30 %	< 1%	0%	0%	0%	0%
Heavy 30-60 %	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	4%	0%	0%	0%	0%

	WASATCH FRONT (M=7.5)
Total Number	Utah 107
Light Damage 1-10 %	15%
Moderate 10-30 %	23%
Heavy 30-60 %	0%
Major to Destructive 60-100 %	0%

	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)					
Total Number	California 869	California 869	Washington 364	Illinois 547	Missouri 425	Arkansas 177	Tennessee 196	Kentucky 149	Mississippi 193
Light Damage 1-10 %	9%	12%	15%	< 1%	< 1%	31%	19%	7%	32%
Moderate 10-30 %	2%	14%	6%	0%	2%	12%	< 1%	0%	0%
Heavy 30-60 %	0%	< 1%	6%	0%	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	0%	0%	12%	0%	3%	1%	2%	0%	0%

Table 5-1b Damage Percent for Air Transportation Runways for Each Scenario Earthquake (Percent of Airports in State)

NEW MADRID (M=8.0)

Total Number	Illinois 547	Missouri 425	Arkansas 177	Tennessee 196	Kentucky 149	Mississippi 193
Light Damage 1-10 %	< 1%	< 1%	20%	3%	< 1%	17%
Moderate 10-30 %	0%	5%	15%	< 1%	0%	0%
Heavy 30-60 %	0%	1%	0%	2%	0%	0%
Major to Destructive 60-100 %	0%	6%	0%	0%	0%	0%

CHARLESTON (M=7.5)

Total Number	South Carolina 147	North Carolina 309	Georgia 343
Light Damage 1-10 %	2%	1%	1%
Moderate 10-30 %	3%	0%	2%
Heavy 30-60 %	1%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%

CAPE ANN (M=7.0)

Total Number	Massachusetts 149	Connecticut 115	Delaware 37	Rhode Island 55	New Hampshire 63
Light Damage 1-10 %	< 1%	0%	0%	0%	0%
Moderate 10-30 %	4%	0%	0%	0%	0%
Heavy 30-60 %	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%	0%	0%

WASATCH FRONT (M=7.5)

Total Number	Utah 107
Light Damage 1-10 %	5%
Moderate 10-30 %	0%
Heavy 30-60 %	0%
Major to Destructive 60-100 %	0%

	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)					
Total Number	California 869	California 869	Washington 364	Illinois 547	Missouri 425	Arkansas 177	Tennessee 196	Kentucky 149	Mississippi 193
Light Damage 1-10 %	4%	7%	6%	0%	2%	12%	< 1%	0%	2%
Moderate 10-30 %	2%	14%	16%	0%	3%	1%	< 2%	0%	0%
Heavy 30-60 %	0%	< 1%	0%	0%	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 5-2 Damage Percent for Ports for Selected Scenario Earthquakes (Percent of Ports in State)

	CHARLESTON (M=7.5)			CAPE ANN (M=7.0)				
Total Number	South Carolina 20	North Carolina 16	Georgia 30	Massachusetts 34	Connecticut 22	Delaware 10	Rhode Island 22	New Hampshire 9
Light Damage 1-10 %	0%	0%	10%	100%	0%	0%	86%	0%
Moderate 10-30 %	0%	0%	0%	0%	0%	0%	0%	0%
Heavy 30-60 %	100%	0%	73%	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%	0%	0%	0%	0%	0%

	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)
Total Number	California 125	California 125	Washington 77
Light Damage 1-10 %	4%	0%	25%
Moderate 10-30 %	22%	34%	26%
Heavy 30-60 %	0%	0%	14%
Major to Destructive 60-100 %	0%	0%	0%

Table 5-3 Damage Percent for Medical Care Facilities for Each Scenario Earthquake (Percent of Facilities in State)

	NEW MADRID (M=8.0)							*CHARLESTON (M=7.5)*		
Total Number	*Illinois* 249	*Missouri* 171	*Arkansas* 99	*Tennessee* 167	*Kentucky* 125	*Indiana* 102	*Mississippi* 127	*South Carolina* 91	*North Carolina* 161	*Georgia* 207
Light Damage 1-10 %	22%	6%	16%	18%	20%	7%	62%	30%	15%	32%
Moderate 10-30 %	0%	0%	29%	14%	< 1%	0%	17%	7%	2%	1%
Heavy 30-60 %	0%	0%	3%	0%	0%	0%	0%	10%	0%	0%
Major to Destructive 60-100 %	0%	3%	7%	< 1%	0%	0%	0%	3%	0%	1%

	CAPE ANN (M=7.0)					*WASATCH FRONT (M=7.5)*
Total Number	*Massachusetts* 167	*Connecticut* 66	*Delaware* 13	*Rhode Island* 22	*New Hampshire* 40	*Utah* 53
Light Damage 1-10 %	90%	50%	46%	82%	48%	17%
Moderate 10-30 %	0%	0%	0%	0%	0%	51%
Heavy 30-60 %	0%	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	2%	0%	0%	0%	0%	0%

	HAYWARD (M=7.5)	*FORT TEJON (M=8.0)*	*PUGET SOUND (M=7.5)*
Total Number	*California* 478	*California* 478	*Washington* 102
Light Damage 1-10%	12%	16%	7%
Moderate 10-30%	16%	20%	18%
Heavy 30-60 %	9%	10%	5%
Major to Destructive 60-100 %	0%	0%	10%

the hospitals in South Carolina (12 in total) would sustain heavy or major-to-destructive damage (30 to 100%). In the New Madrid magnitude-8.0 event, 10% of the hospitals in Arkansas (10 in total) and 3% of the hospitals in Missouri (5 in total) would sustain similar damage. In California, 10% and 9%, or 48 and 43 hospitals, respectively, would sustain heavy damage (30-to-60%) in the Fort Tejon and Hayward scenarios. It is worth noting that results from a separate study by Applied Technology Council (ATC, 1991) appear to be comparable for the magnitude-7.5 Hayward fault scenario.

As in the case of airports, the reason for severe damage to hospital facilities in the Puget Sound, New Madrid, and Charleston events is assumed to be strongly correlated with poor ground conditions and construction practices.

5.3.4 Police and Fire Stations

As in the case of medical care facilities, direct damage data for police and fire stations (Tables 5-4 and 5-5) suggest that damage to this facility type will be more severe for the New Madrid, Charleston, and Puget Sound events than for the California, Wasatch Front, and Cape Ann events. For example, data for the New Madrid magnitude-8.0 event indicate that 9% of the fire stations and 8% of the police stations in Arkansas would sustain heavy or major-to-destructive damage (30 to 100%). Thirteen and twelve percent, respectively, of fire and police stations in South Carolina would be similarly damaged in the Charleston scenario event, and 15% and 8%, respectively, would be similarly affected by the Puget Sound magnitude-7.5 scenario event.

The reason for severe damage to fire and police stations in the Puget Sound, New Madrid, and Charleston events is assumed to be strongly correlated with poor ground conditions and construction practices.

5.3.5 Broadcast Stations

Direct damage to broadcast stations for the eight scenario earthquakes follows a slightly different pattern than for the other site-specific lifelines. As indicated in Table 5-6, direct damage is relatively high for the magnitude-8 New Madrid, Charleston, and Puget Sound events and slightly less for the Wasatch Front and Fort Tejon events. Data for the New Madrid magnitude-8.0 earthquake scenario indicate that 17% of the broadcast stations in Arkansas (approximately 78 in total) would sustain heavy damage or major-to-destructive damage (30 to 100%). For the Charleston event, 23% or 87 broadcast stations would be similarly affected, and for the Puget Sound event, 14% (122 in total) would be similarly affected. Percentages for the Wasatch Front and Fort Tejon equal approximately 5%, representing 54 damaged broadcast stations in Utah and 77 or fewer in California.

5.4 Direct Damage Estimates for Extended Lifeline Networks

This section presents direct damage estimates for extended network lifelines, such as highways, railroads and other networks at the bulk and/or regional level. The inventory data provided in Chapter 2 were used to define the location of all nodes and links. For all systems except pipelines, direct damage is estimated using the methodology specified above. Results are presented in terms of (1) the same four damage states used for site-specific lifelines, and (2) maps indicating the damaged portions of each extended network for the various scenario earthquakes.

For pipelines, direct damage is estimated (1) using the damage curves specified in Appendix B (in terms of breaks per kilometer), (2) a model that estimates the probability of breaks occurring within given lengths of pipe subjected to given earthquake shaking intensities (Khater, M., et al., 1989), and (3) a special procedure for estimating damage due to liquefaction. Breaks are assumed to occur according to a nonhomogeneous Poisson process. The probability P_f of having at least one break in a line with length L is given by

$$P_f(L, MMI(x)) = 1 - \prod_{k=1}^{N} P_s(l_k, MMI_k) \qquad (5.4)$$

where

$$P_s(l_k, MMI_k) = \exp(-\lambda_k x\, l_k) \quad k=1,...,N \qquad (5.5)$$

in which Π is the multiplier operator; N is the number of grid cells through which the pipeline

Table 5-4 Damage Percent for Fire Stations for Each Scenario Earthquake (Percent of Stations in State)

	NEW MADRID (M=8.0)						CHARLESTON (M=7.5)		
Total Number	Illinois 923	Missouri 41	Arkansas 185	Tennessee 378	Kentucky 285	Mississippi 200	South Carolina 275	North Carolina 570	Georgia 490
Light Damage 1-10 %	4%	2%	15%	18%	6%	14%	18%	2%	14%
Moderate 10-30 %	2%	1%	15%	5%	0%	10%	1%	0%	1%
Heavy 30-60 %	0%	2%	9%	0%	0%	0%	13%	0%	1%
Major to Destructive 60-100 %	0%	< 1%	0%	< 1%	0%	0%	0%	0%	0%

	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)				
Total Number	California 2230	California 2230	Washington 361	Missouri 410	Arkansas 185	Tennessee 378	Kentucky 285	Mississippi 200
Light Damage 1-10 %	7%	15%	3%	0%	15%	10%	< 1%	5%
Moderate 10-30 %	3%	27%	18%	1%	8%	0%	0%	0%
Heavy 30-60 %	0%	0%	15%	1%	0%	< 1%	0%	0%
Major to Destructive 60-100 %	0%	< 1%	0%	0%	0%	0%	0%	0%

	CAPE ANN (M=7.0)		WASATCH FRONT (M=7.5)
Total Number	Massachusetts 459	Rhode Island 69	Utah 140
Light Damage 1-10%	57%	5%	51%
Moderate 10-30%	0%	0%	11%
Heavy 30-60 %	2%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%

Table 5-5 Damage Percent for Police Stations for Each Scenario Earthquake (Percent of Stations in State)

	NEW MADRID (M=8.0)						CHARLESTON (M=7.5)		
Total Number	Illinois 232	Missouri 102	Arkansas 48	Tennessee 98	Kentucky 74	Mississippi 52	South Carolina 70	North Carolina 132	Georgia 126
Light Damage 1-10 %	4%	2%	14%	10%	5%	13%	16%	2%	13%
Moderate 10-30 %	2%	1%	10%	5%	0%	9%	1%	0%	1%
Heavy 30-60 %	0%	2%	8%	0%	0%	0%	12%	0%	1%
Major to Destructive 60-100 %	0%	<1%	0%	<1%	0%	0%	0%	0%	0%

	CAPE ANN (M=7.0)		WASATCH FRONT (M=7.5)	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)				
Total Number	Massachusetts 118	Rhode Island 18	Utah 34	California 580	California 580	Washington 94	Missouri 102	Arkansas 48	Tennessee 98	Kentucky 74	Mississippi 52
Light Damage 1-10 %	26%	5%	22%	6%	14%	3%	0%	14%	9%	<1%	5%
Moderate 10-30 %	0%	0%	10%	3%	8%	16%	1%	7%	0%	0%	0%
Heavy 30-60 %	2%	0%	0%	0%	0%	8%	1%	0%	<1%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%	0%	<1%	0%	0%	0%	0%	0%	0%

Table 5-6 Damage Percent for Broadcast Stations for Each Scenario Earthquake (Percent of Stations in State)

	NEW MADRID (M=8.0)							CHARLESTON (M=7.5)		
Total Number	Illinois 600	Missouri 524	Arkansas 456	Tennessee 587	Kentucky 474	Indiana 407	Mississippi 416	South Carolina 377	North Carolina 697	Georgia 604
Light Damage 1-10 %	8%	6%	16%	6%	16%	4%	51%	15%	17%	23%
Moderate 10-30 %	< 1%	0%	14%	20%	7%	0%	16%	24%	4%	16%
Heavy 30-60 %	0%	0%	12%	4%	< 1%	0%	12%	5%	1%	1%
Major to Destructive 60-100 %	0%	4%	5%	1%	1%	0%	0%	18%	0%	2%

	CAPE ANN (M=7.0)					WASATCH FRONT M=7.5)
Total Number	Massachusetts 274	Connecticut 155	Delaware 42	Rhode Island 53	New Hampshire 112	Utah 900
Light Damage 1-10 %	38%	50%	74%	70%	40%	10%
Moderate 10-30 %	35%	0%	0%	26%	0%	27%
Heavy 30-60 %	0%	0%	0%	0%	0%	5%
Major to Destructive 60-100 %	1%	0%	0%	0%	0%	0%

	HAYWARD (M7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)					
Total Number	California 1,538	California 1,538	Washington 872	Illinois 600	Missouri 524	Arkansas 456	Tennessee 587	Kentucky 474	Mississippi 416
Light Damage 1-10 %	4%	16%	2%	0%	1%	12%	13%	6%	15%
Moderate 10-30 %	8%	4%	8%	< 1%	0%	15%	11%	2%	3%
Heavy 30-60 %	1%	4%	5%	0%	1%	4%	< 1%	1%	0%
Major to Destructive 60-100 %	0%	< 1%	9%	0%	2%	0%	1%	0%	0%

Table 5-7 **Damage to Railroad System (Length of Roadbed, Km)**

Events	Light Damage 1-10%	Moderate 10-30%	Heavy 30-60%	Major to Destructive 60-100%
Cape Ann	0	0	63	0
Charleston	890	85	980	0
Fort Tejon	640	340	825	47
Hayward	988	47	445	140
New Madrid (M=8.0)	3,000	670	1,780	485
New Madrid (M=7.0)	1,198	0	640	0
Puget Sound	340	0	650	0
Wasatch Front	770	300	0	0
Total System Length = 270,611 km				

passes; l_k and MMI_k are the length of the lifeline element and the Modified Mercalli Intensity, respectively, within grid cell k; and λ_k is the mean break rate (taken from Appendix B).

Maps are provided showing sections of pipeline for which the probability of failure exceeds 60% for the various scenario earthquakes. For soil conditions where liquefaction is possible, a break is assumed at each location where the pipeline crosses into a liquefiable zone.

5.4.1 Railroad System

The railroad system is a highly redundant system, and damage to the system due to the selected events was found to be relatively localized to the epicentral area. Direct damage to the railroad system for each scenario event is summarized in Table 5-7, which lists the length (km) of damaged railroad right-of-way within each damage state. The damage estimates are based on damage curves for track/roadbed and exclude damage to related facility types not included in the project inventory--railway terminals, railway bridges and tunnels.

The direct damage data suggest that the magnitude-8 New Madrid, Fort Tejon, and Hayward events would cause the most extensive damage, with 2,265 km, 872 km, and 585 km of roadbed, respectively, sustaining damage in the 30 to 100% range. Damage in the Charleston, Puget Sound, and magnitude-7.0 New Madrid events would also be severe, with 980, 650, and 640 km of roadbed, respectively, sustaining heavy damage (30-to-60 %). Maps showing the distribution of damage to the railroad system for each of the 8 events are provided in Figures 5-1 to 5-8.

5.4.2 Highway System

The highway system is also a highly redundant system, consisting of freeways/highways and bridges. As is in the case of the railroad system, damage to the highway system for each scenario event was found to be localized to the epicentral area. Direct damage to freeways/highways, expressed in terms of km of roadway in the various damage states, are summarized in Table 5-8 and plotted on Figures 5-9 to 5-16 for the eight scenario earthquakes. Bridge damage, expressed in terms of the percent of bridges in each damage state, is summarized in Table 5-9. The roadway and bridge damage data are based, respectively, on damage curves for freeways/highways and for conventional bridges; the estimates exclude damage to tunnels, which are not included in the project inventory. We note also that all bridges are assumed to be conventional bridges because of (1) lack of capacity/size information in the project inventory and (2) the very small percentage of major bridges in the overall national database.

Tables 5-8 and 5-9 indicate that direct damage is not expected to be as severe for freeways/highways as it is for bridges. For

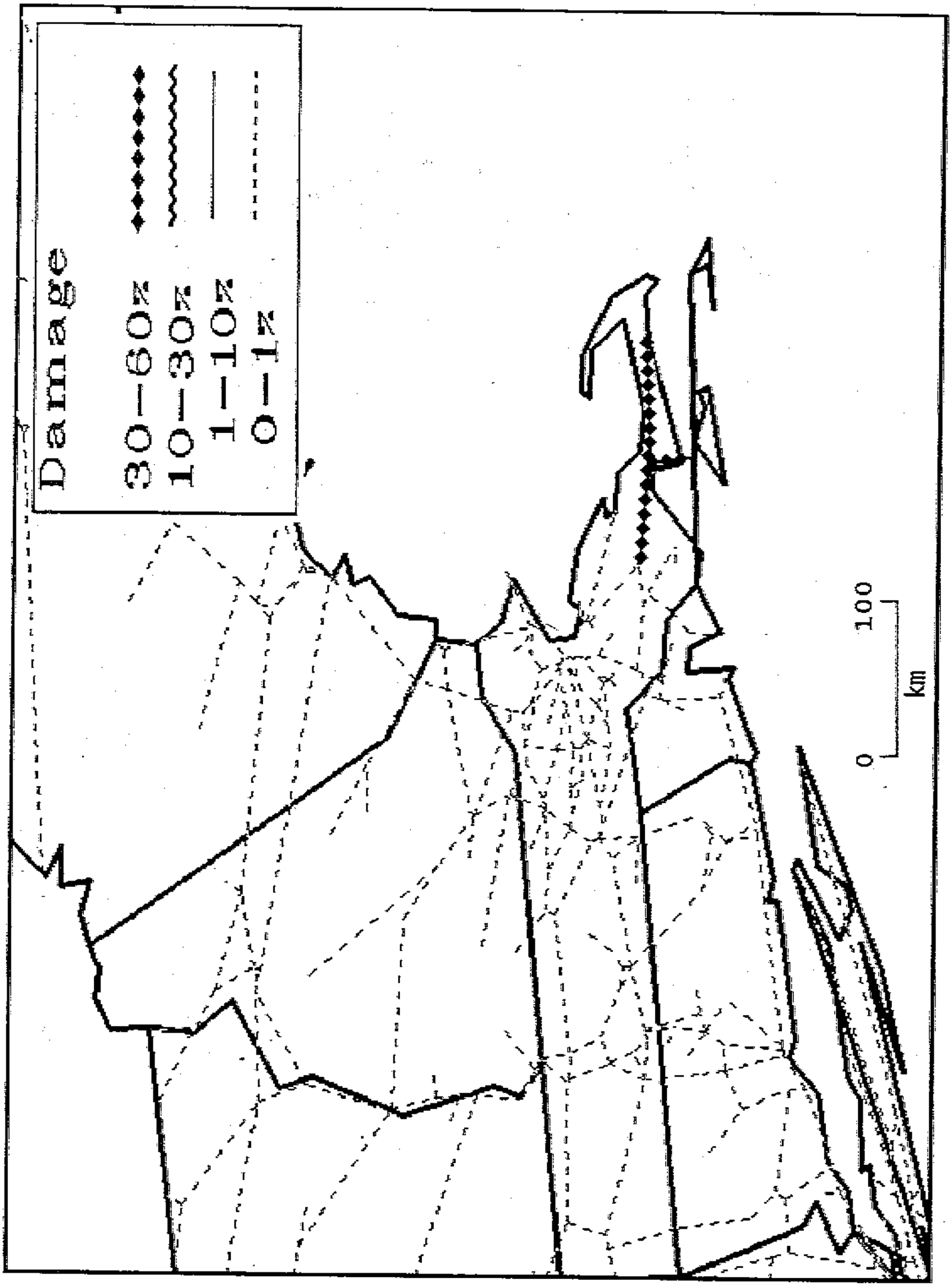


Figure 5-1 *Damage to railroad system following Cape Ann event (M=7.0).*

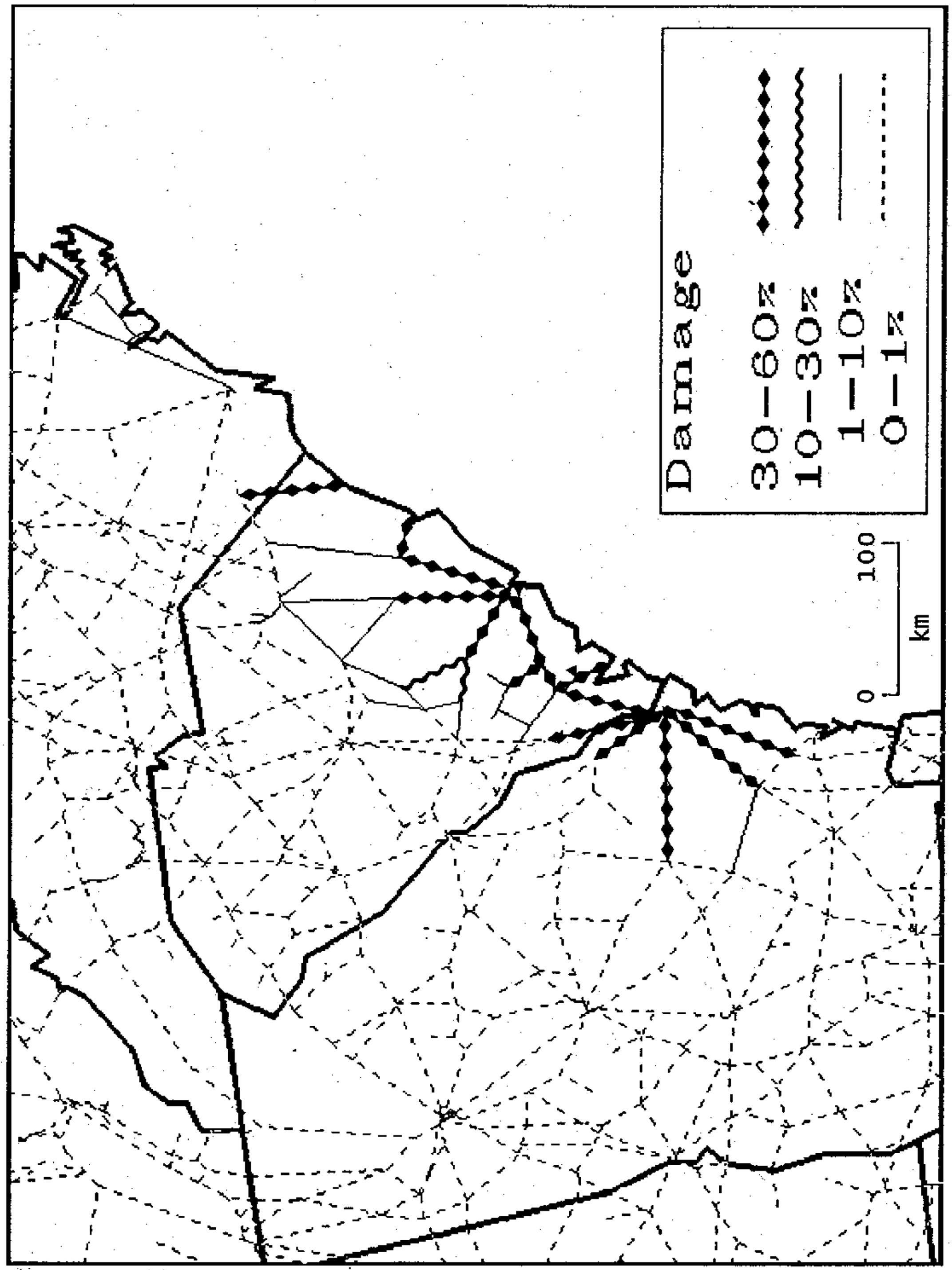


Figure 5-2. *Damage to railroad system following Charleston event (M=7.5).*

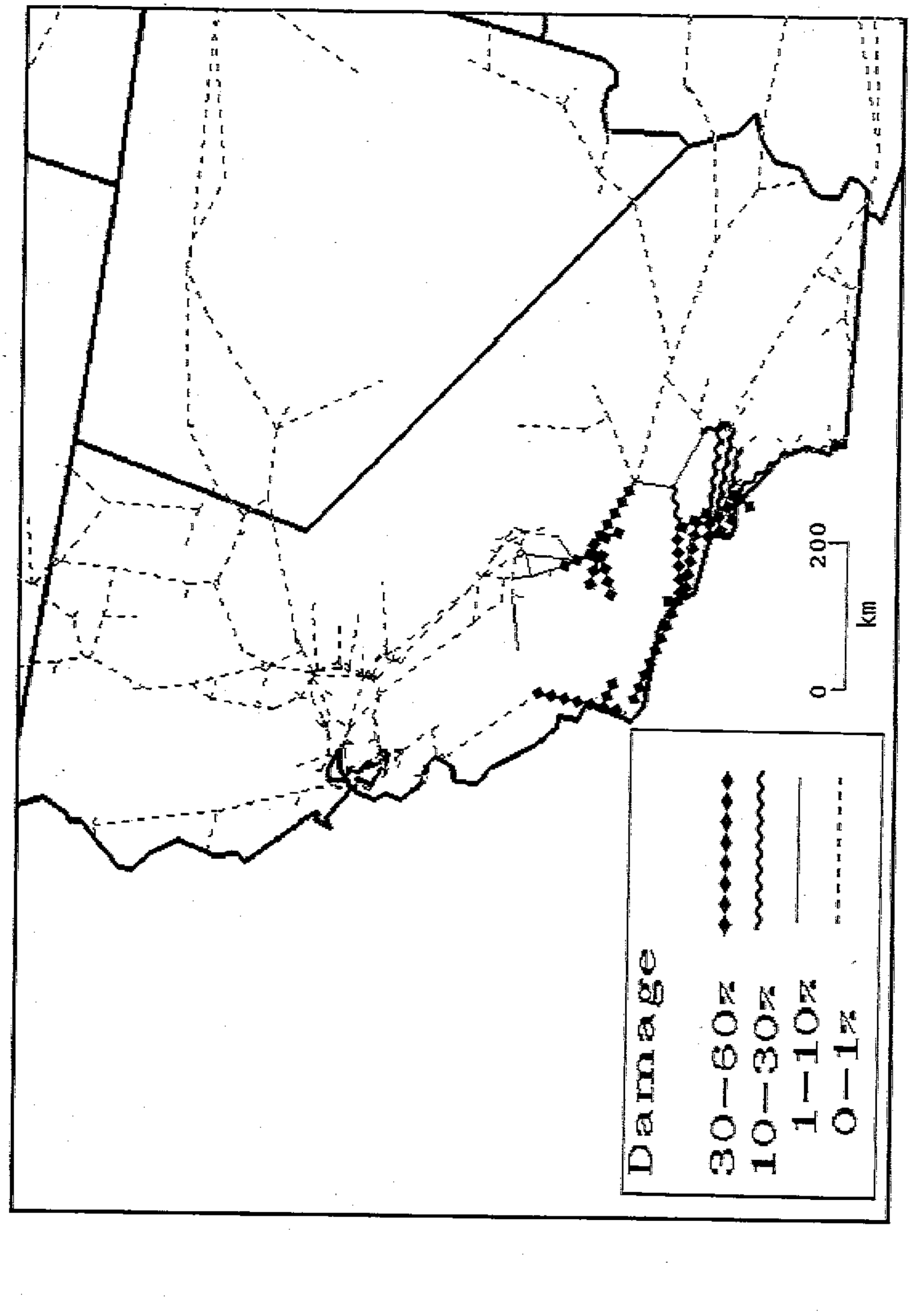


Figure 5-3 *Damage to railroad system following Fort Tejon event (M=8.0).*

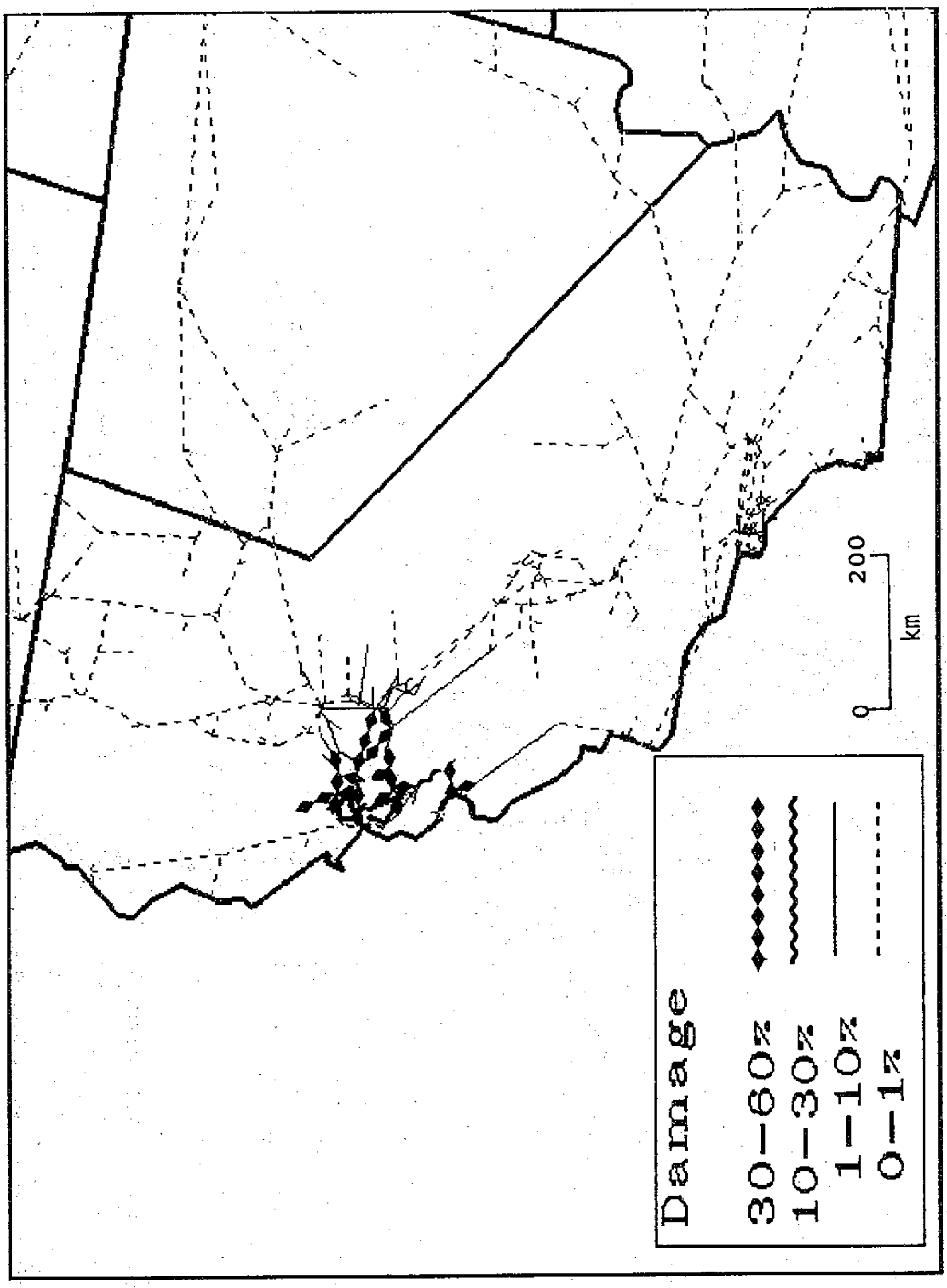


Figure 5-4 *Damage to railroad system following Hayward event (M=7.5).*

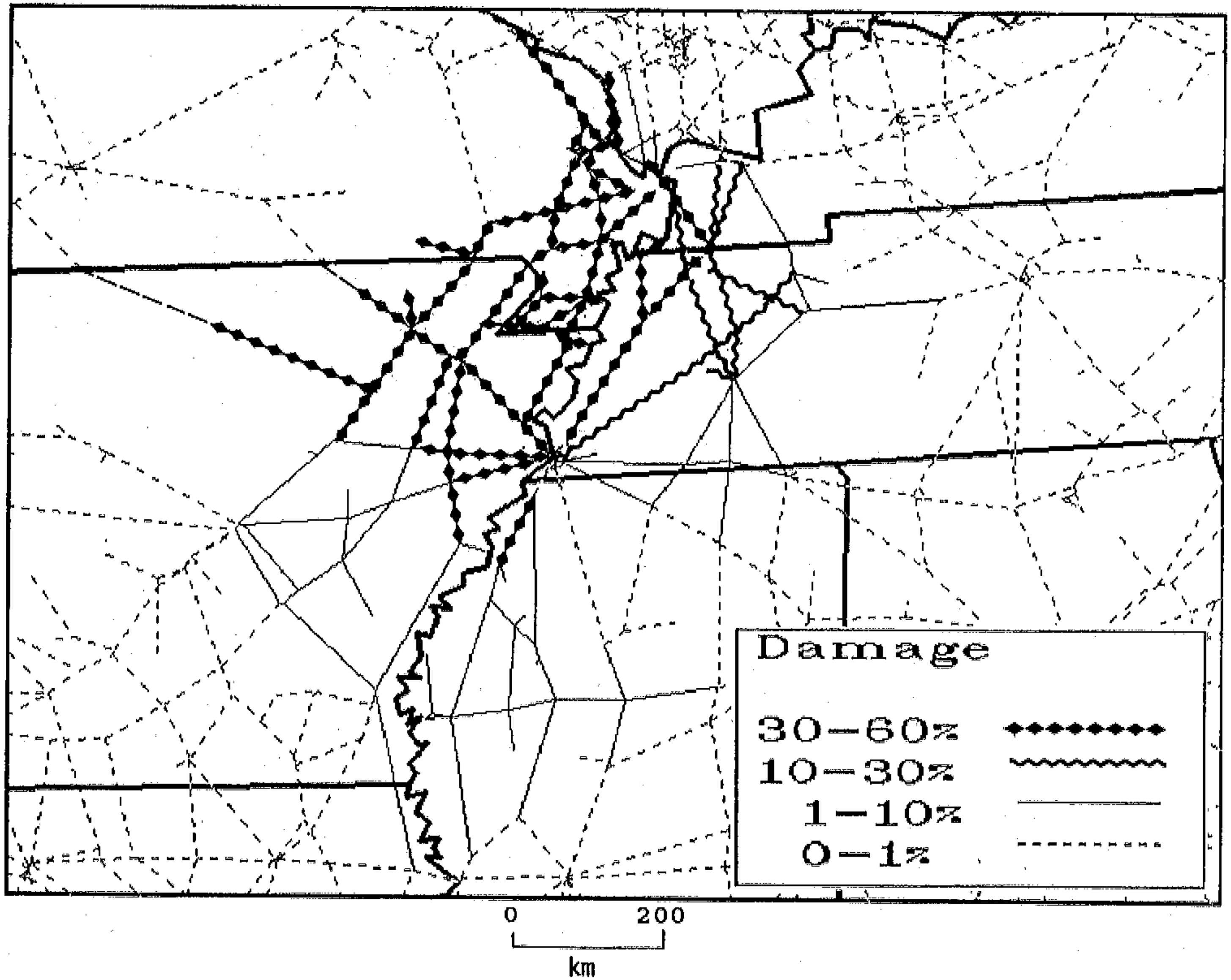


Figure 5-5 Damage to railroad system following New Madrid event (M=8.0).

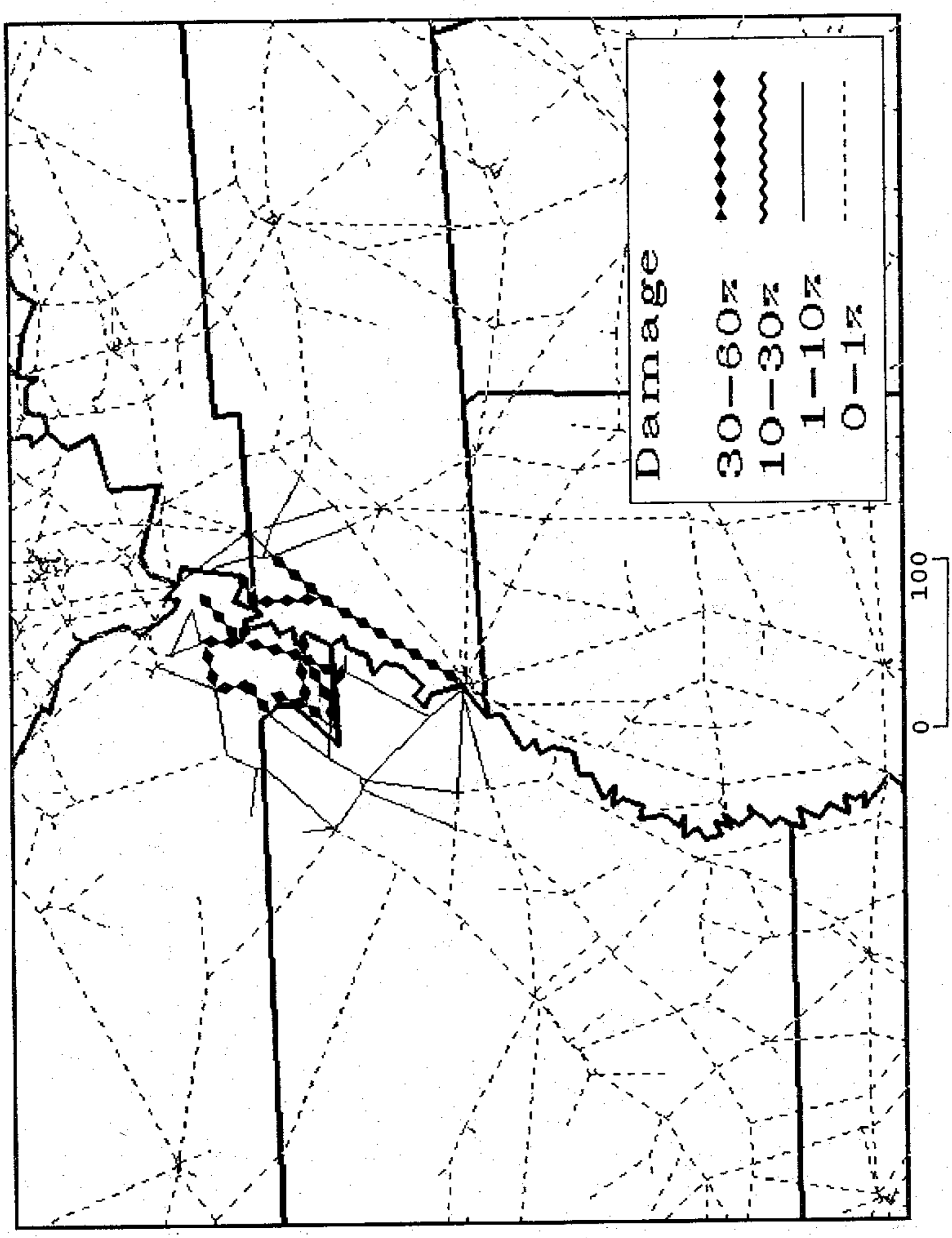


Figure 5-6 *Damage to railroad system following New Madrid event (M=7.0).*

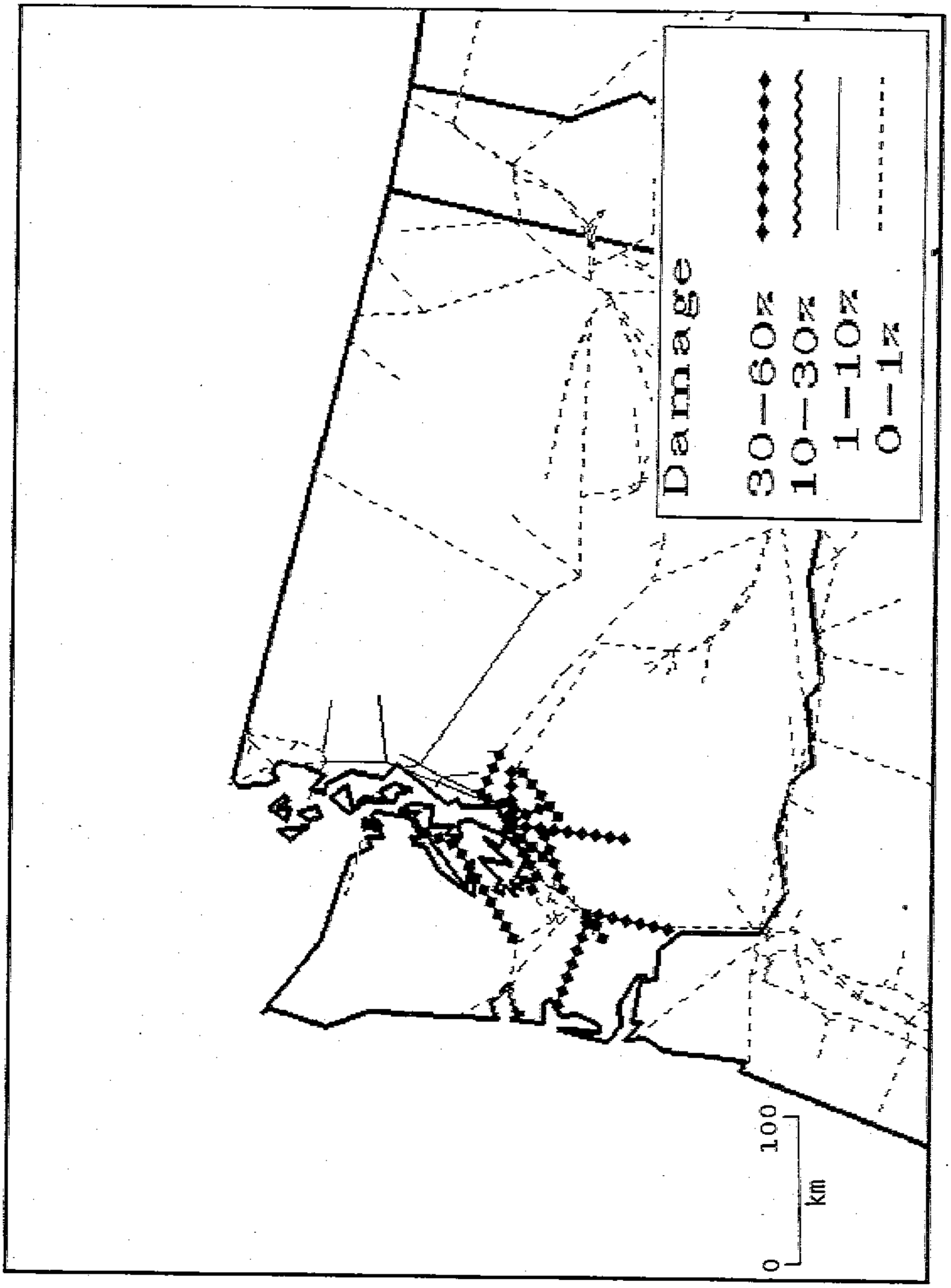


Figure 5-7 *Damage to railroad system following Puget Sound event (M=7.5).*

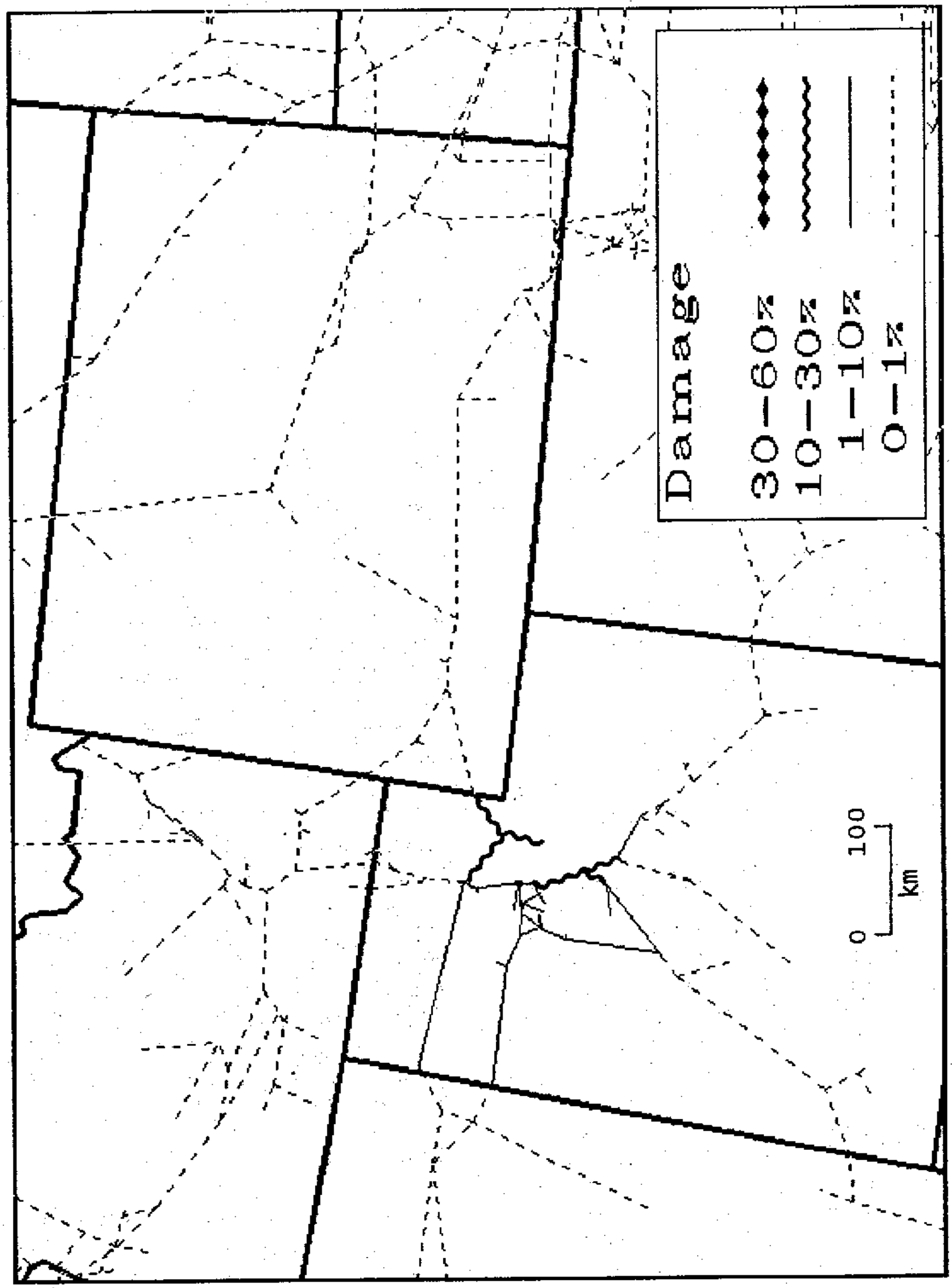


Figure 5-8 *Damage to railroad system following Wasatch Front event (M=7.5).*

Table 5-8 Damage to Freeway/Highway System (Length of Highway, Km)

Event	*Light Damage 1-10%*	*Moderate 10-30%*	*Heavy 30-60%*	*Major to Destructive 60-100%*
Cape Ann	74	182	0	0
Charleston	2,182	999	0	0
Fort Tejon	2,174	1,557	0	0
Hayward	1,567	476	0	0
New Madrid (M=8.0)	4,967	2,753	0	0
New Madrid (M=7.0)	1,800	720	0	0
Puget Sound	665	769	0	0
Wasatch Front	1,392	0	0	0

Total System Length = 489,892 km

example, direct damage to freeways/highways is not expected to exceed 30% at any location for any scenario earthquake. Data for bridges (Table 5-9), however, suggest that direct damage will range from 30-to-100 % for various locations affected by the Charleston, New Madrid (magnitude-8.0), Puget Sound, and Wasatch Front events. Bridges in Utah appear to be at the greatest risk, with 25 percent of the bridges (approximately 287 bridges) expected to sustain damage in the 30-to-100 % range. Eighteen percent of the bridges in Arkansas (approximately 423), 16 % in Washington (approximately 305), and eleven percent in Tennessee (approximately 407) would sustain similar levels of damage. The difference in expected performance between highways and bridges results from the difference in damage curves for these two structure types.

5.4.3 *Electric System*

Direct damage estimates for the electric system are based on curves for transmission lines and transmission substations and exclude damage to related facility types not included in the project inventory--nuclear and fossil-fuel power plants, and hydroelectric power plants (dams). Damage data for each scenario earthquake are summarized in Tables 5-10 and 5-11, which provide the length of transmissions lines and percent of substations, respectively, in each damage state. Maps provided in Figures 5-17 through 5-24 show plots of damage to transmission lines for the eight scenario earthquakes.

Damage data for transmission lines (Table 5-10 and Figures 5-17 through 5-24) indicate that damage to this facility type is expected to be greatest for the New Madrid (magnitude 8.0) and Fort Tejon events, in which 800 km and 1370 km, respectively, would sustain damage ranging from 10-to-30 %.

Direct damage data for transmission substations, summarized in Table 5-11, indicate that this facility type would be severely impacted in all scenario events. The impacts are most severe in the Puget Sound, magnitude-8.0 New Madrid, Wasatch Front, Charleston, and Hayward events. For these scenario earthquakes, 46 % of the transmission substations in Washington, 39 % in Arkansas, 30 % in South Carolina, 30 % in Utah and 27 % in California would sustain damage in the 30-to-100 % range.

5.4.4 *Water System*

Direct damage to those water transmission systems for which inventory data are available are summarized in Tables 5-12 and 5-13. These estimates are based on damage curves for aqueducts and exclude damage to pumping stations and dams, which are not included in the project inventory. The data indicate that 38 and 20 km of the aqueduct system (Table 5-12), respectively, would sustain moderate to heavy damage (10-to-60 %) in the Fort Tejon and

Table 5-9 Damage Percent for Highway Bridges for Each Scenario Earthquake (Percent of Bridges in State)

	NEW MADRID (M=8.0)							CHARLESTON (M=7.5)		
Total Number	Illinois 4,674	Missouri 4,496	Arkansas 2,353	Tennessee 3,698	Kentucky 2,797	Indiana 3,326	Mississippi 3,096	South Carolina 2,134	North Carolina 3,120	Georgia 4,193
Light Damage 1-10 %	10%	6%	16%	8%	16%	2%	56%	15%	9%	17%
Moderate 10-30 %	1%	0%	12%	9%	3%	0%	16%	15%	1%	17%
Heavy 30-60 %	0%	0%	5%	4%	0%	0%	0%	6%	< 1%	< 1%
Major to Destructive 60-100 %	< 1%	0%	13%	7%	3%	0%	8%	1%	< 1%	2%

	CAPE ANN (M=7.0)					WASATCH FRONT (M=7.5)
Total Number	Massachusetts 2,013	Connecticut 1,878	Delaware 297	Rhode Island 283	New Hampshire 1,020	Utah 1,149
Light Damage 1-10 %	46%	45%	21%	76%	53%	7%
Moderate 10-30 %	37%	0%	0%	15%	1%	11%
Heavy 30-60 %	0%	0%	0%	0%	0%	10%
Major to Destructive 60-100 %	0%	0%	0%	0%	0%	15%

	HAYWARD (M=7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)
Total Number	California 7,948	California 7,948	Washington 1,908
Light Damage 1-10 %	4%	22%	8%
Moderate 10-30 %	2%	< 1%	12%
Heavy 30-60 %	0%	0%	3%
Major to Destructive 60-100 %	0%	0%	13%

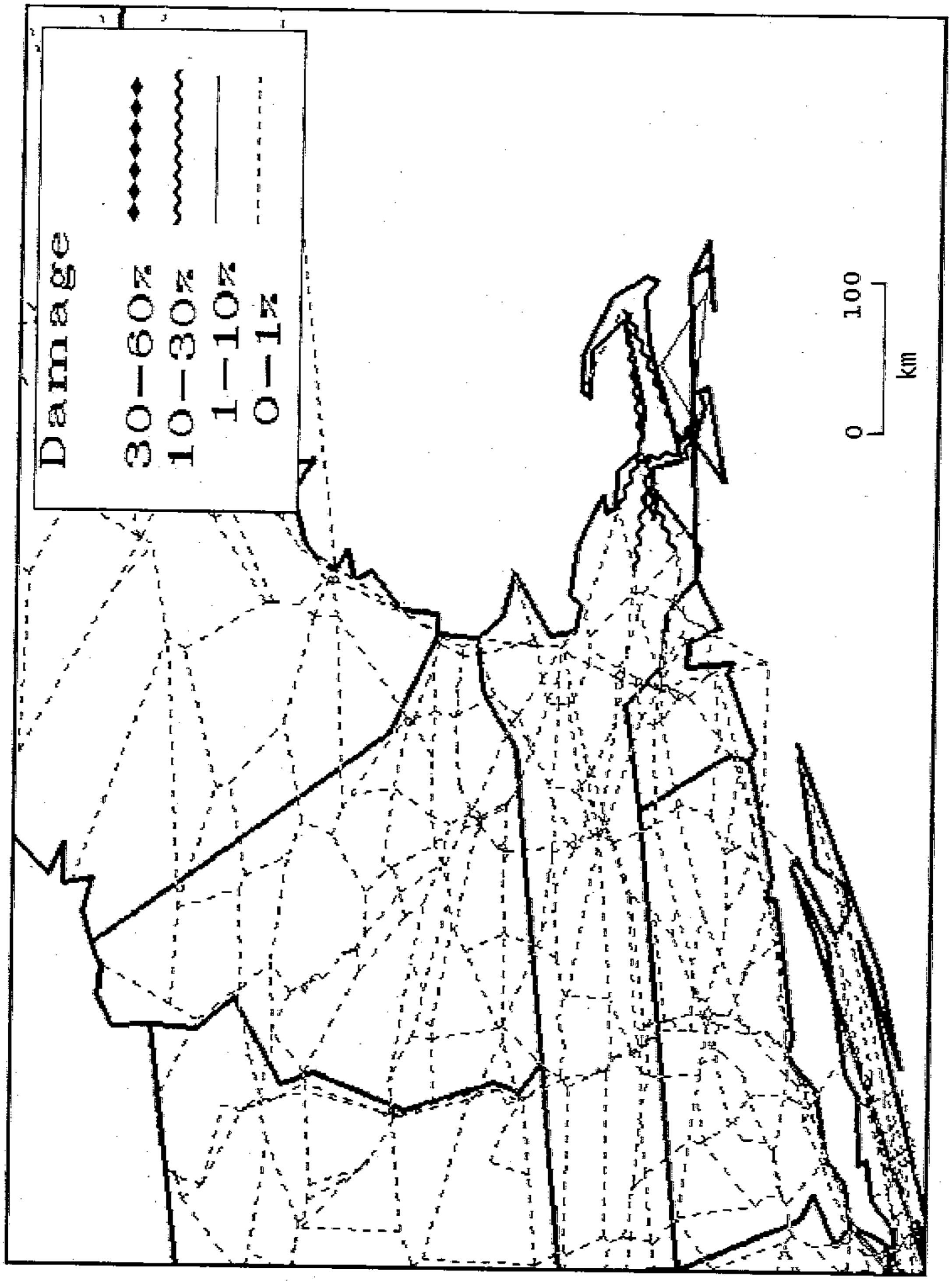


Figure 5-9 *Damage to highways following Cape Ann event (M=7.0).*

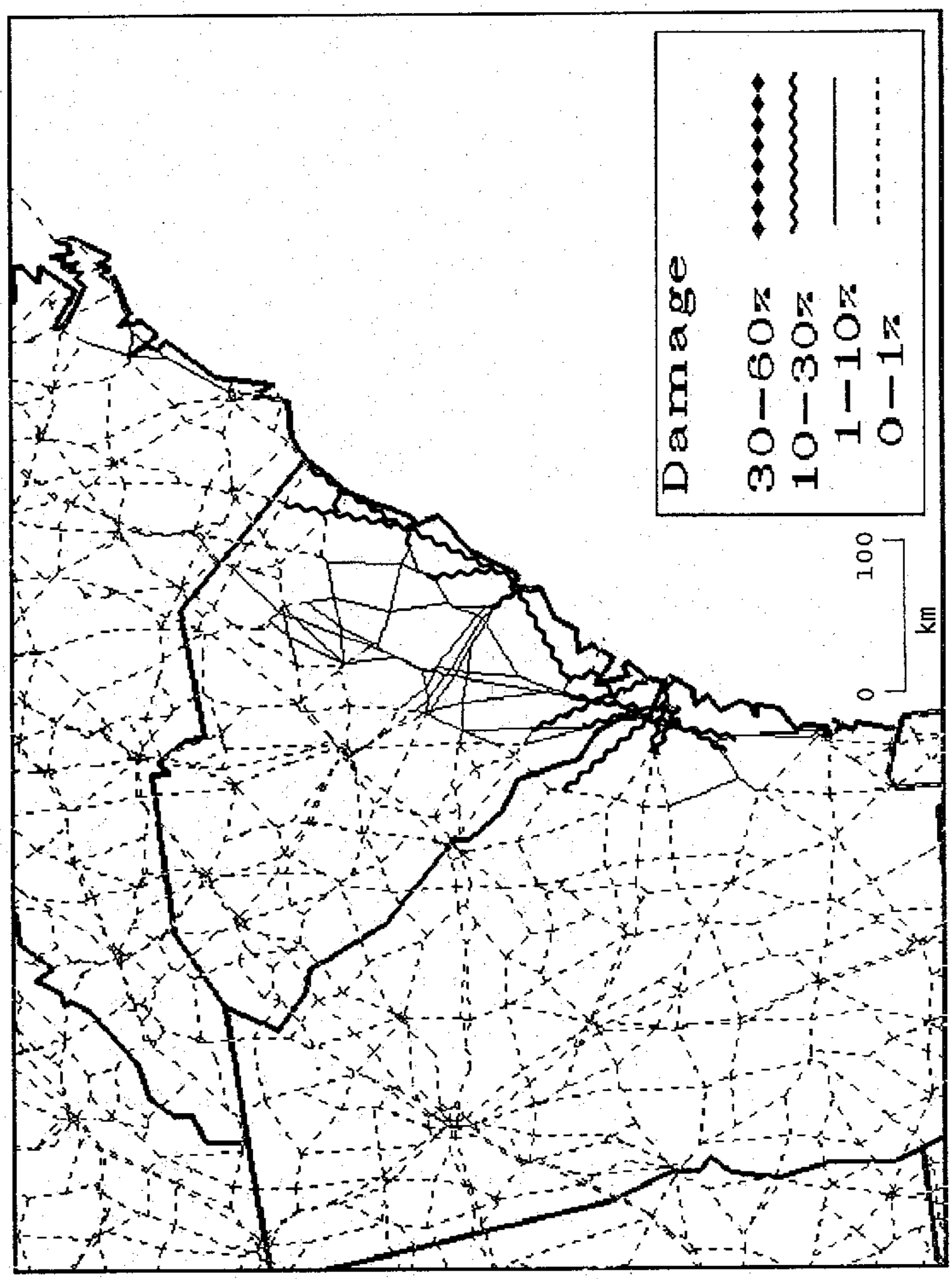


Figure 5-10 *Damage to highways following Charleston event (M=7.5).*

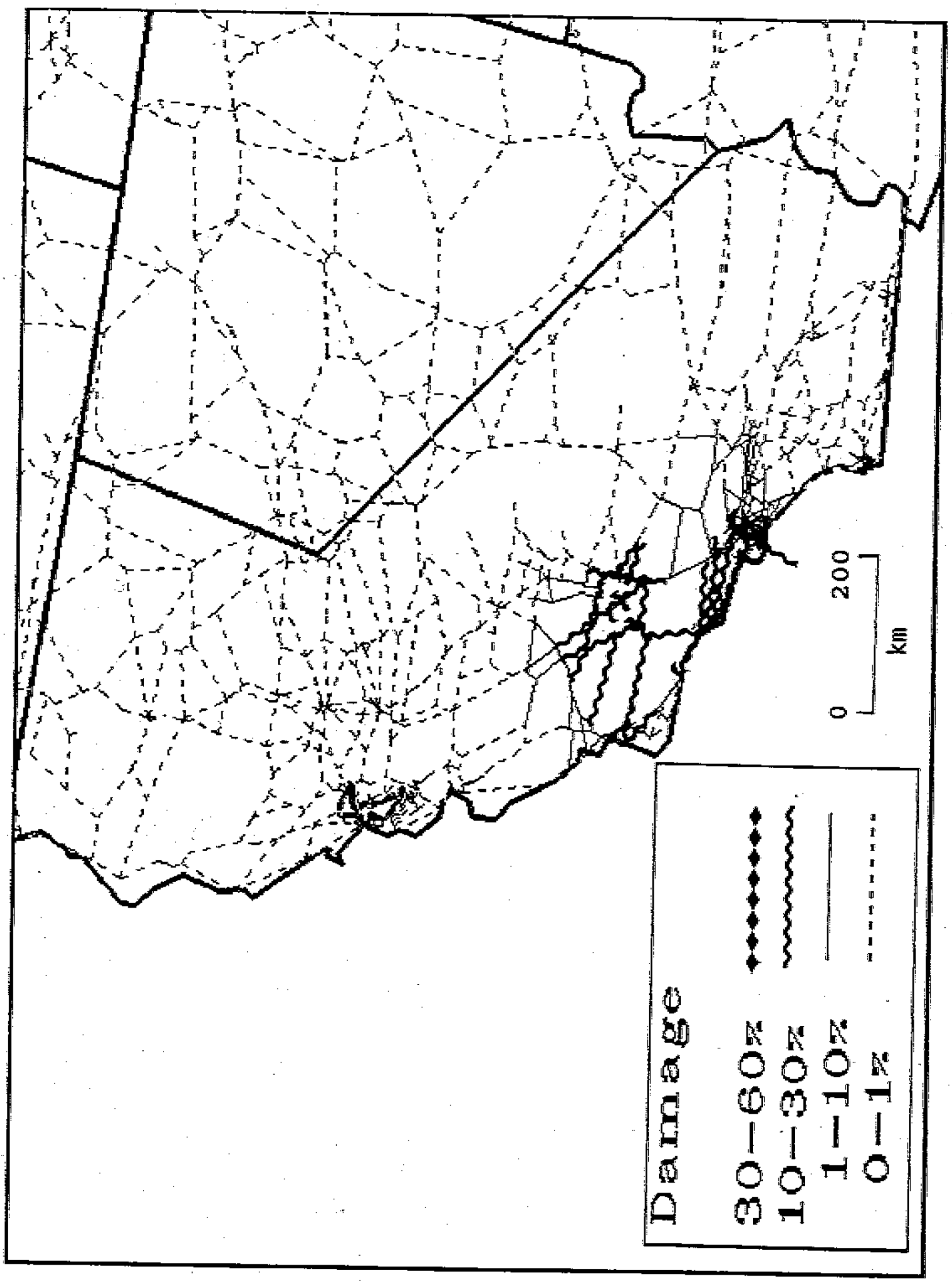


Figure 5-11 *Damage to highways following Fort Tejon event (M=8.0).*

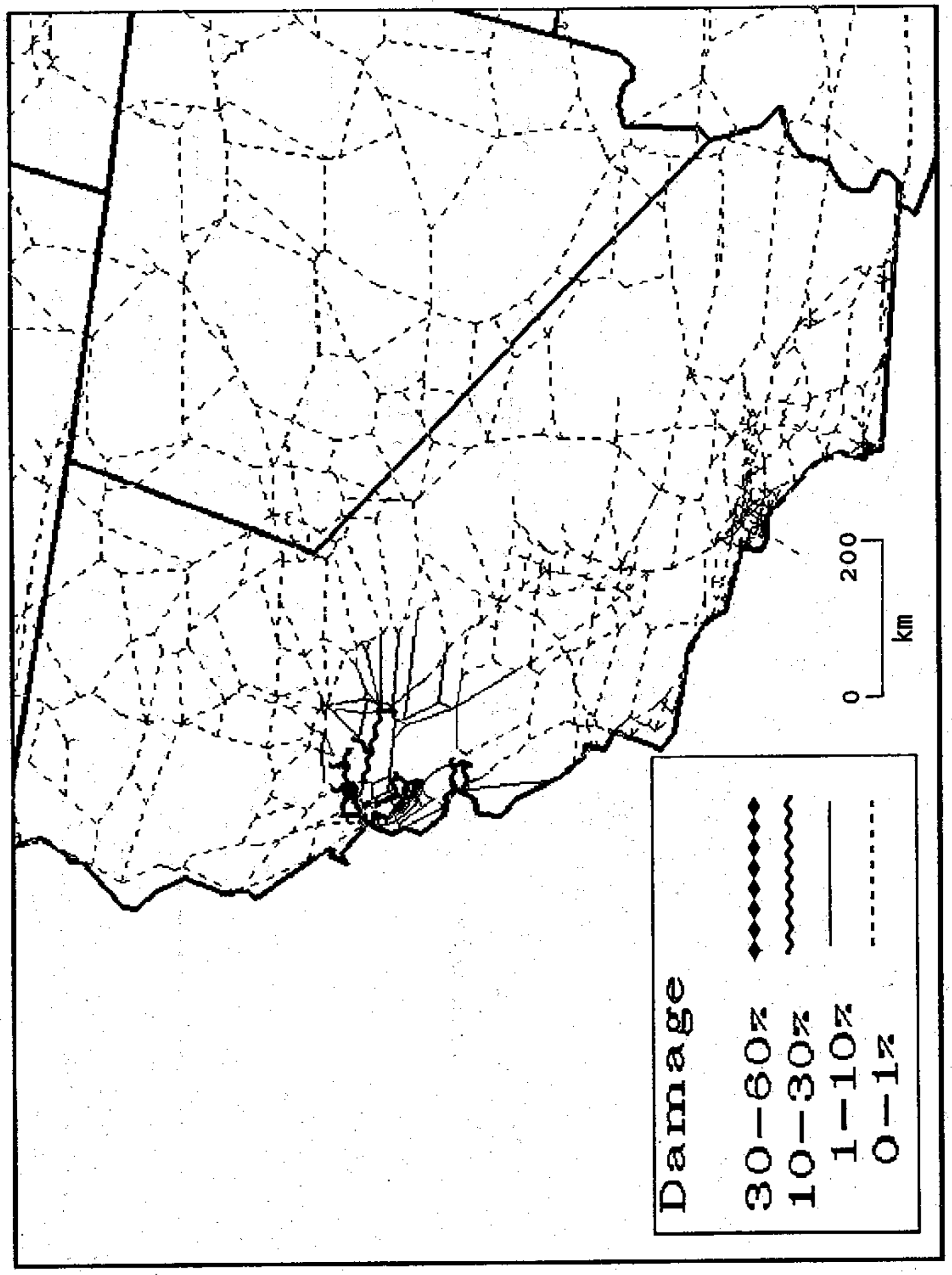


Figure 5-12 *Damage to highways following Hayward event (M=7.5).*

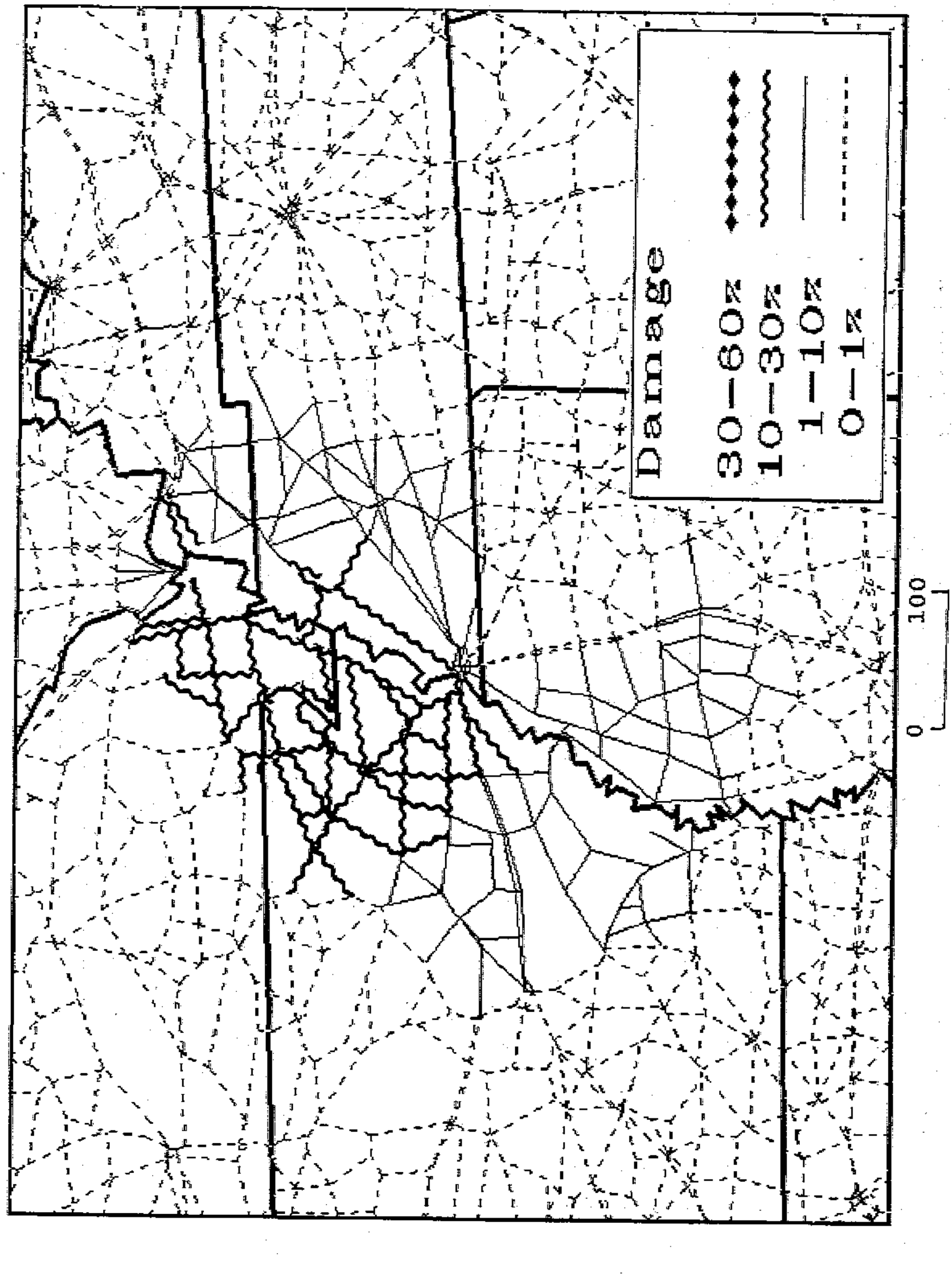


Figure 5-13 *Damage to highways following New Madrid event (M=8.0).*

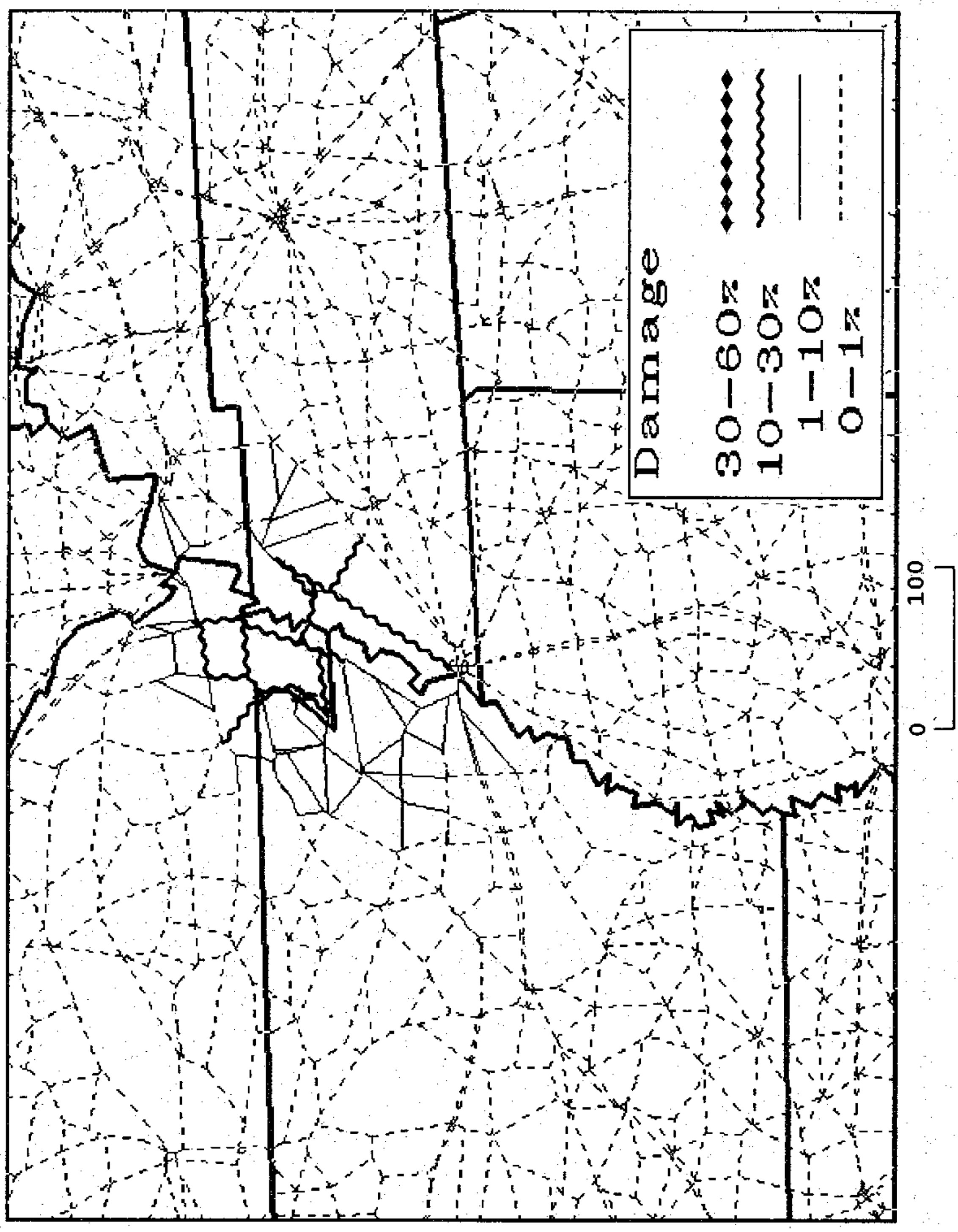


Figure 5-14 *Damage to highways following New Madrid event (M=7.0).*

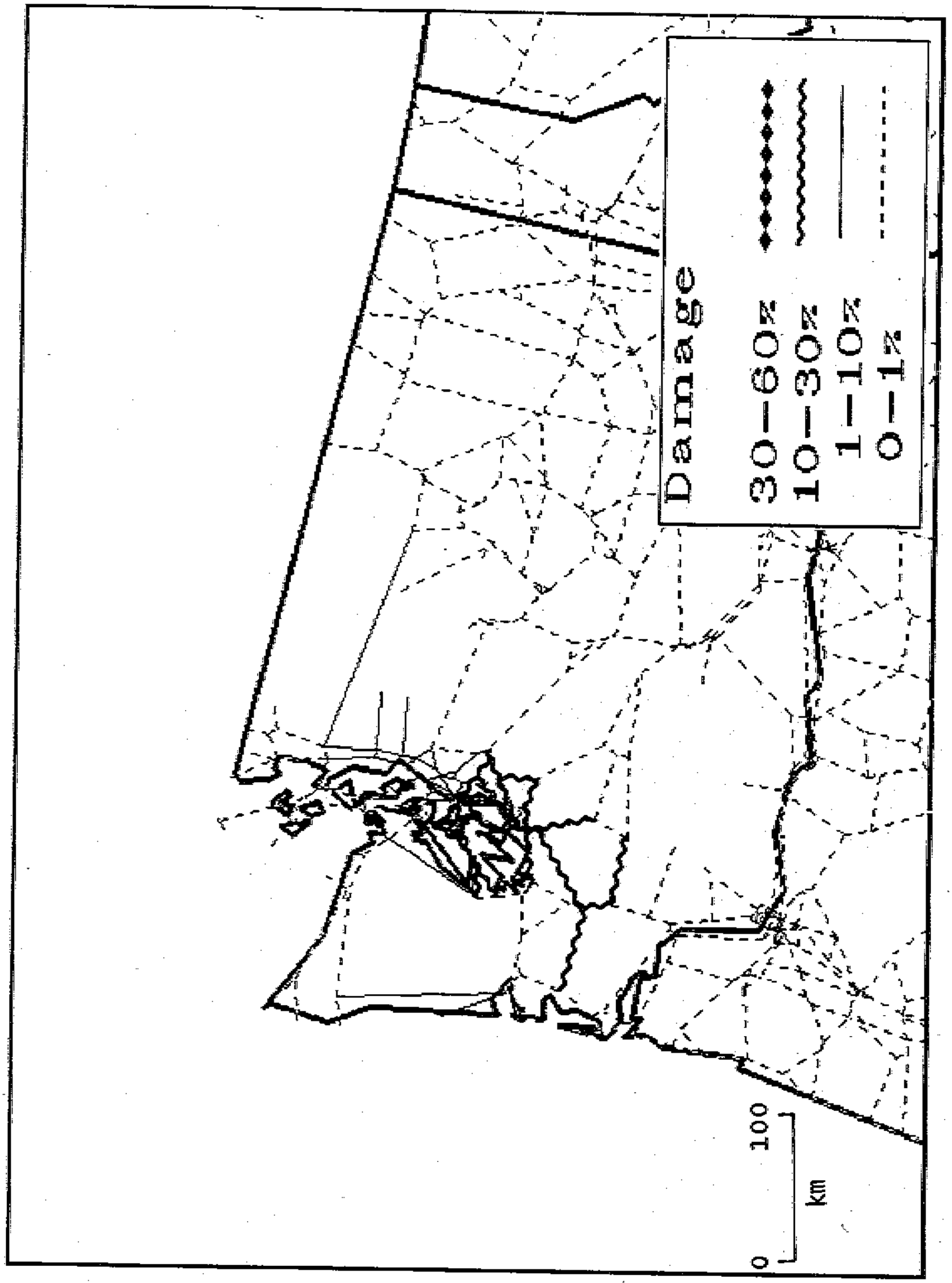


Figure 5-15 Damage to highways following Puget Sound event (M=7.5).

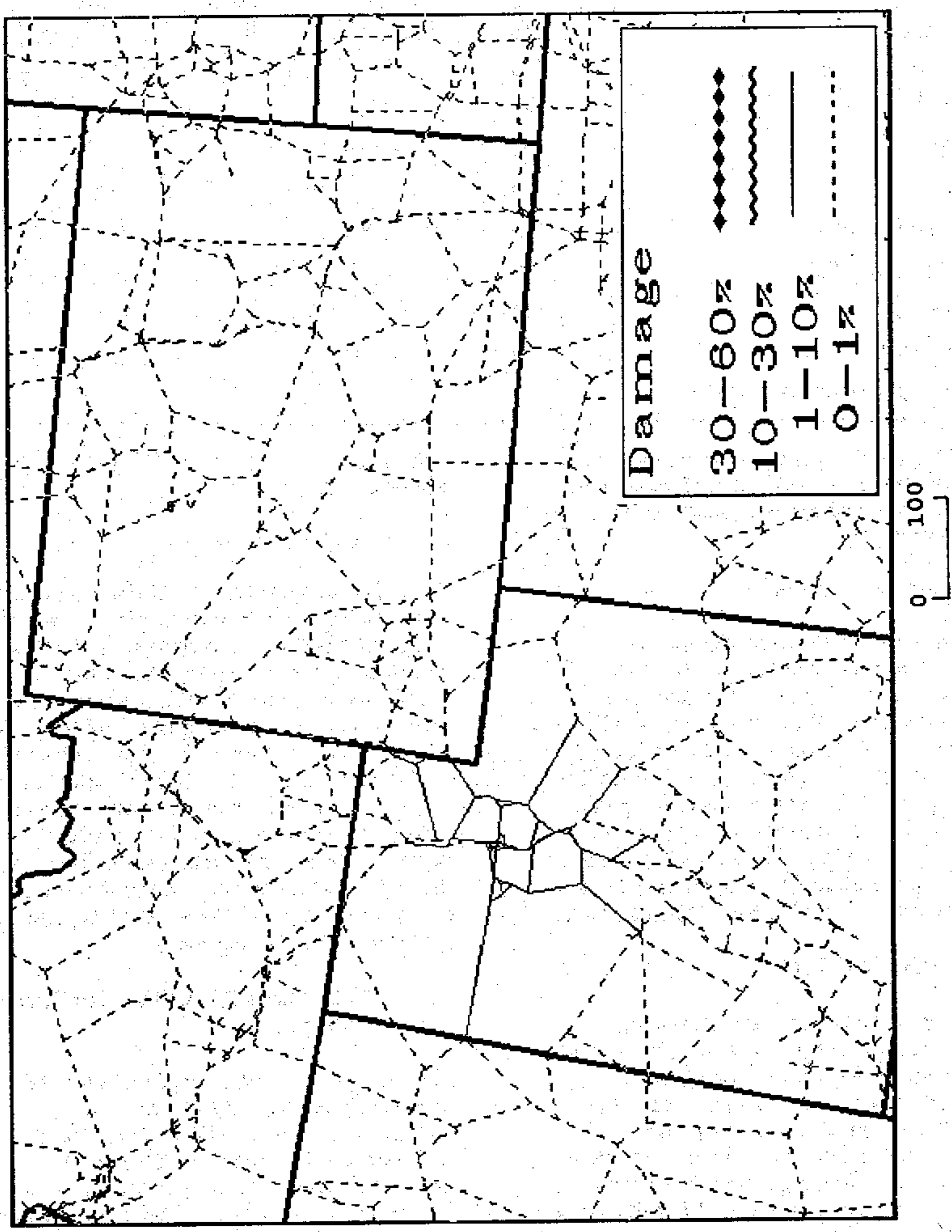


Figure 5-16 *Damage to highways following Wasatch Front event (M=7.5).*

Table 5-10 Damage to Electric Transmission Lines (Length of Line, Km)

Event	Light Damage 1-10%	Moderate 10-30%	Heavy 30-60%	Major to Destructive 60-100%
Cape Ann	275	0	0	0
Charleston	4,840	27	0	0
Fort Tejon	6,645	1,370	0	0
Hayward	6,320	0	0	0
New Madrid (M=8.0)	6,840	800	0	0
New Madrid (M=7.0)	2,610	0	0	0
Puget Sound	3,860	0	0	0
Wasatch Front	1,370	0	0	0

Total System Length = 441,981 km

Hayward scenario events, respectively. Maps provided in Figures 5-25 and 5-26 show plots of damage to water aqueduct systems for these two California events.

5.4.5 Crude Oil System

Direct damage to the crude oil system, estimated using damage curves for transmission pipelines and the special probabilistic model for pipelines described above, are plotted in Figures 5-27 through 5-29. Data are included for only those events for which damage to this facility type is expected: the two New Madrid events and the Fort Tejon earthquake. Figures 5-27 through 5-29 show pipeline section(s) damaged due to the magnitude-8.0 New Madrid, Fort Tejon, and magnitude-7.0 New Madrid events.

5.4.6 Refined Oil System

Direct damage to the refined oil system, estimated using damage curves for transmission pipelines and refineries and the special probabilistic model for pipelines described above, are plotted in Figures 5-30 and 5-31. These plots indicate that one major section of pipeline would be damaged, with probability of 60% or greater, due to the New Madrid events. We note also that a major refinery (capacity 150,000 barrel/day) would sustain light damage (1-to-10 %) due the Hayward event, and two major refineries with capacities of 420,000 and 100,000 barrels/day, respectively, would sustain light damage due to the Fort Tejon and Puget Sound events.

5.4.7 Natural Gas System

As in the case of crude and refined oil pipelines, direct damage to the natural gas system was estimated using damage curves for transmission pipelines and the special probabilistic model for pipelines described above. Damage to this facility type, plotted in Figures 5-32 through 5-37, is expected for six of the eight scenario earthquakes; excluded are the Charleston and Cape Ann scenario events for which direct damage to natural gas pipelines is estimated to be zero. Broken pipelines shown (Figures 5-32 through 5-37) are node-to-node sections having one or more links estimated as damaged with a probability of 60% or greater.

5.5 Dollar Loss Resulting from Direct Damage

The total direct damage dollar loss for the various lifeline systems and scenario earthquakes were calculated on the basis of the damage statistics summarized above and assumed replacement costs for the lifeline facility types considered (Table 5-13). Assumed replacement cost values are based on data collected for various facility sizes and regions, which were then weighted to account for the estimated distribution of facility sizes in the national database.

Table 5-11 Damage Percent for Electric Transmission Substations for Each Scenario Earthquake (Percent of Substations in State)

	NEW MADRID (M=8.0)							CHARLESTON (M=7.5)		
Total Number	Illinois 108	Missouri 95	Arkansas 124	Tennessee 70	Kentucky 68	Indiana 89	Mississippi 93	South Carolina 100	North Carolina 76	Georgia 86
Light Damage 1-10 %	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	14%	8%	22%	16%	24%	2%	63%	43%	20%	33%
Heavy 30-60 %	0%	0%	10%	9%	7%	0%	8%	14%	0%	3%
Major to Destructive 60-100 %	0%	8%	29%	6%	1%	0%	10%	16%	1%	2%

	CAPE ANN (M=7.0)					WASATCH FRONT (M=7.5)
Total Number	Massachusetts 153	Connecticut 69	Delaware 3	Rhode Island 22	New Hampshire 22	Utah 10
Light Damage 1-10 %	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	82%	42%	33%	100%	45%	30%
Heavy 30-60 %	0%	0%	0%	0%	0%	20%
Major to Destructive 60-100 %	5%	0%	0%	0%	0%	10%

	HAYWARD (M7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)					
Total Number	California 205	California 205	Washington 155	Illinois 108	Missouri 95	Arkansas 124	Tennessee 70	Kentucky 68	Mississippi 93
Light Damage 1-10 %	8%	11%	0%	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	13%	6%	12%	0%	2%	21%	16%	16%	14%
Heavy 30-60 %	14%	< 1%	3%	0%	0%	16%	0%	0%	2%
Major to Destructive 60-100 %	13%	12%	43%	0%	6%	6%	3%	0%	0%

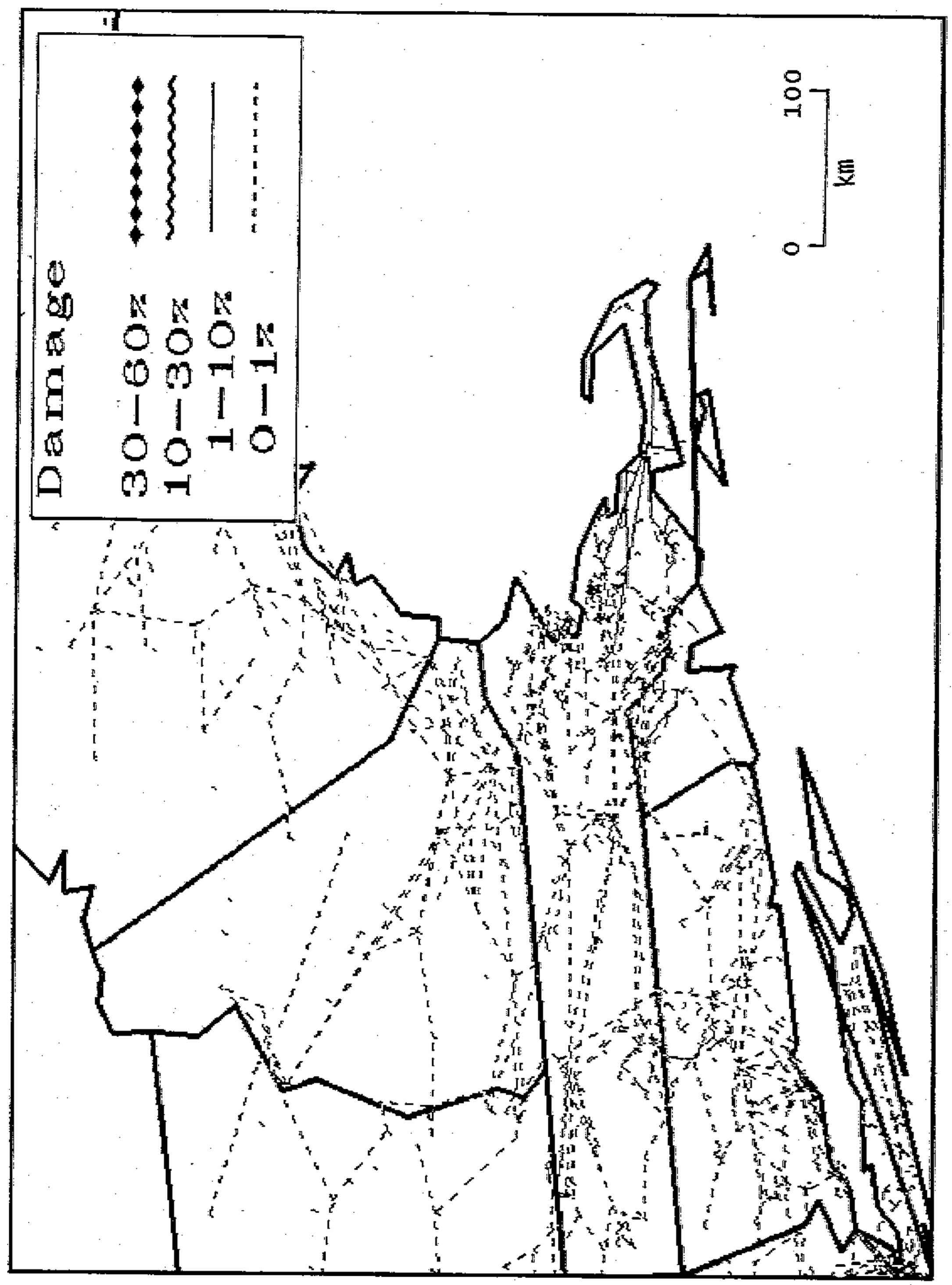


Figure 5-17 *Damage to electric power transmission lines following Cape Ann event (M=7.0).*

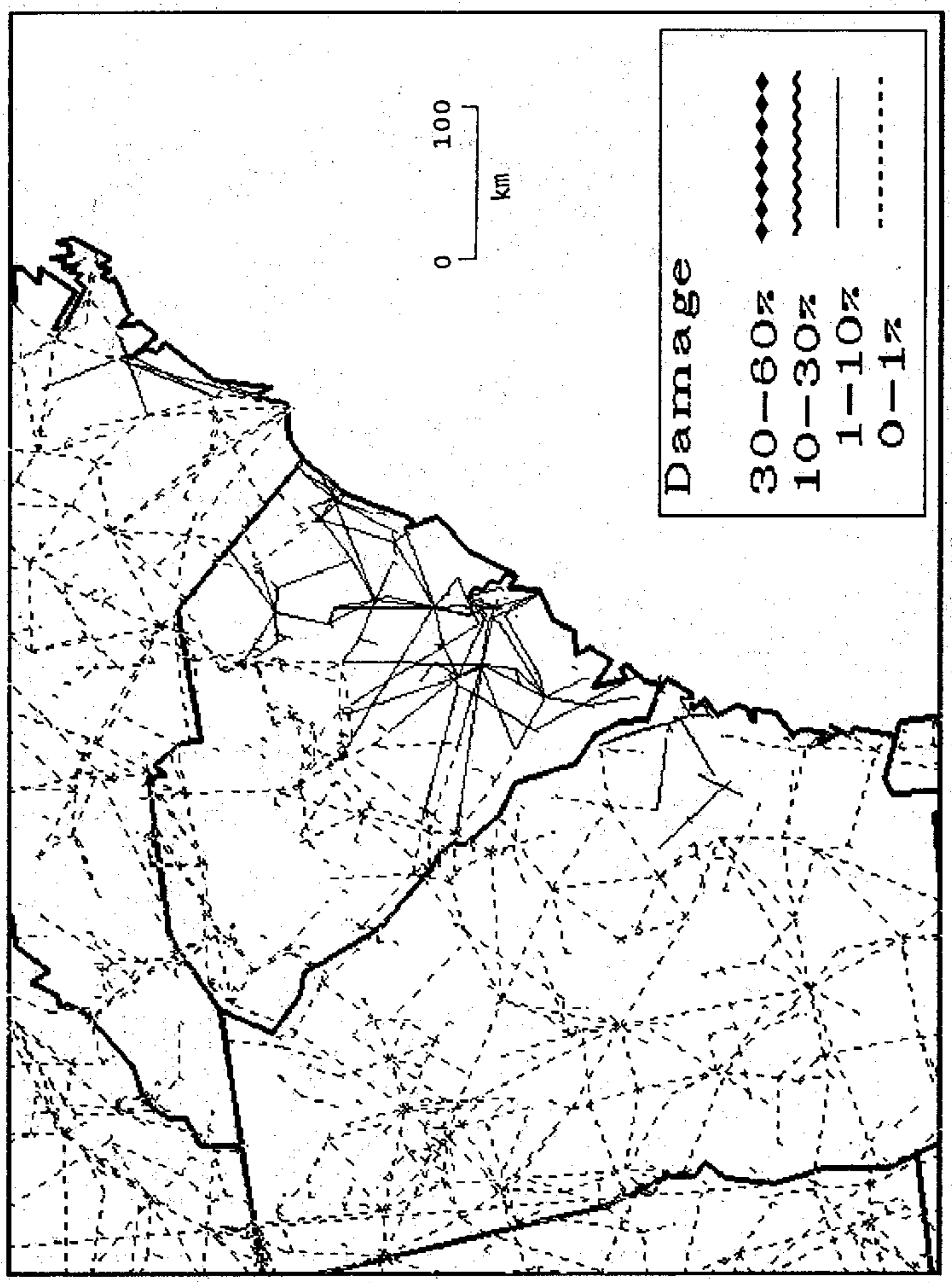


Figure 5-18 *Damage to electric power transmission lines following Charleston event (M=7.5).*

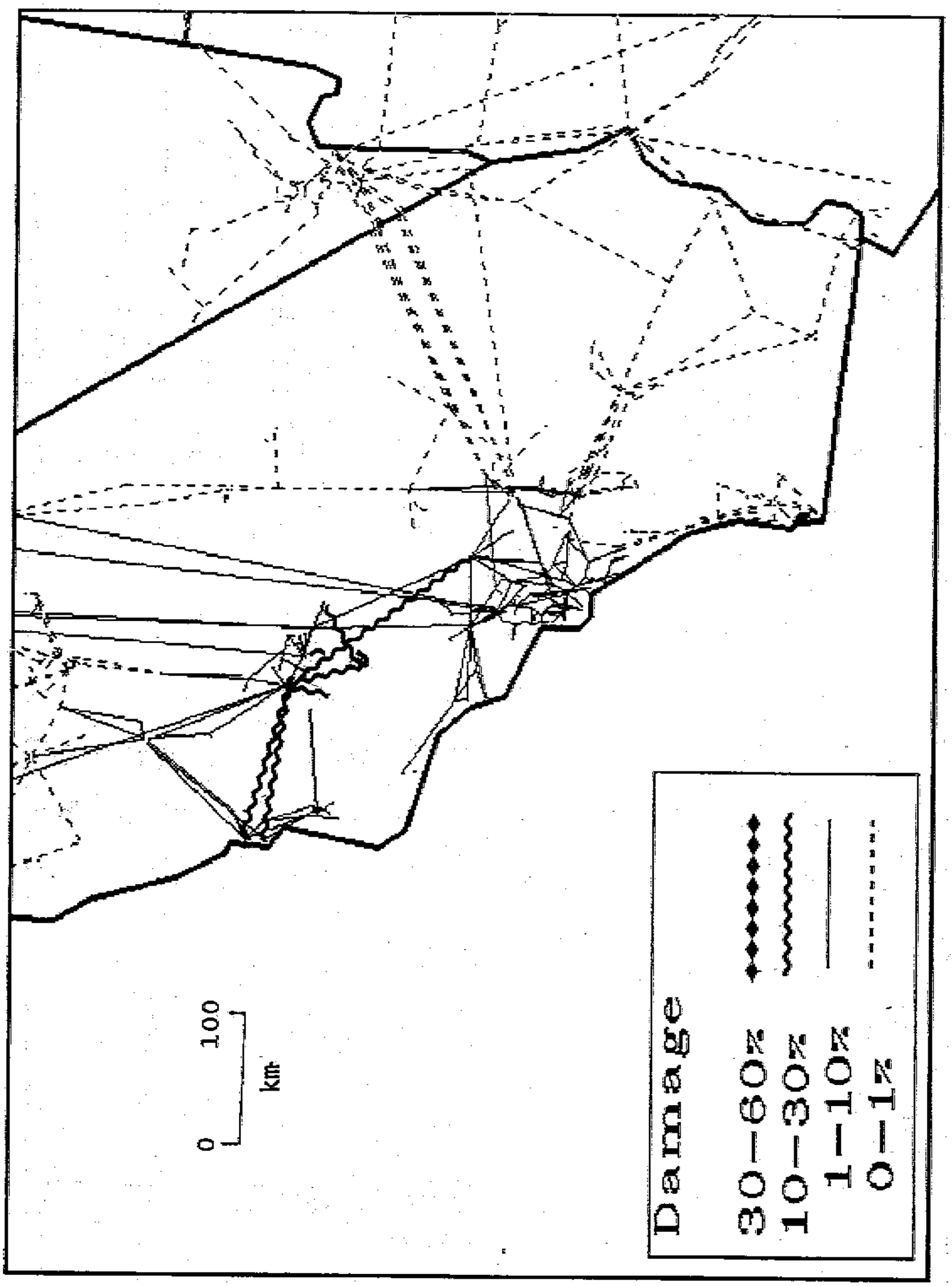


Figure 5-19 *Damage to electric power transmission lines following Fort Tejon event (M=8.0).*

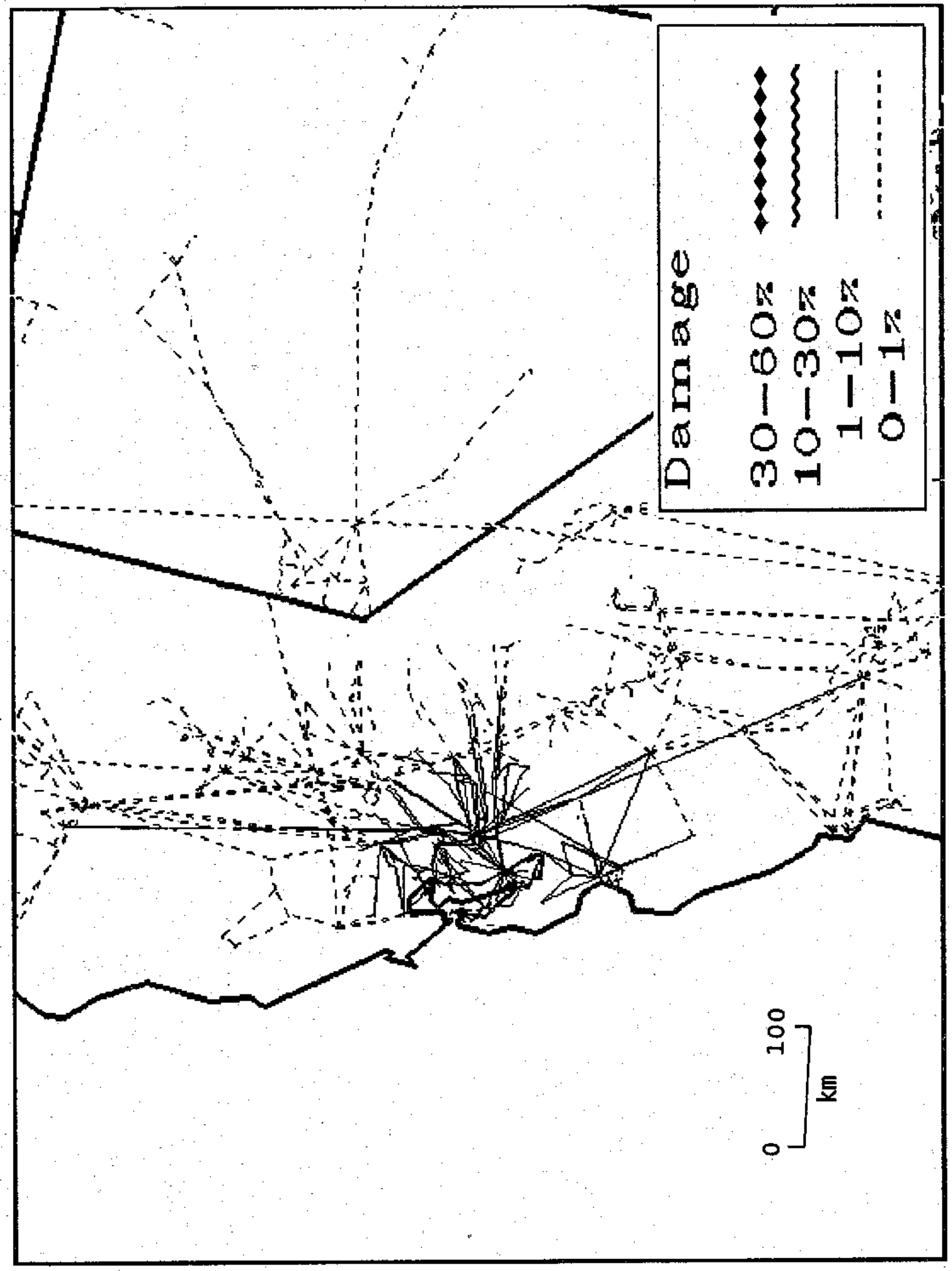


Figure 5-20 *Damage to electric power transmission lines following Hayward event (M=7.5).*

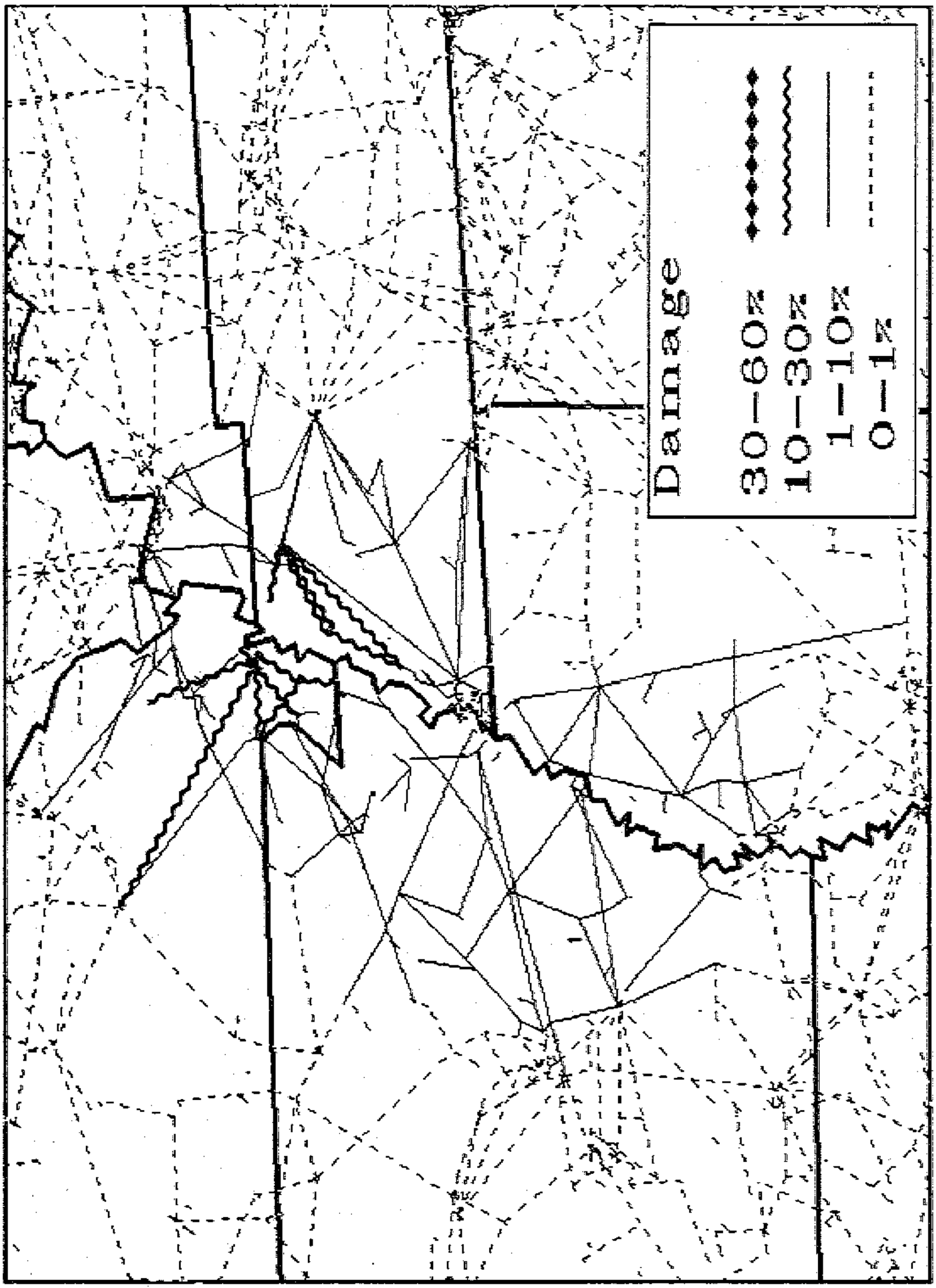


Figure 5-21 *Damage to electric power transmission lines following New Madrid event (M=8.0).*

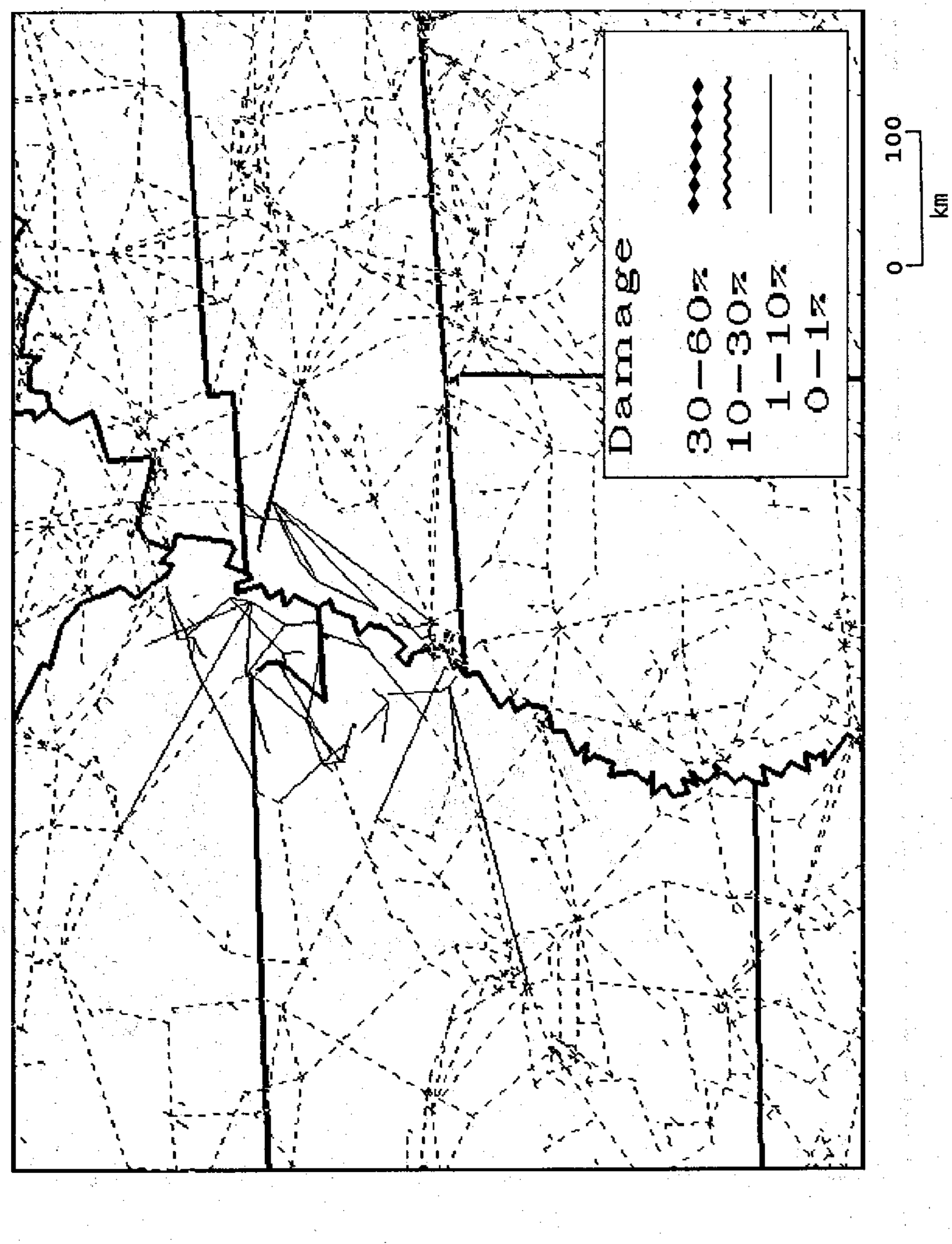


Figure 5-22 *Damage to electric power transmission lines following New Madrid event (M=7.0).*

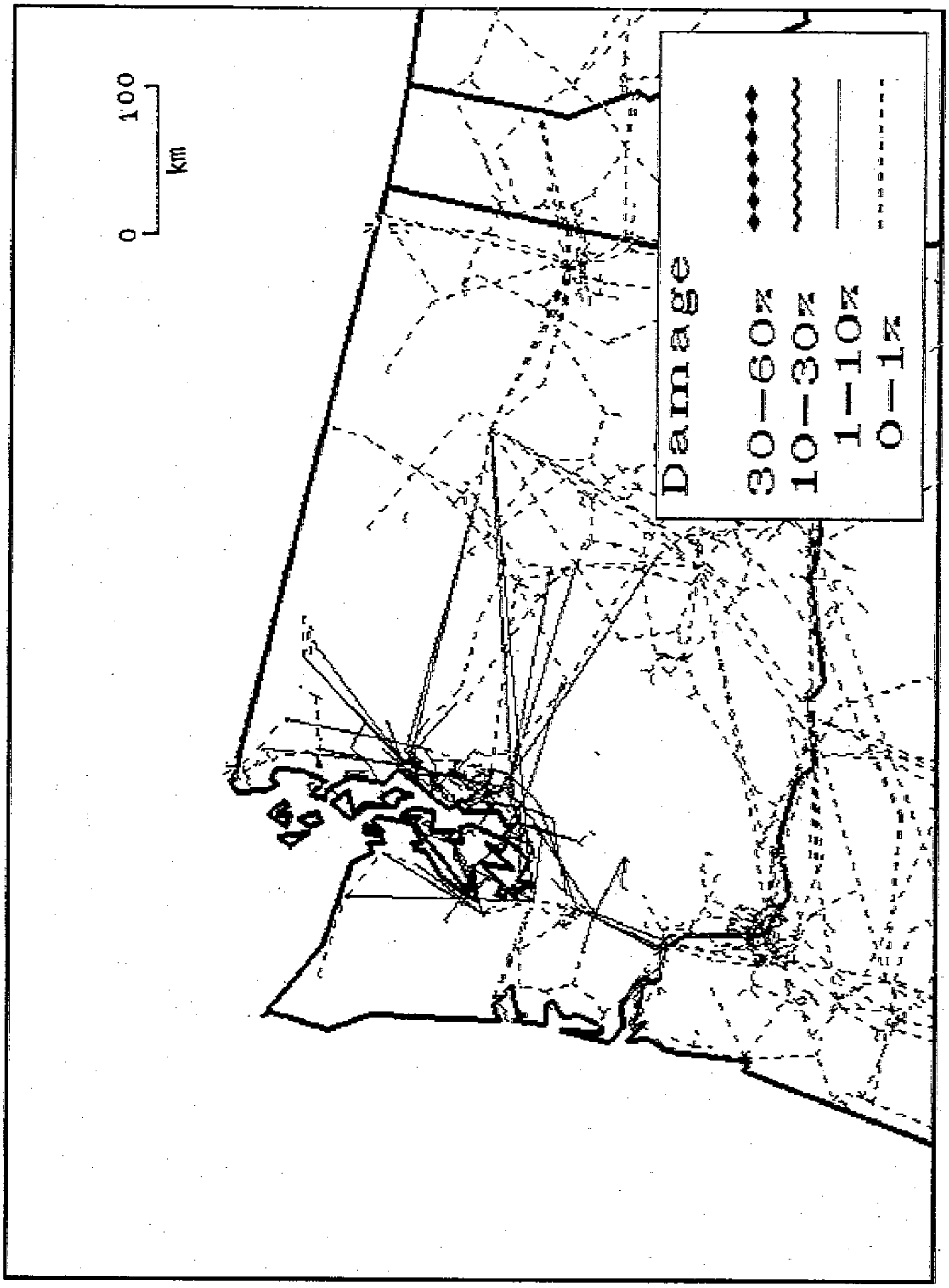


Figure 5-23 *Damage to electric power transmission lines following Puget Sound event (M=7.5).*

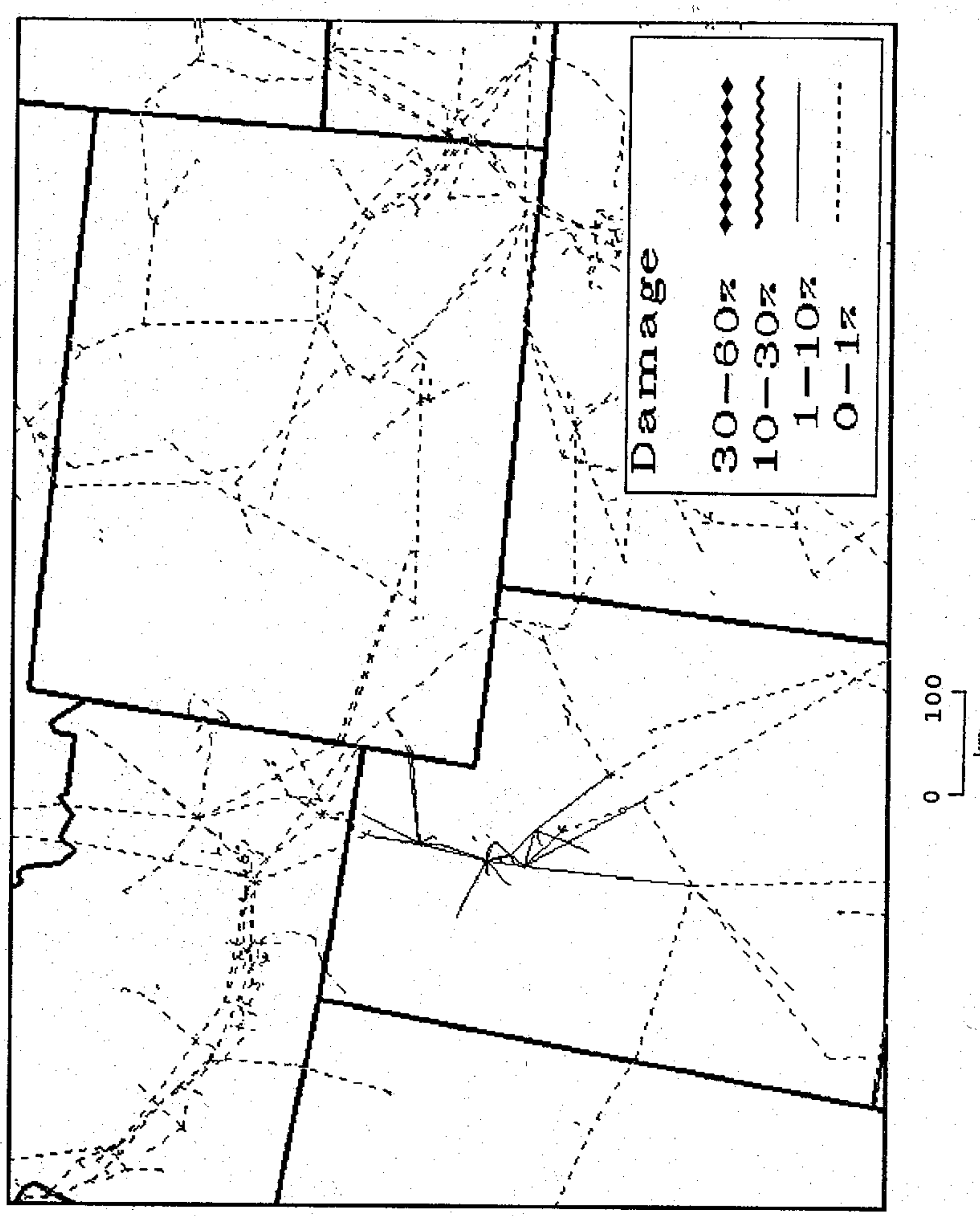


Figure 5-24 *Damage to electric power transmission lines following Wasatch Front event (M=7.5).*

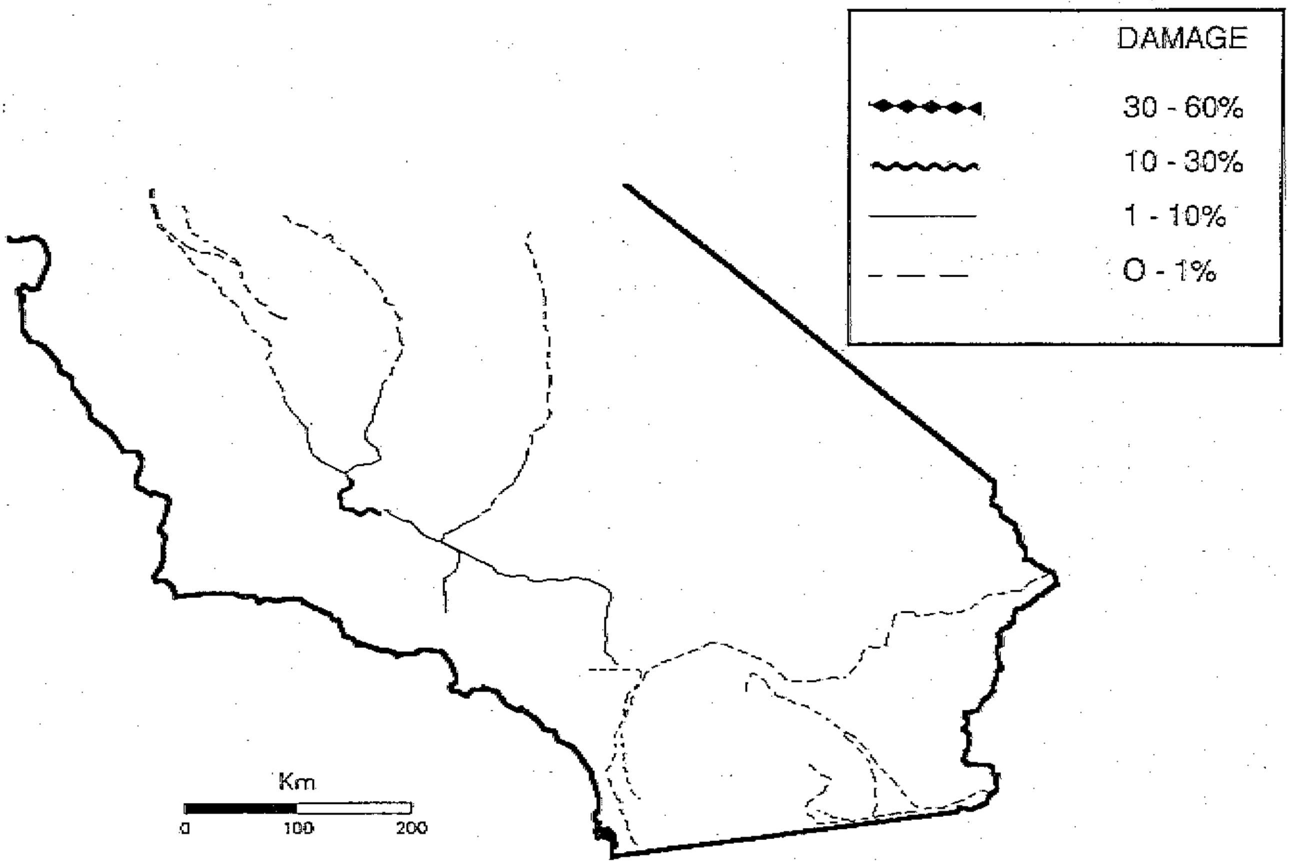


Figure 5-25 *Damage to water aqueduct system following Fort Tejon event (M=8.0).*

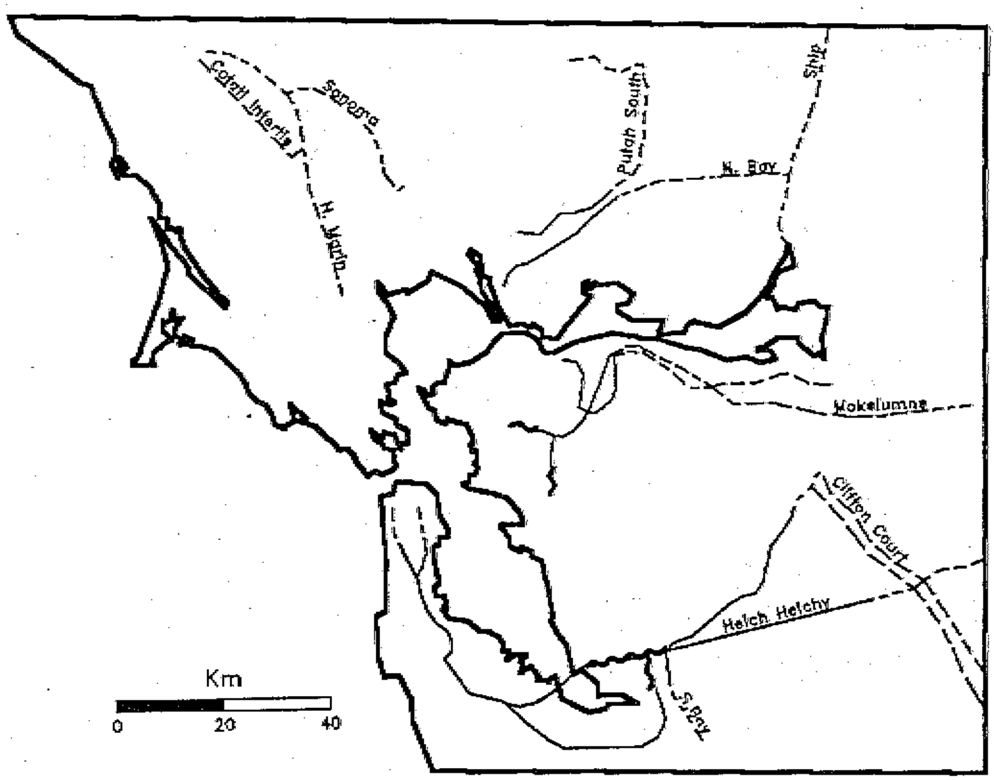


Figure 5-26 *Damage to water aqueduct system following Hayward event (M=7.5).*

Table 5-12 Damage to Water Aqueduct System (Length of Aqueduct, Km)

Event	*Light Damage 1-10%*	*Moderate 10-30%*	*Heavy 30-60%*	*Major to Destructive 60-100%*
Fort Tejon	350	36	2	0
Hayward	240	20	1	0
Puget Sound	60	0	0	0

Table 5-13 Cost Estimates for Lifeline Components

System	*Component*	*Cost Estimate**
Railway	Tracks/Roadbeds	$500,000/mile**
Highway	Conventional highway bridge	$1,200,000
	Freeway/Highway	$1,400,000/mile**
	Local Roads	$300,000/mile**
Air Transportation	Terminals	$4,000,000
	Runways/Taxiways	$1,000,000/runway
Sea/Water Transportation	Ports/Cargo Handling Equipment	$20,000,000
Electric	Distribution Lines	$150,000/mile**
	Transmission Lines	$500,000/mile**
	Transmission Substations	$400/person***
Water Supply	Transmission Aqueducts	$5,000,000/mile**
Natural Gas	Transmission Aqueducts	$300,000/mile**
Petroleum Fuels	Transmission Pipelines	$300,000/mile**
Emergency Service	Medical Care Facilities (assumes 85,000 square foot average size)	$35,000,000
	Fire Stations (assumes 5,000 square foot average size)	$400,000
	Police Stations (assumes 11,000 square foot average size)	$1,000,000

*1991 Dollars
**1 mile = 1.609 km.
***in service area

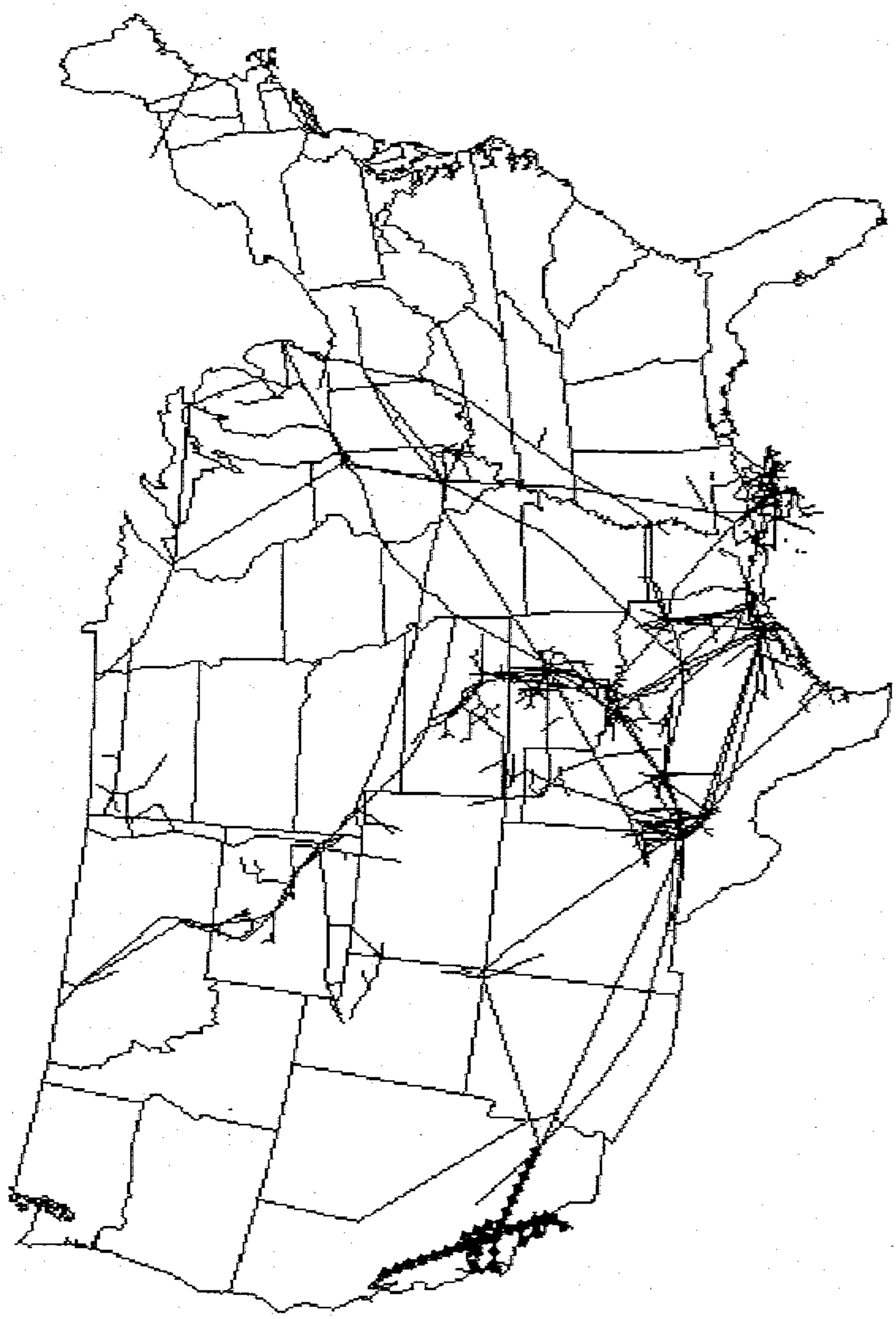


Figure 5-27 *Damage to crude oil system following Fort Tejon event (M=8.0). Broken pipelines are shown with solid diamonds.*

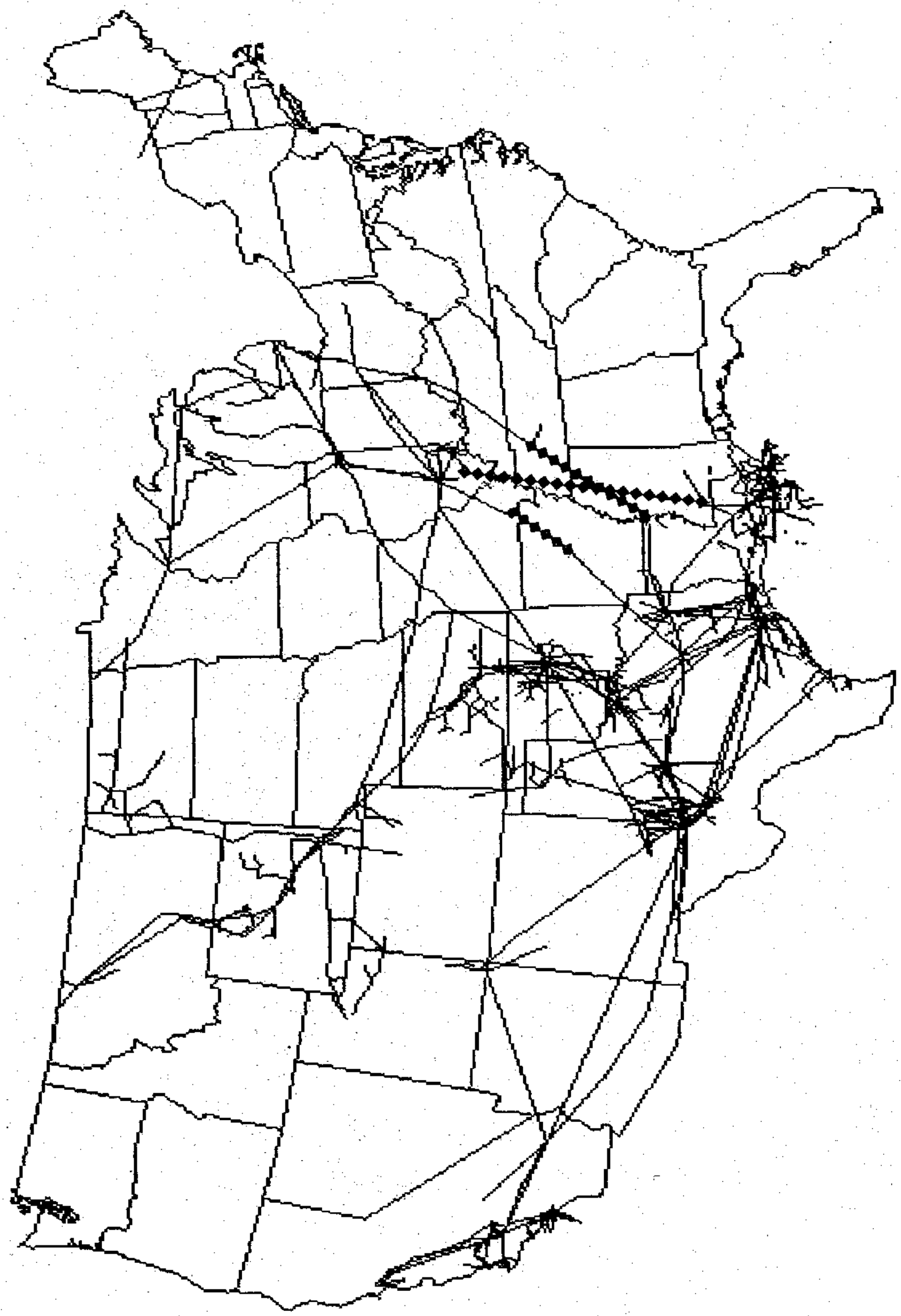


Figure 5-28 *Damage to crude oil system following New Madrid event (M=8.0). Broken pipelines are shown with solid diamonds.*

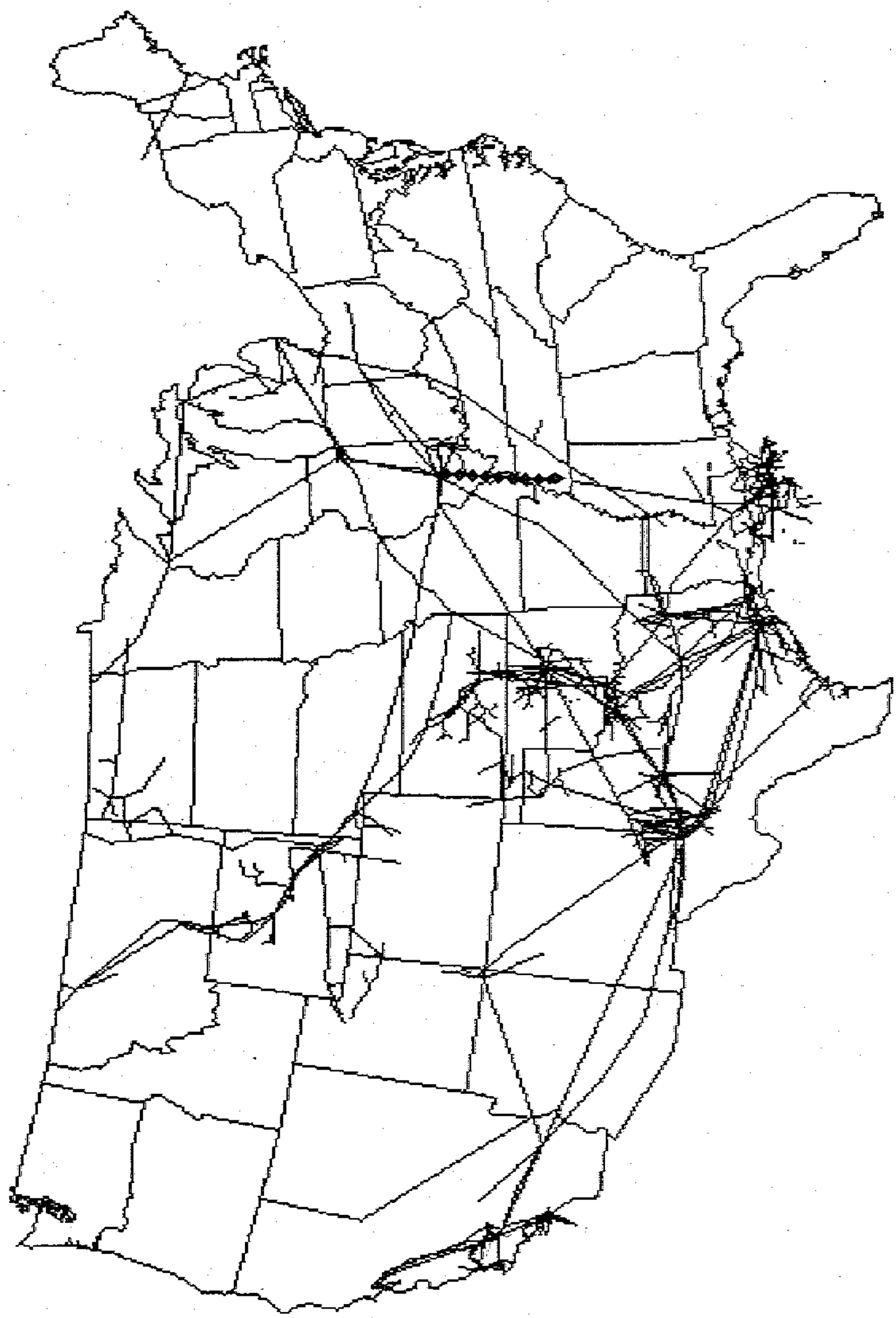


Figure 5-29 *Damage to crude oil system following New Madrid event (M=7.0). Broken pipelines are shown with solid diamonds.*

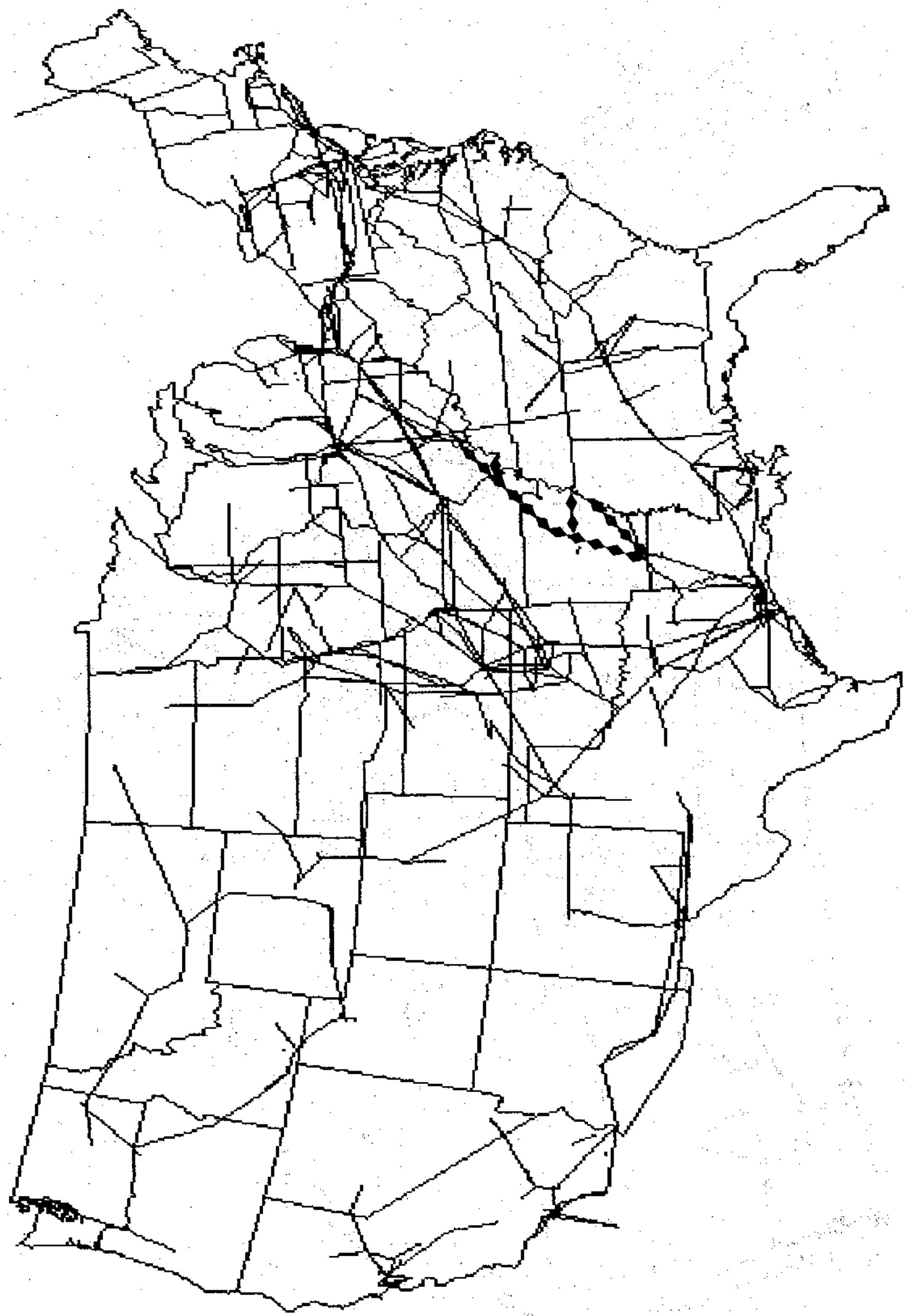


Figure 5-30 *Damage to refined oil system following New Madrid event (M=8.0). Broken pipelines are shown with solid diamonds.*

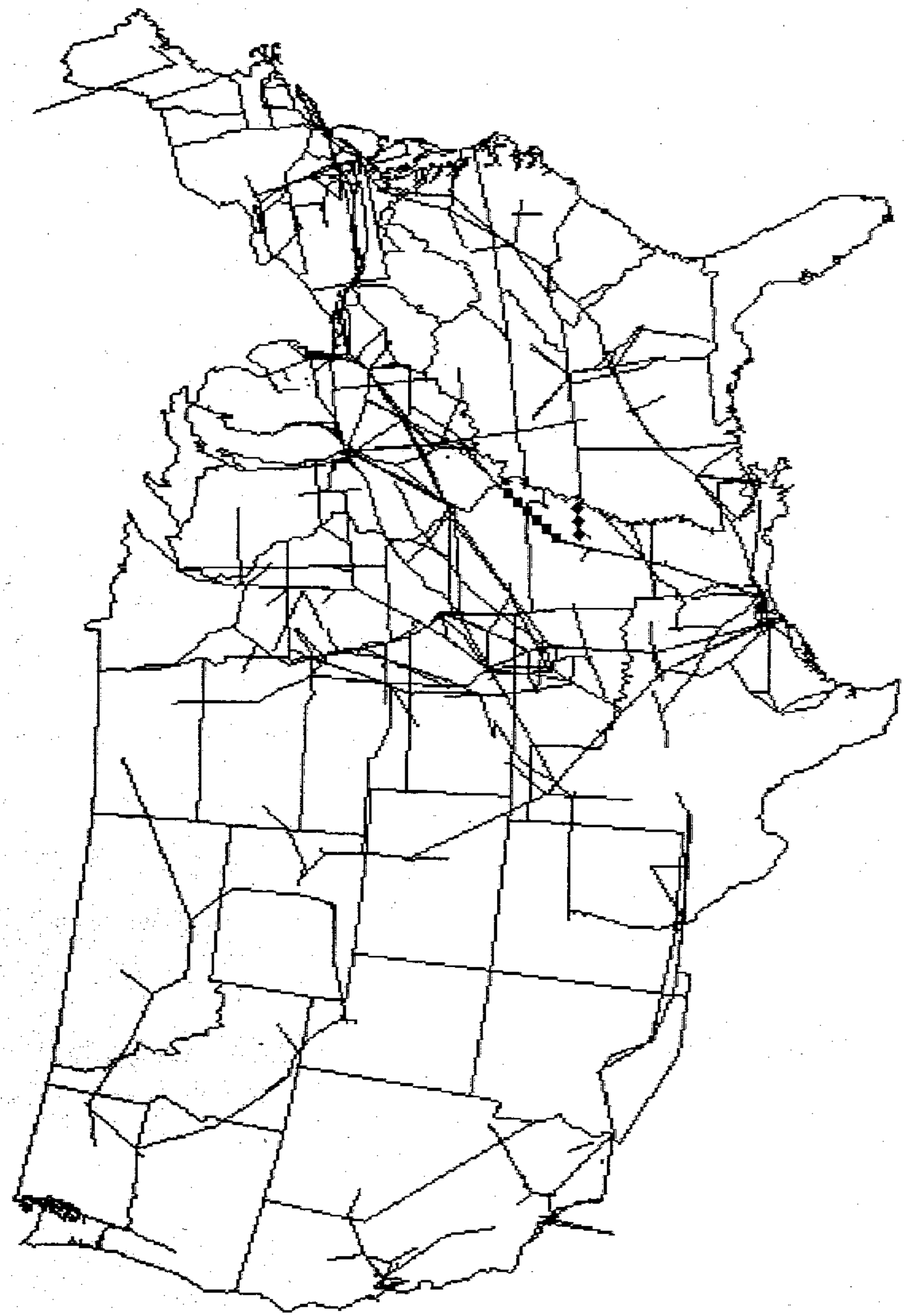


Figure 5-31 *Damage to refined oil system following New Madrid event (M=7.0). Broken pipelines are shown with solid diamonds.*

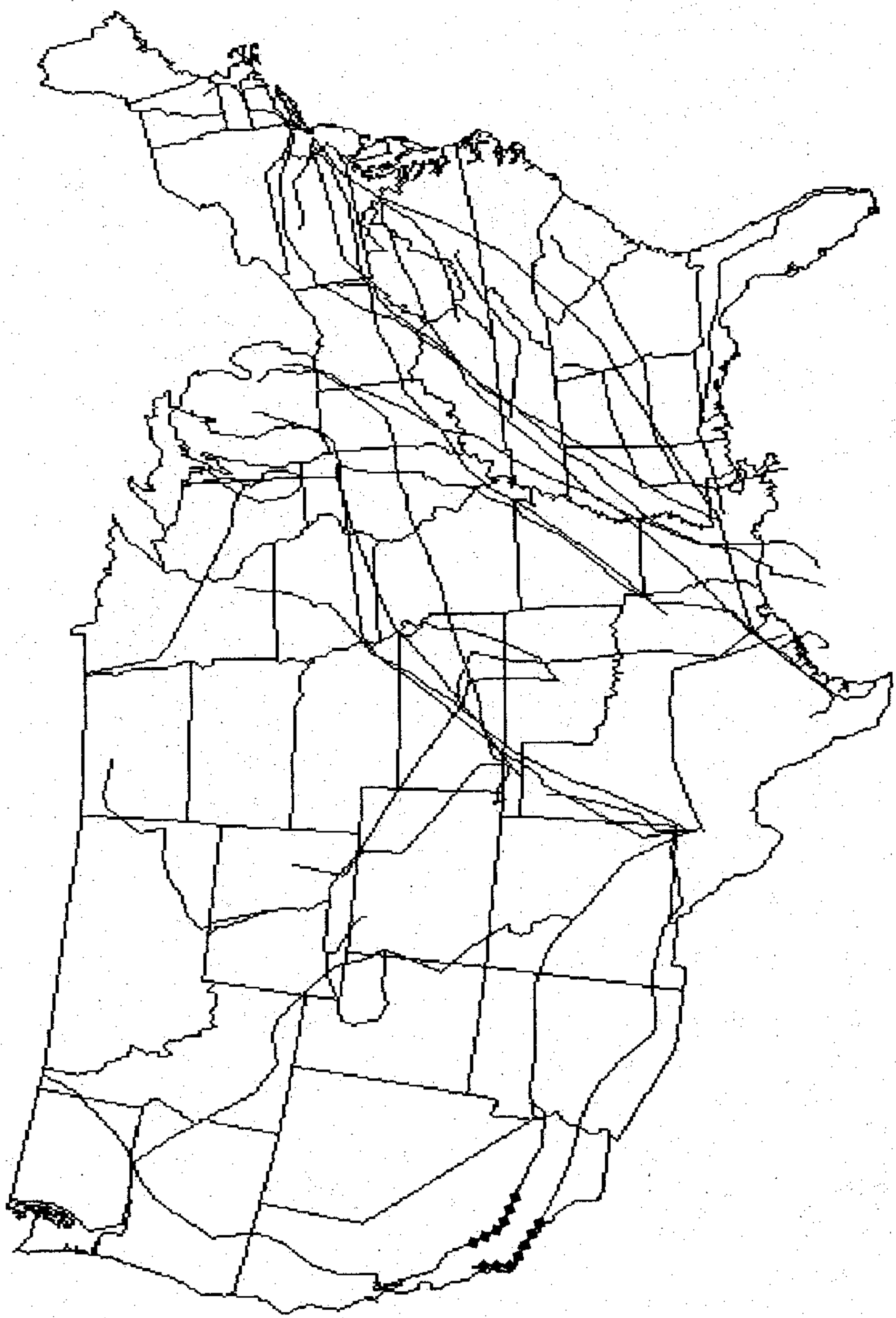


Figure 5-32 *Damage to natural gas system following Fort Tejon event (M=8.0). Broken pipelines are shown with solid diamonds.*

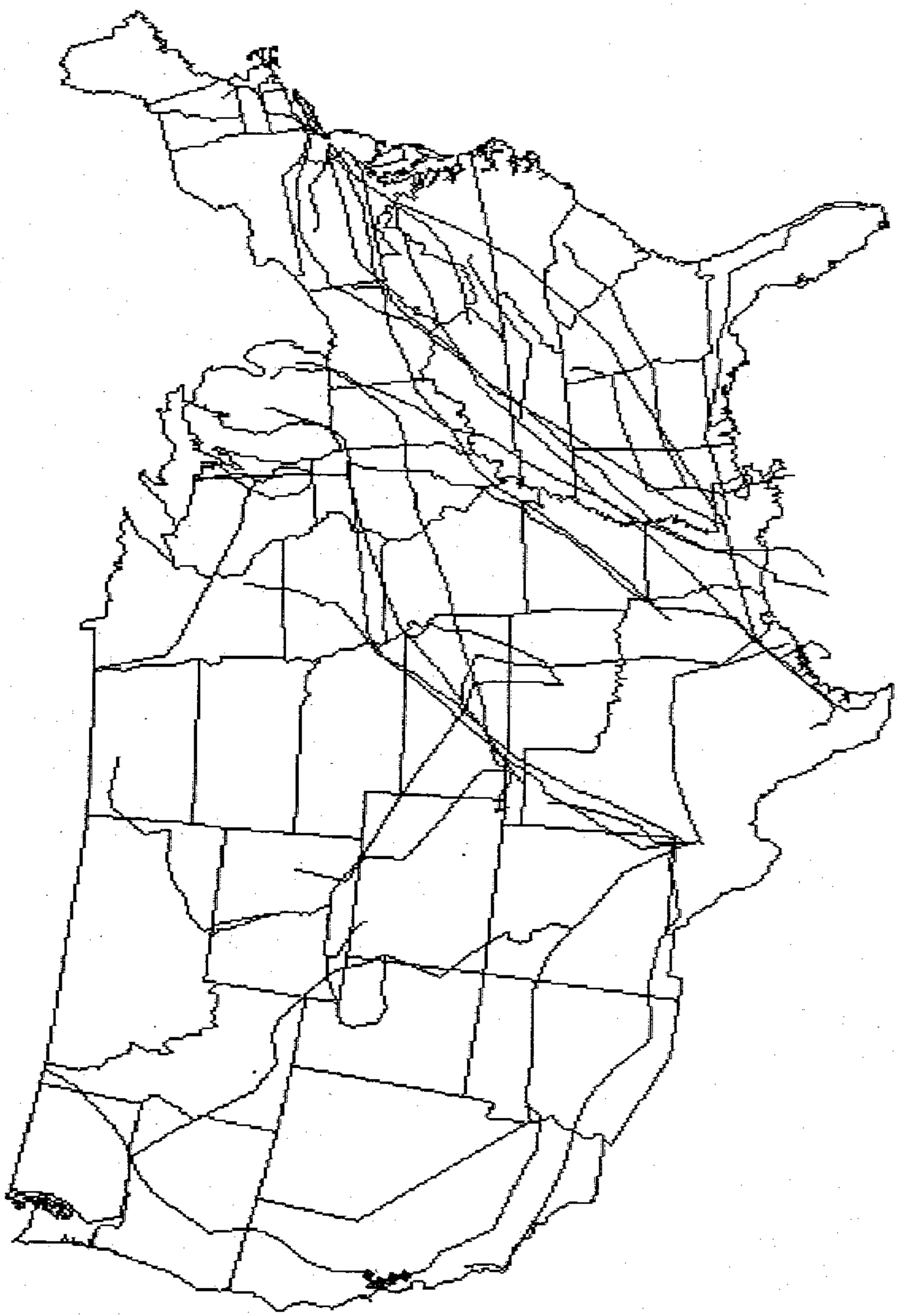


Figure 5-33 *Damage to natural gas system following Hayward event (M=7.5). Broken pipelines are shown with solid diamonds.*

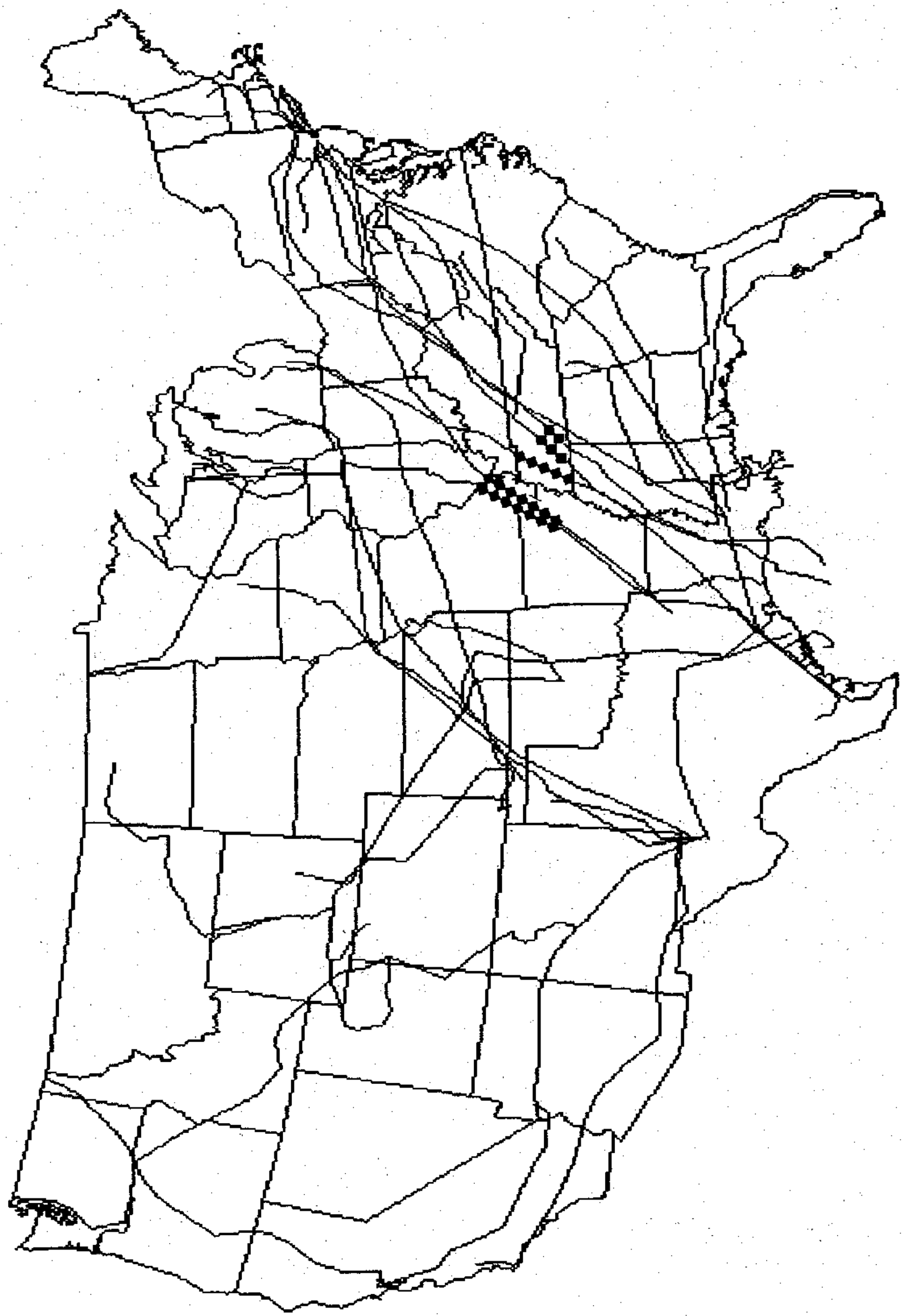


Figure 5-34 *Damage to natural gas system following New Madrid event (M=8.0). Broken pipelines are shown with solid diamonds.*

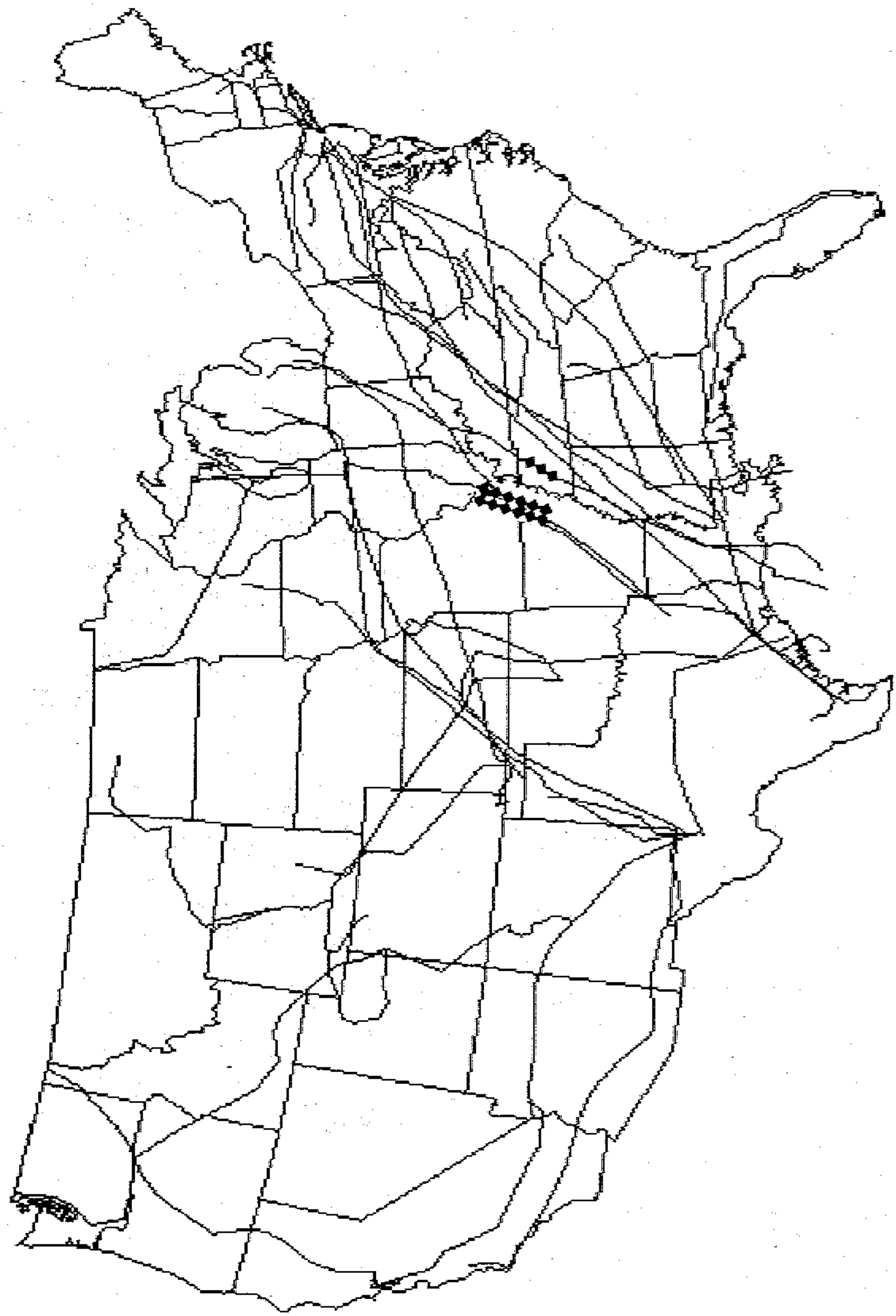


Figure 5-35 *Damage to natural gas system following New Madrid event (M=7.0). Broken pipelines are shown with solid diamonds.*

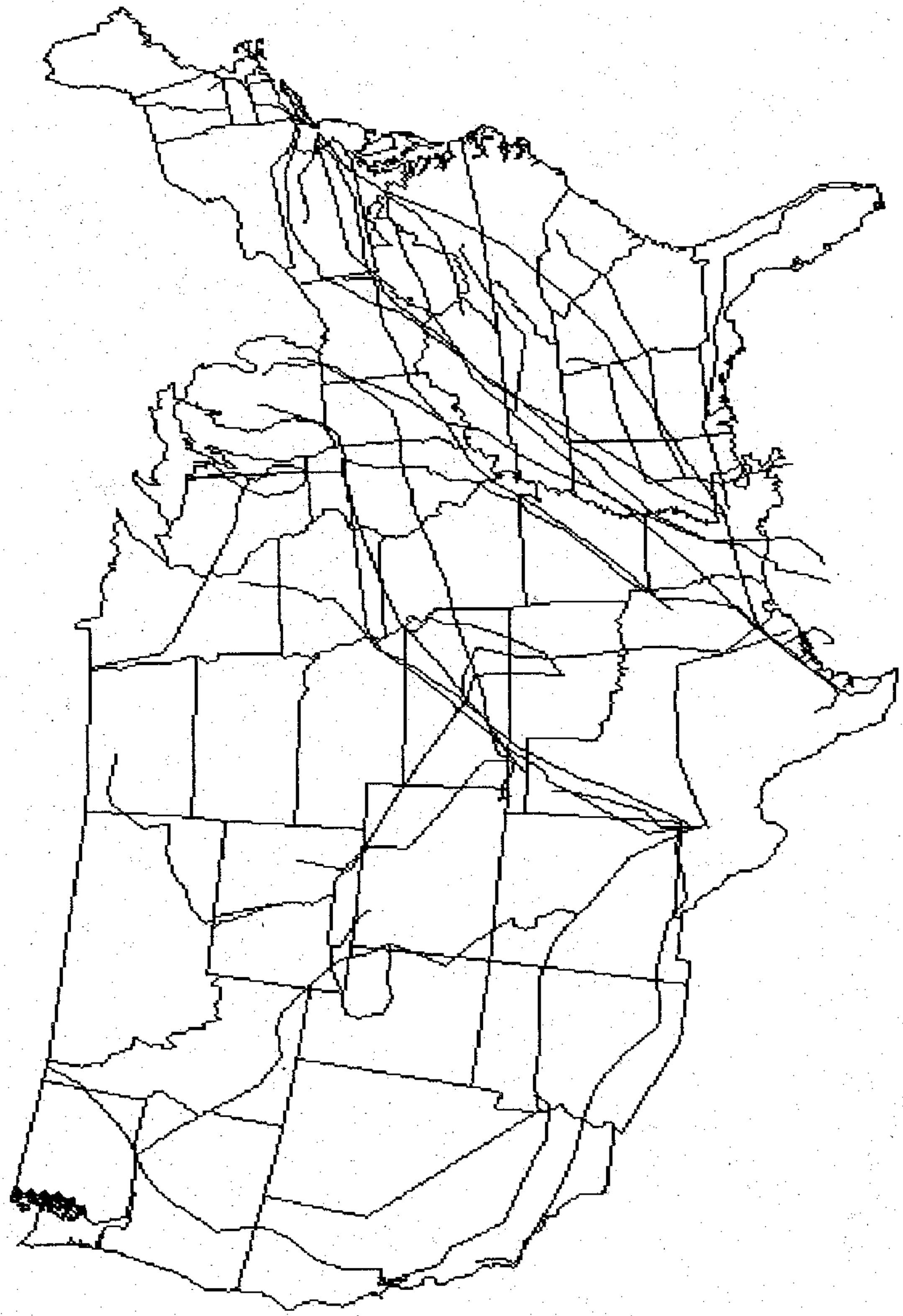


Figure 5-36 *Damage to natural gas system following Puget Sound event (M=7.5). Broken pipelines are shown with solid diamonds.*

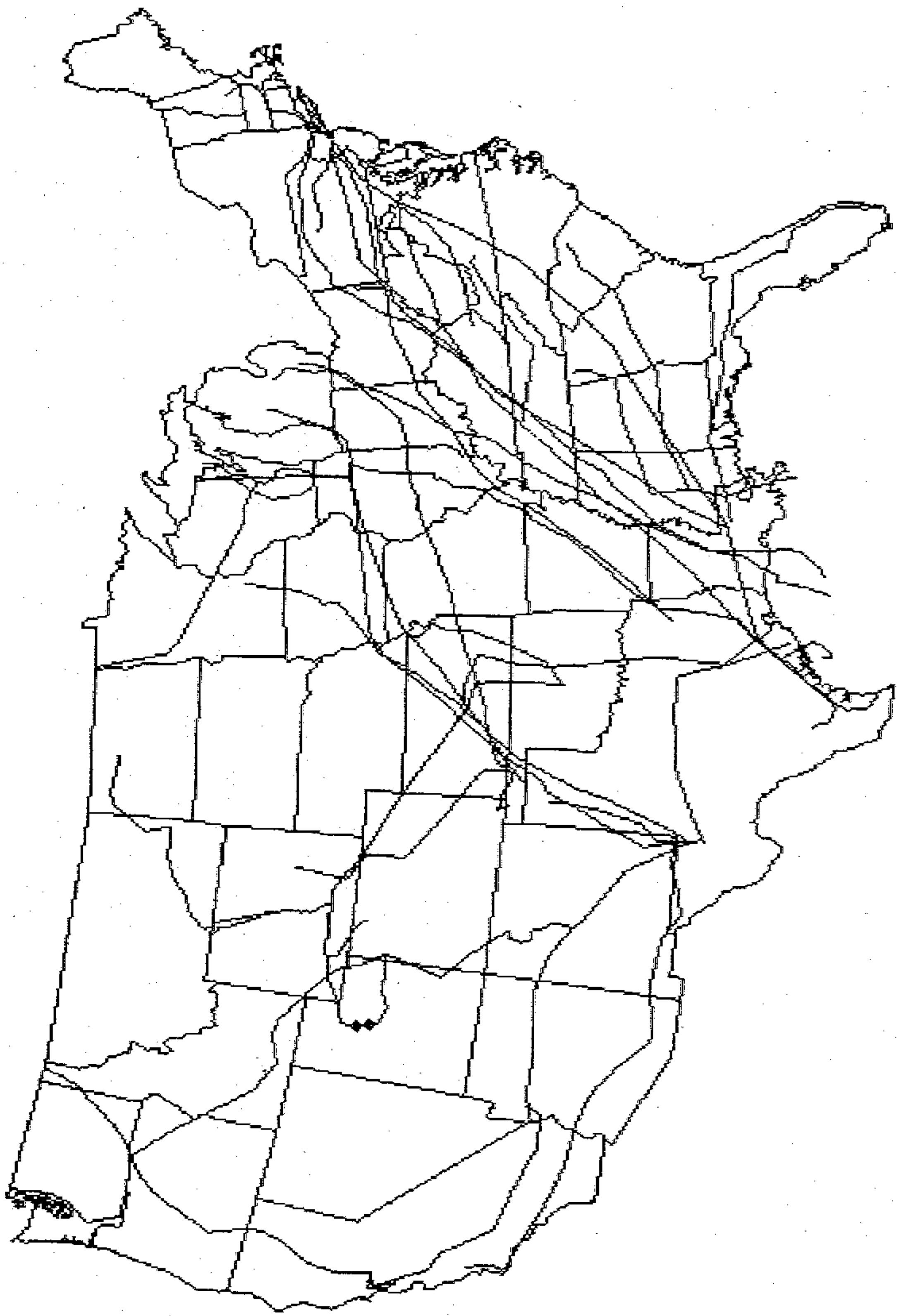


Figure 5-37 *Damage to natural gas system following Wasatch Front event. Broken pipelines are shown with solid diamonds.*

Summaries of dollar loss estimates for direct damage to site-specific systems and extended regional lifeline networks during the eight scenario earthquakes are provided in Table 5-14. Estimated dollar losses due to direct damage to local electric, water, and highway distribution systems are provided in Table 5-15. We note that damage distribution dollar loss estimates for direct damage to local distribution systems were estimated using cost data from Table 5-13 and damage curves from Appendix B for electric distribution lines, local roads, and water trunk lines. Intensities were estimated at the center of the Standard Metropolitan Statistical Areas, assuming the distribution systems were lumped at these locations.

The estimates provided in Tables 5-14 and 5-15 are based on the available inventory data and other assumptions and models described in this report. As a result, the accuracy of these estimates may vary from lifeline to lifeline. Estimates for electric systems, in particular, are believed to be more sensitive to the lack of capacity information than are the other lifelines.

By combining the data from Tables 5-14 and 5-15, we estimate the total direct damage dollar losses (in billions of U. S. dollars) for the eight scenario earthquakes as follows:

Earthquake	Direct Dollar Loss (in Billions, 1991$)
Cape Ann	$4.2
Charleston	$4.9
Fort Tejon	$4.9
Hayward	$4.6
New Madrid, M = 8.0	$11.8
New Madrid, M = 7.0	$3.4
Puget Sound	$4.4
Wasatch Front	$1.5

5.6 Comparison with Previous Studies

The foregoing presents a methodology and results for understanding the direct damage impacts of earthquakes on U.S. lifelines. No previous study has examined lifelines in comparable breadth or scale, so that comparisons are difficult. Several studies have examined the effect of earthquakes on lifelines for various regions, including:

- Earthquake Vulnerability Analysis of the Charleston, South Carolina Area (Citadel, 1988),
- Earthquake Planning Scenario for a Magnitude 7.5 Earthquake on the Hayward Fault in the San Francisco Bay Area (Steinbrugge et al., 1987) (representative of several studies in California, including others for the Newport Inglewood Fault Zone, the San Andreas Fault in northern and southern portions of California (e.g., Davis et al., 1982),
- A study of the Wasatch Front, Utah, water and gas systems (Taylor, Wiggins, Harper and Ward, 1986), and
- A pilot study on vulnerability of crude oil transmission systems in the New Madrid area (Ariman, et al., 1990).

Compared to the present study, these previous studies were typically limited in being either confined to one or a few lifelines, qualitative rather than quantitative, and/or geographically localized. Nevertheless, to the extent possible, comparison of this study's results with that of previous studies is of value, in order to compare each aspect of the methodology. The Charleston, South Carolina study is recent, probably the most comprehensive of the studies in scope, and provides quantitative results. We therefore next examine that study and its results, vis-a-vis this study.

Comparison with a study on the Charleston event. Researchers at The Citadel, the Military College of South Carolina, estimated damage to critical facilities and other resources in the epicentral region, assuming a repeat of the 31 August 1886 Charleston event. The study region comprised three counties of the Charleston, South Carolina area: Charleston County, Berkeley County, and Dorchester County. The Citadel analysis and conclusions appear in *An Earthquake Vulnerability Analysis of the Charleston, South Carolina, Area*, of July 1988. Their methodology relied significantly upon ATC-13 procedures, so The Citadel study and the present study take comparable approaches and use similar classifications for structures and

Table 5-14 Direct Damage Losses ($ Millions)

Scenario	Highways	Electric	Fire Stations	Broadcasting Station	Medical Care	Ports	Airports	Railroads	Natural Gas	Refined Oil	Crude Oil	Water	Total
Cape Ann	$382	$1,312	$6	$19	$490	$53	$91	$9	$0	$0	$0	$	2,362
Charleston	$773	$1,264	$9	$68	$565	$380	$142	$156	$0	$0	$0	$	$3,358
Fort Tejon	$470	$886	$48	$26	$1,431	$170	$148	$158	$11	$0	$28	$140	3,517
Hayward	$208	$1,310	$7	$17	$1,297	$115	$37	$115	$6	$0	$0	$91	3,203
New Madrid 8	$2,216	$2,786	$13	$91	$1,297	$0	$411	$458	$56	$28	$47	$	$7,403
New Madrid 7	$204	$1,077	$3	$34	$396	$0	$145	$108	$19	$9	$19	$	2,013
Puget Sound	$496	$1,834	$13	$49	$507	$196	$210	$96	$6	$0	$0	$18	3,425
Wasatch Front	$323	$90	$2	$44	$205	$0	$29	$31	$6	$0	$0	$	730

Table 5-15 Direct Losses Due to Damage to Distribution Systems

Event	Electric $ Billion	Water $ Billion	Highways $ Billion
Cape Ann	$0.89	$0.30	$0.60
Charleston	0.74	0.31	0.50
Fort Tejon	0.91	0.23	0.23
Hayward	0.90	0.20	0.25
New Madrid (M=8.0)	2.07	0.88	1.40
New Madrid (M=7.0)	0.65	0.28	0.44
Puget Sound	0.58	0.09	0.28
Wasatch Front	0.38	0.13	0.26

structural damage. The Citadel researchers studied direct damage to lifelines, as well as to housing, schools, and other components of the built environment in the three county area, but they did not investigate economic impacts as the current study does.

The following sections compare the assumptions and conclusions of the current study with those of The Citadel researchers. Note that the current study provided aggregate damage for the whole of South Carolina, and damage is not broken out by county, as it is in The Citadel study. Nonetheless, since the three counties enclose the bulk of the damaged South Carolina lifelines, the results should be comparable. The first section compares the scenario earthquake assumed by the two studies. The second section compares the results of the direct damage analyses for lifelines.

Scenario Earthquake. The Citadel researchers employed more severe ground shaking than the current study's use of the Evernden Model produced for the same event. The Citadel posted MMI IX to MMI X ground shaking within 25 miles of the epicenter, MMI VII to MMI VIII ground shaking within a 100 mile outer radius, and MMI VI or less ground shaking beyond this. This agrees well with a *broad* regional isoseismal map based on the historical record presented by Bollinger (1977). This broad map was developed by enveloping a detailed map also developed by Bollinger (1977) (i.e., the broad map was developed by the maximum MMI within a region taken from the detailed map, and using that as the MMI value for the broad map--both maps are presented in Figure 4-6). The Evernden Model used in the current study provided estimates of ground shaking on a detailed scale similar to that of the detailed map by Bollinger. In the Evernden model, MMI contours were calculated on a 25 km square basis. These contours agree fairly well with the detailed isoseismal map Bollinger presented. As a consequence of these interpretations of seismic intensity, differing results of The Citadel study tend to reflect the more conservative (i.e., higher) ground shaking estimates by generally more severe damage estimates.

Estimated Lifeline Damage. Both studies evaluated direct damage to a number of common lifeline elements. This section compares the two studies' results for direct damage to hospitals, fire stations, police stations, railroads, and electric transmission substations.

- **Hospitals.** The Citadel researchers inventoried 11 facilities in the three counties, in which 14% of the entire state population lives. They estimated a 43% probable maximum loss to hospitals, and a 21% average expected loss. The current study inventoried 91 health care facilities in South Carolina, and estimated 27 facilities would sustain light damage (damage between 1% and 10%), 6 facilities would sustain moderate damage (damage between 10% and 30%), 9 facilities would sustain heavy damage (damage between 30% and 60%) and 3 facilities would sustain major to destructive damage (damage between 60% and 100%). These figures represent an average gross dollar damage of 10%. Note that this 10% figure reflects damage to all health care facilities in South Carolina. It is to be expected that statewide average damage should be significantly less than damage within the epicentral region, which The Citadel's 21% figure reflects.

- **Airports.** The Citadel researchers inventoried 5 facilities in the three counties. They estimated functionality for operational pavements such as runways and taxiways, and for key operational vertical structures such as control towers and terminals. For runways and taxiways, The Citadel researchers estimated 30% functionality within 1 day, 60% functionality within 3 days, and full functionality within 8 days. For vertical structures, The Citadel researchers estimated 60% functionality within 2 days, and full functionality within 2-1/2 weeks. The current study inventoried 147 facilities in South Carolina, It estimated 59% functionality of South Carolina airports during the first week, 85% functionality during the second week, and full restoration during the tenth week. The present study also evaluated damage to airports as individual units, including structures and pavements, finding 49 facilities would sustain light damage, 29 facilities would sustain moderate damage, and 9 facilities would sustain major damage.

- **Fire Stations.** The Citadel researchers inventoried 55 facilities in the three counties. They estimated a 71% probable maximum loss, and a 36% expected loss. The current study estimated 275 South Carolina facilities; 50 are expected to sustain light damage (1% to 10%), 3 are expected to sustain moderate damage (10% to 30%), and 36 are expected to sustain heavy damage (30% to 60%). These figures represent an average 7% damage.

- **Police Stations.** The Citadel researchers inventoried 10 facilities in the three counties. They estimated a 69% probable maximum loss, and a 34% expected loss. The current study estimated 70 South Carolina facilities, and estimated that 10 would sustain light damage (1% to 10%), 1 would sustain moderate damage (10% to 30%), and 8 would sustain heavy damage (30% to 60%). These figures represent an average 6% damage.

- **Railroad.** The Citadel researchers inventoried 196 miles of track in the three counties. They estimated 1 mile of track would sustain 1% damage or less, 145 miles would sustain 1-to-10% damage, and 50 miles of track would sustain 10-to-30% damage. These figures would indicate an average 9% damage to railroad track in the three counties. The current study inventoried approximately 1500 miles of track in South Carolina, and estimated 550 miles of track would sustain light damage (1% to 10%), 52 miles would sustain moderate damage (10-to-30%), and 600 miles would sustain heavy damage (30-to-60%). These figures represent an average damage of 20% to South Carolina railroad track following a Charleston event. (This is a simple measure of track damage and should not be confused with residual capacity figures, which follow on network analyses (see Chapter 6)). This difference may be explained by the significant damage to railroad track outside the three counties.

- **Electric Transmission Substations.** The Citadel researchers estimated 20% of substations in the three county area would sustain light damage, 70% of substations would sustain moderate damage, and 10% of substations would sustain heavy damage. If one defines light damage as an average 5% damage, moderate damage as an average 20% damage, and heavy damage as an average 45% damage, average expected damage to transmission substations for The Citadel study would be 20%. The present study inventoried 100 substations in South Carolina, and estimated 43% sustain moderate damage (10-to-30%), 14% sustain heavy damage (30-to-60%), and 16% sustain major damage (60-to-100%). These figures represent an average 28% damage to South Carolina transmission substations following a Charleston event. The present study estimated average damage in excess of that estimated by The Citadel. An explanation can be found in that The Citadel study considered transmission and distribution substations, while the present study considered only transmission substations. Transmission substations typically sustain more damage than distribution substations; also substations outside the three counties are significantly damaged. (Note that the average damage discussed here is a simple measure of substation damage and should not be confused with residual capacity figures, which rely on network analyses (see Chapter 6).)

- **Bridges.** The Citadel researchers inventoried 3 major bridges and 216 conventional bridges in the three counties. They estimated "serious damage" to 10 bridges, "repairable damage" to 24 bridges, and "settlement damage" to 51 bridges. They defined "serious damage" as collapse of at least one span. "Repairable damage" means that the bridge could be restored within weeks, and "settlement damage" means damage to abutments. The current study inventoried 2134 bridges in South Carolina and estimated 320, 320, 128, and 20 bridges, respectively, would sustain light damage(damage between 1 and 10%), moderate damage (damage between 10 and 30%), heavy damage (damage between 30 and 60%), and major damage (damage between 60 and 100%). The current study provide an aggregate damage of about 7% for the entire state compared to about 6% given by the Citadel researchers study for the three counties. This difference may be explained by the finding that damage to bridges outside the three counties is expected to be significant.

Conclusion. The present study estimated damage between 1/2 and 1/5th of that estimated by The Citadel study in every classification except transmission substations, railroads, and bridges. These ratios seem reasonable. The Citadel researchers examined damage in a three-county epicentral region alone; while the present study considered South Carolina as a whole. One would expect average damage over the entire state to be substantially lower than average damage in the epicentral region. The exception, transmission substations, railroads, and bridges, were discussed above.

6. Estimates of Indirect Economic Losses

6.1 Introduction

Earthquakes produce both direct and indirect economic effects. The direct effects, such as dollar loss due to fires and collapsed structures, are obvious and dramatic. However, the indirect effects that these disruptions have on the ability of otherwise undamaged enterprises to conduct business may be quite significant. Although the concept of seismic disturbances and their effect on lifelines has been investigated for at least two decades, there is very little literature on indirect economic losses (Cochrane, 1975; Rose, in ASCE-TCLEE, 1981; Scawthorn and Lofting, 1984).

This study provides a first approximation of the indirect economic effects of lifeline interruption due to earthquakes. To accomplish this the relevant literature was surveyed. Then a methodology was developed to relate lifeline interruption estimates to economic effects of lifeline interruption in each economic sector. This required a two-step process:

1. Development of estimates of interruption of lifelines as a result of direct damage
2. Development of estimates of economic loss as a result of lifeline interruption

The general analytical approaches used to develop these estimates are discussed below and illustrated with example calculations. Results defining lifeline interruption and associated economic loss to specific facility types are also provided, but the bulk of this information is given in Appendices C and D. The chapter concludes with regional summaries of economic effects resulting from direct damage to the various lifelines in the eight scenario earthquakes.

6.2 General Analytical Approach for Estimating Lifeline Interruption

Lifeline interruption resulting from direct damage is quantified in this investigation in residual capacity plots that define percent of function restored as a function of time. The curves are estimated for each lifeline type and scenario earthquake using (1) the time-to-restoration curves discussed in Chapter 3 and provided in Appendix B, (2) estimates of ground shaking intensity provided by the seismic hazard model (from Chapter 4), and (3) inventory data specifying the location and type of facilities affected (from Chapter 2).

For site-specific systems (i.e., lifelines consisting of individual sited or point facilities, such as airports or hospitals) the time-to-restoration curves are used directly whereas for extended regional networks, special analysis procedures are used. These procedures consist of:

- connectivity analyses, and
- serviceability analyses.

Connectivity analyses measure post-earthquake completeness, "connectedness," or "cut-ness" of links and nodes in a network. Connectivity analyses ignore system capacities and seek only to determine whether, or with what probability, a path remains operational between given sources and given destinations.

Serviceability analyses seek an additional valuable item of information: If a path or paths connect selected nodes following an earthquake, what is the remaining, or residual, capacity between these nodes? The residual capacity is found mathematically by convolving lifeline element capacities with lifeline completeness.

A complete serviceability analysis of the nation's various lifeline systems, incorporating earthquake effects, was beyond the scope of this project. Additionally, capacity information was generally not available for a number of the lifelines (e.g, for the highway system, routes were available, but not number of lanes). Rather, for this project, a limited serviceability analysis has been performed, based on a set of simplifying assumptions.

The fundamental assumption has been that, on average, all links and nodes of a lifeline have equal capacities, *so that residual capacity has* *serviceable (i.e., surviving) links and nodes to the original number of serviceable links and nodes, for a given source/destination pair, or across some appropriate boundary.* For example, if the state of South Carolina has 100 airports, and 30 of these are determined to be unserviceable at some point in time following a major earthquake, then the air transport lifeline residual capacity is determined to be 70% of the initial capacity.

This assumption does not consider several important factors, including:

1. All nodes or links do not have the same capacities;

2. Links and nodes contributing most to the residual capacity are generally more distant from the heavily damaged area. Thus, the estimated lifeline residual capacity is generally overestimated in the area closest to the disaster area; and

3. Significant elasticity in capacity is generally available for most lifelines.

Factors 2 and 3 tend to offset each other. Further, factor 1 is probably acceptable for the purposes of this project, which aims to describe effects at the regional level.

The foregoing mode of analysis was employed for most of the regional network lifelines. One exception was the gas and liquid fuel transmission pipelines, where capacities were available and were employed, thus taking into account factor 1 above.

6.3 Residual Capacity Analysis of Site-Specific Systems

As indicated above, residual capacities for site specific lifelines were estimated using the restoration curves from Appendix B. For many of these facilities, only locational information was available (i.e., size or capacity information was not available). Because of this limitation, and because the general goal of this study was to determine impacts at the transmission or regional level (an approach that tends to average out differences in facility capacities), an assumption that all facilities of a particular class have the same capacity was often employed.

Using the curves provided in Appendix B, residual capacity was defined in "lifeline interruption plots" that define restoration in one-week-interval step functions. Initially, these step functions were computed for each facility in a region, and then averaged over all facilities of the same type in the region using the following equation:

$$R.C_j = \sum_{i=1}^{N} (C_i \, x \, R_i) / \sum_{i=1}^{N} C_i \qquad (6.1)$$

where $R.C_j$ is the residual capacity at time step j, C_i is the capacity of facility i, and R_i is the restoration of facility i at time step j. If all facilities have the same capacity, Equation 6.1 becomes

$$R.C_j = \sum_{i=1}^{N} R_i / N \qquad (6.2)$$

where N is the number of facilities. This calculation is illustrated in Example 6.1 (Figure 6-1).

Following is a discussion of results from the residual capacity analysis of each site-specific lifeline facility type considered in this investigation.

6.3.1 *Airports*

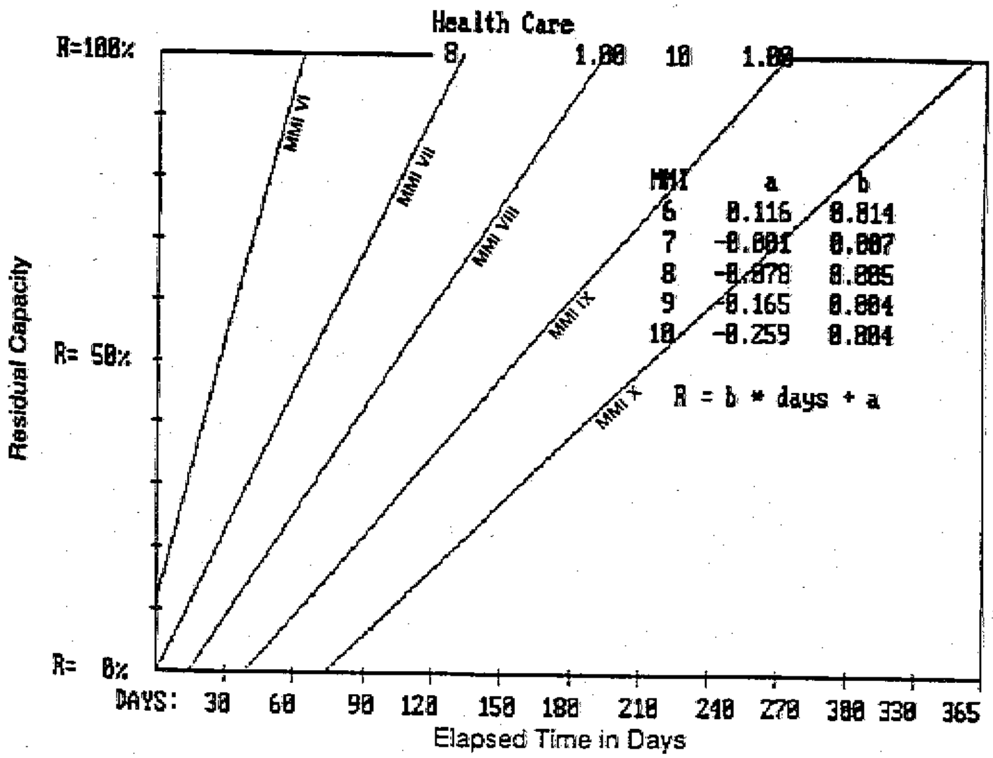
Residual capacities for airports were calculated assuming that all airports have the same capacity and the functionality of airports depends 20% on terminals and 80% on runways. The simplifying assumption that all airports have similar capacities is warranted due to the analysis seeking to determine regional air transport impacts, an approach that tends to average out extremes in airport capacities. Further rationales for this approach include: (1) the large number of general and civil aviation airports, (2) the relatively small difference in number of runways between many airports, (3) many runways have lengths sufficient for large commercial aircraft, (4) under emergency conditions, air traffic control capacity can be rapidly and significantly increased by deploying specialized military units, (5) airport through-put capacity is extremely elastic (under emergency conditions small airport cargo handling capacity can be significantly increased

Example 6.1

This example illustrates the residual capacity calculation algorithm for point source systems, using health care centers in Illinois as an example.

Assume that Illinois, located in "all other areas" of the NEHRP Map, has four health care centers. A scenario earthquake is estimated to result in shaking intensities at the four locations of MMI=5, 6, 7, and 8, respectively. Assume that no liquefaction hazard exists at the four sites. Estimate residual capacity at 0 days, 7 , 14 , 21 , 28 , and 196 days (the latter being the point of full restoration).

Procedure. Use the time-to-restore curve (below) for health care facilities (from Appendix B) for "all other areas" to determine the residual capacity at each health care facility.



This figure indicates residual capacities as follows:

	MMI	Elapsed time (days) 0	7	14	21	28	196
Facility 1	5	100%	100%	100%	100%	100%	100%
Facility 2	6	12%	21%	31%	41%	51%	100%
Facility 3	7	0%	5%	10%	15%	20%	100%
Facility 4	8	0%	0%	0%	3%	6%	100%
Average		**28%**	**32%**	**35%**	**40%**	**44%**	**100%**

The last row in the table provides the residual capacity of the example health care centers in Illinois, assuming that all facilities have the same capacity (i.e., per equation 6.4).

Figure 6-1: Analysis example illustrating residual capacity calculation algorithm for point source systems by staging cargo off-site, and apron space restrictions can be worked around through scheduling and staging aircraft at other airports).

Average residual capacity values over all airports in a given state at each time step were calculated using Equation 6.2. An example plot for Arkansas, one of the worst-case situations, is provided in Figure 6-2. In this example, the initial loss is approximately 31 percent of capacity, and full capacity is not restored until about day 290. Results for each state are plotted in Appendix C for each scenario earthquake (Figures C-1 through C-24). These data indicate that, of all the regional scenario events, the greatest impacts occur in the states of Arkansas, Mississippi, and Tennessee as a result of the New Madrid magnitude-8.0 event (Figures C-3, C-4, C-6). The states of Washington, Massachusetts, South Carolina, Utah, and California would experience the largest impacts due to the Seattle, Cape Ann, Charleston, Utah, and Fort Tejon, scenario events, respectively (Figures C-7, C-10, C-15, C-17, and C-18).

6.3.2 *Ports*

Residual capacities of Ports for all scenario events are presented in Figures C-25 to C-33. An example plot for South Carolina, the worst-case situation, is provided in Figure 6-3. In this example, the initial loss is nearly 100 percent of capacity, and full capacity is not restored until about day 200. Georgia would also experience similarly high losses due to the Charleston event (Figure C-27). Massachusetts and Rhode Island would experience the largest losses due to the Cape Ann event (Figures C-28 and C-29).

6.3.3 *Medical Care Centers*

Residual capacities of medical care centers were calculated using Equation 6.2 and are shown in Appendix C, Figures C-34 through C-57 for all states affected by all scenario events. All medical care centers were assumed to have the same capacity. One of the worst-case situations would occur in Arkansas for the New Madrid magnitude-8.0 earthquake (Figure 6-4). Similar long-term recovery periods are required in California for the Fort Tejon event (Figure C-51), South Carolina, for the Charleston event (Figure C-41), and in Washington, for the Puget Sound event (Figures C-52). Note also the initial high loss in capacity for medical care facilities in Massachusetts for the Cape Ann event (Figure C-44).

6.3.4 *Fire Stations*

Based on the assumption that fire stations have an average capacity, residual capacities of fire stations within the affected states were calculated using Equation 6.2, assuming that all fire stations are lumped at the center of Standard Metropolitan Statistical Areas (SMSAs). Results are presented in Figures C-58 through C-81. One of the worst case situations, which occurs in South Carolina as a result of the Charleston scenario event, is shown in Figure 6-5.

6.3.5 *Police Stations*

Residual capacities of police stations were calculated using Equation 6.2, assuming that all police stations have the same capacity and that stations were lumped at the center of the SMSAs. Results are presented in Appendix C, Figures C-82 to C-101, for all states affected by the scenario events. These plots indicate that, as in the case of fire stations, one of the worst-case situations occurs in Mississippi as a result of the New Madrid magnitude-8.0 scenario event (Figure 6-6).

6.3.6 *Broadcast Stations*

Based on the assumption that all broadcast stations have the same capacity, residual capacities within the affected states were calculated using Equation 6.2. For this facility type, the worst case situation occurs in South Carolina as a result of the Charleston event (Figure 6-7). See Appendix C, Figures C-102 to C-126, for plots of results for all eight scenarios and affected states.

6.4 Residual Capacity Analysis of Extended Regional Networks

In this investigation, residual capacity of extended regional networks (e.g., crude and refined oil pipelines; highways) has been estimated through the following sequence of operations:

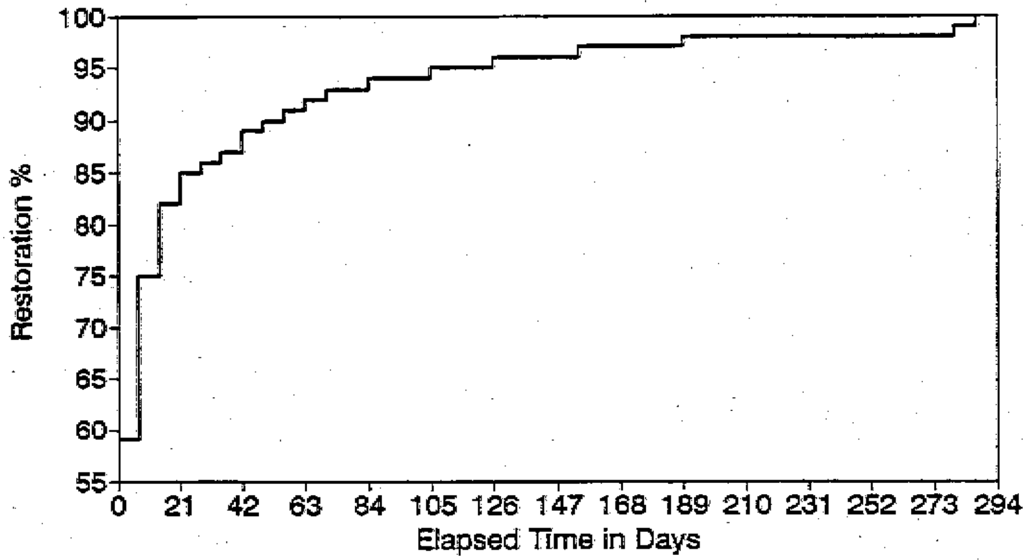


Figure 6-2 *Residual capacity of Arkansas air transportation following New Madrid event (M=8.0).*

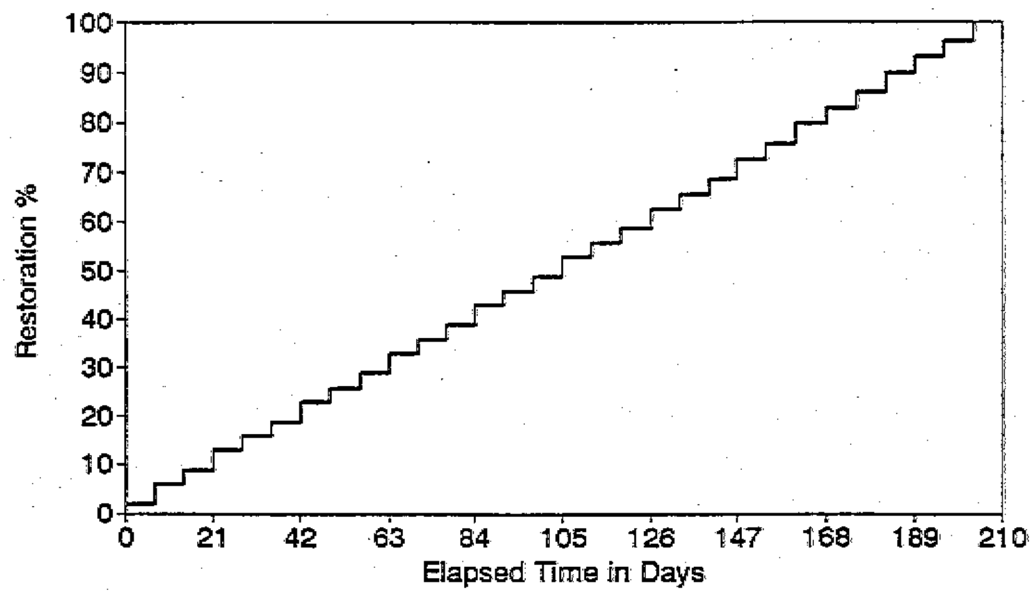


Figure 6-3 *Residual capacity of South Carolina ports following Charleston event (M=7.5).*

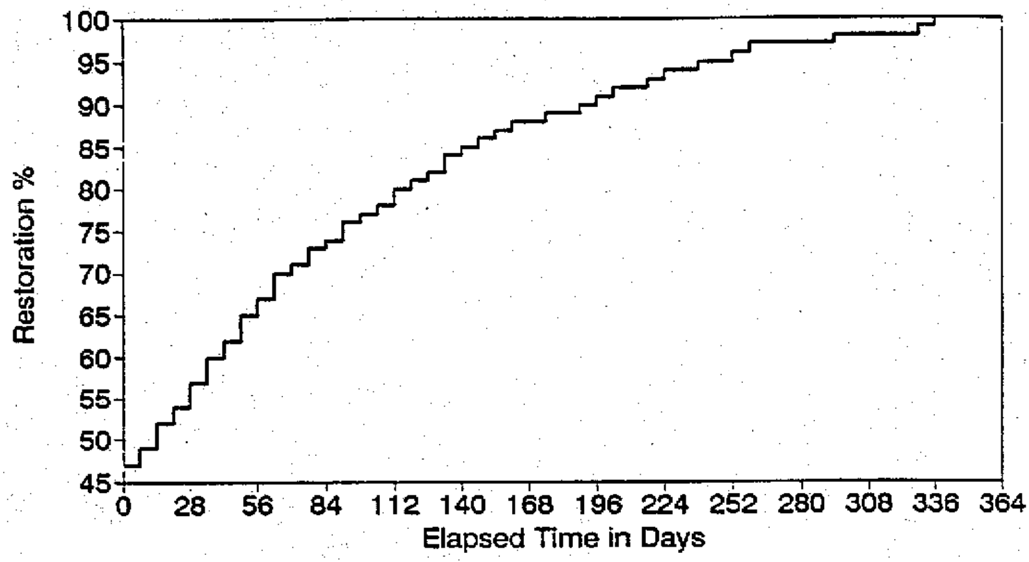


Figure 6-4 *Residual capacity of Arkansas medical care centers following New Madrid event (M=8.0).*

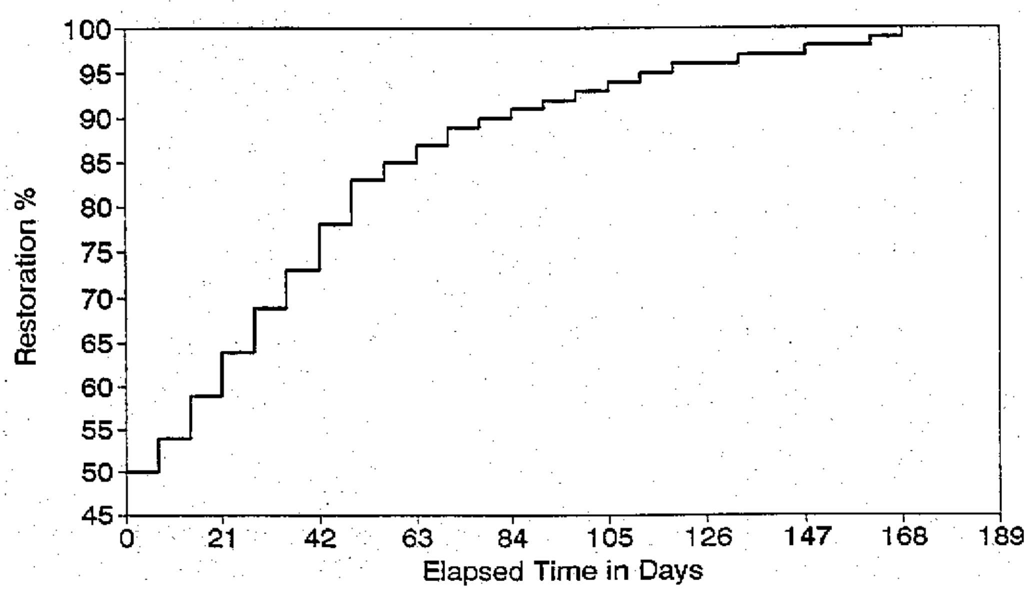


Figure 6-5 *Residual capacity of South Carolina fire stations following Charleston event (M=7.5).*

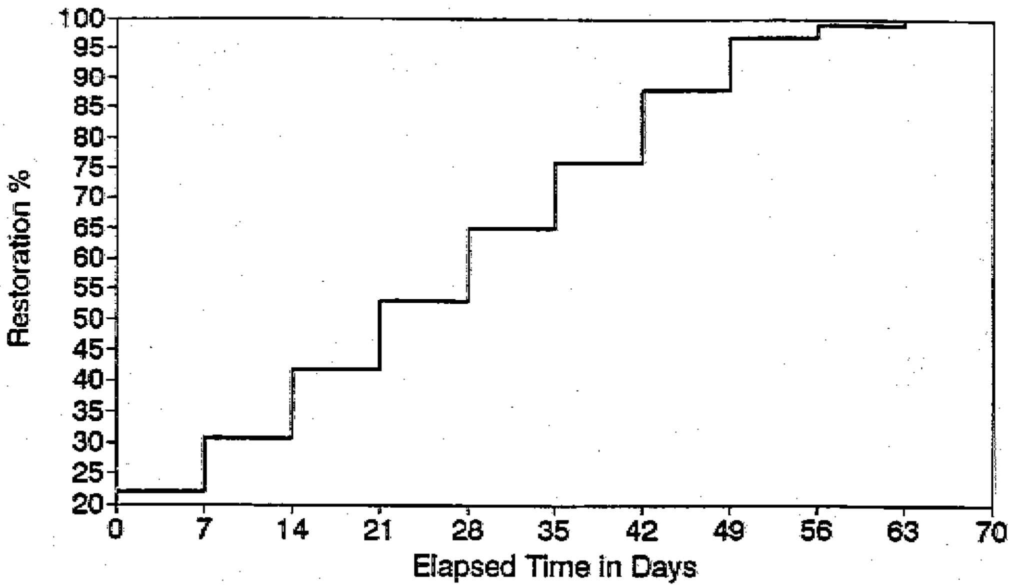


Figure 6-6 *Residual capacity of Mississippi police stations following New Madrid event (M=8.0).*

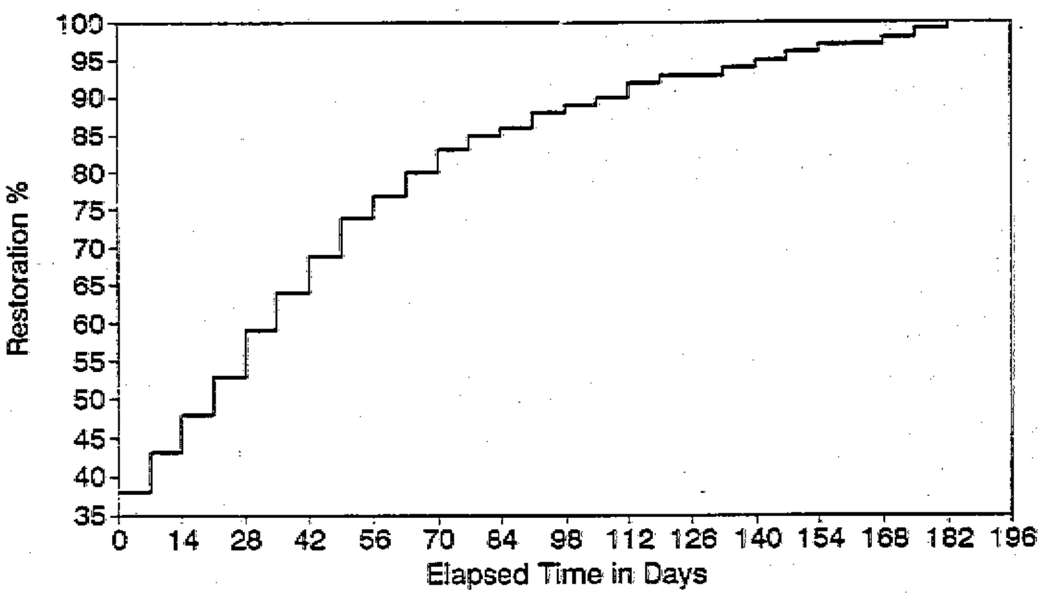


Figure 6-7 *Residual capacity of South Carolina broadcast stations following Charleston event (M=7.5).*

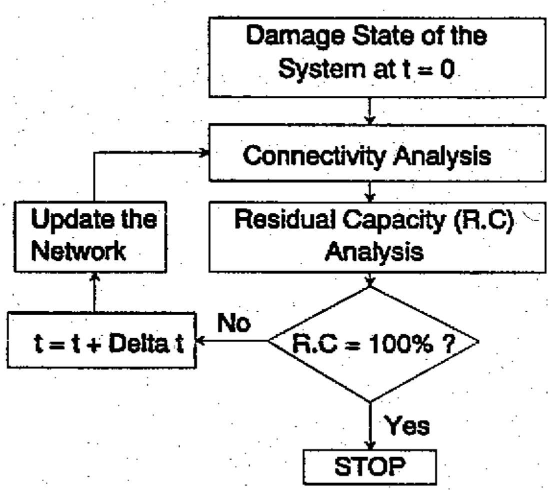
1. Maximum damage for every link in the network was first estimated using the procedures described in Chapter 5.

2. Connectivity analyses were then performed to identify nodes and links that are not connected to the source(s).

3. And finally, serviceability analyses were performed to determine residual capacity of the network as a whole, considering both damaged and undamaged links and nodes.

The networks are assumed to consist of sets of nodes and sets of links connecting these nodes. If a link has a direction, it is called a directed link; otherwise it is called an undirected link. A path is a sequence of nodes and links. The links can be directed in either direction (two-way links) or directed in one direction (one-way links).

Following is a flow chart showing the sequence of operations:



Connectivity Analyses. Connectivity analyses were performed using a technique called Depth-First-Search, or Backtracking (Tarjan, R., 1972). In this method, a network is connected if for every partitioning of the nodes of the network into subsets Y1 and Y2, there is either a link (i-j) or (j-i) between node $i \varepsilon Y1$ and node $j \varepsilon Y2$, where ε denotes membership.

For pipeline systems (crude oil and refined oil pipelines), pipeline sections (node-to-node) with probability of failure (i.e., probability of having at least one break) equal to or greater than about 60% were assumed to be closed until 100% restored. For natural gas systems, pipeline sections with probability of failure equal to or greater 30% were assumed closed until 100% restored. Bridges with more than 15% damage were also assumed out of service until fully restored.

Serviceability Analyses. Residual capacities between sources and destinations were estimated using the minimum-cut-maximum-flow theorem (Ford and Fulkerson, 1962; Hu, 1969; and Harary, 1972) which is the central theorem in network flow theory. This approach was generalized for this project to account for multiple-source multiple-destination problems.

The minimum-cut-maximum-flow theorem simply searches for the cut with the minimum capacity, i. e., the bottleneck, that completely separates the sources from the destinations. That is to say, the maximum flow in a network is always equal to the capacity of the cut that provides the minimum capacity of all cuts separating the source(s), S, and the destination(s), D.

A cut is defined by (Y1,Y2), where Y1 is a subset of nodes of the network and Y2 is its complement (i.e., the remaining subset of nodes). A cut (Y1,Y2) is a set of links (i-j) with either the node $i \varepsilon Y1$ and $j \varepsilon Y2$ or $j \varepsilon Y1$ and $i \varepsilon Y2$. Therefore, a cut is a set of links the removal of which will disconnect the network. A cut separating the source, S, and the destination, D, is a cut (Y1,Y2) with $S \varepsilon Y1$ and $D \varepsilon Y2$.

The capacity of a cut (Y1,Y2), denoted by C(Y1,Y2), is Σc_{ij} with $i \varepsilon Y1$ and $j \varepsilon Y2$, where c_{ij} is the capacity of the link (i-j). Note that in defining a cut, we count all the arcs that are between the set Y1 and the set Y2, but in calculating its capacity we count only the capacity of links from Y1 to Y2, but not the one way links from Y2 to Y1. i.e. C(Y1,Y2) not equal C(Y2,Y1). The cut with the minimum capacity is called the minimum cut.

For example, consider the network in Figure 6-8. Assume that all links are two way links, and that the numbers next to each link represent the capacity of that link. The set Y1 defined above consists of nodes S and 2, while the set Y2 consists of nodes 1 and D. The cut shown in Figure 6-8 is a minimum cut and has the capacity $C(Y1,Y2)= c_{S1}+c_{2D}=2+4= 6$, which

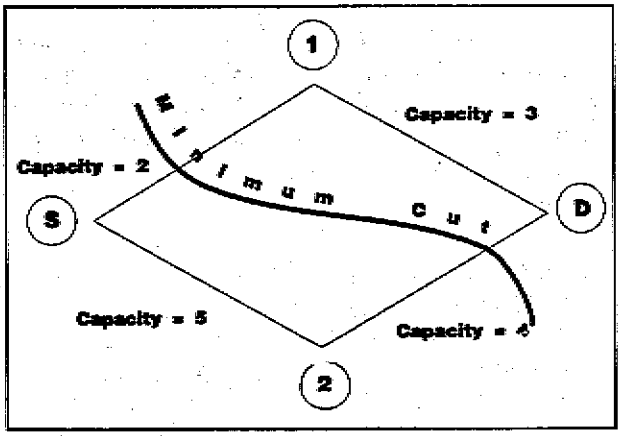


Figure 6-8 *Flow network to illustrate minimum-cut-maximum flow Theorem.*

is the maximum flow that can be delivered between the source S and the destination D.

The maximum flow is a linear programming problem with the objective function

$$Q = \Sigma X_{ij} \tag{6.3}$$

and the constraints

$$\begin{aligned} X_{ij} - X_{jk} &= -Q \text{ if } j = S \\ &= 0 \text{ if } j <> S \text{ or } D \qquad (6.4) \\ &= Q \text{ if } j = D, \end{aligned}$$

and

$$0 < X_{ij} < c_{ij} \quad \text{for all } i,j \tag{6.5}$$

where Q is the out flow value and X_{ij} is the flow in link (i-j). Equation 6.4 expresses conservation of flow at every node, and Equation 6.5 states that the link flow X_{ij} is always bounded by link capacity c_{ij}.

To apply the maximum flow theorem, sources and destinations have to be defined. For the oil systems and the natural gas system, nodes in Texas and Louisiana represent the sources, while nodes in Illinois, California, Seattle, Utah, and Massachusetts represent destinations. Source and destination are more difficult to define for the highway and railroad systems. These networks are highly redundant, so damage and losses are confined to the epicentral regions. In the residual capacity calculations for highway and railroad systems, sources are defined to be the outer nodes of all links that intersect with the smallest boundary around the epicentral area, such that all intersected links remain undamaged following an earthquake. Destinations are defined to be all nodes inside the largest boundary around the epicentral area such that all intersected links are damaged (intersection is assumed at the center of the links). For damaged links, restoration of each link is estimated at each time step using the appropriate restoration curve and the maximum intensity along the link.

The residual capacity at a given destination at any time step, t, is defined to be the ratio between the maximum available flow at the destination for the damaged system, Q_t, to the maximum available flow at the destination for the undamaged system, Q_o, i.e.

$$R.C. = Q_t/Q_o \tag{6.6}$$

where Q_t and Q_o can be calculated using the min-max theorem discussed above, and R.C. is the residual capacity.

Example Calculations. Two examples are provided (Figs 6-9 and 6-10) that demonstrate residual capacity calculations for pipeline networks (Example 6.2) and for non-pipeline networks (Example 6.3).

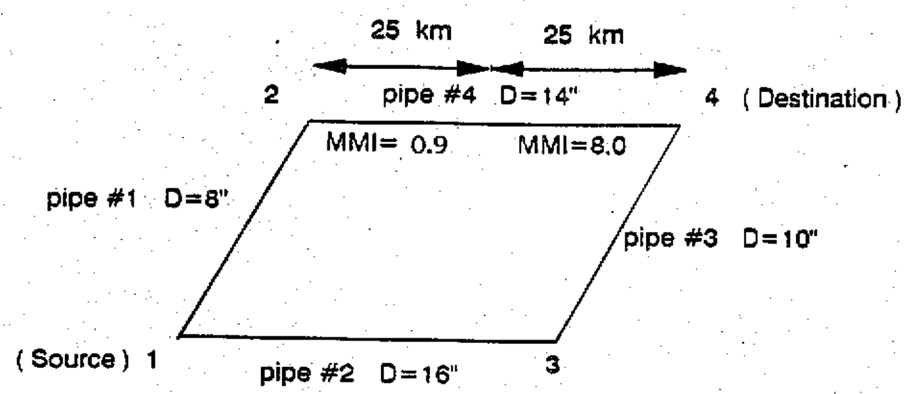
Software Employed. The calculations of damage state, connectivity, and residual capacity were performed using a proprietary computer program, *LLEQE* (*L*ife*L*ine *E*arth*Q*uake *E*ngineering). *LLEQE* employs state-of-the-art computer graphics and was developed to perform four tasks: (1) to perform seismic hazard analyses; (2) to generate lifeline damage states consistent with the calculated site-specific seismic intensities; (3) to perform connectivity analyses; and (4) to estimate residual capacities of lifeline components. Its capabilities include the following components/functions:

- <u>Database</u>. Database capacity can accommodate most major lifeline systems at the transmission level on the national scale, including: transportation, water, electric power generation and supply, gas and liquid fuel supply and emergency service facilities.

Example 6.2

This example illustrates the residual capacity calculation for pipelines systems (e.g., crude oil, refined oil, or natural gas).

Consider the following crude oil pipeline network:



Assume that pipe number 4 is subjected to intensity MMI = 8 along 25 km of its length, and MMI = 9 along 25 km of its length. The pipe lies in the non-California 7 portion of the NEHRP map. Assume the other pipes are unaffected and that there is no liquefaction. Find residual capacity at node 4 at the end of 7 days

<u>Procedure</u>. Use the damage curves for petroleum fuel transmission pipelines (from Appendix B) to determine mean break rate by intensity. Using the data on which this figure is based, the 25 km length of pipe, l_1, experiencing MMI = 8 has an expected mean break rate, λ_1, of 0.036 breaks/km. The 25 km length of pipe, l_2, experiencing MMI = 9 shaking has an expected mean break rate, λ_2, of 0.179 breaks/km. The probability of having at least one break in this pipe is given by equation 5.4, which is

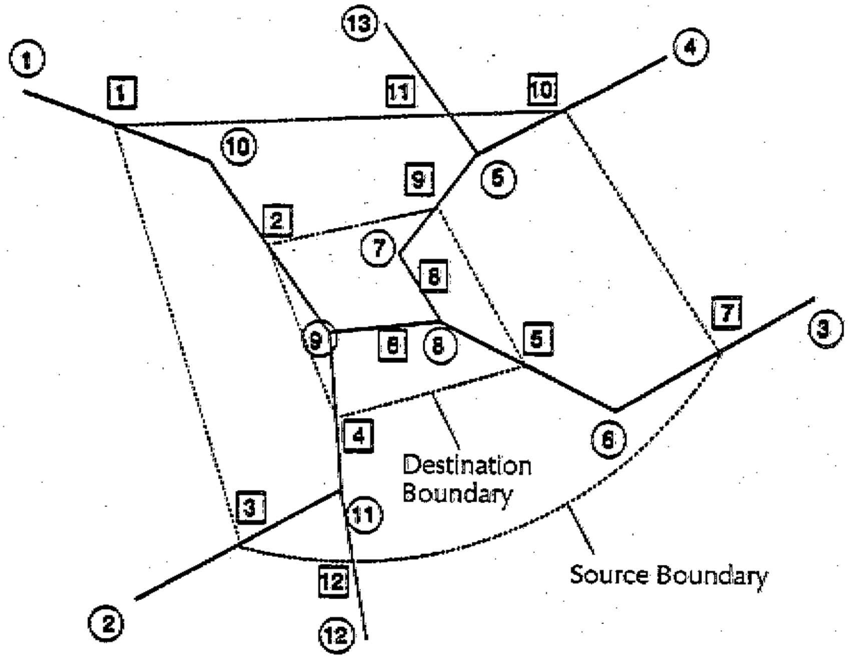
$$
\begin{aligned}
P_f &= 1 - \prod_{i=1}^{2} P_s \\
&= 1 - (\exp(-\lambda_1 \times l_1) \times \exp(-\lambda_2 \times l_2)) \\
&= 1 - (\exp(-0.036 \times 25) \times \exp(-0.179 \times 25)) \\
&= 0.99
\end{aligned}
$$

The diameter square of each pipe will be taken as a measure of capacity of the pipe. For the undamaged system using the min-max theory, the maximum flow Q_o at the destination (i.e., node 4) is 164 (the maximum flow at node 4 equals the capacity of link number 1, i. e. 64, plus the capacity of link number 3, i.e. 100). Since the probability of failure of pipe number 4 is greater than 60%, this pipe will assumed to be closed until it will be fully restored. For the damaged system, at the first time step (i. e., t=0 days) pipe 4 will be closed and the maximum flow Q_1 at node 4 is the capacity of the remaining system, which is 100. The residual capacity at time step t=0 can be estimated using Equation 6.6 and is given by Q_1/Q_o = 61.0%. Using the time-to-restore curve for petroleum transmission lines provided in Appendix B, the time to fully restore pipe sustaining MMI = 9 is 10 days. Thus, at the second time step (t = 7 days) the maximum flow at node 4 equals 100, and the residual capacity at the destination is still 61% (pipe 4 is still closed).

Figure 6-9: Analysis example illustrating residual capacity calculation for crude oil pipeline network.

Example 6.3

This example illustrates the damage and residual capacity calculation for non-pipeline network systems (e.g., railroad or highway system). Consider the following highway network (nodes denoted by circles, links by boxes):



The network lies in the "All Other Areas" portion of the NEHRP map; the intensity distribution for a given scenario earthquake is given below. Assume liquefaction does not occur and that Links 2 and 9 contain bridges. If a bridge experiences damage of 15% or more, it is assumed closed until 100% restored. Characterize restoration at various time intervals.

	Link Number									
	1	2	3	4	5	6	7	8	9	10
length, km	5	5	5	5	5	3	5	3	5	5
MMI	5	6	5	7	8	7	5	8	7	4

Procedure. Using the damage curves provided in Appendix B for highways/freeways, damage to the highway system is estimated as follows:

	Link Number									
	1	2	3	4	5	6	7	8	9	10
Damage, %	0	0	0	1	3	1	0	3	1	0

Using the damage curves for conventional bridges, "other" areas (Appendix B), damage to the bridges in Links 2 and 9 is estimated to be 10% and 30% damage, respectively.

Due to the assumption that a bridge is closed if damage exceeds 15%, the bridges in Link 9 are closed until 100% restored, while bridges in Link 2 are not. Restoration of the network links are estimated from the restoration curves for conventional bridges, "all other areas" (Appendix B) as follows (see following page):

Figure 6-10: Analysis example illustrating the residual capacity calculation for highway networks.

- Damage State. The *LLEQE* user can specify breaks, generate random breaks, or both. To generate a break in a link the user simply select "Specify Break" option and points to the link with a mouse. To simulate a seismic event, random breaks are generated using Monte Carlo simulation and a nonhomogeneous Poisson process with mean break rate based on data from previous earthquakes.

- Connectivity Analysis. Connectivity analysis is performed to identify disconnected regions of damaged systems, tag them with coded colors, and eliminate them from subsequent system analysis. Optimum path and shortest path from source to destination can also be defined.

- Serviceability Analysis. Analysis to estimate the serviceability of lifeline systems under seismic or other events. The process involves connectivity analysis of the system in simulated damage states consistent with site seismicity and statistical analysis of residual capacities available in these damage states. It can provide fragility curves to estimate the functionality and usability of the system.

Following are summaries of residual capacity analytical results for extended regional lifeline networks.

6.4.1 Railroad System

Residual capacities of the railroad system for all scenario earthquakes were estimated using the minimum-cut-maximum-flow theorem defined above; sources and destinations were also defined as above. Residual capacity plots for the railroad system are provided in Appendix C, Figures C-127 through C-134. An example (typical) plot for the Hayward earthquake scenario is provided in Figure 6-11.

6.4.2 Highway System

Residual capacities of the highway system were estimated using the minimum-cut-maximum-flow theorem and the sources and destinations as defined above. The residual capacities are shown in Figures C-135 to C-142. An example plot for the epicentral regional of the magnitude-8.0 New Madrid event, one of the worst case situations, is provided in Figure 6-12. In this case nearly 95% of the highway system capacity is initially lost, and full restoration of the system is not achieved until about day 420. Losses in highway system capacity are similar for Utah, as a result of the Wasatch Front scenario.

6.4.3 Electric System

Residual capacities of the electric system were estimated taking into account nodes only (i.e., transmission substations). The residual capacity for each node was estimated at each time step using the time-to-restore curves for transmission substations from Appendix B. Averages over all nodes in each state affected by the scenario events were calculated using Equation 6.2 and are plotted in Figures C-143 to C-166. One of the worst case situations occurs in Mississippi following the magnitude-8.0 New Madrid event (Figure 6-13). In this case, the initial loss is approximately 75% of capacity, and full restoration is not achieved until about day 130. Losses for Arkansas for this same event are similar.

6.4.4 Water System

Residual capacities of the water system (Figures C-167 to C-169) were estimated using the minimum-cut-maximum-flow theorem discussed above. For the Hayward event the San Francisco Bay area was assumed to be the destination and the outside world, the source. For the Fort Tejon event Los Angeles was assumed to be the destination and the Colorado River Aqueduct (1056 hm^3), California Aqueduct South Coast (692 hm^3), and Los Angeles Aqueduct (574 hm^3) were assumed to be the sources. The worst case situation occurs in Los Angeles as a result of the Fort Tejon event (Figure 6-14).

6.4.5 Crude Oil System

For the residual capacity calculations for the crude oil system, Texas and Louisiana were assumed to represent the source region, while Chicago, Southern and Northern California represented the destinations. Residual capacities of the crude oil system were estimated using the minimum-cut-maximum-flow theorem discussed above. Links with probability of failure greater than or equal to 60% were assumed closed until 100% restored.

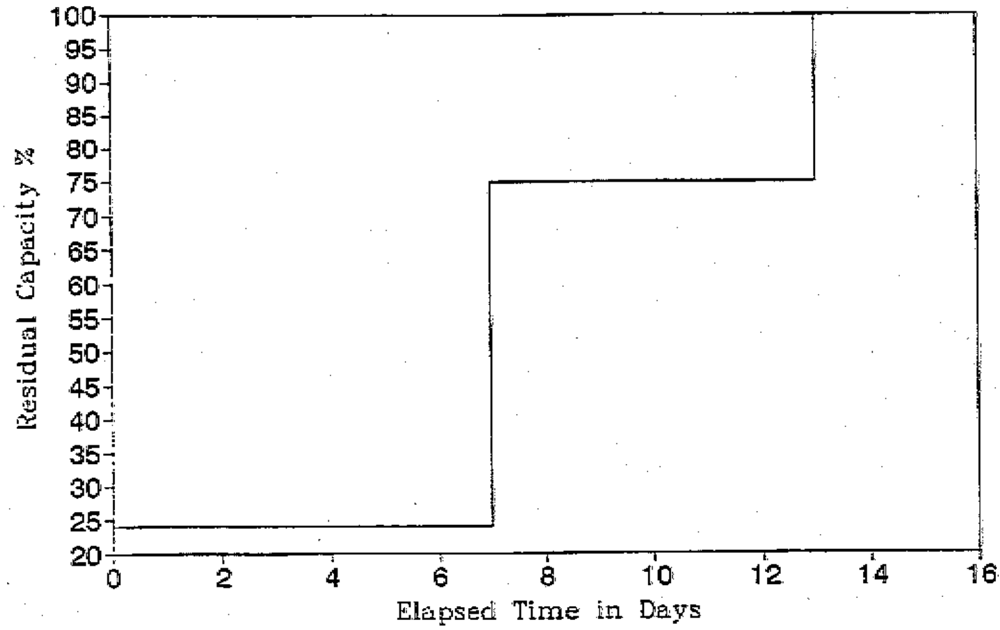


Figure 6-11 *Residual capacity of San Francisco Bay area railroad system following Hayward event (M=7.5).*

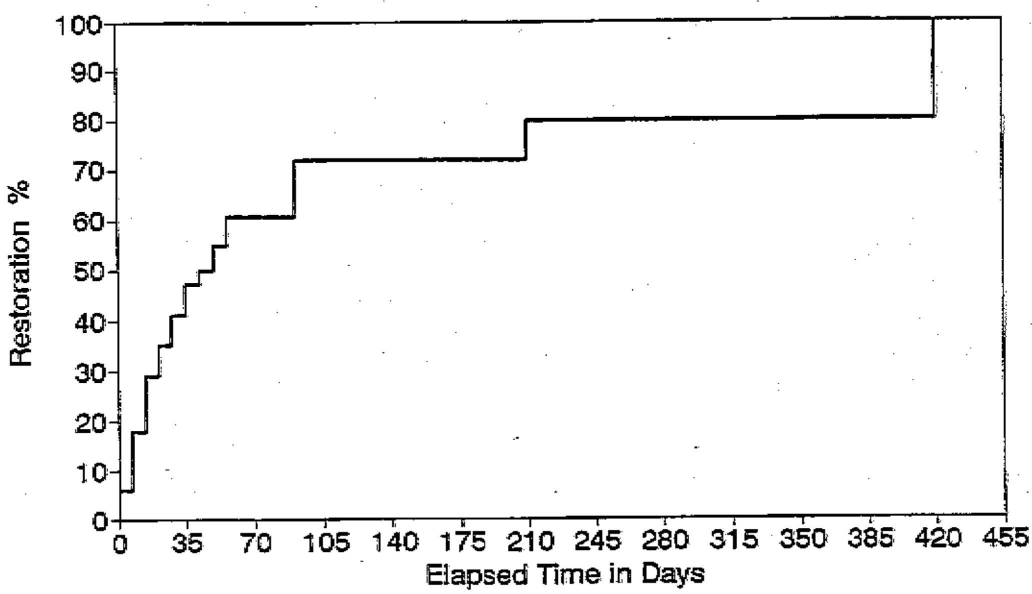


Figure 6-12 *Residual capacity of epicentral region highways following New Madrid event (M=8.0).*

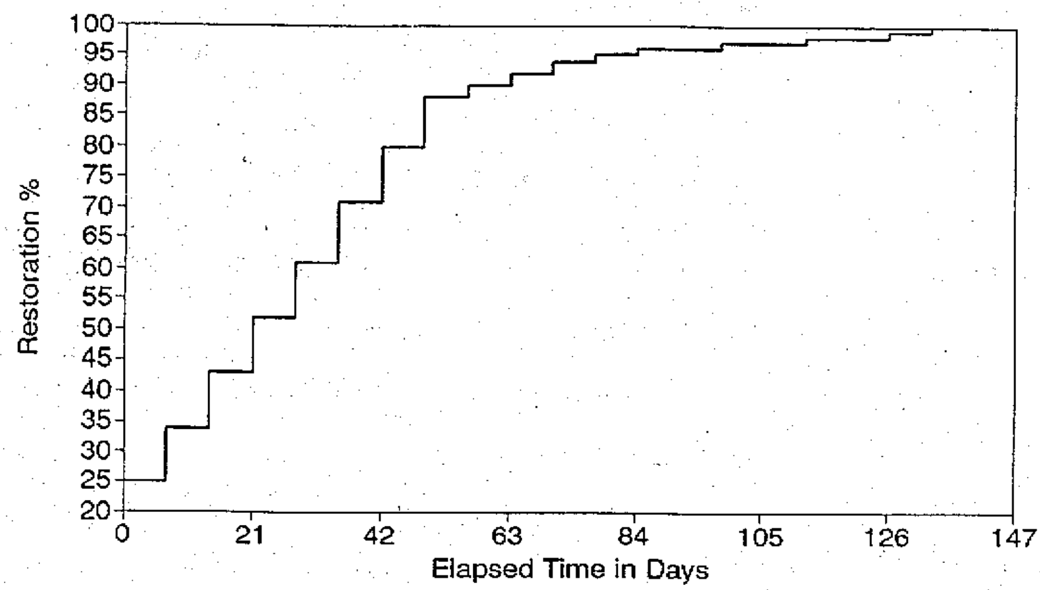


Figure 6-13 *Residual capacity of Mississippi electric system following New Madrid event (M=8.0).*

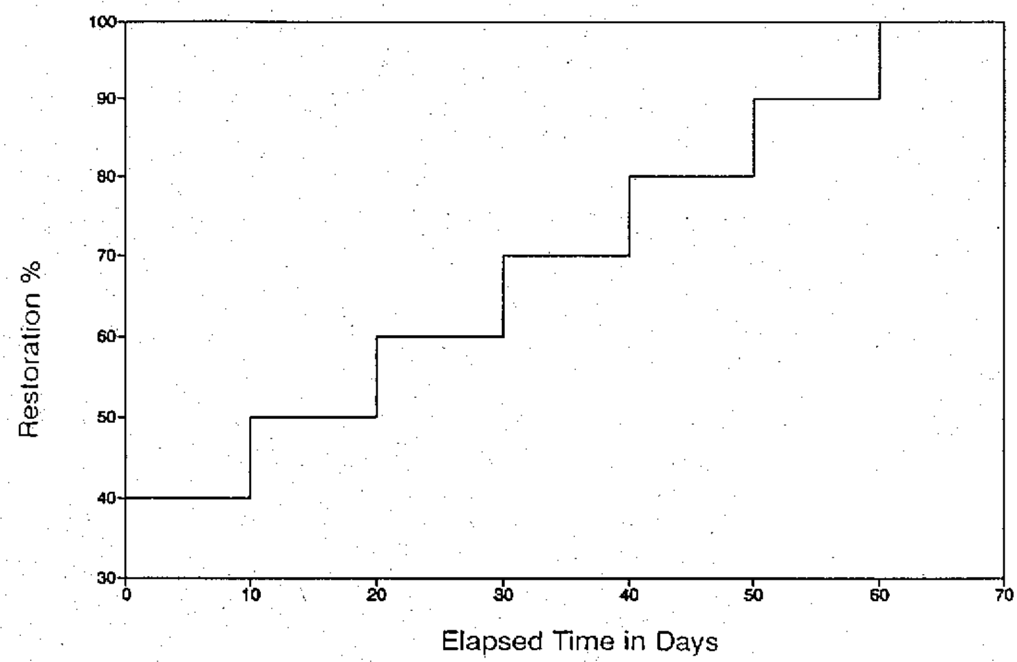


Figure 6-14 *Residual capacity of epicentral region water system following Fort Tejon event (M=8.0).*

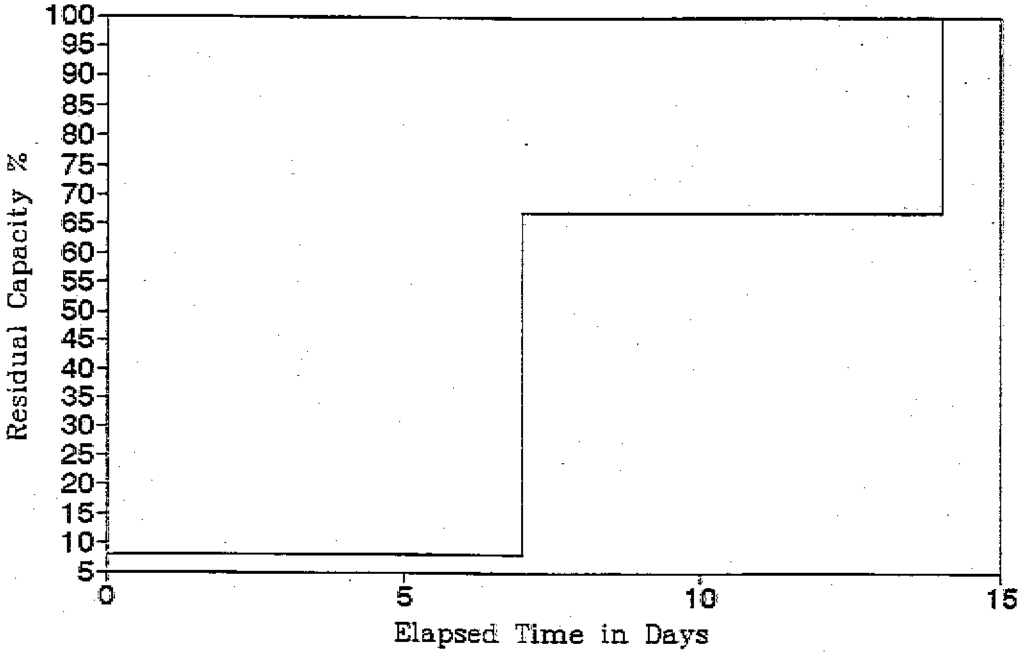


Figure 6-15 *Residual capacity of crude oil delivery system from Texas to Northern California following Fort Tejon event (M=8.0).*

The residual capacities are shown in Figures C-170 to C-173. One of the worst-case situations occurs in California as a result of the Fort Tejon earthquake scenario (Figure 6-15). In this case crude oil delivery capacity from Texas to Northern California is initially reduced to less than 10 percent, and full restoration of capacity is not achieved until about day 14. A similar situation occurs in this same scenario earthquake for crude oil delivery from Texas to Southern California.

6.4.6 *Refined Oil System*

For the residual capacity calculations for the refined oil system, Texas was assumed to be the source, and Chicago was the destination. Residual capacities were estimated using the minimum-cut-maximum-flow theorem discused above. Links with probability of failure greater than or equal to 60% were assumed closed until 100% restored. The residual capacities are shown in Figures C-174 and C-175. Residual capacity plots for the two New Madrid events considered are similar. The plot for the New Madrid magnitude-8.0 event is provided in Figure 6-16.

6.4.7 *Natural Gas System*

For the residual capacity calculations for the natural gas system, Texas and Louisiana were considered as the sources, and Illinois, Massachusetts, Utah, Washington, and California represented the destinations. Residual capacities of the natural gas system were estimated using the minimum-cut-maximum-flow theorem discused above. The residual capacities are shown in Figures C-176 through C-184. An example plot for the Hayward scenario, one of the worst case situations, is provided in Figure 6-17. In this case the capacity for natural gas delivery from Texas to Northern California is reduced to zero for the first seven days after the earthquake; full capacity is restored at about day 14. Losses in delivery capacity to Seattle from Texas, as a result of the Puget Sound scenario, and to California from Texas, as a result of the Fort Tejon event, are similar.

6.4.8 *Distribution Systems*

Residual capacities of the electric, water, and highway distribution systems were estimated using the time-to-restore curves provided in

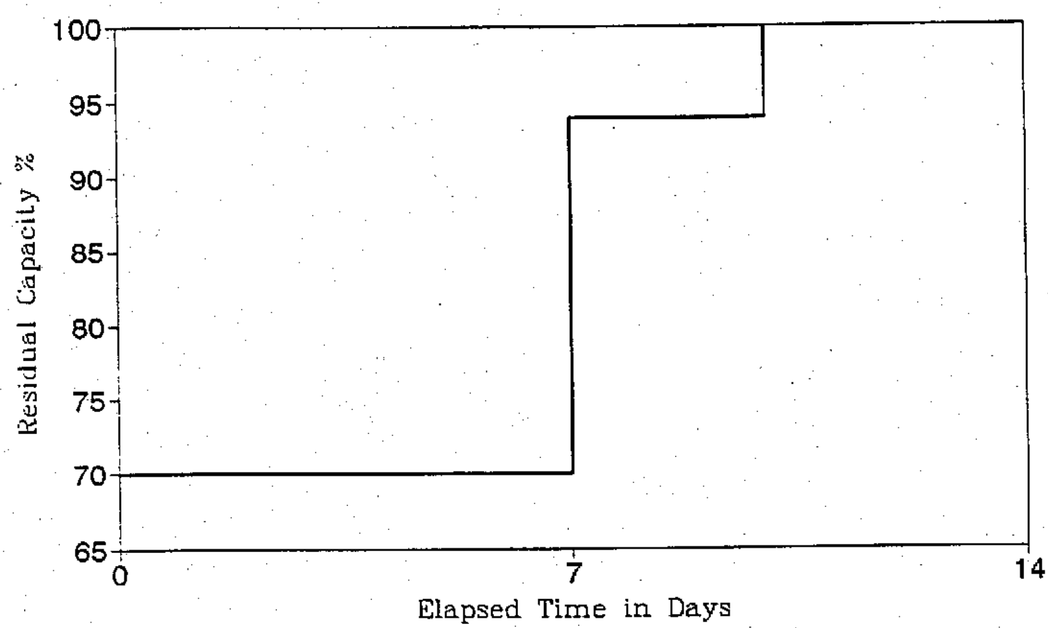


Figure 6-16 *Residual refined oil delivery from Texas to Chicago following New Madrid event (M=8.0).*

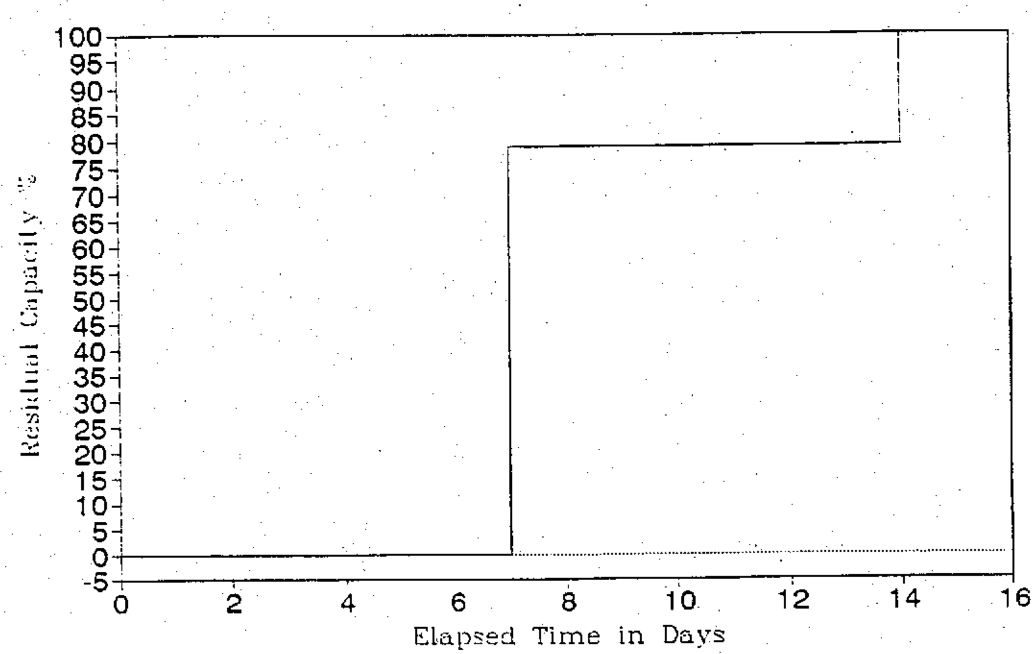


Figure 6-17 *Residual capacity of natural gas delivery from Texas to Northern California following Fort Tejon event (M=8.0).*

Appendix B. Distribution systems were assumed to be lumped at the center of the Standard Metropolitan Statistical Areas (SMSAs), and intensities were estimated at each SMSA for every scenario event. Residual capacity plots for distribution systems have not been included in this report. Economic losses resulting from damage to these systems, however, are included in the summaries provided later in this chapter.

6.5 General Analytical Approach for Estimating Indirect Economic Losses

In order to develop the relationship between lifeline interruption and indirect economic losses it was necessary to generate a set of simplifying assumptions. The general assumptions that apply to all lifelines are listed below.

6.5.1 General Assumptions

1. Duration. The interruption of the lifeline element/system that gives rise to the economic loss is assumed to extend over one or more consecutive month-long time periods. The functionality loss assigned to each month is the average for that month.

2. Independence. Lifeline elements are assumed to be independent. Interruptions in elements of one lifeline do not produce interruptions in other lifeline elements. That is, we ignore lifeline interaction effects, which are sometimes non-trivial.

3. Lifeline Functionality. The quantity under examination here is lifeline functionality as opposed to lifeline capacity. For example, assume the water supply lifeline sustains a loss of 20 percent of its capacity locally, but, because of redundancy and looping, water remains fully available. The functionality loss and consequent indirect economic loss would both be zero. Conversely, if all water supply and transmission facilities remain intact, but damage to the distribution system cuts off water to 20 percent of the industries served, the functionality loss is 20 percent.

4. Distribution of Incidence of Interruption. Lifeline interruptions are assumed to be prioritized as follows:

   Primary: Emergency response and human needs

   Secondary: Industrial needs (Within this class non-interruptible service customers share the loss in capacity equally)

   Tertiary: Interruptible service customers

5. Secondary Impacts Ignored. The loss of capacity in one (non-lifeline) industry would likely reduce the productivity of other industries that obtain inputs from the first industry. These reverberations, which are typically measured using input-output analysis, will be ignored for this first approximation. To the extent that these reverberations are ignored, impacts are understated.

6. Functional Relationships. Each industrial sector of the economy was considered separately with respect to each lifeline. The maximum impact, which would be expected to result from a prolonged total lifeline failure was estimated for each lifeline/sector pair. The effect of less-than-total failure of the lifeline was estimated using the following assumptions:

   - The first 5% interruption could be absorbed without economic loss
   - Subsequent losses would result in proportionate economic losses. Thus as lifeline capacity falls from 95 to 0%, the economic impact is assumed to increase linearly from zero to the maximum effect for each sector/lifeline pair.
   - The product of the percent loss of value added for each sector was summed over all sectors for each decile and lifeline. This sum represents the value-added weighted average of the economic impact of the lifeline for that decile.

7. Linearity. The linearity assumption mentioned above implies that remaining lifeline capacity could be used productively; limited lifeline damage would not cause a complete cessation of economic activity in

the sector. This assumption may unrealistically underestimate the effects of lifeline interruptions in industries (such as primary metals) that might be unable to scale back operations or to close and restart operations in response to reduction and restoration of lifeline capacity.

6.5.2 Data Sources and Methodology

Value Added Data. Economic activity within each industrial sector was measured in terms of value added. Value added refers to the value of shipments (products) less the cost of materials, supplies, contract work and fuels used in the manufacture or cultivation of the product. The United States Bureau of Economic Analysis publishes annual data for value added for each industrial sector. For simplicity, data from the 99 sectors were collapsed into 36 sectors. Data for 1983 were the latest available (published by BEA, 1989), and were used in this study.

As a first approximation, data on the national economy were used to assess the relative economic importance of each sector. The value added for each of the 36 sectors of the economic model is expressed as a percentage of the nationwide total. These data are presented in Table 6-1. For comparison, comparable data for the local San Francisco Bay Area economy (which comprises Santa Clara County and parts of Alameda County) are shown on the same table.

Lifeline Importance Factors. The economic impact of each lifeline was estimated by modifying estimates from ATC 13 (ATC, 1985). Table 9.8 of ATC 13 presents the lifeline importance factors for each social function. To adapt these estimates to the present study, the "social functions" were assigned to each industrial sector. The importance weights provided in ATC-13 distinguish between main and distribution systems for each lifeline. For the present study, the two figures were averaged to produce an importance weight for the entire lifeline system. Further modification of the ATC-13 estimates were made to reflect the difference between the importance of the lifeline and its impact on the economy if it were totally disrupted. These modifications, generally in the upward direction, constitute first approximations of economic impacts. The maximum impact estimates by sector and lifeline are shown in Table 6-2.

Reduction in Value Added Due to Lifeline Interruption. Table 6-3 presents the percent reduction in value added for each sector resulting from increasingly severe crude oil lifeline interruptions. (Similar tables are shown for all lifelines in Appendix D.) Values are shown for each decile of lifeline interruption and are assumed to pertain to *monthly* Gross National Product (GNP). As noted in the assumptions cited above, these percentages are linearly interpolated between the reduction in value added when the lifeline experiences 5% interruption (for a 5% lifeline interruption, there is no reduction in value added) to the reduction in value added when the lifeline experiences 100 percent interruption (maximum impact).

Table 6-4, also assumed to pertain to *monthly* GNP, presents the remaining value added of each sector under alternative levels of crude oil lifeline interruption. Similar tables are shown for all lifelines in Appendix D. These value added estimates are calculated by finding the percent value added of the sector within the total economy (Table 6-1, right column) and the percentage reductions in value added (e.g., Table 6-3 for oil supply). The product of these two variables is subtracted from the uninterrupted value-added for each decile. In the case of oil supply and the livestock sector, the residual valued-added after 10% of loss of capacity = (0.45%) - ((0.45%) x (2.63%)) = (0.45) - (.01) = 0.44% These sums thus represent the weighted average of the sectorial impacts of interruptions to the lifeline.

Figure 6-18 illustrates the value added weighted average economic impacts of crude oil lifeline interruptions (taken from totals at bottom of Table 6-4). Similar figures are shown for all lifelines in Appendix D. The Y-intercept reflects the estimate of the maximum impact, due to total disruption of the lifeline for an extended period of time.

Further Refinements. As noted at the outset, this brief study constitutes a first approximation of the economic effects of lifeline interruption. A number of explicit and implicit assumptions were made in order to simplify the analysis. Using these assumptions limits the accuracy of

Table 6-1 Relative Importance of Industry Sections--U. S. and Santa Clara County, California

	Sector	Santa Clara & Part Alameda Value Added (Mil $1986)	U.S. Econ Value Added (Mil $1983)	U.S. Econ. Value Added Pct. of Tot.	U.S. Econ. Value Added Pct. of Tot.
1	Livestock	4	0.01%	15,227	0.45%
2	Agr. Prod.	78	0.13%	35,567	1.06%
3	AgServ For. Fish	115	0.20%	3,705	0.11%
4	Mining	92	0.16%	130,577	3.89%
5	Construction	1,973	3.39%	185,326	5.52%
6	Food Tobacco	593	1.02%	80,810	2.41%
7	Textile Goods	10	0.02%	12,515	0.37%
8	Misc Text. Prod.	11	0.02%	24,397	0.73%
9	Lumber & Wood	50	0.09%	17,319	0.52%
10	Furniture	60	0.10%	11,378	0.34%
11	Pulp & Paper	153	0.26%	29,253	0.87%
12	Print & Publish	413	0.71%	44,053	1.31%
13	Chemical & Drugs	492	0.84%	47,144	1.40%
14	Petrol. Refining	3	0.01%	32,332	0.96%
15	Rubber & Plastic	127	0.22%	34,579	1.03%
16	Leather Prods.	1	0.00%	4,119	0.12%
17	Glass Stone Clay	199	0.34%	20,758	0.62%
18	Prim. Metal Prod	95	0.16%	34,951	1.04%
19	Fab. Metal Prod.	538	0.92%	55,094	1.64%
20	Mach. Exc. Elec.	5,789	9.95%	52,384	1.56%
21	Elec. & Electron	5,603	9.63%	84,697	2.52%
22	Transport Eq.	924	1.59%	87,942	2.62%
23	Instruments	1,416	2.43%	22,807	0.68%
24	Misc. Manufact.	113	0.19%	23,080	0.69%
25	Transp & Whse.	533	0.92%	116,193	3.46%
26	Utilities	1,173	2.02%	197,676	5.89%
27	Wholesale Trade	4,034	6.93%	189,178	5.63%
28	Retail Trade	2,567	4.41%	189,178	5.63%
29	F.I.R.E. *(Finance, Insurance, Real Estate)*	10,250	17.62%	558,851	16.64%
30	Pers./Prof Serv.	8,755	15.05%	269,683	8.03%
31	Eating Drinking	1,556	2.67%	71,217	2.12%
32	Auto Serv.	1,137	1.95%	36,761	1.09%
33	Amuse & Rec.	223	0.38%	23,385	0.70%
34	Health Ed. Soc.	4,650	7.99%	211,503	6.30%
35	Govt & Govt Ind.	3,870	6.65%	395,936	11.79%
36	Households	574	0.99%	8,442	0.25%
	Inventory & Leak	0.00%	39,135		
	TOTAL	58,174	100.00%	3,397,151	100.00%

Sources: Santa Clara: Dames & Moore, 1987. Regional Economics Of Water Supply Shortages in the South Bay Contractors' Service Area U.S.: U.S. Dept. of Comm. Bureau of Econ. Analysis, 1989 Suvey of Current Business. Input Output Accounts of the U.S. Economy, 1983 Collapsed from 99 to 36 sectors.

Table 6-2 **Importance Weights of Various Lifeline Systems on Economic Sectors (Modified ATC-13 Table 9.8** (ATC, 1985))

	Water	*Waste*	*Electric*	*Natural Gas*	*Oil*	*Highway*	*Railways*	*Air Transportation*	*Water Transportation*	*Phone*
1 Livestock	0.45	0.20	0.50	0.10	0.50	0.50	0.40	0.10	0.40	0.20
2 Agr. Prod.	0.70	0.50	0.50	0.30	0.80	0.80	0.40	0.10	0.40	0.20
3 AgServ For. Fish	0.45	0.50	0.50	0.30	0.80	0.80	0.40	0.10	0.40	0.20
4 Mining	0.15	0.10	0.90	0.10	0.90	0.35	0.35	0.10	0.20	0.10
5 Construction	0.50	0.20	0.40	0.00	0.90	0.40	0.05	0.00	0.20	0.10
6 Food Tobacco	0.70	0.70	0.90	0.25	0.50	0.80	0.20	0.20	0.20	0.15
7 Textile Goods	0.70	0.70	1.00	0.20	0.50	0.75	0.20	0.20	0.20	0.15
8 Misc Text. Prod.	0.70	0.70	1.00	0.20	0.50	0.75	0.20	0.20	0.20	0.15
9 Lumber & Wood	0.50	0.50	1.00	0.20	0.50	0.90	0.40	0.20	0.20	0.15
10 Furniture	0.50	0.50	1.00	0.20	0.50	0.75	0.20	0.20	0.20	0.15
11 Pulp & Paper	0.60	0.80	1.00	0.40	0.50	0.80	0.45	0.10	0.30	0.10
12 Print & Publish	0.30	0.30	1.00	0.20	0.50	0.75	0.20	0.20	0.20	0.15
13 Chemical & Drugs	0.80	0.80	0.90	0.90	0.50	0.80	0.20	0.20	0.20	0.15
14 Petrol. Refining	0.50	0.50	1.00	0.50	1.00	0.90	0.40	0.00	0.80	0.10
15 Rubber & Plastic	0.50	0.50	1.00	0.50	0.50	0.75	0.20	0.20	0.20	0.15
16 Leather Prods.	0.50	0.50	1.00	0.20	0.50	0.75	0.20	0.20	0.20	0.15
17 Glass Stone Clay	0.50	0.50	1.00	0.50	0.50	0.75	0.20	0.20	0.20	0.15
18 Prim. Metal Prod.	0.90	0.80	0.90	0.50	0.90	0.80	0.50	0.10	0.20	0.15
19 Fab. Metal Prod.	0.80	0.80	1.00	0.50	0.50	0.80	0.45	0.10	0.30	0.10
20 Mach. Exc. Elec.	0.60	0.80	1.00	0.50	0.50	0.80	0.45	0.20	0.30	0.10
21 Elec. & Electron	0.90	0.90	1.00	0.50	0.50	0.75	0.20	0.30	0.20	0.15
22 Transport Eq.	0.60	0.80	1.00	0.50	0.90	0.80	0.45	0.30	0.30	0.10
23 Instruments	0.90	0.60	1.00	0.75	0.50	0.80	0.05	0.40	0.10	0.30
24 Misc. Manufact.	0.60	0.60	1.00	0.50	0.50	0.75	0.20	0.20	0.20	0.15
25 Transp & Whse.	0.20	0.10	0.30	0.00	0.90	0.80	0.30	0.30	0.30	0.30
26 Utilities	0.40	0.24	0.80	0.40	0.50	0.40	0.00	0.00	0.00	0.30
27 Wholesale Trade	0.20	0.10	0.90	0.10	0.50	0.70	0.15	0.20	0.20	0.50
28 Retail Trade	0.20	0.20	0.90	0.20	0.90	0.55	0.20	0.20	0.00	0.50
29 F.I.R.E.	0.20	0.20	0.90	0.20	0.60	0.45	0.10	0.20	0.00	0.60
30 Pers./Prof Serv.	0.20	0.20	0.90	0.20	0.60	0.45	0.10	0.20	0.00	0.40
31 Eating Drinking	0.80	0.80	0.80	0.40	0.80	0.50	0.05	0.40	0.00	0.40
32 Auto Serv.	0.10	0.20	0.90	0.05	0.90	0.55	0.00	0.00	0.00	0.40
33 Amuse & Rec.	0.80	0.80	0.80	0.40	0.90	0.50	0.05	0.40	0.00	0.40
34 Health Ed. Soc.	0.40	0.80	0.80	0.20	0.20	0.55	0.05	0.10	0.00	0.15
35 Govt & Govt Ind.	0.25	0.20	0.60	0.20	0.20	0.30	0.10	0.20	0.00	0.20
36 Households	0.40	0.75	0.80	0.35	0.50	0.40	0.00	0.00	0.00	0.20
TOTAL	0.51	0.51	0.86	0.32	0.62	0.67	0.22	0.18	0.19	0.22

Table 6-3 Percent Value-Added Lost Due to Specified Percent Loss of Oil Supply Lifeline

L/L Capacity Loss-->	*U.S. Econ. Value Added (Percent)*	*10%*	*20%*	*30%*	*40%*	*50%*	*60%*	*70%*	*80%*	*90%*	*100%*
1 Livestock	0.45%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
2 Agr. Prod.	1.06%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
3 AgServ For. Fish	0.11%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
4 Mining	3.89%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
5 Construction	5.52%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
6 Food Tobacco	2.41%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
7 Textile Goods	0.37%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
8 Misc Text. Prod.	0.73%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
9 Lumber & Wood	0.52%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
10 Furniture	0.34%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
11 Pulp & Paper	0.87%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
12 Print & Publish	1.31%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
13 Chemical Drugs	1.40%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
14 Petrol. Refining	0.96%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
15 Rubber & Plastic	1.03%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
16 Leather Prods.	0.12%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
17 Glass Stone Clay	0.62%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
18 Prim. Metal Prod.	1.04%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
19 Fab. Metal Prod.	1.64%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
20 Mach. Exc. Elec.	1.56%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
21 Elec. & Electron	2.52%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
22 Transport Eq.	2.62%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
23 Instruments	0.68%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
24 Misc. Manufact.	0.69%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
25 Transp & Whse.	3.46%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
26 Utilities	5.89%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
27 Wholesale Trade	5.63%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
28 Retail Trade	5.63%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
29 F.I.R.E.	16.64%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
30 Pers./Prof. Serv.	8.03%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
31 Eating Drinking	2.12%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
32 Auto Serv.	1.09%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
33 Amuse & Rec.	0.70%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
34 Health Ed. Soc.	6.30%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
35 Govt & Govt Ind.	11.79%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
36 Households	0.25%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
TOTAL	100.00%	3.25% Avg.	9.74% Avg.	16.23% Avg.	22.72% Avg.	29.21% Avg.	35.70% Avg.	42.19% Avg.	48.68% Avg.	55.18% Avg.	61.67% Total V.A Pct. V.A.

Table 6-4 Residual Value-Added After Loss of Capacity of Oil Supply Lifeline

0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0.45%	0.44%	0.42%	0.39%	0.37%	0.35%	0.32%	0.30%	0.27%	0.25%	0.23%
1.06%	1.01%	0.93%	0.84%	0.75%	0.66%	0.57%	0.48%	0.39%	0.30%	0.21%
0.11%	0.11%	0.10%	0.09%	0.08%	0.07%	0.06%	0.05%	0.04%	0.03%	0.02%
3.89%	3.70%	3.34%	2.97%	2.60%	2.23%	1.86%	1.49%	1.13%	0.76%	0.39%
5.52%	5.26%	4.73%	4.21%	3.69%	3.17%	2.64%	2.12%	1.60%	1.07%	0.55%
2.41%	2.34%	2.22%	2.09%	1.96%	1.84%	1.71%	1.58%	1.46%	1.33%	1.20%
0.37%	0.36%	0.34%	0.32%	0.30%	0.28%	0.26%	0.25%	0.23%	0.21%	0.19%
0.73%	0.71%	0.67%	0.63%	0.59%	0.55%	0.52%	0.48%	0.44%	0.40%	0.36%
0.52%	0.50%	0.48%	0.45%	0.42%	0.39%	0.37%	0.34%	0.31%	0.29%	0.26%
0.34%	0.33%	0.31%	0.29%	0.28%	0.26%	0.24%	0.22%	0.21%	0.19%	0.17%
0.87%	0.85%	0.80%	0.76%	0.71%	0.66%	0.62%	0.57%	0.53%	0.48%	0.44%
1.31%	1.28%	1.21%	1.14%	1.07%	1.00%	0.93%	0.86%	0.79%	0.72%	0.66%
1.40%	1.37%	1.29%	1.22%	1.15%	1.07%	1.00%	0.92%	0.85%	0.78%	0.70%
0.96%	0.91%	0.81%	0.71%	0.61%	0.51%	0.41%	0.30%	0.20%	0.10%	0.00%
1.03%	1.00%	0.95%	0.89%	0.84%	0.79%	0.73%	0.68%	0.62%	0.57%	0.51%
0.12%	0.12%	0.11%	0.11%	0.10%	0.09%	0.09%	0.08%	0.07%	0.07%	0.06%
0.62%	0.60%	0.57%	0.54%	0.50%	0.47%	0.44%	0.41%	0.37%	0.34%	0.31%
1.04%	0.99%	0.89%	0.79%	0.70%	0.60%	0.50%	0.40%	0.30%	0.20%	0.10%
1.64%	1.60%	1.51%	1.42%	1.34%	1.25%	1.17%	1.08%	0.99%	0.91%	0.82%
1.56%	1.52%	1.44%	1.35%	1.27%	1.19%	1.11%	1.03%	0.94%	0.86%	0.78%
2.52%	2.46%	2.32%	2.19%	2.06%	1.92%	1.79%	1.66%	1.53%	1.39%	1.26%
2.62%	2.49%	2.25%	2.00%	1.75%	1.50%	1.25%	1.01%	0.76%	0.51%	0.26%
0.68%	0.66%	0.63%	0.59%	0.55%	0.52%	0.48%	0.45%	0.41%	0.38%	0.34%
0.69%	0.67%	0.63%	0.60%	0.56%	0.52%	0.49%	0.45%	0.42%	0.38%	0.34%
3.46%	3.30%	2.97%	2.64%	2.31%	1.99%	1.66%	1.33%	1.00%	0.67%	0.35%
5.89%	5.73%	5.42%	5.11%	4.80%	4.49%	4.18%	3.87%	3.56%	3.25%	2.94%
5.63%	5.49%	5.19%	4.89%	4.60%	4.30%	4.00%	3.71%	3.41%	3.11%	2.82%
5.63%	5.37%	4.83%	4.30%	3.77%	3.23%	2.70%	2.16%	1.63%	1.10%	0.56%
16.64%	16.12%	15.07%	14.01%	12.96%	11.91%	10.86%	9.81%	8.76%	7.71%	6.66%
8.03%	7.78%	7.27%	6.76%	6.26%	5.75%	5.24%	4.73%	4.23%	3.72%	3.21%
2.12%	2.03%	1.85%	1.67%	1.50%	1.32%	1.14%	0.96%	0.78%	0.60%	0.42%
1.09%	1.04%	0.94%	0.84%	0.73%	0.63%	0.52%	0.42%	0.32%	0.21%	0.11%
0.70%	0.66%	0.60%	0.53%	0.47%	0.40%	0.33%	0.27%	0.20%	0.14%	0.07%
6.30%	6.23%	6.10%	5.97%	5.83%	5.70%	5.57%	5.44%	5.30%	5.17%	5.04%
11.79%	11.67%	11.42%	11.17%	10.92%	10.67%	10.43%	10.18%	9.93%	9.68%	9.43%
0.25%	0.24%	0.23%	0.22%	0.21%	0.19%	0.18%	0.17%	0.15%	0.14%	0.13%
100.00%	96.94%	90.83%	84.71%	78.60%	72.48%	66.37%	60.25%	54.14%	48.02%	41.91%
100%	97%	91%	85%	79%	72%	66%	60%	54%	48%	42%

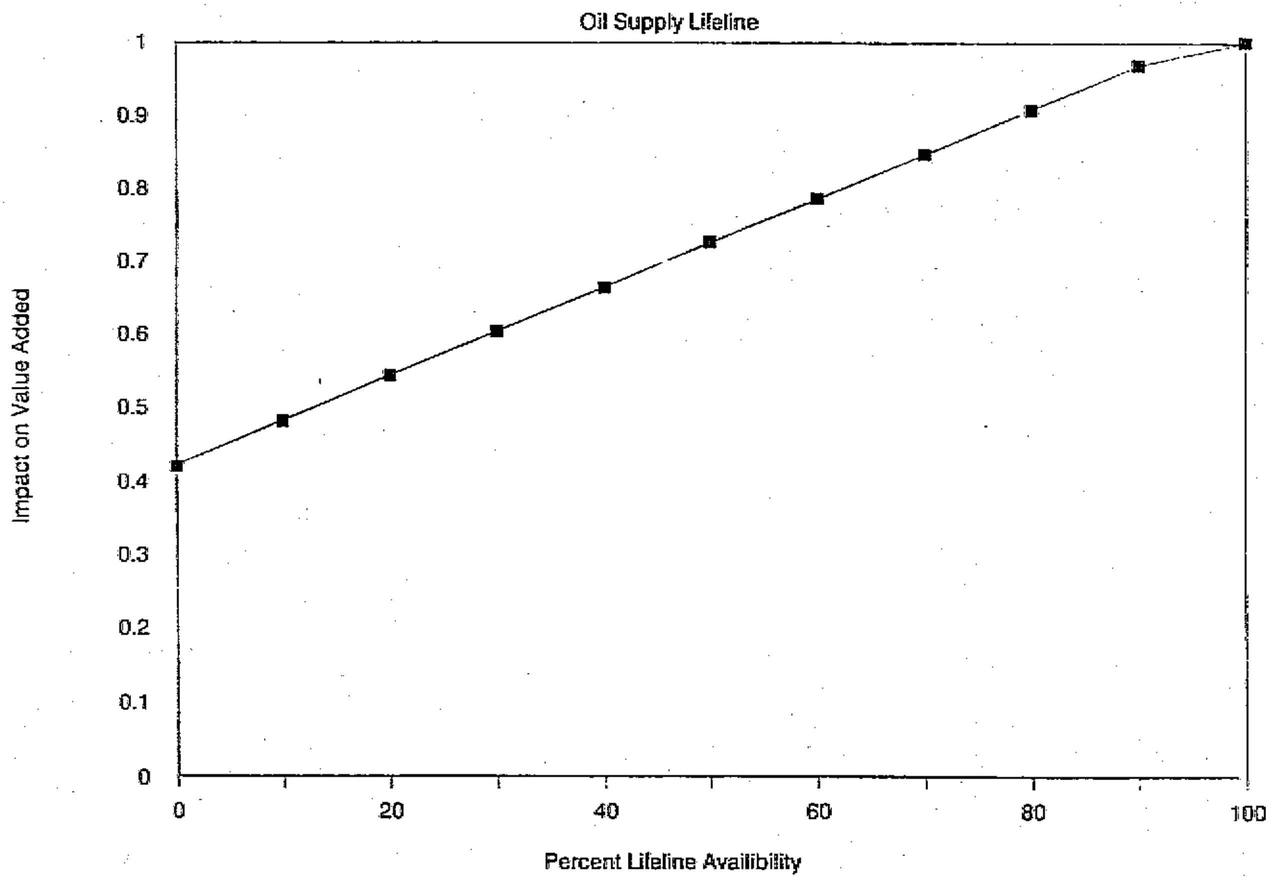


Figure 6-18 Residual Value Added as a function of crude oil lifeline residual capacity

the results. However, the model's parameters could be refined to produce more accurate results, which might also better represent regional and local economic diversity. The following refinements are suggested:

- Regionalization. Data on value added are available on a county-by-county basis for the entire United States. This data could be used in place of the national data presented here to produce local area models of county or multiple-county areas. Such a localized model would more accurately reflect the impacts weighted by the local importance of each of the industrial sectors.

- Maximum Economic Impacts. The estimates of the maximum impacts of lifeline disruptions were modified from the ATC-13 data, based on the judgment of the authors. These estimates could be improved by research into the use of each of the lifeline inputs within each of the economic sectors.

- Linearity Assumption. The economic impact of lifeline interruption was assumed to vary linearly between no impact at 5% interruption, to maximum impact at 100% interruption. This assumption could be investigated and modified as appropriate. Some industries may require uninterrupted use of lifelines in order to operate; they may be unable to operate under certain conditions of reduced lifeline capacity. The linearity assumption ignores these possible threshold effects. Furthermore, many or all industries might respond non-linearly to interruptions. Smaller percentage interruptions might cause a less than proportional impact on value added as lower valued functions or product line are cut first, or as other factors of production are substituted for the damaged lifeline. At high percent interruptions, the response might be more than proportional, as vital functions cannot be maintained. Further research into industry response to scarcity might suggest a convex rather than linear response function.

- Interindustry Effects. The scarcity of productive factors other than lifelines could have major impacts on a regional economy. These interactions were ignored in the present study, thus understating impacts of lifeline interruptions. As noted in Scawthorn and Lofting (1984), input-output economic models could be used to solve for these interactions. Building such a model would be difficult because the impacts caused by lifeline disruptions and the non-lifeline scarcity impacts would have to be solved simultaneously. However, the basic modeling approach proposed in this study is consistent with the type of regional data necessary to drive an input-output model.

6.6 Indirect Economic Loss Estimates

Indirect economic losses were estimated for each lifeline system and scenario event using the residual capacity plots provided in Appendix C and the economic tables described above. The calculation procedure was as follows:

1. Determine the monthly loss in capacity for the lifeline and scenario earthquake under consideration using the appropriate residual capacity plot (Appendix C).

2. Determine Percent-Value-Added Lost for each month and sector of the economy for the lifeline under consideration, using the estimates obtained from Step 1 above and the Percent-Value-Added Lost Tables provided in Appendix D (Table 6-3 is an example). Sum the percentages for all months in each sector to obtain the total Value-Added-Lost in that sector during the time period the lifeline had loss in capacity. Multiply this sum by the percent U. S. Economic Value Added for that sector.

3. Sum the products calculated in Step 2 for each sector to estimate the total percentage value added lost for all economic sectors; multiply this percentage by the percent of U. S. population affected and by the monthly Gross National Product to obtain the total indirect economic loss for the lifeline and earthquake scenario under consideration.

The equation used to calculate indirect economic losses (IEL) is as follows:

$$IEL = \sum_{i=1}^{N1} \sum_{j=1}^{N2} \sum_{k=1}^{N3} (A)(B)(C)(D) \quad (6.7)$$

where:

IEL	=	Indirect Economic Loss
N1	=	number of affected regions
N2	=	number of economic sectors
N3	=	number of months the lifeline has a loss in capacity
A	=	percent Value-Added-Lost per month
B	=	percent U. S. Economy Value Added
C	=	percent of U. S. population affected
D	=	monthly Gross National Product

We note that an average value of loss of functionality during each month of the restoration period is used when estimating the overall indirect economic impact (from Table 6-3 and similar tables in Appendix D). This aspect of the computation is illustrated in Example 6.4 (Figure 6-19), which illustrates the economic loss calculation for a specific lifeline, economic sector, and hypothetical earthquake. Shown in Example 6.5 (Figure 6-20) is an example calculation for estimating total indirect dollar loss in all economic sectors due to damage of the electric system in the state of Utah as a result of the Wasatch Front scenario event.

We have also calculated values of "Percent of Monthly Economic Loss" in each economic sector due to interruption to each lifeline system for each scenario earthquake using the "Residual Capacity Plots" provided in Appendix C and the "Percent Value Added Lost" tables provided in Appendix D. These data are provided in Tables 6-5 through 6-11. Values in these tables are percentage of the monthly GNP of each economic sector that is lost due to the

Example 6.4

For the pipeline network described in Example 6.2 and using the residual capacity results determined there, determine indirect economic losses to the livestock sector for the first month.

Procedure. Immediately following the earthquake, this network experiences a 39% loss of functionality. Ten days later the loss of functionality is 0%. Thus, the average loss of functionality during the first 10 days is about 20%, and for the first month it is 20%/3, or 7%. From Table 6-3, which pertains to average loss of functionality for one month, the Value Added lost for a 7% loss in functionality for the live stock sector of the economy is 1.8%, i.e., 0.7 of 2.63% corresponding to 10% loss of oil supply lifeline for one month. To determine the economic losses in dollars, this percentage would first need to be multiplied by the percent U. S. Economy Value Added for the livestock sector (0.45%) and then prorated by the percent of the national population affected. Actual economic losses in this economic sector due to loss of functionality of this particular pipeline would then be determined by multiplying this prorated percentage by the monthly gross national product

Figure 6-19. Analysis Example Illustrating Economic Loss Calculation for Crude Oil Pipeline Network.

scenario earthquake and resulting lifeline interruption. In Table 6-6, for example, 141% of the monthly GNP of livestock is lost as a result of damage to water transportation systems during the Charleston earthquake scenario. The actual dollar loss would be the product of 1.41 x .0045 x monthly national GNP x percent of national population affected.

Summaries of the total indirect economic losses resulting from damage to site-specific systems and extended regional networks, based on 1986 GNP data, are provided in Table 6-12. Total indirect economic losses resulting from damage to local distribution systems are presented in Table 6-13. We note that Table 6-12 contains total loss amounts expressed in terms of lower bound, upper bound, and best estimate. The lower bound represents economic loss caused by the singular lifeline system causing the greatest loss; the upper bound is the sum of losses caused by all systems; and the best estimate is the square root of the sum of the squares (SRSS) of losses caused by each lifeline. We note also that the SRSS procedure was used to estimate total indirect economic losses resulting from damage to local distribution networks (Table 6-13).

By combining like system data from Tables 6-12 and 6-13 in a least squares (SRSS) fashion, we estimate the total indirect economic losses for the eight scenario earthquakes as follows:

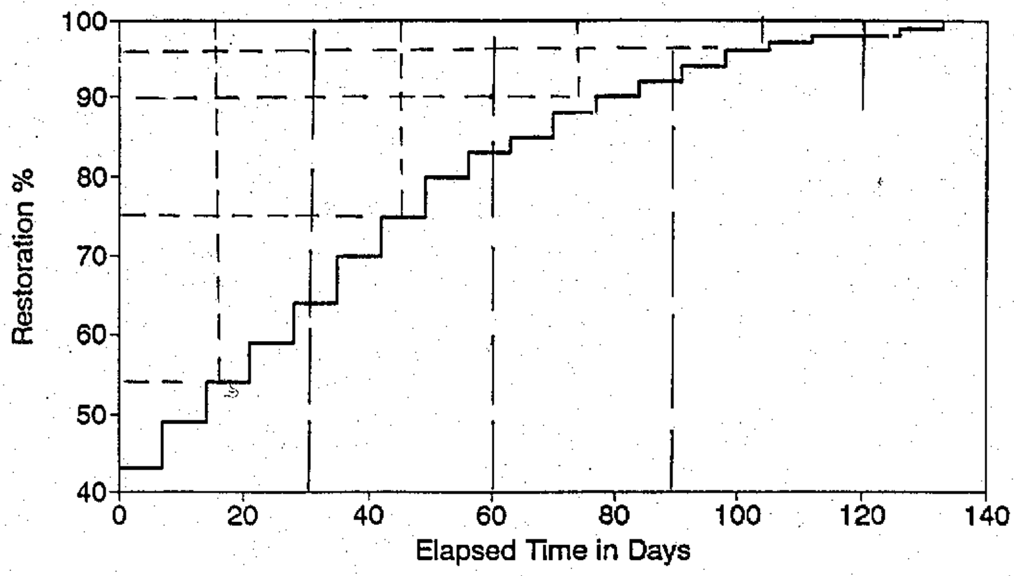
Earthquake	Indirect Loss (in Billions, 1991$)
Cape Ann	$9.1
Charleston	$10.2
Fort Tejon	$11.7
Hayward	$11.1
New Madrid, M = 8.0	$14.6
New Madrid, M = 7.0	$4.9
Puget Sound	$6.1
Wasatch Front	$3.9

Bar charts showing the indirect losses caused by transmission lines (upper bound data) by state for each scenario earthquake are provided in Figures 6-21 through 6-28. We note that estimates of indirect economic losses for each state are sensitive to the assumed location of the source zone for large-magnitude events (e.g., had the assumed source zone for the magnitude-8 New Madrid event been located further north, estimates of direct damage in Missouri would have been substantially larger). Estimates of direct damage (Chapter 6) are similarly affected.

The data provided in Figures 6-21 through 6-28 suggest that Massachusetts would experience the highest indirect losses due to the Cape Ann event with the electric system contributing the highest portion; Mississippi and Arkansas would experience the highest indirect losses due to the magnitude-8.0 New Madrid event; and South Carolina, Utah, Washington, Northern and Southern California would experience the highest indirect losses due to the Charleston, Utah, Seattle, Hayward, and Fort Tejon events, respectively. The electric system contributes the highest indirect losses, among all systems, for most of the events.

Example 6.5

Using the Restoration Capacity Plot shown below for Utah electric power following the scenario Wasatch Front event, estimate the indirect economic losses due to damage of the electric system in the state of Utah.



STEP 1: Estimate the average loss for each month, which is as follows:

Month	Percent Loss
1	45%
2	25%
3	10%
4	5%

STEP 2: From Table D-2, *Percent Value-Added Lost Due to Specified Percent Loss of Electricity Lifeline*, extrapolate percent Value Added Lost for each sector of the economy for each month and sum the results to obtain the estimated percent of Value Added Lost for the entire period. For the livestock sector, this calculation is as follows:

$(23.68+18.42)/2 + (13.16+7.89)/2 + 2.63 + 2.63/2 =$

$21.05 + 10.53 + 2.63 + 1.32 = 35.53\%$

Figure 6-20. Analysis Example Illustrating Economic Loss Calculation for Electric System in State of Utah for the Wasatch Front Scenario Event.

STEP 3: Multiply the sum from Step 2 by the percent of the economy for that sector and sum the products for all economic sectors to obtain the total Percent-Value-Added lost (for all economic sectors):

	Economic Sector	*(1) U. S. Economy Value-Added (percent)*	*(2) Utah Value-Added Lost (percent)*	*(3) Product of (1)x(2) (percent)*
1	Livestock	0.45	35.53	0.16
2	Agr. Prod.	1.06	35.53	0.38
3	AgServ. For. Fish	0.11	35.53	0.04
4	Mining	3.89	63.95	2.49
5	Construction	5.52	28.42	1.57
6	Food Tobacco	2.41	63.95	1.54
7	Textile Goods	0.37	71.05	0.26
8	Misc. Text. Prod.	0.73	71.05	0.52
9	Lumber & Wood	0.52	71.05	0.37
10	Furniture	0.34	71.05	0.24
11	Pulp & Paper	0.87	71.05	0.62
12	Print & Publish	1.31	71.05	0.93
13	Chemical & Drugs	1.40	63.95	0.90
14	Petrol. Refining	0.98	71.05	0.68
15	Rubber & Plastic	1.03	71.05	0.73
16	Leather Prods.	0.12	71.05	0.09
17	Glass Stone Clay	0.62	71.05	0.44
18	Prim. Metal Prod.	1.04	63.95	0.67
19	Fab. Metal Prod.	1.64	71.05	1.17
20	Mach. Exc. Elec.	1.56	71.05	1.11
21	Elec. & Electron	2.52	71.05	1.79
22	Transport Eq.	2.62	71.05	1.86
23	Instruments	0.68	71.05	0.48
24	Misc. Manufact.	0.69	71.05	0.49
25	Transp & Whse.	3.46	21.32	0.74
26	Utilities	5.89	56.84	3.35
27	Wholesale Trade	5.63	63.95	3.60
28	Retail Trade	5.63	63.95	3.60
29	F.I.R.E.	16.64	63.95	10.64
30	Pers./Prof. Serv.	8.03	63.95	5.14
31	Eating Drinking	2.12	56.84	1.21
32	Auto Serv.	1.09	63.95	0.70
33	Amuse & Rec.	0.70	56.84	0.40
34	Health Ed. Soc.	6.30	56.84	3.58
35	Govt & Govt Ind.	11.79	42.63	5.03
36	Households	0.25	56.84	0.14
	Total			**57.63**

The total indirect economic loss resulting from damage to the electric system in the state of Utah is computed as follows:
= 57.63% (Utah population/U.S. population) (U.S. GNP)/12
= 57.63% (1.68/242) ($4,881/12) = $1.63 Billion
where U.S. GNP = $4,881 Billion (1986)

Figure 6-20 (Continued)

Table 6-5 Indirect Economic Loss due to Damage to the Air Transportation Lifeline (Percent Monthly GNP)

			NEW MADRID (M=8.0)				CHARLESTON (M=7.5)		CAPE ANN	WASATCH	HAYWARD	FORT TEJON	PUGET SOUND	NEW MADRID (M=7.0)
		U.S. Econ. Value Added (Percent)	Arkansas	Tennessee	Kentucky	Mississippi	South Carolina	Georgia	Massachusetts	Utah	California	California	Washington	Arkansas
1	Livestock	0.45%	4.74%	1.58%	0.37%	3.42%	2.11%	1.05%	2.95%	1.79%	0.53%	1.79%	3.16%	2.11%
2	Agr. Prod.	1.06%	4.74%	1.58%	0.37%	3.42%	2.11%	1.05%	2.95%	1.79%	0.53%	1.79%	3.16%	2.11%
3	AgServ For. Fish	0.11%	4.74%	1.58%	0.37%	3.42%	2.11%	1.05%	2.95%	1.79%	0.53%	1.79%	3.16%	2.11%
4	Mining	3.89%	4.74%	1.58%	0.37%	3.42%	2.11%	1.05%	2.95%	1.79%	0.53%	1.79%	3.16%	2.11%
5	Construction	5.52%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
6	Food Tobacco	2.41%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
7	Textile Goods	0.37%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
8	Misc Text. Prod.	0.73%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
9	Lumber & Wood	0.52%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
10	Furniture	0.34%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
11	Pulp & Paper	0.87%	4.74%	1.58%	0.37%	3.42%	2.11%	1.05%	2.95%	1.79%	0.53%	1.79%	3.16%	2.11%
12	Print & Publish	1.31%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
13	Chemical & Drugs	1.40%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
14	Petrol. Refining	0.96%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
15	Rubber & Plastic	1.03%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
16	Leather Prods.	0.12%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
17	Glass Stone Clay	0.62%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
18	Prim. Metal Prod.	1.04%	4.74%	1.58%	0.37%	3.42%	2.11%	1.05%	2.95%	1.79%	0.53%	1.79%	3.16%	2.11%
19	Fab. Metal Prod.	1.64%	4.74%	1.58%	0.37%	3.42%	2.11%	1.05%	2.95%	1.79%	0.53%	1.79%	3.16%	2.11%
20	Mach. Exc. Elec.	1.56%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
21	Elec. & Electron	2.52%	14.21%	4.74%	1.11%	10.26%	6.32%	3.16%	8.84%	5.37%	1.58%	5.37%	9.47%	6.32%
22	Transport Eq.	2.62%	14.21%	4.74%	1.11%	10.26%	6.32%	3.16%	8.84%	5.37%	1.58%	5.37%	9.47%	6.32%
23	Instruments	0.68%	18.95%	6.32%	1.47%	13.68%	8.42%	4.21%	11.79%	7.16%	2.11%	7.16%	12.63%	8.42%
24	Misc. Manufact.	0.69%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
25	Transp & Whse.	3.46%	14.21%	4.74%	1.11%	10.26%	6.32%	3.16%	8.84%	5.37%	1.58%	5.37%	9.47%	6.32%
26	Utilities	5.89%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
27	Wholesale Trade	5.63%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
28	Retail Trade	5.63%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
29	F.I.R.E.	16.64%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
30	Pers./Prof Serv.	8.03%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
31	Eating Drinking	2.12%	18.95%	6.32%	1.47%	13.68%	8.42%	4.21%	11.79%	7.16%	2.11%	7.16%	12.63%	8.42%
32	Auto Serv.	1.09%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
33	Amuse & Rec.	0.70%	18.95%	6.32%	1.47%	13.68%	8.42%	4.21%	11.79%	7.16%	2.11%	7.16%	12.63%	8.42%
34	Health Ed. Soc.	6.30%	4.74%	1.58%	0.37%	3.42%	2.11%	1.05%	2.95%	1.79%	0.53%	1.79%	3.16%	2.11%
35	Govt & Govt Ind.	11.79%	9.47%	3.16%	0.74%	6.84%	4.21%	2.11%	5.89%	3.58%	1.05%	3.58%	6.32%	4.21%
36	Households	0.25%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 6-6 Indirect Economic Loss due to Damage to the Water Transportation Lifeline (Percent Monthly GNP)

	U.S. Econ. Value Added (Percent)	CHARLESTON			CAPE ANN			HAYWARD	FORT TEJON	PUGET SOUND
		South Carolina	North Carolina	Georgia	Massachussetts	Rhole Island	New Hampshire	California	California	Washington
1 Livestock	0.45%	141.05%	5.47%	103.16%	14.74%	12.63%	1.58%	11.58%	21.05%	27.37%
2 Agr. Prod.	1.06%	141.05%	5.47%	103.16%	14.74%	12.63%	1.58%	11.58%	21.05%	27.37%
3 AgServ For. Fish	0.11%	141.05%	5.47%	103.16%	14.74%	12.63%	1.58%	11.58%	21.05%	27.37%
4 Mining	3.89%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
5 Construction	5.52%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
6 Food Tobacco	2.41%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
7 Textile Goods	0.37%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
8 Misc Text. Prod.	0.73%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
9 Lumber & Wood	0.52%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
10 Furniture	0.34%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
11 Pulp & Paper	0.87%	105.79%	4.11%	77.37%	11.05%	9.47%	1.18%	8.68%	15.79%	20.53%
12 Print & Publish	1.31%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
13 Chemical & Drugs	1.40%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
14 Petrol. Refining	0.96%	282.11%	10.95%	206.32%	29.47%	25.26%	3.16%	23.16%	42.11%	54.74%
15 Rubber & Plastic	1.03%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
16 Leather Prods.	0.12%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
17 Glass Stone Clay	0.62%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
18 Prim. Metal Prod.	1.04%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
19 Fab. Metal Prod.	1.64%	105.79%	4.11%	77.37%	11.05%	9.47%	1.18%	8.68%	15.79%	20.53%
20 Mach. Exc. Elec.	1.56%	105.79%	4.11%	77.37%	11.05%	9.47%	1.18%	8.68%	15.79%	20.53%
21 Elec. & Electron	2.52%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
22 Transport Eq.	2.62%	105.79%	4.11%	77.37%	11.05%	9.47%	1.18%	8.68%	15.79%	20.53%
23 Instruments	0.68%	35.26%	1.37%	25.79%	3.68%	3.16%	0.39%	2.89%	5.26%	6.84%
24 Misc. Manufact.	0.69%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
25 Transp & Whse.	3.46%	105.79%	4.11%	77.37%	11.05%	9.47%	1.18%	8.68%	15.79%	20.53%
26 Utilities	5.89%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
27 Wholesale Trade	5.63%	70.53%	2.74%	51.58%	7.37%	6.32%	0.79%	5.79%	10.53%	13.68%
28 Retail Trade	5.63%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
29 F.I.R.E.	16.64%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
30 Pers./Prof Serv.	8.03%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
31 Eating Drinking	2.12%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
32 Auto Serv.	1.09%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
33 Amuse & Rec.	0.70%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
34 Health Ed. Soc.	6.30%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
35 Govt & Govt Ind.	11.79%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
36 Households	0.25%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 6-7 Indirect Economic Loss due to Damage to the Oil System (Percent Monthly GNP)

			CRUDE OIL				REFINED OIL	
			New Madrid		Fort Tejon		New Madrid	
		U.S. Econ. Value Added (Percent)	(M=8.0) Chicago	(M=7.0) Chicago	(M=8.0) South California	(M=8.0) North California	(M=8.0) Chicago	(M=7.0) Chicago
1	Livestock	0.45%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
2	Agr. Prod.	1.06%	4.21%	1.05%	12.63%	14.32%	2.11%	1.47%
3	AgServ For. Fish	0.11%	4.21%	1.05%	12.63%	14.32%	2.11%	1.47%
4	Mining	3.89%	4.74%	1.18%	14.21%	16.11%	2.37%	1.66%
5	Construction	5.52%	4.74%	1.18%	14.21%	16.11%	2.37%	1.66%
6	Food Tobacco	2.41%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
7	Textile Goods	0.37%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
8	Misc Text. Prod.	0.73%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
9	Lumber & Wood	0.52%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
10	Furniture	0.34%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
11	Pulp & Paper	0.87%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
12	Print & Publish	1.31%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
13	Chemical & Drugs	1.40%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
14	Petrol. Refining	0.96%	5.26%	1.32%	15.79%	17.89%	2.63%	1.84%
15	Rubber & Plastic	1.03%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
16	Leather Prods.	0.12%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
17	Glass Stone Clay	0.62%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
18	Prim. Metal Prod.	1.04%	4.74%	1.18%	14.21%	16.11%	2.37%	1.66%
19	Fab. Metal Prod.	1.64%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
20	Mach. Exc. Elec.	1.56%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
21	Elec. & Electron	2.52%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
22	Transport Eq.	2.62%	4.74%	1.18%	14.21%	16.11%	2.37%	1.66%
23	Instruments	0.68%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
24	Misc. Manufact.	0.69%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
25	Transp & Whse.	3.46%	4.74%	1.18%	14.21%	16.11%	2.37%	1.66%
26	Utilities	5.89%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
27	Wholesale Trade	5.63%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%
28	Retail Trade	5.63%	4.74%	1.18%	14.21%	16.11%	2.37%	1.66%
29	F.I.R.E.	16.64%	3.16%	0.79%	9.47%	10.74%	1.58%	1.11%
30	Pers./Prof Serv.	8.03%	3.16%	0.79%	9.47%	10.74%	1.58%	1.11%
31	Eating Drinking	2.12%	4.21%	1.05%	12.63%	14.32%	2.11%	1.47%
32	Auto Serv.	1.09%	4.74%	1.18%	14.21%	16.11%	2.37%	1.66%
33	Amuse & Rec.	0.70%	4.74%	1.18%	14.21%	16.11%	2.37%	1.66%
34	Health Ed. Soc.	6.30%	1.05%	0.26%	3.16%	3.58%	0.53%	0.37%
35	Govt & Govt Ind.	11.79%	1.05%	0.26%	3.16%	3.58%	0.53%	0.37%
36	Households	0.25%	2.63%	0.66%	7.89%	8.95%	1.32%	0.92%

Table 6-8 Indirect Economic Loss due to Damage to the Natural Gas System (Percent Monthly GNP)

	U.S. Econ. Value Added (Percent)	NEW MADRID (M=8.0)		WASATCH	HAYWARD		FORT TEJON		NEW MADRID (M=7.0)	
		Texas to Chicago	Louisiana to Northeast	Utah	Texas to North Carolina	Texas to Washington	Texas to California	Texas to Seattle	Texas to Chicago	Louisiana to Northeast
1 Livestock	0.45%	0.26%	0.53%	0.74%	2.11%	0.37%	2.11%	2.11%	0.21%	0.26%
2 Agr. Prod.	1.06%	0.79%	1.58%	2.21%	6.32%	1.11%	6.32%	6.32%	0.63%	0.79%
3 AgServ For. Fish	0.11%	0.79%	1.58%	2.21%	6.32%	1.11%	6.32%	6.32%	0.63%	0.79%
4 Mining	3.89%	0.26%	0.53%	0.74%	2.11%	0.37%	2.11%	2.11%	0.21%	0.26%
5 Construction	5.52%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
6 Food Tobacco	2.41%	0.66%	1.32%	1.84%	5.26%	0.92%	5.26%	5.26%	0.53%	0.66%
7 Textile Goods	0.37%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
8 Misc Text. Prod.	0.73%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
9 Lumber & Wood	0.52%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
10 Furniture	0.34%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
11 Pulp & Paper	0.87%	1.05%	2.11%	2.95%	8.42%	1.47%	8.42%	8.42%	0.84%	1.05%
12 Print & Publish	1.31%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
13 Chemical & Drugs	1.40%	2.37%	4.74%	6.63%	18.95%	3.32%	18.95%	18.95%	1.89%	2.37%
14 Petrol. Refining	0.96%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
15 Rubber & Plastic	1.03%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
16 Leather Prods.	0.12%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
17 Glass Stone Clay	0.62%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
18 Prim. Metal Prod.	1.04%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
19 Fab. Metal Prod.	1.64%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
20 Mach. Exc. Elec.	1.56%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
21 Elec. & Electron	2.52%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
22 Transport Eq.	2.62%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
23 Instruments	0.68%	1.97%	3.95%	5.53%	15.79%	2.76%	15.79%	15.79%	1.58%	1.97%
24 Misc. Manufact.	0.69%	1.32%	2.63%	3.68%	10.53%	1.84%	10.53%	10.53%	1.05%	1.32%
25 Transp & Whse.	3.46%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
26 Utilities	5.89%	1.05%	2.11%	2.95%	8.42%	1.47%	8.42%	8.42%	0.84%	1.05%
27 Wholesale Trade	5.63%	0.26%	0.53%	0.74%	2.11%	0.37%	2.11%	2.11%	0.21%	0.26%
28 Retail Trade	5.63%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
29 F.I.R.E.	16.64%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
30 Pers./Prof Serv.	8.03%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
31 Eating Drinking	2.12%	1.05%	2.11%	2.95%	8.42%	1.47%	8.42%	8.42%	0.84%	1.05%
32 Auto Serv.	1.09%	0.13%	0.26%	0.37%	1.05%	0.18%	1.05%	1.05%	0.11%	0.13%
33 Amuse & Rec.	0.70%	1.05%	2.11%	2.95%	8.42%	1.47%	8.42%	8.42%	0.84%	1.05%
34 Health Ed. Soc.	6.30%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
35 Govt & Govt Ind.	11.79%	0.53%	1.05%	1.47%	4.21%	0.74%	4.21%	4.21%	0.42%	0.53%
36 Households	0.25%	0.92%	1.84%	2.58%	7.37%	1.29%	7.37%	7.37%	0.74%	0.92%

Table 6-9 Indirect Economic Loss due to Damage to the Railroad Lifeline (Percent Monthly GNP)

	U.S. Econ. Value Added (Percent)	*(M=8.0) New Madrid*	*Charleston*	*Cape Ann*	*Utah*	*Hayward*	*Fort Tejon*	*Seattle*	*(M7=.0) New Madrid*
1 Livestock	0.45%	4.21%	7.58%	7.58%	3.37%	5.47%	7.58%	7.58%	3.37%
2 Agr. Prod.	1.06%	4.21%	7.58%	7.58%	3.37%	5.47%	7.58%	7.58%	3.37%
3 AgServ For. Fish	0.11%	4.21%	7.58%	7.58%	3.37%	5.47%	7.58%	7.58%	3.37%
4 Mining	3.89%	3.68%	6.63%	6.63%	2.95%	4.79%	6.63%	6.63%	2.95%
5 Construction	5.52%	0.53%	0.95%	0.95%	0.42%	0.68%	0.95%	0.95%	0.42%
6 Food Tobacco	2.41%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
7 Textile Goods	0.37%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
8 Misc Text. Prod.	0.73%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
9 Lumber & Wood	0.52%	4.21%	7.58%	7.58%	3.37%	5.47%	7.58%	7.58%	3.37%
10 Furniture	0.34%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
11 Pulp & Paper	0.87%	4.74%	8.53%	8.53%	3.79%	6.16%	8.53%	8.53%	3.79%
12 Print & Publish	1.31%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
13 Chemical & Drugs	1.40%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
14 Petrol. Refining	0.96%	4.21%	7.58%	7.58%	3.37%	5.47%	7.58%	7.58%	3.37%
15 Rubber & Plastic	1.03%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
16 Leather Prods.	0.12%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
17 Glass Stone Clay	0.62%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
18 Prim. Metal Prod.	1.04%	5.26%	9.47%	9.47%	4.21%	6.84%	9.47%	9.47%	4.21%
19 Fab. Metal Prod.	1.64%	4.74%	8.53%	8.53%	3.79%	6.16%	8.53%	8.53%	3.79%
20 Mach. Exc. Elec.	1.56%	4.74%	8.53%	8.53%	3.79%	6.16%	8.53%	8.53%	3.79%
21 Elec. & Electron	2.52%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
22 Transport Eq.	2.62%	4.74%	8.53%	8.53%	3.79%	6.16%	8.53%	8.53%	3.79%
23 Instruments	0.68%	0.53%	0.95%	0.95%	0.42%	0.68%	0.95%	0.95%	0.42%
24 Misc. Manufact.	0.69%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
25 Transp & Whse.	3.46%	3.16%	5.68%	5.68%	2.53%	4.11%	5.68%	5.68%	2.53%
26 Utilities	5.89%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
27 Wholesale Trade	5.63%	1.58%	2.84%	2.84%	1.26%	2.05%	2.84%	2.84%	1.26%
28 Retail Trade	5.63%	2.11%	3.79%	3.79%	1.68%	2.74%	3.79%	3.79%	1.68%
29 F.I.R.E.	16.64%	1.05%	1.89%	1.89%	0.84%	1.37%	1.89%	1.89%	0.84%
30 Pers./Prof Serv.	8.03%	1.05%	1.89%	1.89%	0.84%	1.37%	1.89%	1.89%	0.84%
31 Eating Drinking	2.12%	0.53%	0.95%	0.95%	0.42%	0.68%	0.95%	0.95%	0.42%
32 Auto Serv.	1.09%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
33 Amuse & Rec.	0.70%	0.53%	0.95%	0.95%	0.42%	0.68%	0.95%	0.95%	0.42%
34 Health Ed. Soc.	6.30%	0.53%	0.95%	0.95%	0.42%	0.68%	0.95%	0.95%	0.42%
35 Govt & Govt Ind.	11.79%	1.05%	1.89%	1.89%	0.84%	1.37%	1.89%	1.89%	0.84%
36 Households	0.25%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%

Table 6-10 Indirect Economic Loss due to Damage to the Electric System (Percent Monthly GNP)

		U.S. Econ. Value Added (Percent)	NEW MADRID (M=8.0)						CHARLESTON			CAPE ANN		
			Illinois	Missouri	Arkansas	Tennessee	Kentucky	Mississippi	South Carolina	North Carolina	Georgia	Massachusetts	Connecticut	Delaware
1	Livestock	0.45%	3.95%	6.58%	32.89%	13.16%	13.16%	44.74%	46.05%	7.89%	18.42%	44.74%	15.79%	10.53%
2	Agr. Prod.	1.06%	3.95%	6.58%	32.89%	13.16%	13.16%	44.74%	46.05%	7.89%	18.42%	44.74%	15.79%	10.53%
3	AgServ For. Fish	0.11%	3.95%	6.58%	32.89%	13.16%	13.16%	44.74%	46.05%	7.89%	18.42%	44.74%	15.79%	10.53%
4	Mining	3.89%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
5	Construction	5.52%	3.16%	5.26%	26.32%	10.53%	10.53%	35.79%	36.84%	6.32%	14.74%	35.79%	12.63%	8.42%
6	Food Tobacco	2.41%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
7	Textile Goods	0.37%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
8	Misc Text. Prod.	0.73%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
9	Lumber & Wood	0.52%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
10	Furniture	0.34%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
11	Pulp & Paper	0.87%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
12	Print & Publish	1.31%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
13	Chemical & Drugs	1.40%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
14	Petrol. Refining	0.96%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
15	Rubber & Plastic	1.03%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
16	Leather Prods.	0.12%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
17	Glass Stone Clay	0.62%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
18	Prim. Metal Prod.	1.04%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
19	Fab. Metal Prod.	1.64%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
20	Mach. Exc. Elec.	1.56%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
21	Elec. & Electron	2.52%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
22	Transport Eq.	2.62%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
23	Instruments	0.68%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
24	Misc. Manufact.	0.69%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
25	Transp & Whse.	3.46%	2.37%	3.95%	19.74%	7.89%	7.89%	26.84%	27.63%	4.74%	11.05%	26.84%	9.47%	6.32%
26	Utilities	5.89%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%
27	Wholesale Trade	5.63%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
28	Retail Trade	5.63%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
29	F.I.R.E.	16.64%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
30	Pers./Prof Serv.	8.03%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
31	Eating Drinking	2.12%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%
32	Auto Serv.	1.09%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
33	Amuse & Rec.	0.70%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%
34	Health Ed. Soc.	6.30%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%
35	Govt & Govt Ind.	11.79%	4.74%	7.89%	39.47%	15.79%	15.79%	53.68%	55.26%	9.47%	22.11%	53.68%	18.95%	12.63%
36	Households	0.25%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%

Table 6-10 Indirect Economic Loss due to Damage to the Electric System (Percent Monthly GNP) (Continued)

		CAPE ANN		*WASATCH*	*CALIFORNIA*		*PUGET SOUND*	*NEW MADRID (M=7.0)*			
	U.S. Econ. Value Added (Percent)	*Rhode Island*	*New Hampshire*	*Utah*	*Hayward*	*Fort Tejon*	*Washington*	*Arkansas*	*Tennessee*	*Kentucky*	*Mississippi*
1 Livestock	0.45%	42.11%	14.47%	35.53%	23.68%	13.16%	47.37%	23.68%	7.89%	3.95%	3.95%
2 Agr. Prod.	1.06%	42.11%	14.47%	35.53%	23.68%	13.16%	47.37%	23.68%	7.89%	3.95%	3.95%
3 AgServ For. Fish	0.11%	42.11%	14.47%	35.53%	23.68%	13.16%	47.37%	23.68%	7.89%	3.95%	3.95%
4 Mining	3.89%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
5 Construction	5.52%	33.68%	11.58%	28.42%	18.95%	10.53%	37.89%	18.95%	6.32%	3.16%	3.16%
6 Food Tobacco	2.41%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
7 Textile Goods	0.37%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
8 Misc Text. Prod.	0.73%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
9 Lumber & Wood	0.52%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
10 Furniture	0.34%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
11 Pulp & Paper	0.87%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
12 Print & Publish	1.31%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
13 Chemical & Drugs	1.40%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
14 Petrol. Refining	0.96%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
15 Rubber & Plastic	1.03%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
16 Leather Prods.	0.12%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
17 Glass Stone Clay	0.62%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
18 Prim. Metal Prod.	1.04%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
19 Fab. Metal Prod.	1.64%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
20 Mach. Exc. Elec.	1.56%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
21 Elec. & Electron	2.52%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
22 Transport Eq.	2.62%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
23 Instruments	0.68%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
24 Misc. Manufact.	0.69%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
25 Transp & Whse.	3.46%	25.26%	8.68%	21.32%	14.21%	7.89%	28.42%	14.21%	4.74%	2.37%	2.37%
26 Utilities	5.89%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%
27 Wholesale Trade	5.63%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
28 Retail Trade	5.63%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
29 F.I.R.E.	16.64%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
30 Pers./Prof Serv.	8.03%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
31 Eating Drinking	2.12%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%
32 Auto Serv.	1.09%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
33 Amuse & Rec.	0.70%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%
34 Health Ed. Soc.	6.30%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%
35 Govt & Govt Ind.	11.79%	50.53%	17.37%	42.63%	28.42%	15.79%	56.84%	28.42%	9.47%	4.74%	4.74%
36 Households	0.25%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%

Table 6-11 Indirect Economic Loss due to Damage to the Highway System (Percent Monthly GNP)

	U.S. Econ Value Added (Percent)	*New Madrid (M8.0)*	*Charleston*	*Cape Ann*	*Wasatch*	*Hayward*	*Fort Tejon*	*Puget Sound*	*New Madrid (M=7.0)*
1 Livestock	0.45%	85.53%	36.84%	78.95%	83.96%	42.11%	52.63%	60.53%	63.16%
2 Agr. Prod.	1.06%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
3 AgServ For. Fish	0.11%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
4 Mining	3.89%	59.87%	25.79%	55.26%	58.77%	29.47%	36.84%	42.37%	44.21%
5 Construction	5.52%	68.42%	29.47%	63.16%	67.17%	33.68%	42.11%	48.42%	50.53%
6 Food Tobacco	2.41%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
7 Textile Goods	0.37%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
8 Misc Text. Prod.	0.73%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
9 Lumber & Wood	0.52%	153.95%	66.32%	142.11%	151.13%	75.79%	94.74%	108.95%	113.68%
10 Furniture	0.34%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
11 Pulp & Paper	0.87%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
12 Print & Publish	1.31%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
13 Chemical & Drugs	1.40%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
14 Petrol. Refining	0.96%	153.95%	66.32%	142.11%	151.13%	75.79%	94.74%	108.95%	113.68%
15 Rubber & Plastic	1.03%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
16 Leather Prods.	0.12%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
17 Glass Stone Clay	0.62%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
18 Prim. Metal Prod.	1.04%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
19 Fab. Metal Prod.	1.64%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
20 Mach. Exc. Elec.	1.56%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
21 Elec. & Electron	2.52%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
22 Transport Eq.	2.62%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
23 Instruments	0.68%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
24 Misc. Manufact.	0.69%	128.29%	55.26%	118.42%	125.94%	63.16%	78.95%	90.79%	94.74%
25 Transp & Whse.	3.46%	136.84%	58.95%	126.32%	134.34%	67.37%	84.21%	96.84%	101.05%
26 Utilities	5.89%	68.42%	29.47%	63.16%	67.17%	33.68%	42.11%	48.42%	50.53%
27 Wholesale Trade	5.63%	119.74%	51.58%	110.53%	117.54%	58.95%	73.68%	84.74%	88.42%
28 Retail Trade	5.63%	94.08%	40.53%	86.84%	92.36%	46.32%	57.89%	66.58%	69.47%
29 F.I.R.E.	16.64%	76.97%	33.16%	71.05%	75.56%	37.89%	47.37%	54.47%	56.84%
30 Pers./Prof Serv.	8.03%	76.97%	33.16%	71.05%	75.56%	37.89%	47.37%	54.47%	56.84%
31 Eating Drinking	2.12%	85.53%	36.84%	78.95%	83.96%	42.11%	52.63%	60.53%	63.16%
32 Auto Serv.	1.09%	94.08%	40.53%	86.84%	92.36%	46.32%	57.89%	66.58%	69.47%
33 Amuse & Rec.	0.70%	85.53%	36.84%	78.95%	83.96%	42.11%	52.63%	60.53%	63.16%
34 Health Ed. Soc.	6.30%	94.08%	40.53%	86.84%	92.36%	46.32%	57.89%	66.58%	69.47%
35 Govt & Govt Ind.	11.79%	51.32%	22.11%	47.37%	50.38%	25.26%	31.58%	36.32%	37.89%
36 Households	0.25%	68.42%	29.47%	63.16%	67.17%	33.68%	42.11%	48.42%	50.53%

Table 6-12 Indirect Economic Losses Due to Damage to Lifeline Transmission Systems

Scenario Earthquakes	*Natural Gas*		*Crude Oil*		*Refined Oil*		*Air Transportation*		*Railroads*		*Ports*		*Electric*		*Water*		*Highways*	
	%	*$ Bil*	*%*	*$ Bil*	*%*	*$ Bil*	*%*	*$ Bil*	*%*	*$ Bil*	*%*	*$ Bil*	*%*	*$ Bil*	*%*	*$ Bil*	*%*	*$ Bil*
Cape Ann		$0.00		$0.00		$0.00	0.12	$0.49	0.01	$0.02	0.11	$0.45	2.20	$8.95	N/A	N/A	0.16	$0.65
Charleston		$0.00		$0.00		$0.00	0.11	$0.45	0.01	$0.02	1.21	$4.92	2.15	$8.75	N/A	N/A	0.08	$0.33
Fort Tejon	0.41	$1.67	1.07	$4.35		$0.00	0.35	$1.42	0.06	$0.25	0.61	$2.48	1.90	$7.73	1.2	$4.88	1.10	$4.47
Hayward	0.22	$0.89		$0.00		$0.00	0.10	$0.41	0.03	$0.11	0.33	$1.34	2.43	$9.88	1	$4.07	0.50	$2.03
Madrid, MO M=8	0.07	$0.28	0.10	$0.41	0.05	$0.20	0.2	$0.81	0.06	$0.25		$0.00	2.55	$10.37	N/A	N/A	2.30	$9.36
Madrid, MO M=7	0.04	$0.16	0.03	$0.11	0.04	$0.15	0.04	$0.16	0.01	$0.04		$0.00	0.81	$3.29	N/A	N/A	0.84	$3.42
Puget Sound	0.05	$0.20		$0.00		$0.00	0.10	$0.41	0.03	$0.11	0.13	$0.53	1.43	$5.82	0.19	$0.77	0.27	$1.10
Wasatch Front	0.01	$0.38		$0.00		$0.00	0.02	$0.08	0.01	$0.02		$0.00	0.40	$1.63	N/A	N/A	0.80	$3.25

Scenario Earthquakes	*ESTIMATED TOTAL ECONOMIC LOSS/EVENT*		
	Lower Bound	*Upper Bound*	*Best Estimate*
Cape Ann	$8.95	$10.56	$9.00
Charleston	$8.75	$14.46	$10.05
Fort Tejon	$7.73	$27.26	$11.56
Hayward	$9.88	$18.73	$11.01
Madrid, MO M=8	$10.37	$21.69	$14.00
Madrid, MO M=7	$3.42	$7.33	$4.76
Puget Sound	$5.82	$8.94	$6.01
Wasatch Front	$3.25	$5.02	$3.64

Table 6-13 Indirect Economic Losses Due to Damage to Lifeline Distribution Systems

Scenario Earthquakes	Electric %	Electric $ Bil	Water %	Water $ Bil	Highways %	Highways $ Bil	SRSS
Cape Ann	0.32	$1.3	0.15	$.61	0.21	$0.86	$1.6
Charleston	0.27	$1.1	0.15	$.63	0.17	$0.71	$1.4
Fort Tejon	0.34	$1.4	0.11	$.47	0.08	$0.33	$1.5
Hayward	0.37	$1.5	0.10	$.41	0.09	$0.36	$1.6
New Madrid, M=8	0.76	$3.1	0.44	$1.8	0.49	$2.0	$4.1
New Madrid, M=7	0.23	$1.0	0.14	$.57	0.15	$0.63	$1.3
Puget Sound	0.22	$0.9	0.04	$.18	0.10	$0.40	$1.0
Wasatch Front	0.15	$0.6	0.06	$.27	0.09	$0.37	$1.25

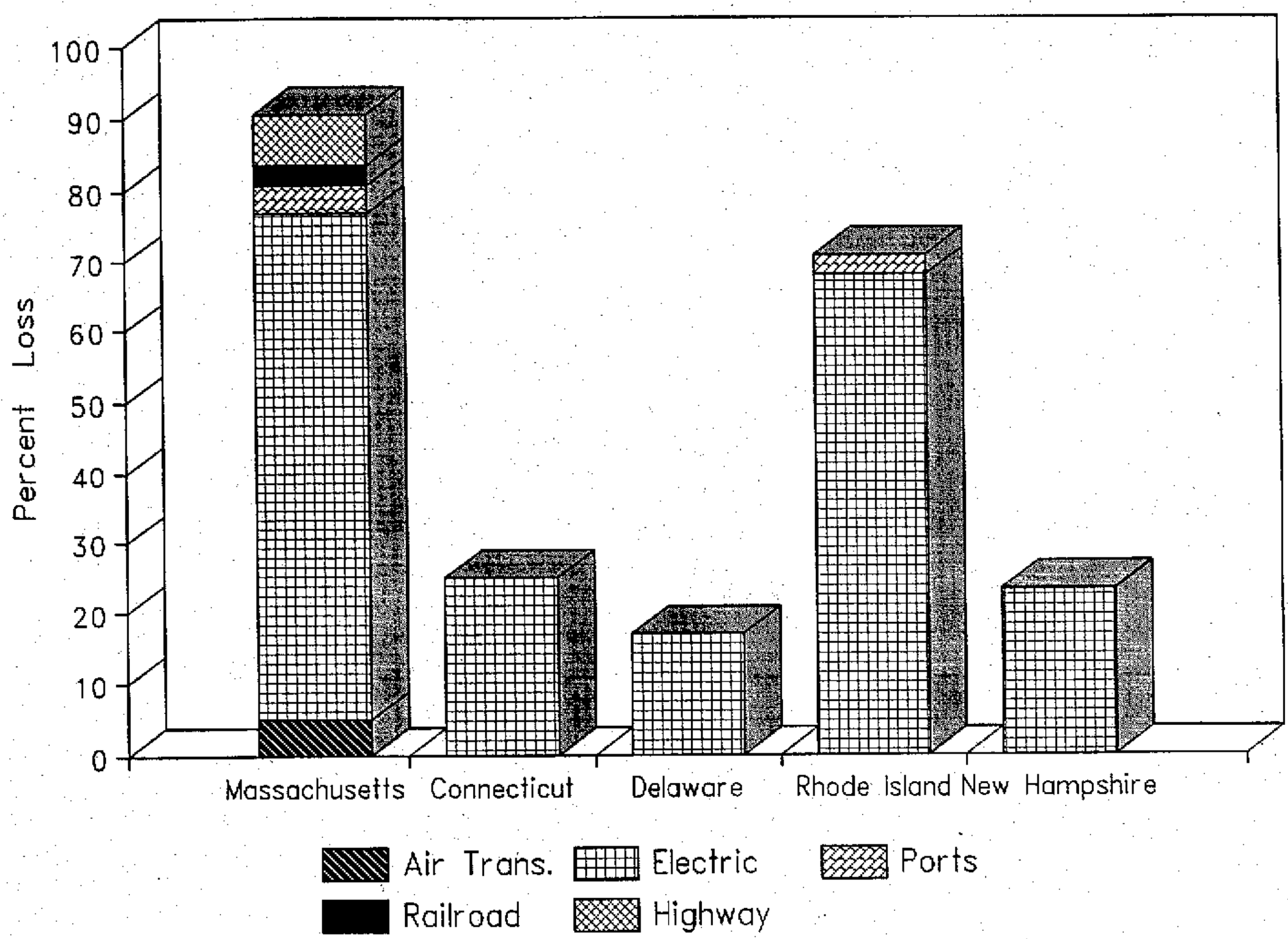


Figure 6-21 *Percent indirect economic loss by state (monthly GNP) resulting from damage to various lifelines, Cape Ann event (M=7.0).*

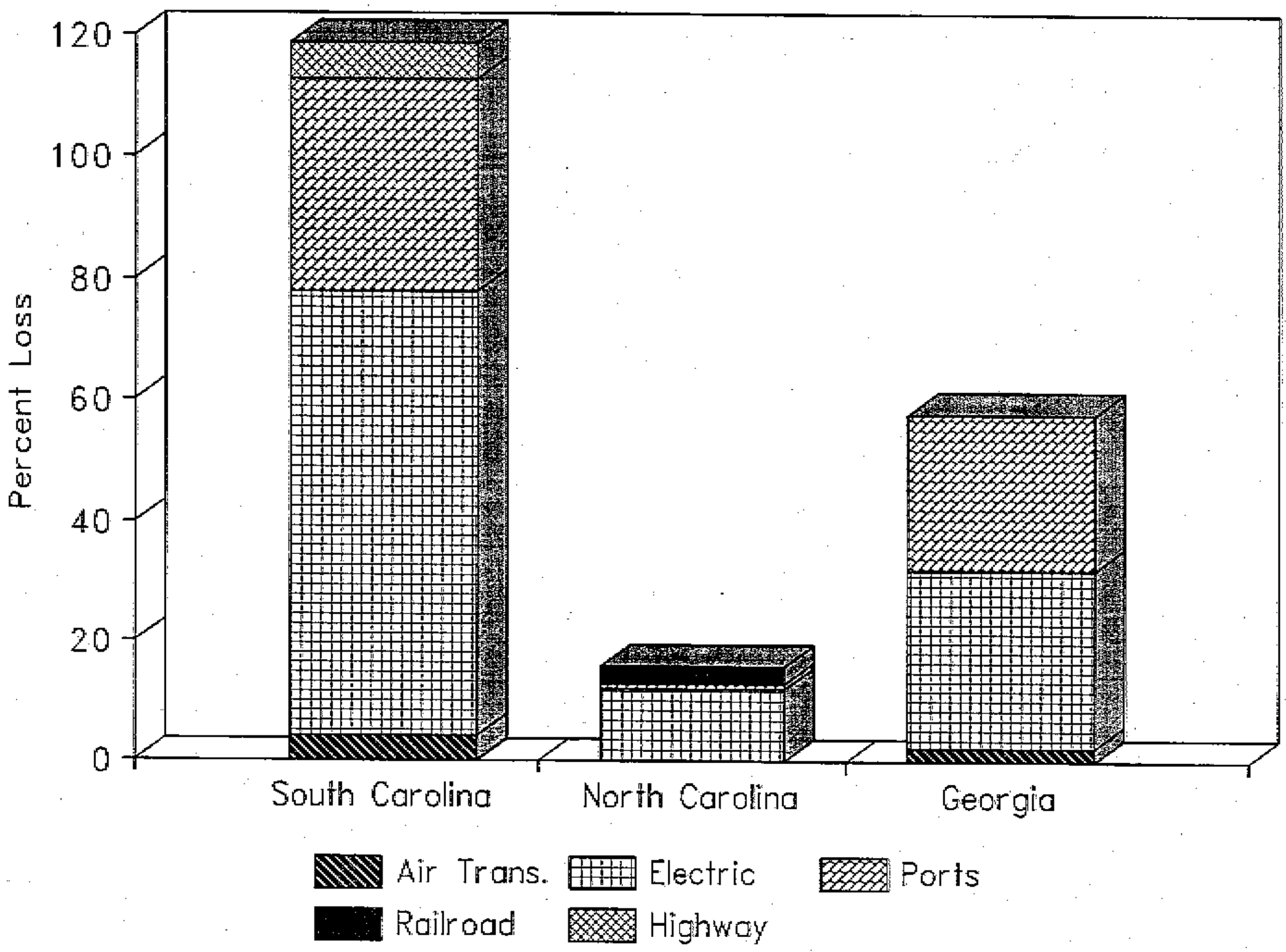


Figure 6-22. Percent indirect economic loss by state (monthly GNP) resulting from damage to various lifelines, Charleston event (M=7.5).

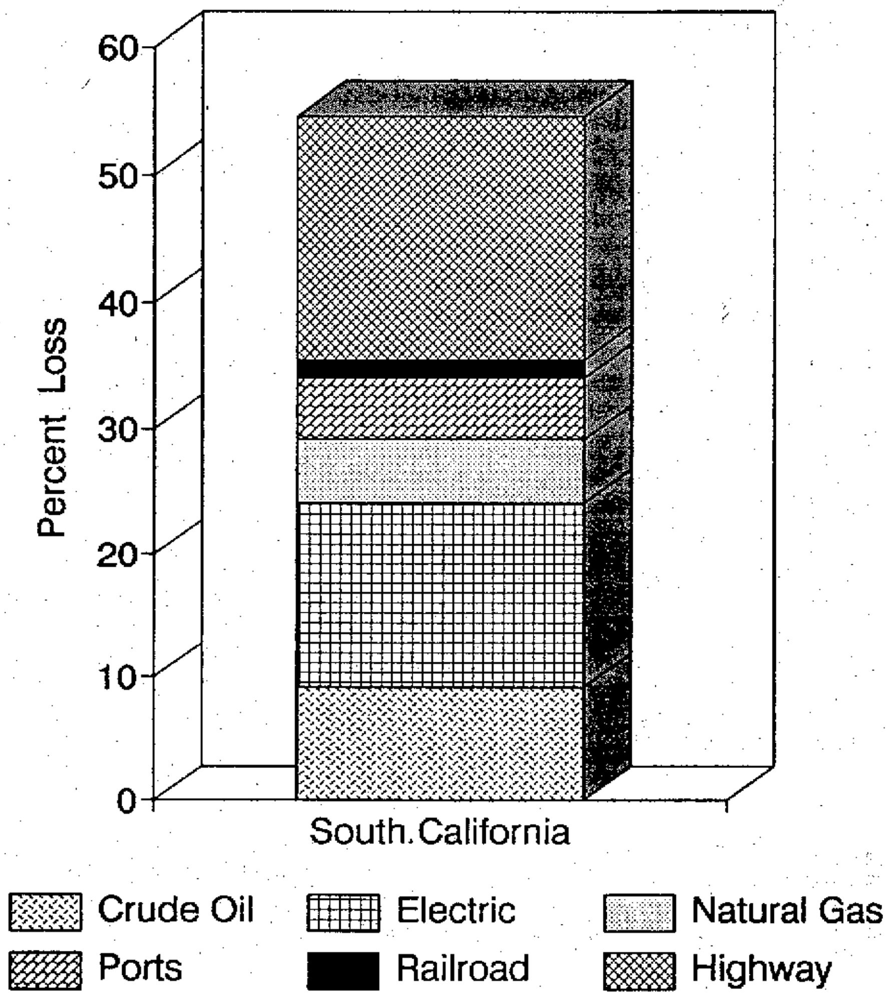


Figure 6-23 *Percent indirect economic loss in Southern California (monthly GNP) resulting from damage to various lifelines, Fort Tejon event (M=8.0).*

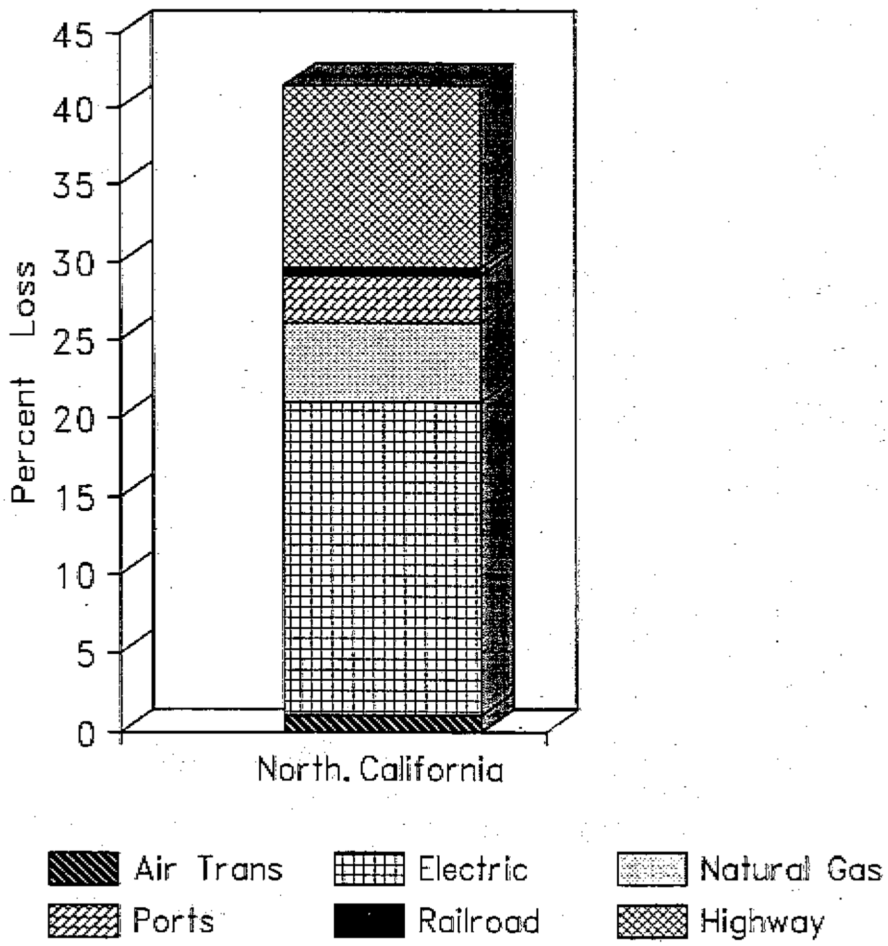


Figure 6-24 *Percent indirect economic loss in Northern California (monthly GNP) resulting from damage to various lifelines, Hayward event (M=7.5).*

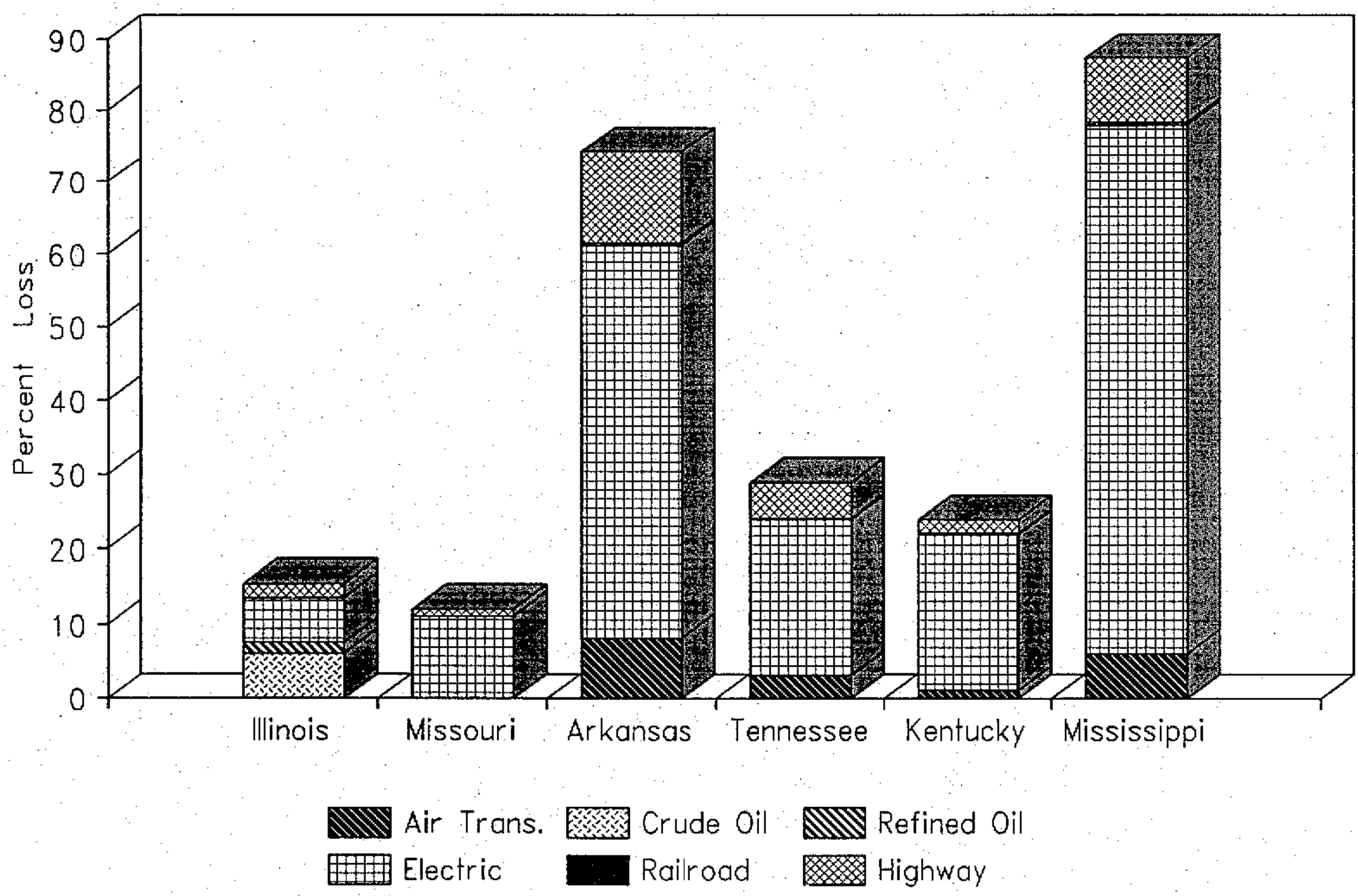


Figure 6-25 *Percent indirect economic loss by state (monthly GNP) resulting from damage to various lifelines, New Madrid event (M=8.0). Note that the relatively low losses for Missouri reflect the assumed location of the scenario earthquake source zone and the estimated distribution of intensity (see Figure 4-17).*

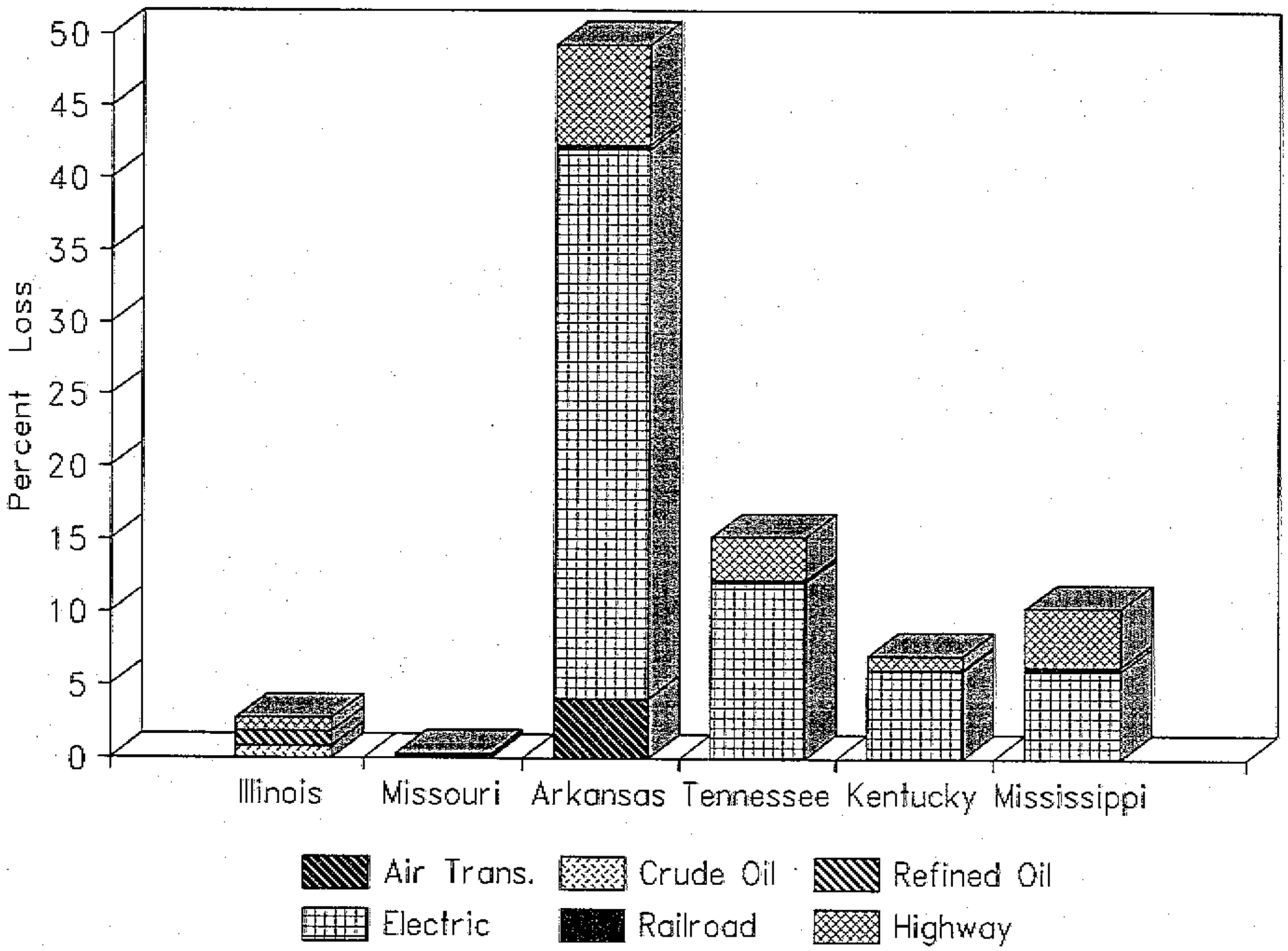


Figure 6-26 *Percent indirect economic loss by state (monthly GNP) resulting from damage to various lifelines, New Madrid event (M=7.0). Note that the relatively low losses for Missouri reflect the assumed location of the scenario earthquake source zone and the estimated distribution of intensity (see Figure 4-18).*

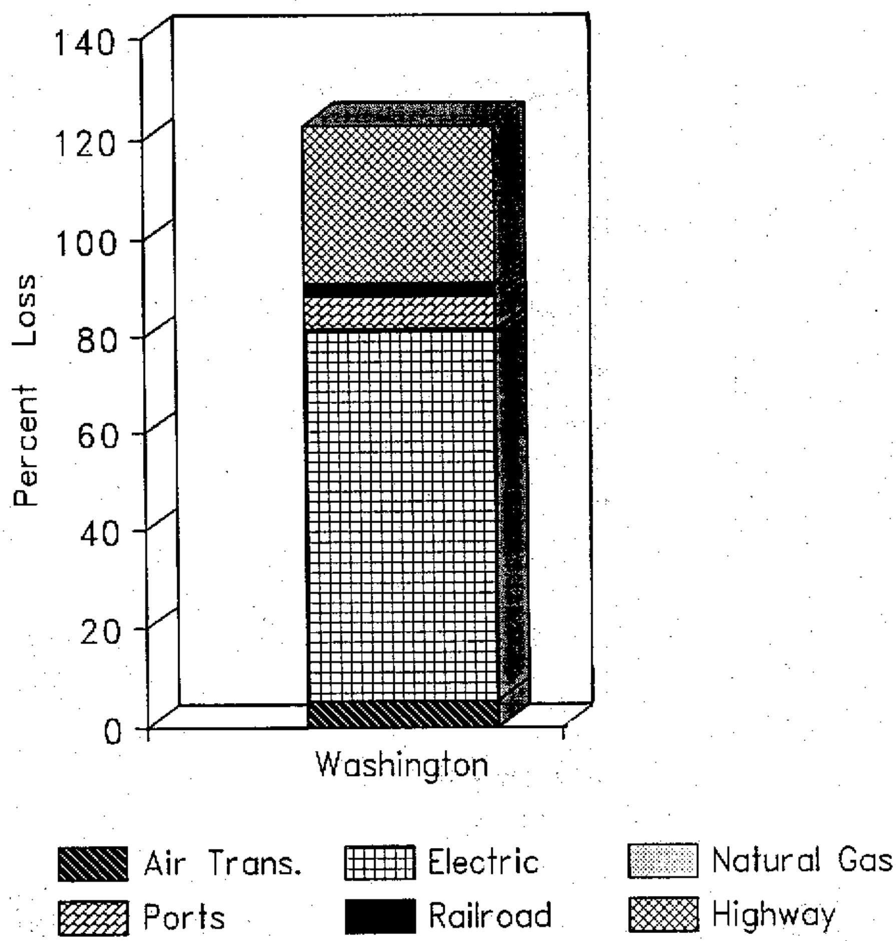


Figure 6-27 *Percent indirect economic loss in state of Washington (monthly GNP) resulting from damage to various lifelines, Puget Sound event (M=7.5).*

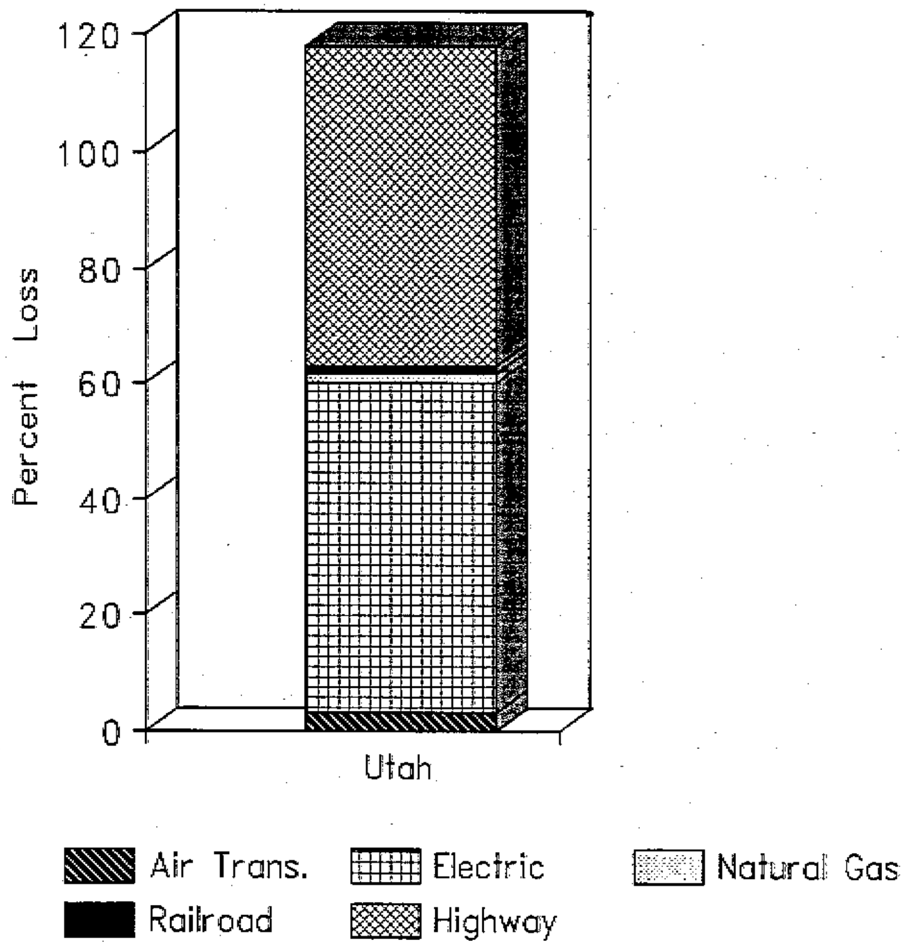


Figure 6-28 *Percent indirect economic loss in state of Utah (monthly GNP) resulting from damage to various lifelines, Wasatch Front event (M=7.5).*

7. Combined Economic Losses, Deaths, and Injuries

7.1 Introduction

In this chapter we provide an overview of combined economic losses, consisting of direct and indirect economic losses, and a discussion of deaths and injuries.

At this point it is important to reiterate the purposes and key limitations of this study. As previously indicated, the overall purpose is to provide an overview of the national economic impact resulting from the seismic vulnerability of lifelines and the impact of their disruption. The Federal Emergency Management Agency is planning to use this report to emphasize the importance of maintaining functionality of lifelines after earthquakes and to assist in the identification and prioritization of hazard mitigation measures and policies.

Lifelines considered are transportation systems, energy systems, emergency service facilities, and water systems. Excluded from consideration because of the unavailability of inventory data or the need for more in-depth studies are telecommunication systems, nuclear and fossil-fuel power plants, dams, and certain highway, electric, and water facilities at the local distribution level.

Also excluded from consideration in the results are interaction effects between lifelines, secondary economic effects (the impact of a reduced capacity of one economic sector on a dependent sector), and damage resulting from landslide (due to lack of inventory data nationwide). These limitations and others described in Chapters 2, 4, and 5 tend to underestimate losses; other limitations (e.g., application of ATC-13 vulnerability functions to a relatively few structures) tend to overestimate the losses. Lack of capacity information for most lifelines was also a definite limitation. In the aggregate, due primarily to the exclusion of systems (e.g., dams and telecommunication systems), we believe the estimates presented in this report are, in fact, quite conservative.

This report is a macroscopic investigation at the national level and the results should not be used for microscopic interpretations. The results are not intended to be used to evaluate any particular regional utility or lifeline and no specific information on such specific facilities has been included.

7.2 Human Death and Injury

It is generally felt that lifeline performance and continuity of operation is vital to human survival in the modern, urban, world. Most observers believe that damage to lifelines would result in human death and injury. Analogous to direct damage to property and indirect economic losses, human death and injury resulting from lifeline damage can be categorized as follows:

1. Human death and injury caused by lifeline functional curtailment, where persons suffer as a result of deprivation of vital services; and

2. Human death and injury resulting from direct damage to lifelines (e.g., occupant injuries resulting from the collapse of an air terminal building).

Analysis and data on both of these aspects are virtually nonexistent. Following are discussions of these death and injury causes:

7.2.1 Casualties Due to Lifeline Functional Curtailment

Without the benefit of hard data it is difficult to estimate with high confidence the number of casualties that will result from curtailment of lifeline function. Our preliminary assessment is that human death and injury due to functional curtailment of lifelines can generally be expected to be very low. This is a fundamental assumption of this study, and will probably cause some debate. Each lifeline was considered, and this conclusion was found to hold, based on the following assumptions: (1) most vital installations that normally require a lifeline service have back-up emergency supplies, and (2) most lifelines have considerable elasticity in demand, and the level of service necessary for life maintenance is very low. Examples follow:

- Electricity. Persons can survive without power, even in the Northeast in the winter. Most hospitals and similar installations have emergency generators. Those that lack emergency generators can transfer patients to other sites.

- Water. Water for human survival is very minimal. Humans can survive without water for 48 or more hours, and water for human survival can be imported if necessary.

- Gas and Liquid Fuels. Gas and liquid fuel systems are probably the most critical of all lifelines, yet capacity is very elastic, and only short-term shortages are expected. Fuel for heating in the Northeast in the winter can be conserved if necessary by clustering people in school gymnasia, national guard armories, and so on.

- Rail, Air, and Highway Transportation. Transportation lifelines are highly redundant and thus very elastic; emergency food and medicines would be expected to be deliverable regardless of earthquake damage.

7.2.2 *Casualties Resulting From Lifeline Direct Damage*

Casualties can result from direct damage, especially catastrophic collapse, of lifeline components. Although few deaths occurred directly as a result of lifeline damage in U. S. earthquakes prior to 1989, life-loss due to lifeline failure was tragically demonstrated during the October 17, 1989, Loma Prieta, California, earthquake. Approximately two thirds of the 62 deaths from this earthquake resulted from the failure of a lifeline component--partial collapse of the Cypress structure, a double-decked highway viaduct in Oakland approximately 100 km from the earthquake source zone.

Although it can be argued that the deaths and injuries caused by lifeline failure in the Loma Prieta earthquake were the exception, not the rule, the vulnerability functions developed for this project suggest that substantial life-loss from lifeline component failure should be anticipated. Lifeline failures that could cause substantial life loss or injury include bridge failure, railroad derailment, and pipeline failure.

Unfortunately, data necessary for estimating life loss associated with these component failures are not readily available, precluding development of reliable casualty estimation methodology and data for lifeline structures.

7.3 Combined Direct and Indirect Economic Losses

Total dollar losses from direct damage and indirect economic losses have been taken from Chapters 5 and 6 and are combined and summarized herein for each scenario earthquake and lifeline in Table 7-1. The total losses for each scenario earthquake are as follows:

Earthquake	Direct Plus Indirect Losses (in Billions, 1991$)
Cape Ann	$13.3
Charleston	$15.1
Fort Tejon	$16.6
Hayward	$15.7
New Madrid, M = 8.0	$26.4
New Madrid, M = 7.0	$8.3
Puget Sound	$10.5
Wasatch Front	$5.4

Table 7-1 Total Direct Plus Indirect Dollar Losses for Each Scenario Earthquake and Lifeline (Billions of Dollars)

Scenario	*Electric*	*Highways*	*Water*	*Medical Care*	*Ports*	*Railroads*	*Airport*	*Natural Gas*	*Crude Oil*	*Refined Oil*	*Broadcasting Stations*	*Fire Stations*	*Total*
Cape Ann	$11.24	$2.06	$0.91	$0.49	$0.50	$0.03	$0.58	$0.00	$0.00	$0.00	$0.02	$0.01	$13.25
Charleston	$10.82	$2.05	$0.94	$0.57	$5.30	$0.18	$0.59	$0.00	$0.00	$0.00	$0.07	$0.01	$15.11
Fort Tejon	$9.66	$5.18	$5.27	$1.43	$2.65	$0.41	$1.57	$1.68	$4.38	$0.00	$0.03	$0.05	$16.58
Hayward	$12.21	$2.52	$4.38	$1.30	$1.46	$0.22	$0.44	$0.09	$0.00	$0.00	$0.02	$0.01	$15.66
New Madrid 8	$15.68	$13.19	$2.68	$1.30	$0.00	$0.71	$1.22	$0.34	$0.46	$0.23	$0.09	$0.01	$26.37
New Madrid 7	$5.17	$4.12	$0.85	$0.40	$0.00	$0.15	$0.31	$0.18	$0.13	$0.16	$0.03	$0.00	$8.29
Puget Sound	$8.29	$1.95	$0.90	$0.51	$0.73	$0.21	$0.62	$0.21	$0.00	$0.00	$0.05	$0.01	$10.48
Wasatch Front	$2.21	$3.85	$0.40	$0.20	$0.00	$0.05	$0.11	$0.04	$0.00	$0.00	$0.04	$0.00	$5.41

8. Hazard Mitigation Measures and Benefits

8.1 Introduction

A primary objective of this study is to identify the most critical lifelines and develop a prioritized series of steps for reduction of lifeline seismic vulnerability, based on overall benefits. In this chapter we identify the most critical lifelines and provide a relative ranking of the criticality of these different lifelines in terms of the estimated impact of damage and economic disruption. Also included are recommended key measures for reducing the earthquake vulnerability of these lifeline systems, and results from analytical computations to illustrate the reduction in losses if such hazard mitigation strategies are employed.

8.2 Identification of Critical Lifelines

Based on the combined direct and indirect economic losses presented in Chapter 7 and with due consideration of the assumptions and limitations expressed throughout this report, we offer the following relative ranking of the criticality of different lifelines in terms of the estimated impact of damage and disruption:

Rank	Lifeline	Event/Location
1.	Electric System	New Madrid (M=8.0)
		Hayward
		Cape Ann, Charleston, Fort Tejon
2.	Highways	New Madrid (M=8.0)
		Fort Tejon
		Hayward, New Madrid (M=7.0)
3.	Water System*	Fort Tejon
4.	Ports	Charleston
5.	Crude Oil	Fort Tejon

*The ranking for the water system may be underestimated because critical components such as pumping stations and dams were not included in the study.

8.3 Measures for Reducing Vulnerability of Lifeline Systems

The seismic vulnerability of lifeline systems, from the point of view of fulfilling function, can be reduced through three primary approaches:

1. **Damage reduction measures.** In this approach reliability of function is enhanced by reducing damage. This approach may take the form of:

   - Strengthening a building, bracing equipment, or performing other corrective retrofit measures to mitigate shaking effects;
   - Densifying the soil beneath a structure, or placing a structure on piles, or using other techniques to mitigate hazardous geotechnical conditions, e.g., liquefaction potential,
   - Other component improvements, depending on the component and potential earthquake impacts, e.g., replacement of vulnerable systems/components with new systems/components that will provide improved seismic resistance.

2. **Provision for system redundancy.** In this approach, reliability of function is enhanced by providing additional and alternative links (e.g., new highways, pipelines, other transmission or distribution links). Because earthquake damage is fundamentally a random phenomena, addition of system links will tend to increase system reliability.

3. **Operational improvements.** In this approach reliability of function is enhanced by providing emergency response planning and the capability to rapidly and effectively repair damage, redirect functions, or otherwise mitigate earthquake damage impacts on system operations and thereby re-establish system function.

Of these measures, the most common are component strengthening/retrofit measures, which are discussed at length in Appendix B of this report. The proposed measures (Appendix B) include generic solutions, such as designing structures to meet current seismic design or retrofit standards of the local community, or anchoring equipment. In addition, there are numerous specific measures that relate to unique systems or components within each lifeline. Special attention should be directed to those systems and conditions that are of greatest concern, such as porcelain components in electric substations.

Following are recommended steps when implementing a program to reduce seismic hazards of existing lifelines:

1. Review existing descriptions of seismic performance and rehabilitation measures for the lifeline(s) of concern, i.e., familiarize yourself and your organization with the overall problem. Sources include Appendix B and Chapter 10 (References) of this report.

2. Conduct an investigation of the seismic vulnerability and impact of disruption for the lifeline(s) and region(s) of concern. Lifeline seismic evaluation methodologies and other potential resources for this purpose have been developed by the ASCE Technical Council for Lifeline Earthquake Engineering (see references, Chapter 10), the Applied Technology Council (ATC, in preparation) and others.

3. Focus first on the most vulnerable lifelines, components, and conditions (e.g., liquefaction or landslide potential). Vulnerable components include:

   For electric systems:
   - Substations
   - Power stations

   For water systems:
   - Pumping stations
   - Tanks and reservoirs
   - Treatment plants
   - Transmissions aqueducts

   For highway systems
   - Bridges
   - Tunnels
   - Roadbeds

   For water transportation systems:
   - Port/cargo handling equipment
   - Inland waterways

   For gas and liquid fuels:
   - Distribution storage tanks
   - Transmission pipelines
   - Compressor, metering and pressure reduction stations

4. Conduct cost-benefit studies to determine the most cost effective measures. We note that, in some cases, retrofit measures may not be very cost effective. In regions where the return period for large earthquakes is quite long, for example, replacement over the life cycle of the facility or component may be a reasonable approach.

5. Implement the selected hazard reduction measures.

8.4 Estimated Overall Benefits of Implementing Hazard Reduction Measures

In order to provide an indication of the overall benefit of implementing hazard mitigation measures, we have computed and compare estimated direct damage and indirect economic losses for the existing and an upgraded extended regional electric network, with specific focus on the most vulnerable component for this lifeline--substations. Estimated direct damage and indirect economic losses for the existing network are taken from Chapters 5 and 6, respectively. Estimated direct damage and indirect economic losses for the hypothetical upgraded network have been computed using the same techniques and data as used for the existing network, but seismic intensities have been shifted downward two units to reflect the improved performance of the upgraded system. While this is a rather simplistic approach, we believe the results reasonably indicate the extent of benefit provided by rehabilitation.

Direct Damage Comparisons. Percentages of substations in the existing and upgraded system in the various damage states are provided in Tables 8-1 and 8-2 respectively. With the exception of 1% of the upgraded substations in Missouri and Tennessee that would sustain major-to-destructive damage in the magnitude-8.0 New Madrid event, none of the substations in other locations for this event or in other events would sustain damage this severe. In contrast, 43 percent of the transmission substations in Washington, 29 percent in Arkansas, 16 percent in South Carolina, 13 percent in California, 10 percent in Utah, 8 percent in Missouri, and 6 percent in Tennessee would sustain damage in this range in the various earthquake scenarios. Trends for lower damage states are similar, as are trends for transmission lines (not shown here).

Indirect Economic Loss Comparisons. Indirect economic losses resulting from damage to the existing and upgraded systems are provided in Tables 8-3 and 8-4. Table 8-3 includes data for all affected states, whereas Table 8-4 does not include data for states for which damage to the upgraded system was zero or insignificant. Data for the upgraded system are based on residual capacity plots provided in Appendix C (Figures C-185 through C-200).

By comparing the results in Tables 8-3 and 8-4, it is clear that indirect economic losses are substantially reduced through seismic upgrade measures. For example, the ratio of indirect economic loss to the retail trade sector resulting from damage to the existing system versus loss resulting from damage to the upgraded system ranges from 2.5 to 34 for the 7 events and 8 states considered in both analyses. A comparison of data for the other economic sectors shows similar trends.

Table 8-1 Damage Percent for Existing Electric Transmission Substations for Each Scenario Earthquake (Percent of Substations in State)

	NEW MADRID (M=8.0)							CHARLESTON (M=7.5)		
Total Number	Illinois 108	Missouri 95	Arkansas 124	Tennessee 70	Kentucky 68	Indiana 89	Mississippi 93	South Carolina 100	North Carolina 76	Georgia 86
Light Damage 1-10 %	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	14%	8%	22%	16%	24%	2%	63%	43%	20%	33%
Heavy 30-60 %	0%	0%	10%	9%	7%	0%	8%	14%	0%	3%
Major to Destructive 60-100 %	0%	8%	29%	6%	1%	0%	10%	16%	1%	2%

	CAPE ANN (M=7.0)					WASATCH FRONT (M=7.5)
Total Number	Massachusetts 153	Connecticut 69	Delaware 3	Rhode Island 22	New Hampshire 22	Utah 10
Light Damage 1-10 %	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	82%	42%	33%	100%	45%	30%
Heavy 30-60 %	0%	0%	0%	0%	0%	20%
Major to Destructive 60-100 %	5%	0%	0%	0%	0%	10%

	HAYWARD (M7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)					
Total Number	California 205	California 205	Washington 155	Illinois 108	Missouri 95	Arkansas 124	Tennessee 70	Kentucky 68	Mississippi 93
Light Damage 1-10 %	8%	11%	0%	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	13%	6%	12%	0%	2%	21%	16%	16%	14%
Heavy 30-60 %	14%	< 1%	3%	0%	0%	16%	0%	0%	2%
Major to Destructive 60-100 %	13%	12%	43%	0%	6%	6%	3%	0%	0%

Table 8-2 Damage Percent for Upgraded Electric Transmission Substations for Each Scenario Earthquake (Percent of Substations in State)

	NEW MADRID (M=8.0)							CHARLESTON (M=7.5)		
Total Number	Illinois 108	Missouri 95	Arkansas 124	Tennessee 70	Kentucky 68	Indiana 89	Mississippi 93	South Carolina 100	North Carolina 76	Georgia 86
Light 0-10 %	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	0%	0%	21%	11%	9%	0%	10%	24%	1%	1%
Heavy 30-60 %	0%	7%	8%	1%	0%	0%	0%	6%	0%	1%
Major to Destructive 60-100 %	0%	1%	0%	1%	0%	0%	0%	0%	0%	0%

	CAPE ANN (M=7.0)					WASATCH FRONT (M=7.5)
Total Number	Massachusetts 153	Connecticut 69	Delaware 3	Rhode Island 22	New Hampshire 22	Utah 10
Light 0-10 %	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	1%	0%	0%	0%	0%	30%
Heavy 30-60 %	5%	0%	0%	0%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%	0%	0%	0%

	HAYWARD (M7.5)	FORT TEJON (M=8.0)	PUGET SOUND (M=7.5)	NEW MADRID (M=7.0)					
Total Number	California 205	California 205	Washington 155	Illinois 108	Missouri 95	Arkansas 124	Tennessee 70	Kentucky 68	Mississippi 93
Light 0-10 %	12%	6%	0%	0%	0%	0%	0%	0%	0%
Moderate 10-30 %	21%	11%	21%	0%	3%	6%	1%	0%	0%
Heavy 30-60 %	0%	1%	22%	0%	3%	0%	1%	0%	0%
Major to Destructive 60-100 %	0%	0%	0%	0%	0%	0%	0%	0%	0%

Table 8-3 Indirect Economic Loss Due to Damage to the Existing Electric System (Percent Monthly GNP)

			NEW MADRID (M=8.0)						CHARLESTON			CAPE ANN		
		U.S. Econ. Value Added (Percent)	Illinois	Missouri	Arkansas	Tennessee	Kentucky	Mississippi	South Carolina	North Carolina	Georgia	Massachusetts	Connecticut	Delaware
1	Livestock	0.45%	3.95%	6.58%	32.89%	13.16%	13.16%	44.74%	46.05%	7.89%	18.42%	44.74%	15.79%	10.53%
2	Agr. Prod.	1.06%	3.95%	6.58%	32.89%	13.16%	13.16%	44.74%	46.05%	7.89%	18.42%	44.74%	15.79%	10.53%
3	AgServ For. Fish	0.11%	3.95%	6.58%	32.89%	13.16%	13.16%	44.74%	46.05%	7.89%	18.42%	44.74%	15.79%	10.53%
4	Mining	3.89%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
5	Construction	5.52%	3.16%	5.26%	26.32%	10.53%	10.53%	35.79%	36.84%	6.32%	14.74%	35.79%	12.63%	8.42%
6	Food Tobacco	2.41%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
7	Textile Goods	0.37%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
8	Misc Text. Prod.	0.73%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
9	Lumber & Wood	0.52%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
10	Furniture	0.34%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
11	Pulp & Paper	0.87%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
12	Print & Publish	1.31%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
13	Chemical & Drugs	1.40%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
14	Petrol. Refining	0.96%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
15	Rubber & Plastic	1.03%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
16	Leather Prods.	0.12%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
17	Glass Stone Clay	0.62%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
18	Prim. Metal Prod.	1.04%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
19	Fab. Metal Prod.	1.64%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
20	Mach. Exc. Elec.	1.56%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
21	Elec. & Electron	2.52%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
22	Transport Eq.	2.62%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
23	Instruments	0.68%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
24	Misc. Manufact.	0.69%	7.89%	13.16%	65.79%	26.32%	26.32%	89.47%	92.11%	15.79%	36.84%	89.47%	31.58%	21.05%
25	Transp & Whse.	3.46%	2.37%	3.95%	19.74%	7.89%	7.89%	26.84%	27.63%	4.74%	11.05%	26.84%	9.47%	6.32%
26	Utilities	5.89%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%
27	Wholesale Trade	5.63%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
28	Retail Trade	5.63%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
29	F.I.R.E.	16.64%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
30	Pers./Prof Serv.	8.03%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
31	Eating Drinking	2.12%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%
32	Auto Serv.	1.09%	7.11%	11.84%	59.21%	23.68%	23.68%	80.53%	82.89%	14.21%	33.16%	80.53%	28.42%	18.95%
33	Amuse & Rec.	0.70%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%
34	Health Ed. Soc.	6.30%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%
35	Govt & Govt Ind.	11.79%	4.74%	7.89%	39.47%	15.79%	15.79%	53.68%	55.26%	9.47%	22.11%	53.68%	18.95%	12.63%
36	Households	0.25%	6.32%	10.53%	52.63%	21.05%	21.05%	71.58%	73.68%	12.63%	29.47%	71.58%	25.26%	16.84%

Table 8-3 Indirect Economic Loss Due to Damage to the Existing Electric System (Percent Monthly GNP) (Continued)

			CAPE ANN		WASATCH	CALIFORNIA		PUGET SOUND	NEW MADRID (M=7.0)			
		U.S. Econ. Value Added (Percent)	Rhode Island	New Hampshire	Utah	Hayward	Fort Tejon	Washington	Arkansas	Tennessee	Kentucky	Mississippi
1	Livestock	0.45%	42.11%	14.47%	35.53%	23.68%	13.16%	47.37%	23.68%	7.89%	3.95%	3.95%
2	Agr. Prod.	1.06%	42.11%	14.47%	35.53%	23.68%	13.16%	47.37%	23.68%	7.89%	3.95%	3.95%
3	AgServ For. Fish	0.11%	42.11%	14.47%	35.53%	23.68%	13.16%	47.37%	23.68%	7.89%	3.95%	3.95%
4	Mining	3.89%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
5	Construction	5.52%	33.68%	11.58%	28.42%	18.95%	10.53%	37.89%	18.95%	6.32%	3.16%	3.16%
6	Food Tobacco	2.41%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
7	Textile Goods	0.37%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
8	Misc Text. Prod.	0.73%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
9	Lumber & Wood	0.52%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
10	Furniture	0.34%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
11	Pulp & Paper	0.87%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
12	Print & Publish	1.31%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
13	Chemical & Drugs	1.40%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
14	Petrol. Refining	0.96%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
15	Rubber & Plastic	1.03%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
16	Leather Prods.	0.12%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
17	Glass Stone Clay	0.62%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
18	Prim. Metal Prod.	1.04%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
19	Fab. Metal Prod.	1.64%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
20	Mach. Exc. Elec.	1.56%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
21	Elec. & Electron	2.52%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
22	Transport Eq.	2.62%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
23	Instruments	0.68%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
24	Misc. Manufact.	0.69%	84.21%	28.95%	71.05%	47.37%	26.32%	94.74%	47.37%	15.79%	7.89%	7.89%
25	Transp & Whse.	3.46%	25.26%	8.68%	21.32%	14.21%	7.89%	28.42%	14.21%	4.74%	2.37%	2.37%
26	Utilities	5.89%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%
27	Wholesale Trade	5.63%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
28	Retail Trade	5.63%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
29	F.I.R.E.	16.64%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
30	Pers./Prof Serv.	8.03%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
31	Eating Drinking	2.12%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%
32	Auto Serv.	1.09%	75.79%	26.05%	63.95%	42.63%	23.68%	85.26%	42.63%	14.21%	7.11%	7.11%
33	Amuse & Rec.	0.70%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%
34	Health Ed. Soc.	6.30%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%
35	Govt & Govt Ind.	11.79%	50.53%	17.37%	42.63%	28.42%	15.79%	56.84%	28.42%	9.47%	4.74%	4.74%
36	Households	0.25%	67.37%	23.16%	56.84%	37.89%	21.05%	75.79%	37.89%	12.63%	6.32%	6.32%

Table 8-4 Indirect Economic Loss Due to Damage to the Upgraded Electric System (Percent Monthly GNP)

		U.S. Econ. Value-Added (Percent)	NEW MADRID (M=8.0)		CHARLESTON	CAPE ANN	WASATCH	HAYWARD	FT. TEJON	WASHINGTON
			Arkansas	Tennessee	S Carolina	Massachusetts	Utah	California	California	Washington
1	Livestock	0.45%	13.16%	5.26%	15.79%	1.32%	10.53%	5.26%	2.63%	18.42%
2	Agr. Prod.	1.06%	13.16%	5.26%	15.79%	1.32%	10.53%	5.26%	2.63%	18.42%
3	AgServ For. Fish	0.11%	13.16%	5.26%	15.79%	1.32%	10.53%	5.26%	2.63%	18.42%
4	Mining	3.89%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
5	Construction	5.52%	10.53%	4.21%	12.63%	1.05%	8.42%	4.21%	2.11%	14.74%
6	Food Tobacco	2.41%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
7	Textile Goods	0.37%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
8	Misc Text. Prod.	0.73%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
9	Lumber & Wood	0.52%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
10	Furniture	0.34%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
11	Pulp & Paper	0.87%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
12	Print & Publish	1.31%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
13	Chemical & Drugs	1.40%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
14	Petrol. Refining	0.96%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
15	Rubber & Plastic	1.03%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
16	Leather Prods.	0.12%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
17	Glass Stone Clay	0.62%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
18	Prim. Metal Prod.	1.04%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
19	Fab. Metal Prod.	1.64%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
20	Mach. Exc. Elec.	1.56%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
21	Elec. & Electron	2.52%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
22	Transport Eq.	2.62%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
23	Instruments	0.68%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
24	Misc. Manufact.	0.69%	26.32%	10.53%	31.58%	2.63%	21.05%	10.53%	5.26%	36.84%
25	Transp & Whse.	3.46%	7.89%	3.16%	9.47%	0.79%	6.32%	3.16%	1.58%	11.05%
26	Utilities	5.89%	21.05%	8.42%	25.26%	2.11%	16.84%	8.42%	4.21%	29.47%
27	Wholesale Trade	5.63%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
28	Retail Trade	5.63%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
29	F.I.R.E.	16.64%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
30	Pers./Prof Serv.	8.03%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
31	Eating Drinking	2.12%	21.05%	8.42%	25.26%	2.11%	16.84%	8.42%	4.21%	29.47%
32	Auto Serv.	1.09%	23.68%	9.47%	28.42%	2.37%	18.95%	9.47%	4.74%	33.16%
33	Amuse & Rec.	0.70%	21.05%	8.42%	25.26%	2.11%	16.84%	8.42%	4.21%	29.47%
34	Health Ed. Soc.	6.30%	21.05%	8.42%	25.26%	2.11%	16.84%	8.42%	4.21%	29.47%
35	Govt & Govt Ind.	11.79%	15.79%	6.32%	18.95%	1.58%	12.63%	6.32%	3.16%	22.11%
36	Households	0.25%	21.05%	8.42%	25.26%	2.11%	16.84%	8.42%	4.21%	29.47%

9. Recommendations for Further Work

9.1 Introduction

The ATC-25 project has raised a number of questions and indicated areas in which knowledge is inadequate or nonexistent with respect to the impact of lifeline disruption due to earthquake. Following is a discussion of recommendations for further research and other efforts. This list is not meant to be all inclusive but rather an overview of some of the more important issues that should be pursued.

9.2 Lifeline Inventory

This project has initiated the development of a comprehensive national lifelines inventory database. Completion of this monumental task will require many person-years of effort. Organizations such as the Federal Emergency Management Agency, Department of Transportation, and American Society of Civil Engineers Technical Council of Lifeline Earthquake Engineering are encouraged to build on the work performed in this project, develop standards for complete lifeline inventories, and coordinate the acquisition of the needed additional and updated data from various lifeline owners. Capacity data in the National Petroleum Council's oil/gas transmission line inventory is an example of the kind and extent of information that is needed in lifeline inventory databases. An integral part of any project to augment the existing ATC-25 lifeline database should be its wide availability in the public domain.

9.3 Lifeline Component Vulnerability

This project employed lifeline component vulnerability functions developed in the ATC-13 project (ATC, 1985) on the basis of expert opinion obtained by surveys. While the ATC-13 expert-opinion data are extremely useful, comprehensive information based on hard field data would provide an improved basis for estimating lifeline vulnerability. We recommend a major effort to acquire data on lifeline seismic performance and damage, and conduct analysis towards the development of improved component vulnerability functions. This effort should also investigate lifeline recovery data, and incorporate the extensive experience realized during the 17 October 1989 Loma Prieta, California, earthquake, as well as from other damaging earthquakes.

9.4 Seismic Hazard Data

The project has uncovered the relative paucity of seismic hazard models and resources at the regional/national scale. Only two models are available, those of Evernden and Thompson (1985) and Algermissen et al. (1990), the latter of which does not incorporate a soils database. While a nationally agreed upon seismic hazard model may be desirable, this is less of a priority than the need for a digitized soils database. That is, existing models (e.g., attenuation relations, seismicity databases, seismotectonic models) are sufficient for a number of site-specific purposes, and can be expanded to regional modeling, given an adequate soils database. We suggest that the U. S. Geological Survey develop, or coordinate through the various states' Office of Geologists, a series of digitized soils/geologic databases.

9.5 Economic Analysis and Impacts Data and Methodology

This project has presented a rational comprehensive model for the estimation of the economic impacts due to lifeline disruption. Many steps of the process necessarily involved approximations and limited analyses. We recommend further research, especially in economic areas such as:

- Economic impacts associated with lifeline disruption,
- Second-order economic effects (e.g., interaction between lifelines, such as the effect of disrupted electric power on the water supply),
- Elasticities of demand, or substitution of a lesser disrupted lifeline (e.g., fuel oil) for a more disrupted lifeline (e.g., natural gas),

- Inter-regional impacts (e.g., economic impacts in New York due to disruption in California), and
- So-called "benefits," such as increased economic activity associated with repair, or replacement of older equipment with new technology.

Lastly, we note that this study did not address environmental consequences associated with lifeline disruption, especially the potential for oil spills from broken pipelines in the nation's waterways following a New Madrid event. Investigation of this issue is critically important.

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Appendix B: Lifeline Vulnerability Functions

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Included in this appendix are vulnerability functions used to describe the expected or assumed earthquake performance characteristics of lifelines as well as the time required to restore damaged facilities to their pre-earthquake capacity, or usability. Functions have been developed for all lifelines inventoried for this project, for lifelines estimated by proxy, and for other important lifelines not available for inclusion in the project inventory. The methodology used to calculate the quantitative relationships for direct damage and residual capacity are described in Chapter 3.

The vulnerability function for each lifeline consists of the following components:

- *General* information, which consists of (1) a *description* of the structure and its main components, (2) *typical seismic damage* in qualitative terms, and (3) *seismically resistant design* characteristics for the facility and its components in particular. This information has been included to define the assumed characteristics and expected performance of each facility and to make the functions more widely applicable (i.e., applicable for other investigations by other researchers).

- *Direct damage* information, which consists of (1) a description of its *basis* in terms of structure type and quality of construction (degree of seismic resistance), (2) default estimates of the quality of construction for *present conditions*, (3) default estimates of the quality of construction for *upgraded conditions*, and (4) *time-to-restoration* curves.

B.1 Highway

B.1.1 Major Bridges

1. General

   Description: Major bridges include all highway system bridges with individual spans over 500 feet. Steel bridges of this type include suspension, cable-stayed, or truss. Reinforced concrete arch or prestressed concrete segmental bridges are also common. The main components include the bridge piers and supporting foundation (commonly piers, piles, or caissons) and the superstructure including the bridge deck, girders, stringers, truss members, and cables. Approaches may consist of conventional highway bridge construction and/or abutments.

   Typical Seismic Damage: Major bridges are typically well- engineered structures designed for lateral loading (seismic loading was not typically considered until the 1970s). In most cases, damage will be limited to ground and structural failures at bridge approaches. However, major ground failures including liquefaction and submarine landsliding could lead to significant damage to bridge foundations and superstructures.

   Earthquake-resistant Design: Seismically resistant design practices include dynamic analysis, which takes soil-structure interaction into account. Foundations should be designed and detailed to withstand any soil failures that are expected due to unstable site conditions.

2. Direct Damage

   Basis: Damage curves for highway system major bridges are based on ATC-13 data for FC 30, major bridges (greater than 500-foot spans). Standard construction is assumed to represent typical California major bridges under present conditions (i.e., a composite of older non-seismically designed bridges as well as modern bridges designed for site-specific seismic loads).

   Present Conditions: In the absence of data on the type of construction, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	*MMI Intensity Shift*
California 7	0
California 3-6	+1
Non-California 7	+1
Puget Sound 5	+1
All other areas	+2

The modified motion-damage curves for major bridges are shown in Figure B-1.

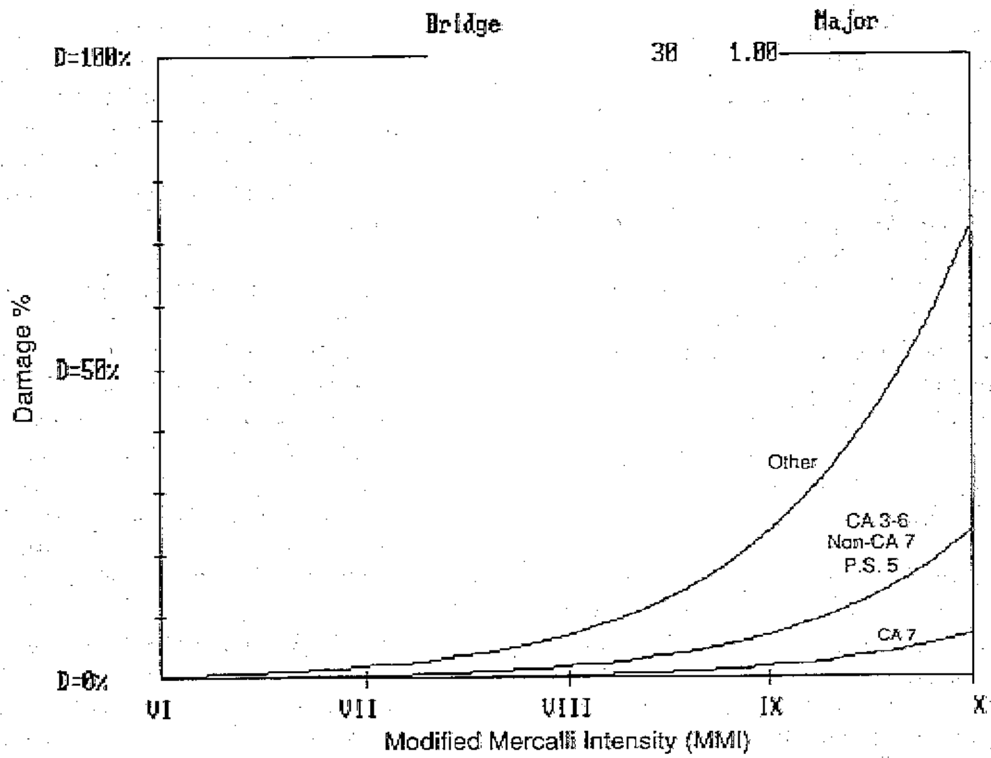

Figure B-1 Damage percent by intensity for major bridges.

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 25a, major bridges for highway systems, are assumed to apply to all major bridges. By combining these data with the damage curves for FC 30, the time-to-restoration curves shown in Figures B-2 through B-4 were derived for the various NEHRP Map Areas.

B.1.2 Tunnels

1. General

Description: In general, tunnels may pass through alluvium or rock, or may be of cut and cover construction. Tunnels may be lined or unlined, and may be at any depth below the ground surface. Tunnel lengths may range from less than 100 feet to several miles. Lining materials include brick and both reinforced and unreinforced concrete. Heavy timbers and wood lagging (grouted and ungrouted) may also be used to support tunnel walls and ceilings. Tunnels may change in shape and/or construction material over their lengths.

Typical Seismic Damage: Tunnels may experience severe damage in areas affected by permanent ground movements caused by landslides or surface fault rupture, but rarely suffer significant internal damage from ground shaking alone. Landslides at tunnel portals can cause blockage. Damage has been noted at tunnel weak spots such as intersections; bends, or changes in shape, construction materials, or soil conditions. Damage to lined tunnels has typically been limited to cracked lining.

Seismically Resistant Design: Lined tunnels have performed better than unlined tunnels. Consequently, general Seismically resistant design practices for tunnels include providing reinforced concrete lining; strengthening areas that have been traditionally weak such as intersections, bends, and changes in shape and in construction materials; and siting tunnels to

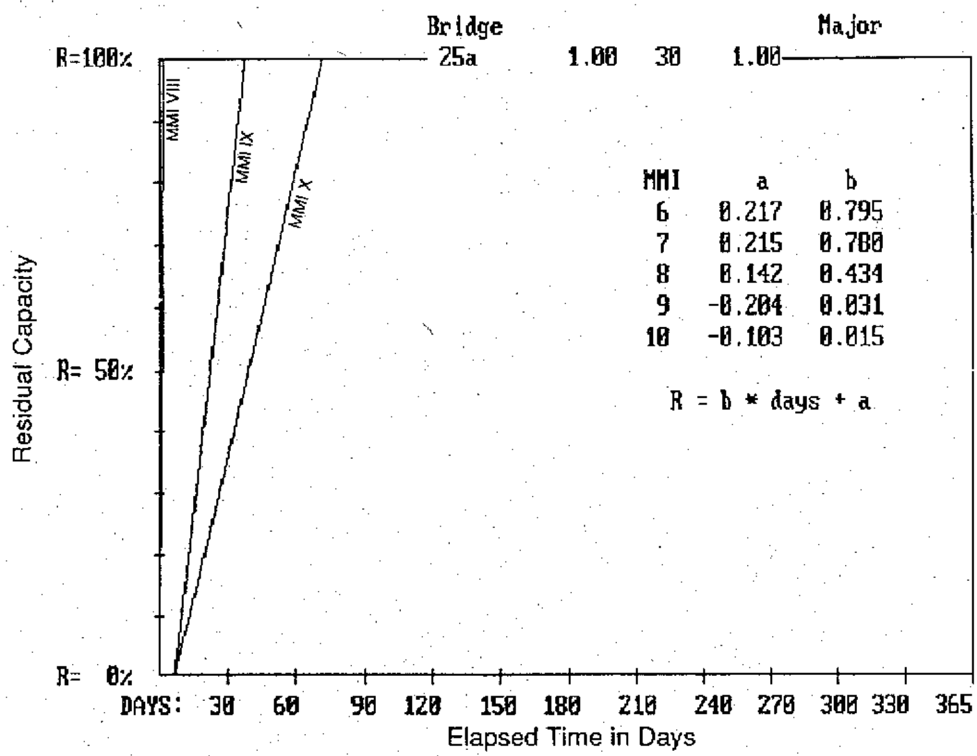

Figure B-2 Residual capacity for major bridges (NEHRP California 7).

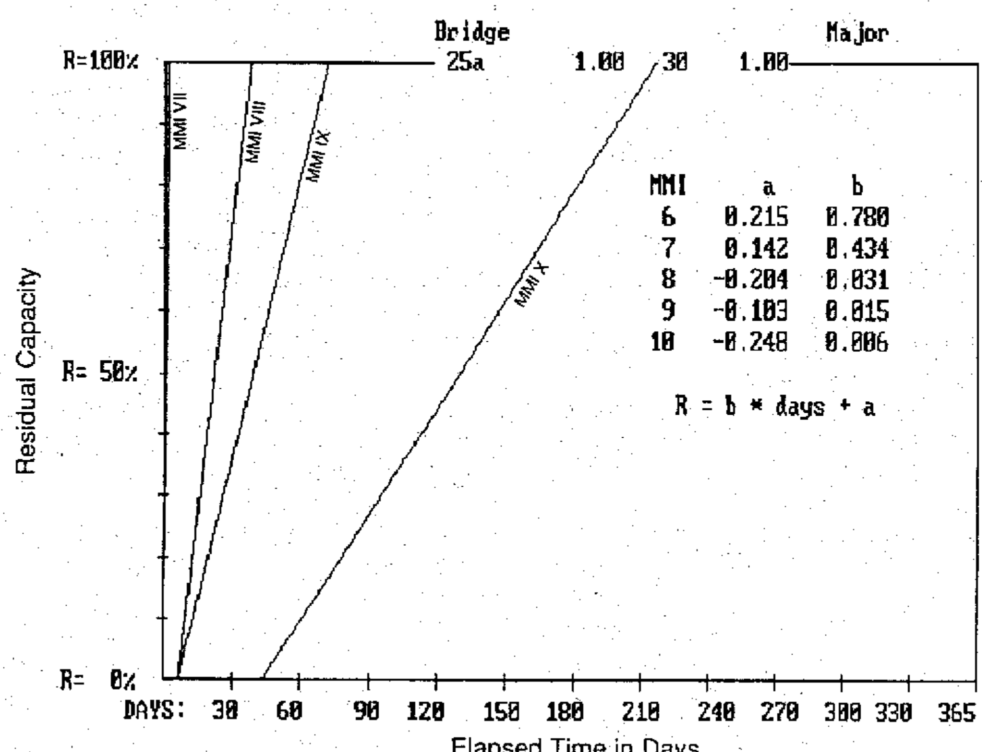

Figure B-3 Residual capacity for major bridges (NEHRP Map Area 3-6, Non-California 7, and Puget Sound 5).

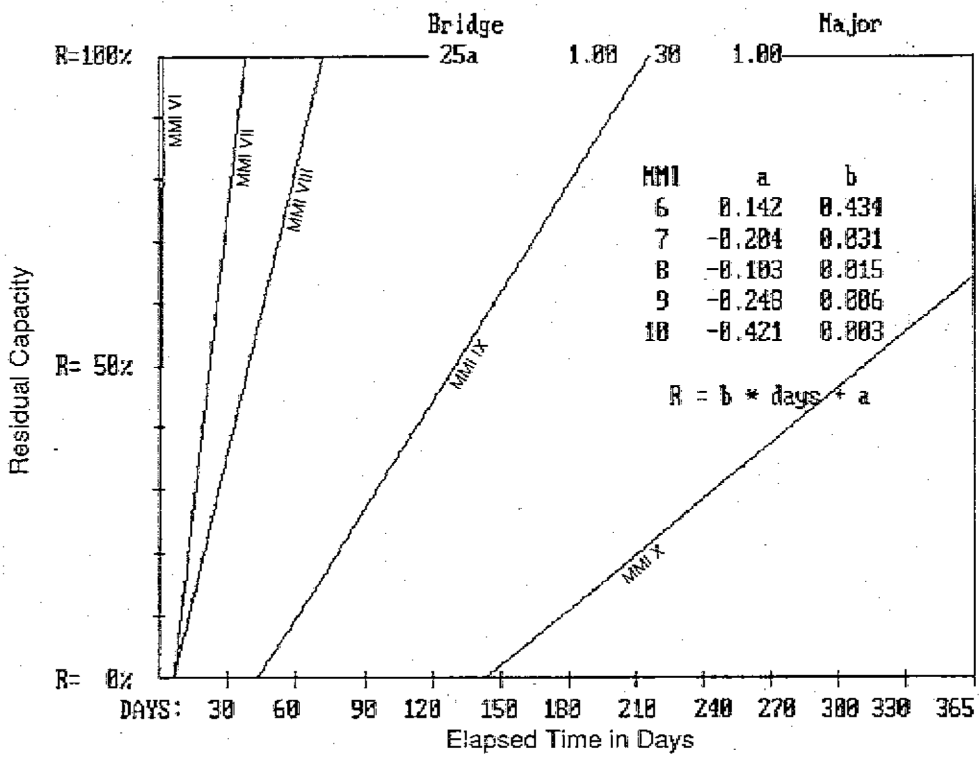

Figure B-4 Residual capacity for major bridges (All other areas).

eliminate fault crossings. Slope stability at portals should be evaluated and stabilization undertaken if necessary.

2. Direct Damage

Basis: Damage curves for highway tunnels are based on ATC-13 data for FC 38, tunnels passing through alluvium (see Figure B-5). Tunnels passing through alluvium are less vulnerable than cut-and-cover tunnels, and more vulnerable than tunnels passing through rock; they were chosen as representative of all existing tunnels. If inventory data identify tunnels as cut-and-cover or passing through rock, then use FC 40 or 39, respectively, in lieu of FC 38.

Standard construction is assumed to represent typical California highway tunnels under present conditions (i.e., a composite of older and more modern tunnels). Only minimal regional variation in construction quality is assumed.

Present Conditions: In the absence of data on the type of lining, age, etc., use the following factors to modify the mean curves, under present conditions:

NEHRP Map Area	MMI Intensity Shift
California 7	0
California 3-6	0
Non-California 7	0
Puget Sound 5	0
All other areas	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The Social Function class time-to-restoration data assigned to SF 25b, tunnel for highway system, are assumed to apply to all tunnels. By combining these data with the damage curves for FC 38, the time-to-restoration curves shown in Figures

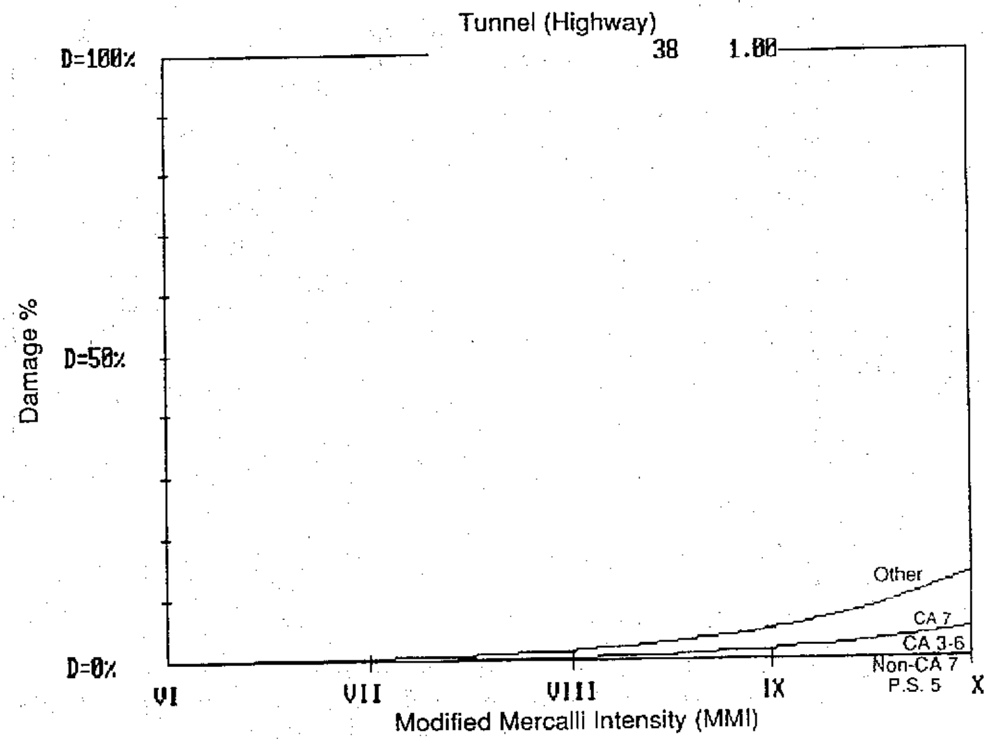

Figure B-5 Damage percent by intensity for highway tunnels.

B-6 and B-7 were derived for the various NEHRP Map Areas.

B.1.3 Conventional Bridges

1. General

Description: Conventional bridges in the highway system include all bridges with spans less than 500 feet. Construction may include simple spans (single or multiple) as well as continuous/monolithic spans. Bridges may be straight or skewed, fixed, moveable (draw bridge, or rotating, etc.), or floating. Reinforced concrete is the most common construction material while steel, masonry, and wood construction are common at water crossings. Typical foundation systems include abutments, spread footings, battered and vertical pile groups, single-column drilled piers, and pile bent foundations. Bents may consist of single or multiple columns, or a pier wall. The superstructure typically comprises girders and deck slabs. Fixed (translation prevented, rotation permitted) and expansion (translation and rotation permitted) bearings of various types are used for girder support to accommodate temperature and shrinkage movements. Shear keys are typically used to resist transverse loads at abutments. Abutment fills are mobilized during an earthquake as the bridge moves into the fill (longitudinal direction), causing passive soil pressures to occur on the abutment wall.

Typical Seismic Damage: The most vulnerable components of a bridge include support bearings, abutments, piers, footings, and foundations. A common deficiency is that unrestrained expansion joints are not equipped to handle large relative displacements (inadequate support length), and simple bridge spans fall. Skewed bridges in particular have performed poorly in past earthquakes because they respond partly in rotation, resulting in an unequal distribution of forces to bearings and supports. Rocker bearings have proven most vulnerable. Roller bearings generally remain stable in earthquakes, except they may become misaligned and horizontally displaced. Elastomeric bearing pads are relatively stable although they have been known to

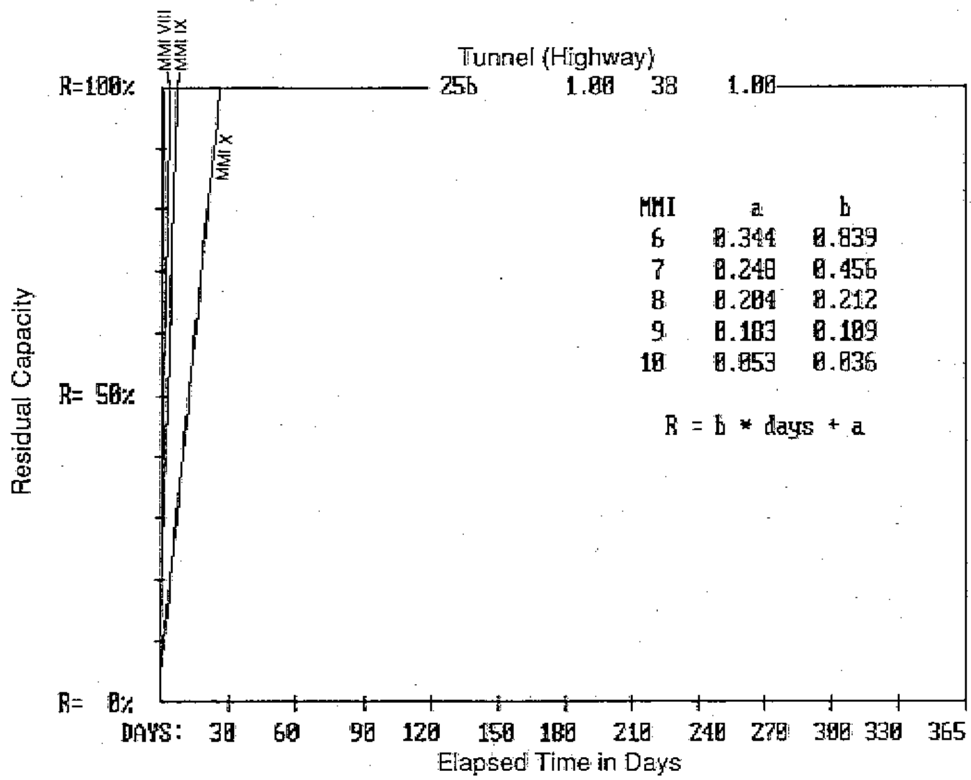

Figure B-6 Residual capacity for highway tunnels (NEHRP Map Area: California 3-6, California 7, Non-California 7, and Puget Sound 5).

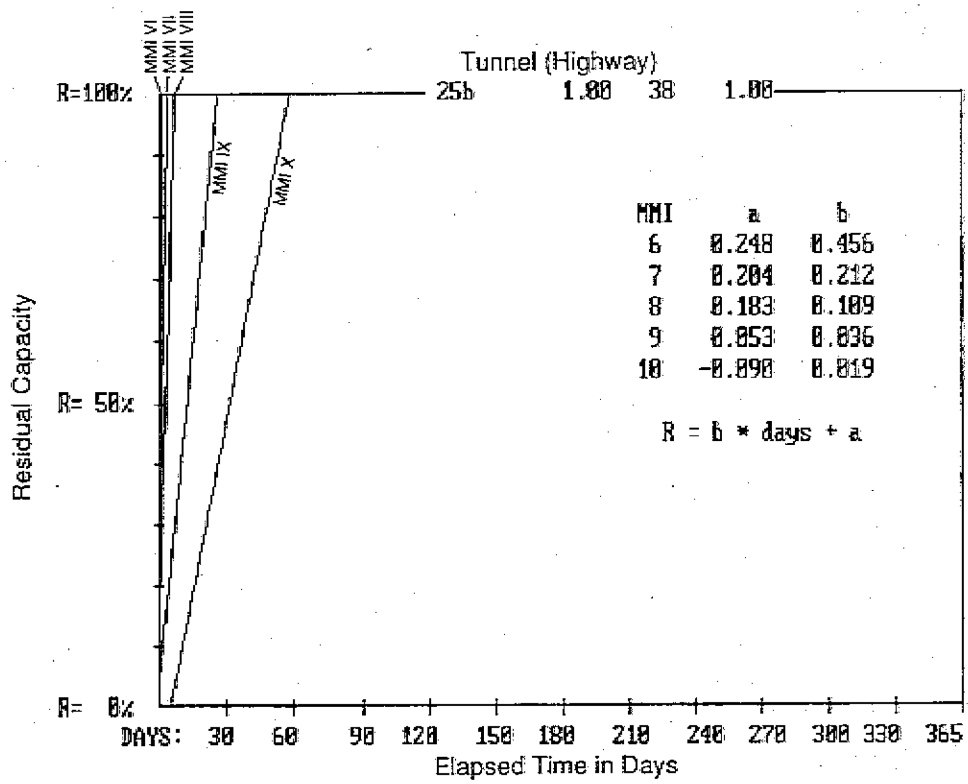

Figure B-7 Residual capacity for highway tunnels (All other areas).

"walk out" under severe shaking. Failure of backfill near abutments is common and can lead to tilting, horizontal movement or settlement of abutments, spreading and settlement of fills, and failure of foundation members. Abutment damage rarely leads to bridge collapse. Liquefaction of saturated soils in river channels and floodplains and subsequent loss of support have caused many bridge failures in past earthquakes. Pounding of adjacent, simply supported spans can cause bearing damage and cracking of the girders and deck slab. Piers have failed primarily because of insufficient transverse confining steel, and inadequate longitudinal steel splices and embedment into the foundation. Bridge superstructures have not exhibited any particular weaknesses other than being dislodged from their bearings.

Seismically Resistant Design: Bridge behavior during an earthquake can be very complex. Unlike buildings, which generally are connected to a single foundation through the diaphragm action of the base slab, bridges have multiple supports with varying foundation and stiffness characteristics. In addition, longitudinal forces are resisted by the abutments through a combination of passive backwall pressures and foundation embedment when the bridge moves toward an abutment, but by only the abutment foundation as the bridge moves away from an abutment. Significant movement must occur at bearings before girders impact abutments and bear against them, further complicating the response. To accurately assess the dynamic response of all but the simplest bridges, a three-dimensional dynamic analysis should be performed. Special care is required for design of hinges for continuous bridges. Restraint for spans or adequate bearing lengths to accommodate motions are the most effective way to mitigate damage. Damage in foundation systems is hard to detect, so bridge foundations should be designed to resist earthquake forces elastically. In order to prevent damage to piers, proper confinement, splices, and embedment into the foundation should be provided. Similarly, sufficient steel should be provided in footings. Loads resisted by bridges may be reduced through use of energy absorption features including ductile columns, lead-filled elastomeric bearings, and restrainers. Foundation failure can be prevented by ensuring sufficient bearing capacity, proper foundation embedment, and sufficient consolidation of soil behind retaining structures.

2. Direct Damage

Basis: Damage curves for highway system conventional bridges are based on ATC-13 data for FC 24, multiple simple spans, and FC 25, continuous/monolithic bridges (includes single-span bridges). Highway system conventional bridges in California located within NEHRP Map Area 7 have either been constructed after 1971 or have been recently analyzed or are in the process of being seismically retrofitted, or both. These bridges are assumed to be best represented by a damage factor half of FC 25, continuous/monolithic (see Figure B-8). The conventional bridges located outside California NEHRP Map Area 7 are assumed to be a combination of 50% multiple simple spans (FC 24) and 50% continuous/monolithic construction (FC 25) (see attached figure). If inventory data identify bridges as simple span, or continuous/monolithic, then use the appropriate ATC-13 data in lieu of the above.

Standard construction is assumed to represent typical California bridges under present conditions (i.e., a composite of older and more modern bridges).

Present Conditions: In the absence of data on the type of spans, age, or implementation of seismic retrofit, etc., the following factors were used to modify the mean curves, under present conditions:

	MMI Intensity Shift	
NEHRP Map Area	*FC 24*	*FC 25*
California 7	NA	NA*
California 3-6	+1	+1
Non-California 7	+1	+1
Puget Sound 5	0	+1
All other areas	+3	+3

* Special case, damage half of FC 25

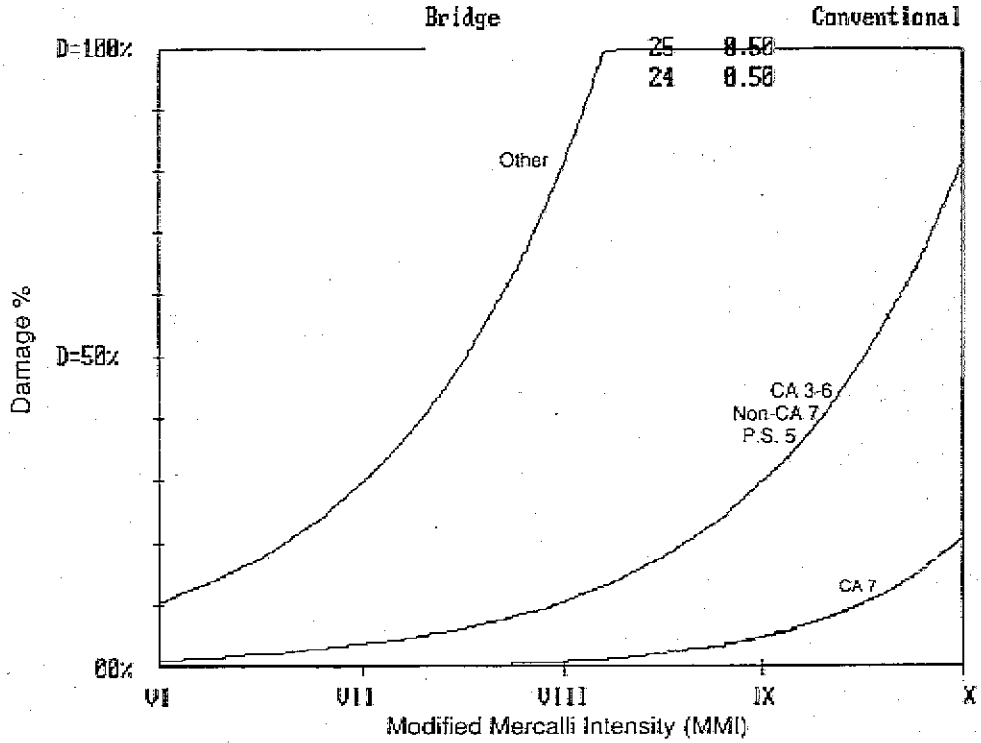

Figure B-8 Damage percent by intensity for conventional major bridges.

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in an beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 25c, conventional bridges for the highway system, are assumed to apply to all bridges with spans shorter than 500 feet. By combining these data with the damage data from FC 25, the attached time-to-restoration curves for conventional bridges within California NEHRP Map Area 7 were derived. By combining the time-to-restoration data for SF 25c with the damage curves derived by using the data for FC 24 and 25, the time-to-restoration curves shown in Figures B-9 through B-11 were derived for the various NEHRP Map Areas.

B.1.4 Freeways/Highways

1. General

Description: Freeways/highways includes urban and rural freeways (divided arterial highway with full control of access), divided highways, and highways. Freeway/highway includes roadways, embankments, signs, and lights. Roadways include pavement, base, and subbase. Pavement types may be either portland cement concrete or asphaltic concrete. Base and subbase materials include aggregate, cement treated aggregate, and lime-stabilized, bituminous, and soil cement bases. Embankments may or may not include retaining walls.

Typical Seismic Damage: Roadway damage can result from failure of the roadbed or failure of an embankment adjacent to the road. Roadbed damage can take the form of soil slumping under the pavement, and settling, cracking, or heaving of pavement. Embankment failure may occur in combination with liquefaction, slope failure, or failure of retaining walls. Such damage is manifested by misalignment, cracking of the roadway surface, local uplift or subsidence, or buckling or blockage of the roadway. Sloping margins of fills where compaction is

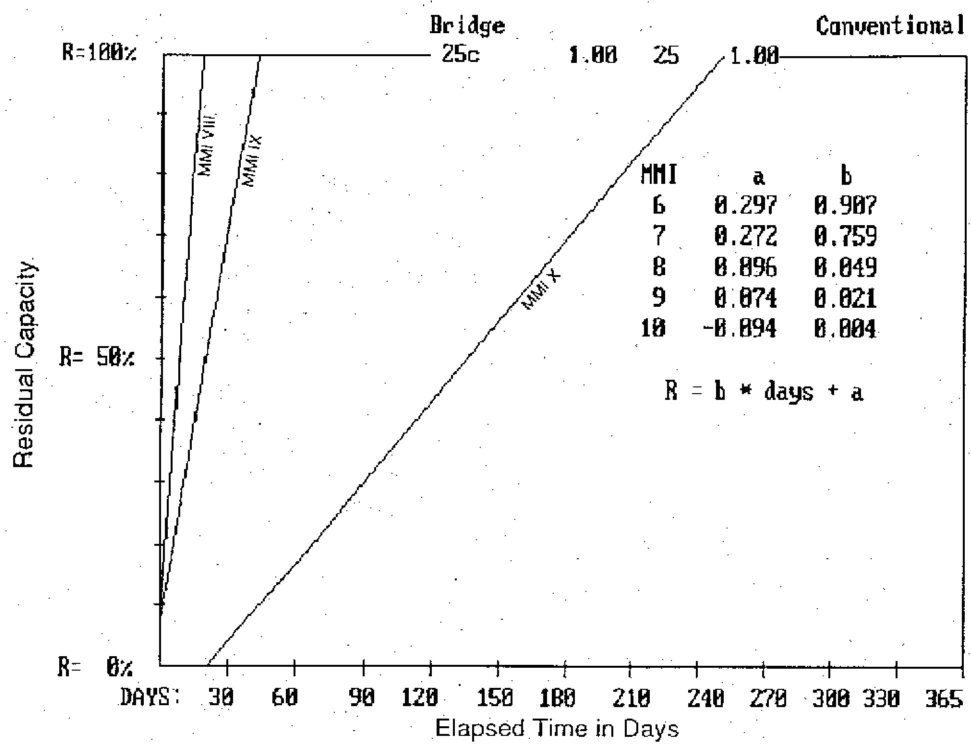

Figure B-9 Residual capacity for conventional bridges (NEHRP California 7).

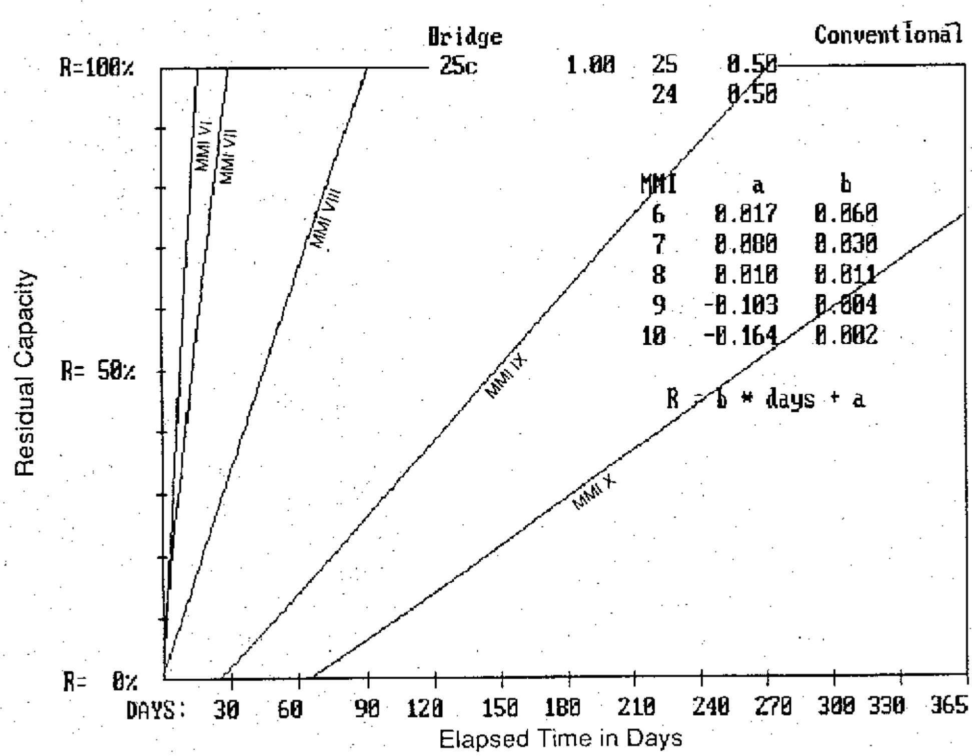

Figure B-10 Residual capacity for conventional bridges (NEHRP Map Area 3-6, Non-California 7, and Puget Sound 5).

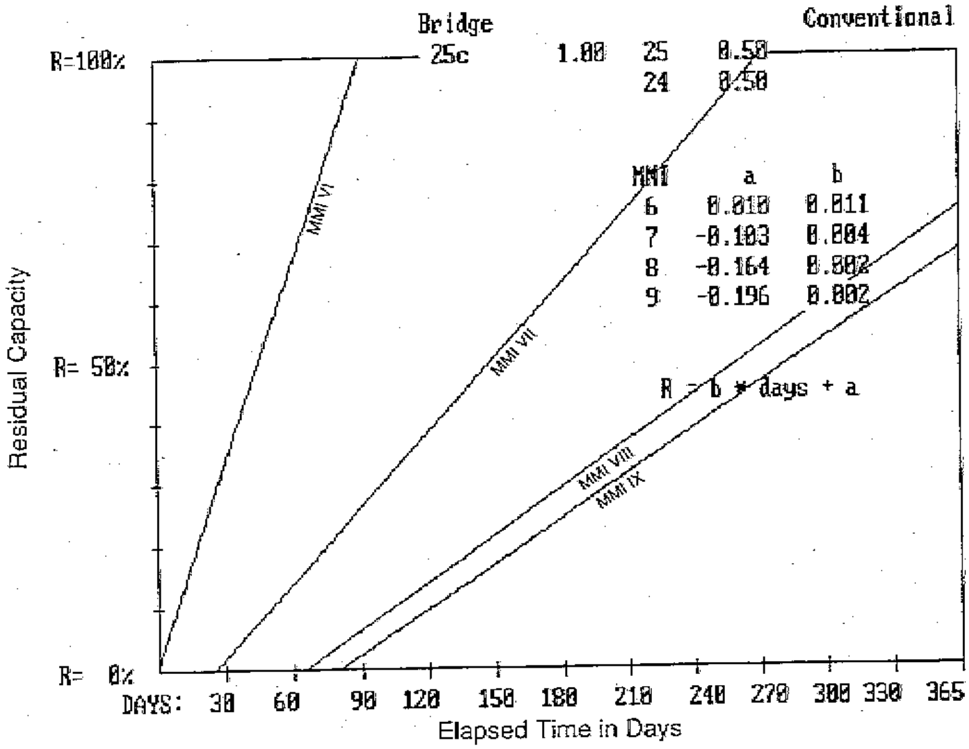

Figure B-11 Residual capacity for conventional bridges (All other areas).

commonly poor are particularly vulnerable to slope failure. Dropped overpass spans can effectively halt traffic on otherwise undamaged freeways/highways.

Seismically Resistant Design: Seismically resistant design practices include proper gradation and compaction of existing soils as well as bases and subbases. Roadway cuts and fills should be constructed as low as practicable and natural slopes abutting highways should be examined for failure potential.

2. Direct Damage

Basis: Damage curves for freeways/highways are based on ATC-13 data for FC 48, highways (see Figure B-12). Standard construction is assumed to represent typical California freeways/highways under present conditions (i.e., a composite of older and more modern freeways/highways). It is assumed that no regional variation in construction quality exists.

Present Conditions: In the absence of data on the type of construction, age, surrounding terrain, truck usage, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	*MMI Intensity Shift*
California 7	0
California 3-6	0
Non-California 7	0
Puget Sound 5	0
All other areas	0

Upgraded Conditions: It is not anticipated that it will be cost-effective to upgrade facilities for the sole purpose of improving seismic performance, except perhaps in very isolated areas where supporting soils and/or adjacent embankments are unstable. The effect on overall facility performance in earthquakes will be minimal, and no intensity shifts are recommended.

Time-to-restoration: The time-to-restoration data assigned to SF 25d, freeways and conventional highways, are

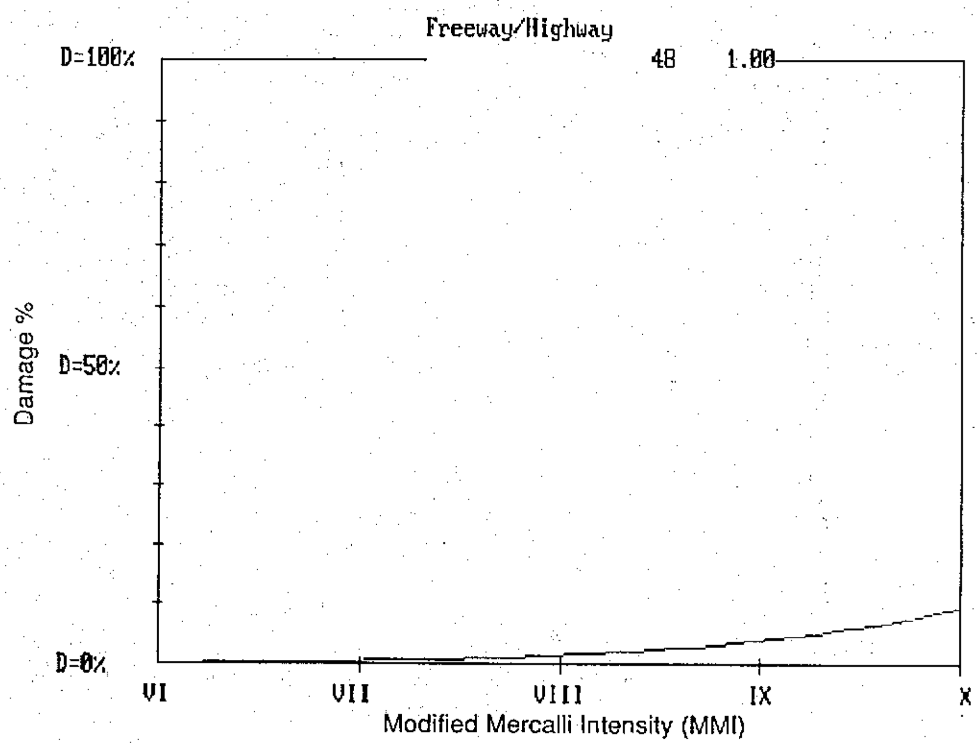

Figure B-12 Damage percent by intensity for freeways/highways.

assumed to apply to all freeways/highways. By combining these data with the damage curves for FC 48, the time-to-restoration curves shown in Figure B-13 were derived.

B.1.5 Local Roads

1. General

Description: Local roads include roadways, embankments, signs, lights, and bridges in urban and rural areas. Local roads, on the average, are older than freeways/highways and are frequently not designed for truck traffic (inferior quality). Local roads may travel through more rugged terrain and include steeper grades and sharper corners, and may be paved or unpaved (gravel or dirt), engineered, or nonengineered. Paved roads are typically asphaltic concrete over grade and subgrade materials. Traffic could be blocked by damaged buildings, broken underground water and sewer pipes, downed power lines, etc.

Typical Seismic Damage: Roadway damage can result from the failure of the roadbed or failure of an embankment adjacent to the road. Pavement damage may include cracking, buckling, misalignment, or settling. Failed embankments may include damaged retaining walls, or landslides that block roadways or result in loss of roadbed support. Damage to bridges--including dropped spans, settlement of abutment fills, and damage to supporting piers--can restrict or halt traffic, depending on the severity of the damage.

Seismically Resistant Design: Seismically resistant design practices are not typically incorporated into local road design, expect perhaps for bridges. Proper gradation and compaction are necessary for good seismic performance. Cuts and fills should be constructed as low as practicable and the stability of slopes adjacent to roads in steep terrains should be evaluated. Seismically resistant design practices for bridges include providing restraint for spans and/or adequate bearing lengths to accommodate motions. Approach fills should be properly compacted and graded and pier foundations

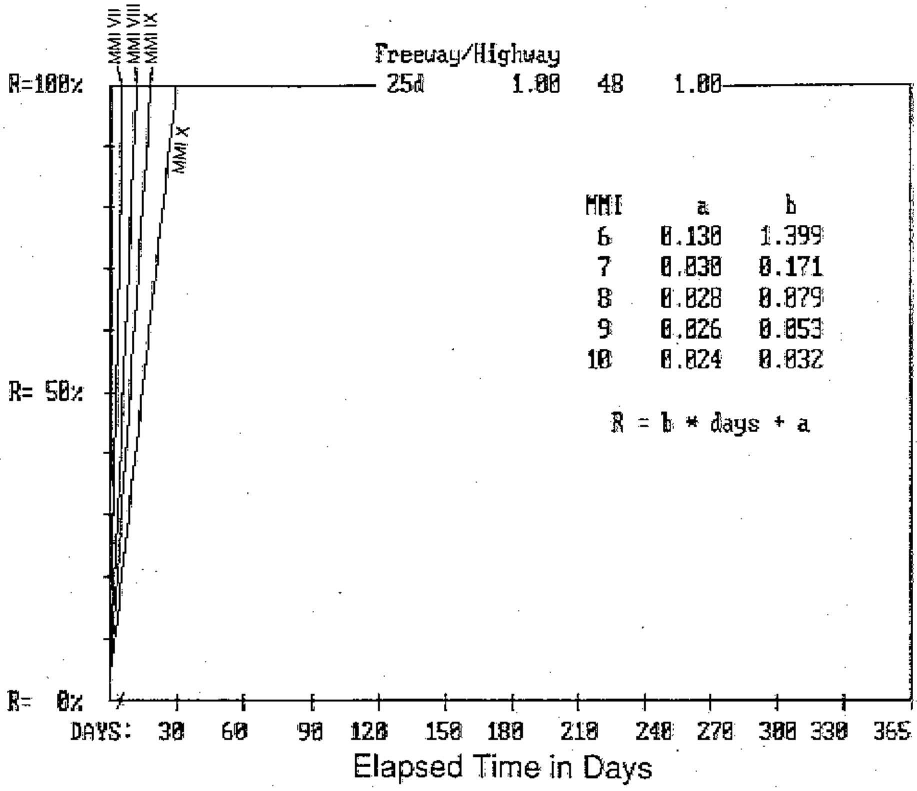

Figure B-13 Residual capacity for major bridges (NEHRP Map Area: California 3-6, California 7, Puget Sound, and all other areas).

should be adequate to support bridge spans if soil failure occurs.

2. Direct Damage

Basis: Damage curves for highway system local roads are based on ATC-13 data for FC 48, highways, and FC 25, continuous/monolithic bridge (includes single-span, see Figure B-14). All local roads were assumed to be a combination of 80% roadways and 20% bridges. If inventory data permit a more accurate breakdown of the relative value of roadway and bridges, such data should be used and the damage curves re-derived.

Standard construction is assumed to represent typical California local roads (i.e., a composite of older and more modern local roads). It is assumed that no regional variation in construction quality exists.

Present Conditions: In the absence of data on the type of surrounding terrain, construction material, age, etc., the following factors were used to modify the mean curves for the two facility classes listed above, under present conditions:

	MMI Intensity Shift	
NEHRP Map Area	FC 25	FC 48
California 7	0	0
California 3-6	+1	0
Non-California 7	+1	0
Puget Sound 5	+1	0
All other areas	+2	0

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions. In most cases upgrades will be limited to strengthening of bridges, and perhaps areas where embankments and adjacent slopes are most unstable.

Time-to-restoration: The time-to-restoration data assigned to SF 25e, city streets for highway systems, are assumed to

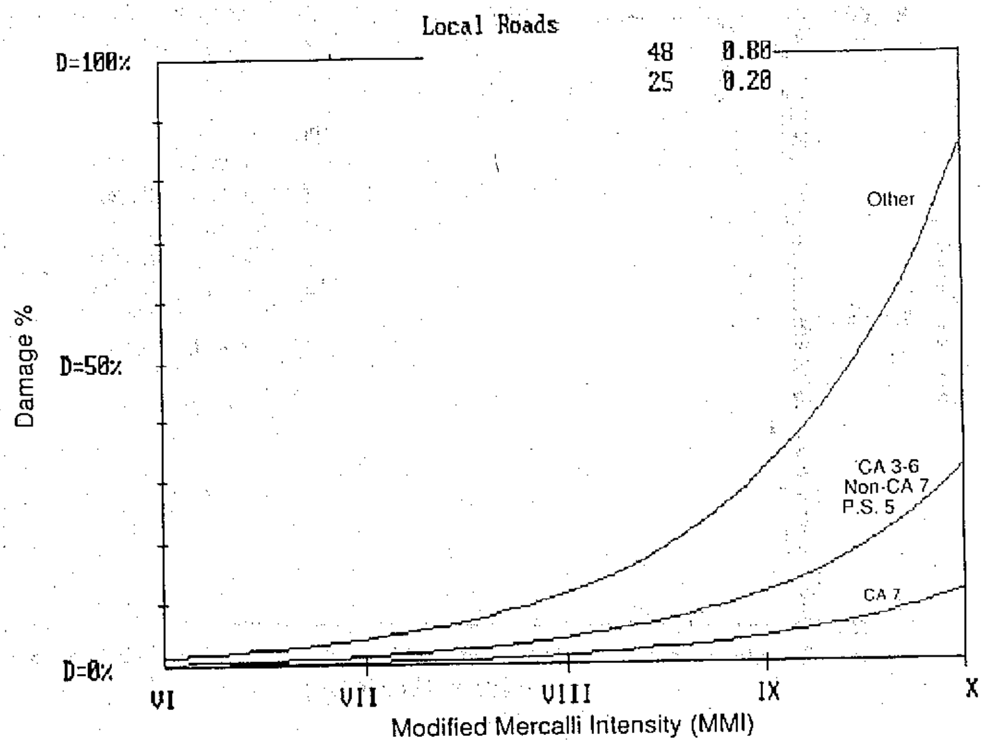

Figure B-14 Damage percent by intensity for local roads.

apply to all local roads. By combining these data with the damage curves derived using the data for FC 25 and 48, the time-to-restoration curves shown in Figures B-15 through B-17 were derived.

B.2 Railway

B.2.1 Bridges

1. General

Description: In general, railway bridges may be steel, concrete, wood or masonry construction, and their spans may be any length. Included are open and ballasted trestles, drawbridges, and fixed bridges. Bridge components include a bridge deck, stringers and girder, ballast, rails and ties, truss members, piers, abutments, piles, and caissons. Railroads sometimes share major bridges with highways (suspension bridges), but most railway bridges are older and simpler than highway bridges. Bridges that cross streams or narrow drainage passages typically have simple-span deck plate girders or beams. Longer spans use simple trusses supported on piers. Only a few of the more recently constructed bridges have continuous structural members.

Typical Seismic Damage: The major cause of damage to trestles is displacement of unconsolidated sediments on which the substructures are supported, resulting in movement of pile-supported piers and abutments. Resulting superstructure damage has consisted of compressed decks and stringers, as well as collapsed spans. Shifting of the piers and abutments may shear anchor bolts. Girders can also shift on their piers. Failures of approaches or fill material behind abutments can result in bridge closure. Movable bridges are more vulnerable than fixed bridges; slight movement of piers supporting drawbridges can result in binding so that they cannot be opened without repairs. Movable span railroads are subject to misalignments, and extended closures are required for repairs.

Seismically Resistant Design: Seismically resistant design practice should include proper siting considerations and details to

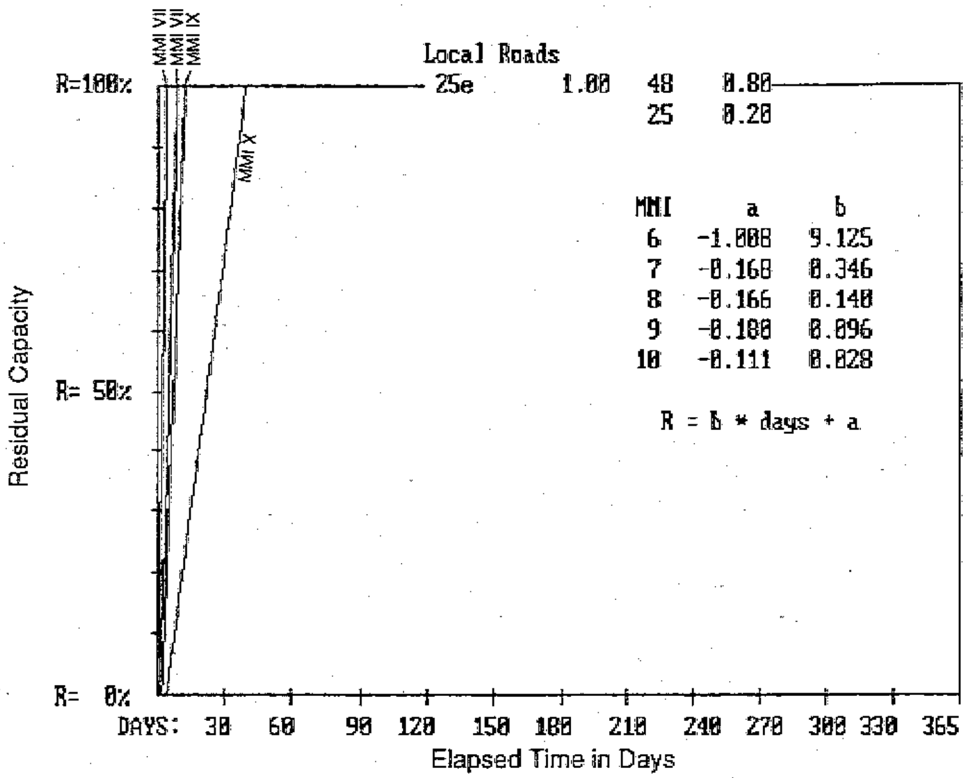

Figure B-15 Residual capacity for local roads (NEHRP California 7).

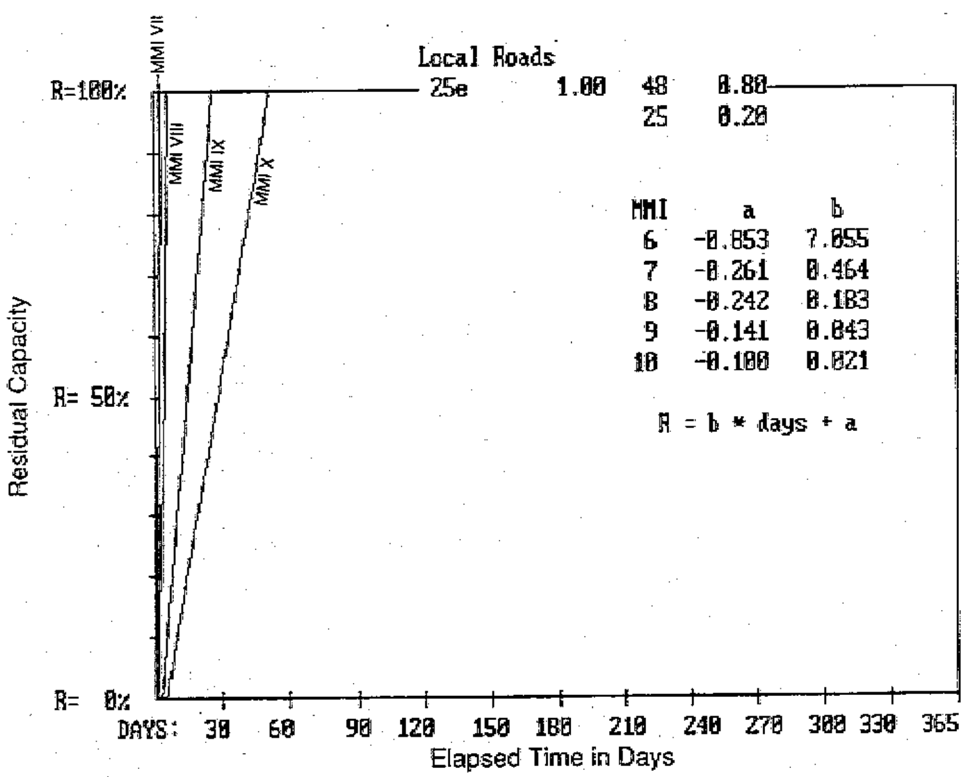

Figure B-16 Residual capacity for local roads (NEHRP Map Area 3-6, Non-California 7, and Puget Sound 5).

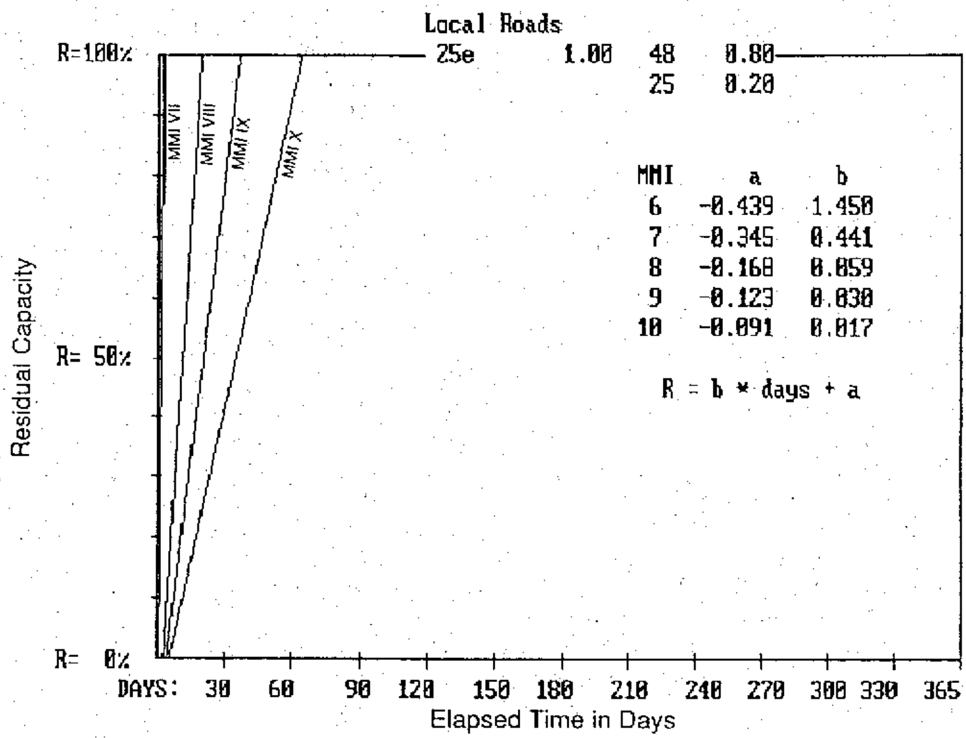

Figure B-17 Residual capacity for local roads (All other areas).

prevent foundation failure. Restraint for spans and/or adequate bearing lengths to accommodate motions are effective ways to mitigate damage. Reinforced concrete piers should be provided with proper confinement and adequate longitudinal splices and embedment into the foundation.

2. Direct Damage

Basis: Damage curves for railway system bridges are based on ATC-13 data for FC 25, continuous/monolithic bridges (see Figure B-18). Railroad bridges tend to be both older and simpler than highway bridges and have survived in some areas where highway bridges (simple-span bridges) have collapsed. Possible reasons for this superior performance are the lighter superstructure weight of the railroad bridges due to the absence of the roadway slab, the beneficial effects of the rails tying the adjacent spans together, and the design for other transverse and longitudinal loads even when no seismic design is done. Consequently, railroad system bridge performance is assumed to be represented by shifting the mean damage curve for continuous/monolithic bridges by one beneficial intensity unit.

Standard construction is assumed to represent typical California railway bridges under present conditions (i.e., a composite of older and more modern bridges).

Present Conditions: In the absence of data to the type of construction (fixed or movable), age, type (fixed or movable) etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	MMI Intensity Shift
California 7	-1
California 3-6	-1
Non-California 7	0
Puget Sound 5	0
All other areas	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one

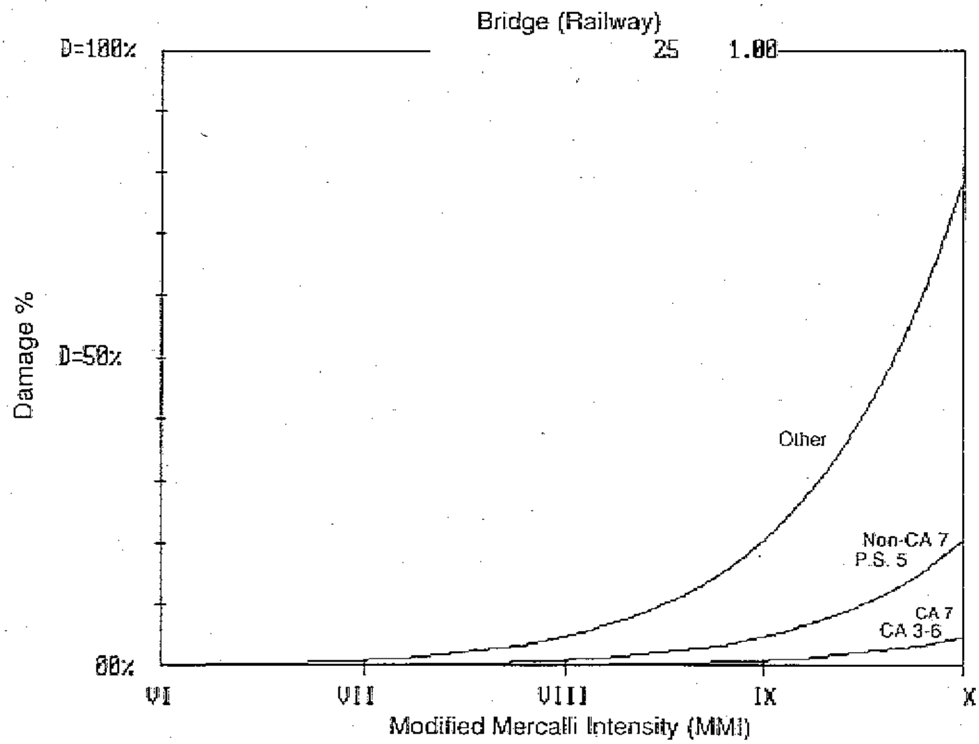

Figure B-18 Damage percent by intensity for railway bridges.

unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 26a, railway bridges, are assumed to apply to all railway bridges. By combining these data with the damage curves for FC 25, the time-to-restoration curves shown in Figures B-19 through B-21 were derived.

B.2.2 Tunnels

1. General

Description: In general, tunnels may pass through alluvium or rock, or may be of cut-and-cover construction. Tunnels may be lined or unlined, and may be at any depth below the ground surface. Tunnel lengths may range from less than 100 feet to several miles. Lining materials include brick, reinforced and unreinforced concrete, and steel. Heavy timbers and wood lagging (grouted and ungrouted) may also be used to support tunnel walls and ceilings. Tunnels may change in shape and/or construction material over their lengths.

Typical Seismic Damage: Tunnels may experience severe damage in areas affected by permanent ground movements due to landslides or surface fault rupture, but rarely suffer significant internal damage from ground shaking alone. Landslides at tunnels portals can cause blockage. Damage has been noted at tunnel weak spots such as intersections; bends; or changes in shape, construction materials, or soil conditions. Damage to lined tunnels has typically been limited to cracked lining.

Seismically Resistant Design: Lined tunnels have performed better than unlined tunnels. Consequently, general Seismically resistant design practices for tunnels include providing reinforced concrete lining; strengthening areas that have been traditionally weak such as intersections, bends, changes in shape and in construction materials; and siting tunnels to eliminate fault crossings. Slope stability at portals

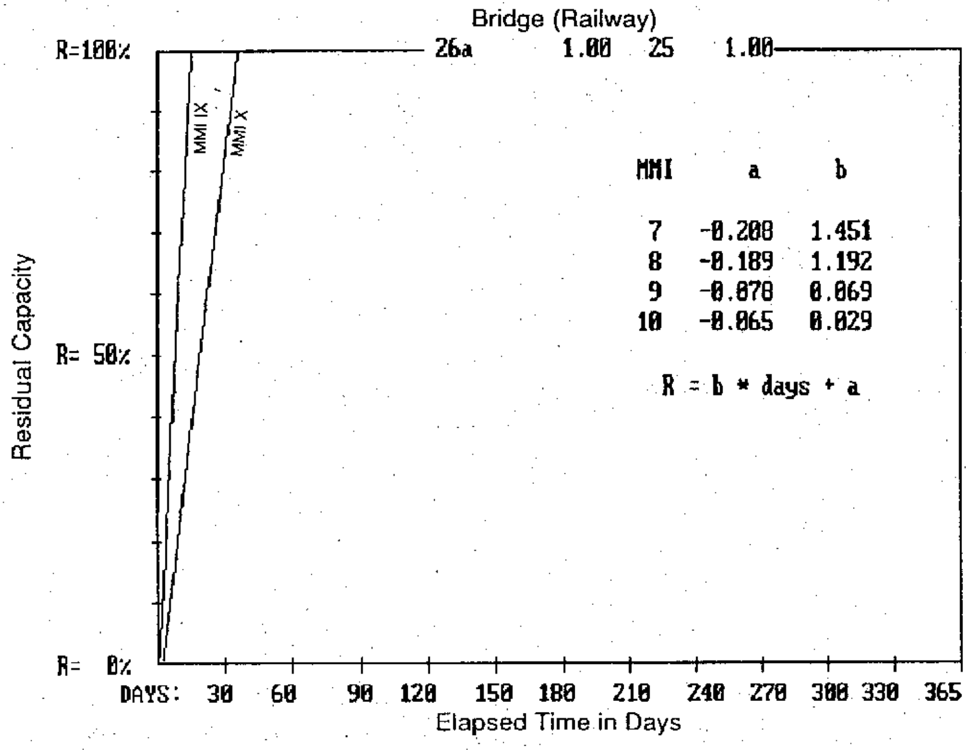

Figure B-19 Residual capacity for railway bridges (NEHRP California 7).

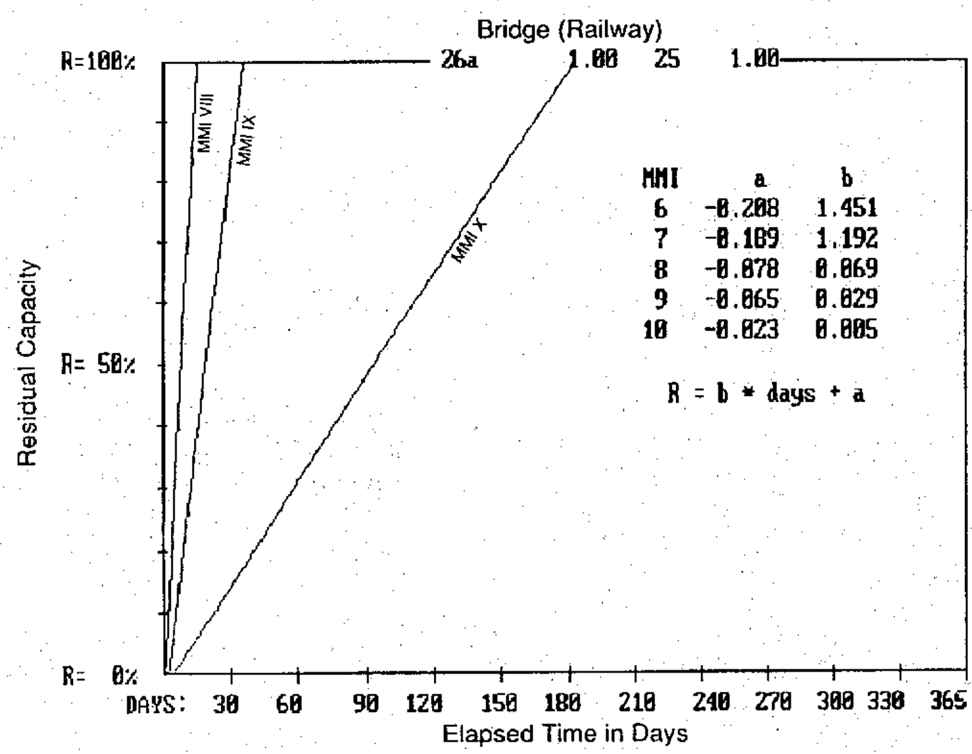

Figure B-20 Residual capacity for railway bridges (NEHRP Map Area 3-6, Non-California 7, and Puget Sound 5).

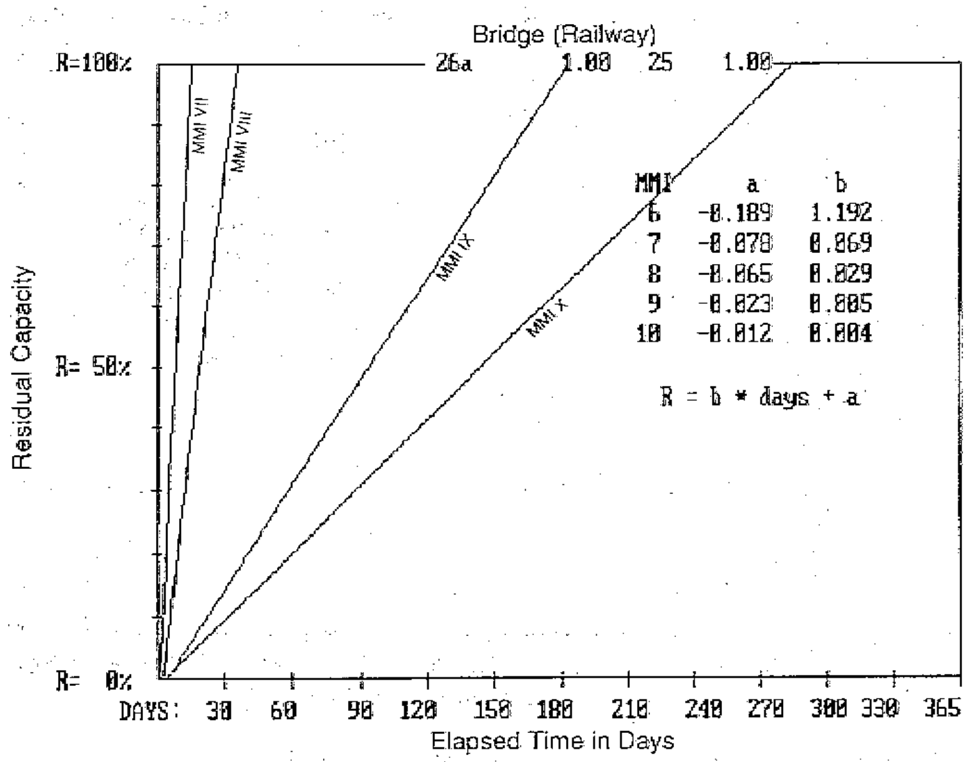

Figure B-21 Residual capacity for railway bridges (All other areas).

should be evaluated and stabilization undertaken if necessary.

2. Direct Damage

Basis: Damage curves for railway tunnels are based on ATC-13 data for FC 38, tunnels passing through alluvium (see Figure B-22). Tunnels passing through alluvium are less vulnerable than cut-and-cover tunnels, and more vulnerable than tunnels passing through rock; they were chosen as representative of all existing tunnels. If inventory data identify tunnels as cut-and-cover or passing through rock, then use ATC-13 FC 40 or 39, respectively, in lieu of FC 38.

Standard construction is assumed to represent typical California railroad tunnels under present conditions (i.e., a composite of older and more modern tunnels). Only minimal regional variation in construction quality is assumed.

Present Conditions: In the absence of data to the type of lining, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	*MMI Intensity Shift*
California 7	0
California 3-6	0
Non-California 7	0
Puget Sound 5	0
All other areas	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 26b, railroad system tunnels, are assumed to apply to all tunnels. By combining these data with the damage curves for FC 38, the time-to-restoration curves shown in Figures B-23 and B-24 were derived.

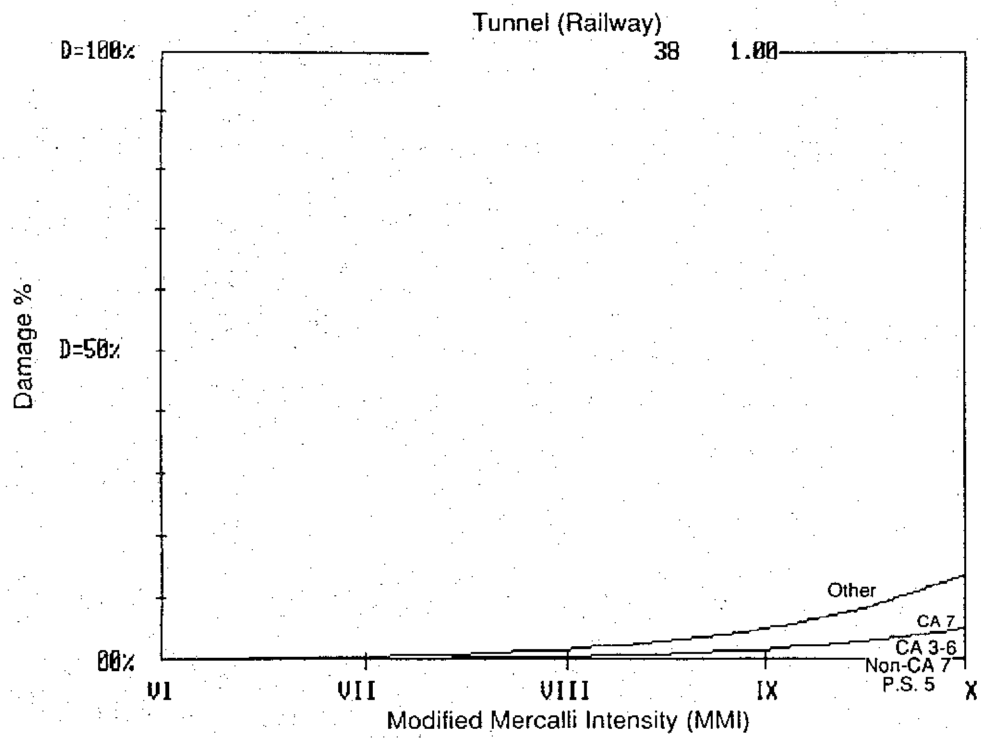

Figure B-22 Damage percent by intensity for railway tunnels.

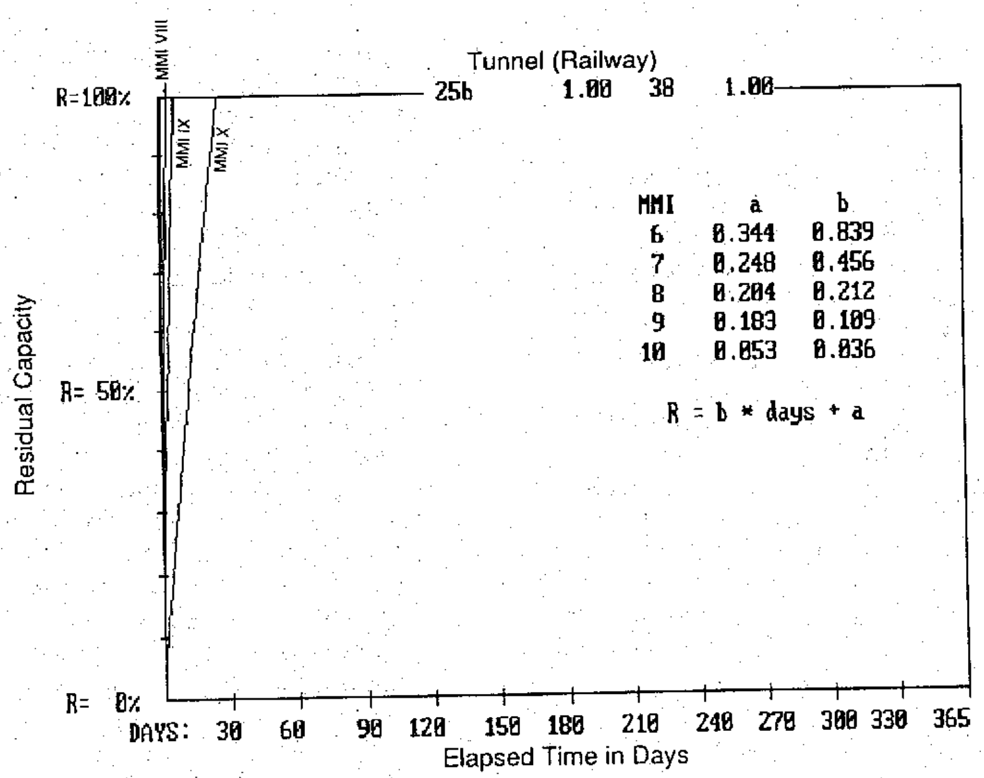

Figure B-23 Residual capacity for railway tunnels (NEHRP Map Area: California 3-6, California 7, Non-California 7, and Puget Sound 5).

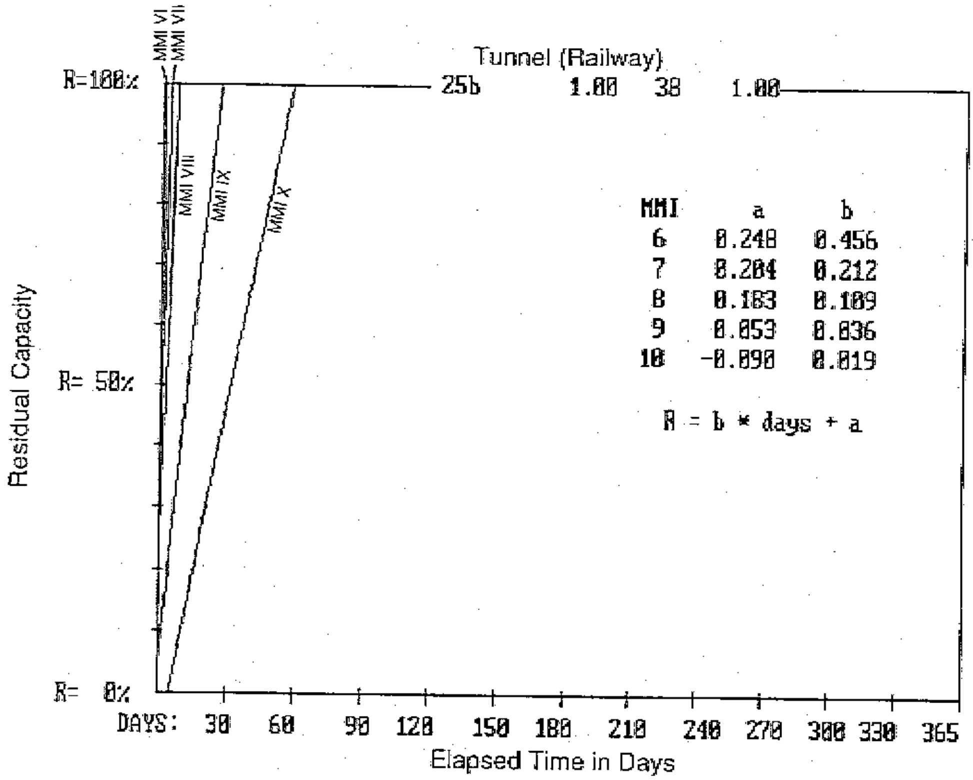

Figure B-24 Residual capacity for railway tunnels (All other areas).

B.2.3 Tracks/Roadbeds

1. General

Description: In general, track/roadbed in the railway system includes ties, rail, ballast or roadbed, embankments, and switches. Ties may be wood or prestressed concrete. Rail is exclusively steel and is periodically fastened to ties with spikes and/or steel clips. Roadbed typically includes imported aggregate on prepared subgrade.

Typical Seismic Damage: The most frequent source of damage to track/roadbed is settlement or slumping of embankments. Landslides can block or displace tracks. Settlement or liquefaction of roadbeds in alluvial areas is also a source of damage. Only in extreme cases are rails and roadbeds damaged by shaking alone.

Seismically Resistant Design: Seismic design practice includes providing special attention to the potential for failure of slopes adjacent to the tracks; cut slopes and fills are particularly susceptible. The potential for track failure can be reduced by properly grading and compacting imported track bed materials and by keeping cuts and fills as low as practicable. Track alignments must be precise and the track clear of debris for train operations.

2. Direct Damage

Basis: Damage curves for railroad system tracks/roadbeds are based on ATC-13 data for FC 47, railroads (see Figure B-25). Standard construction is assumed to represent typical California tracks/roadbeds (i.e., a composite of older and more modern tracks/roadbeds). Age may not be as important a factor for tracks/roadbeds as it is for other facilities, because the compaction of soils in poor grounds through usage may improve their behavior significantly. Only minimal regional variation in construction quality is assumed.

Present Conditions: In the absence of data to the type of material, age, etc., the following factors were used to modify the mean curves, under present conditions:

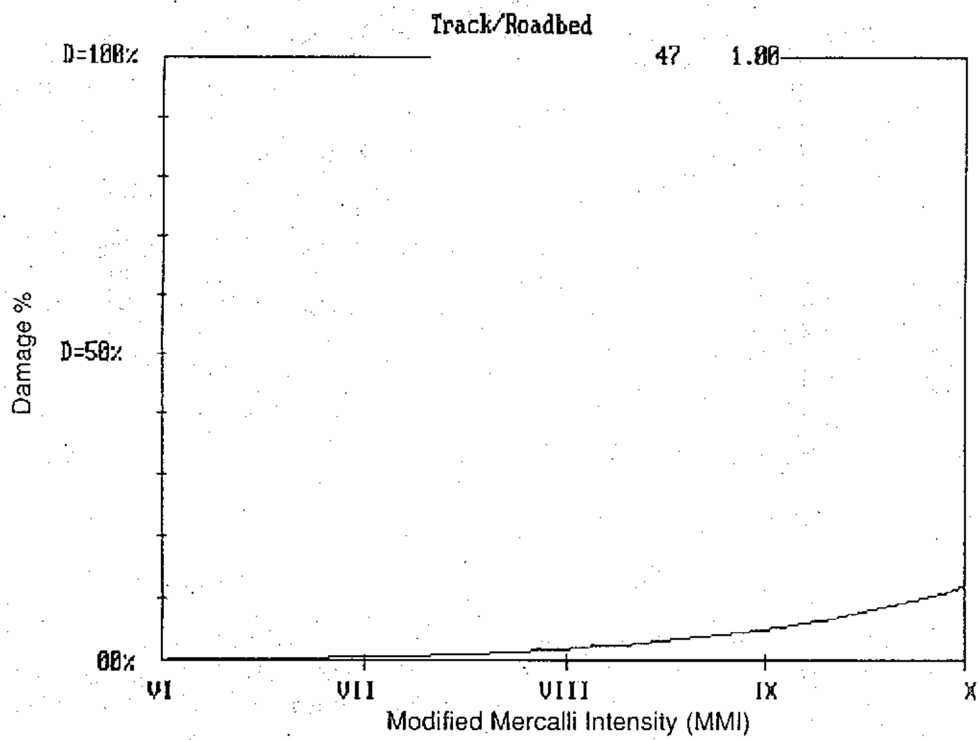

Figure B-25 Damage percent by intensity for tracks/roadbeds.

NEHRP Map Area	MMI Intensity Shift
California 7	0
California 3-6	0
Non-California 7	0
Puget Sound 5	0
All other areas	0

Upgraded Conditions: It is not anticipated that it will be cost-effective to retrofit facilities for the sole purpose of improving seismic performance, except perhaps in very isolated areas where the slopes and soils are unstable. The effect on overall facility performance in earthquakes will be minimal, and no intensity shifts are recommended.

Time-to-restoration: The time-to-restoration data assigned to SF 26c, railways, are assumed to apply to all tracks/roadbeds. By combining these data with the damage curves for FC 47, the time-to-restoration curves shown in Figure B-26 were derived.

B.2.4 Terminal Stations

1. General

Description: Terminal stations may be large or small. The structure housing the station may generally be any type of construction from steel frame to unreinforced masonry bearing walls. The terminal station typically includes switching and control equipment, as well as electrical and mechanical equipment commonly found in commercial buildings. Limited lengths of rails are also included in terminal stations.

Typical Seismic Damage: In general, terminal stations in railway systems may experience generic building and equipment damage. Building damage may range from cracks in walls and frames to partial and total collapse. Unanchored or improperly anchored equipment may slide or topple, experiencing damage or causing attached piping and conduit to fail. Rail damage in the switching yard will occur due to severe shaking or ground failure only.

Seismically Resistant Design: Seismically resistant design practice includes performing all building design in accordance with seismic provisions of national or local

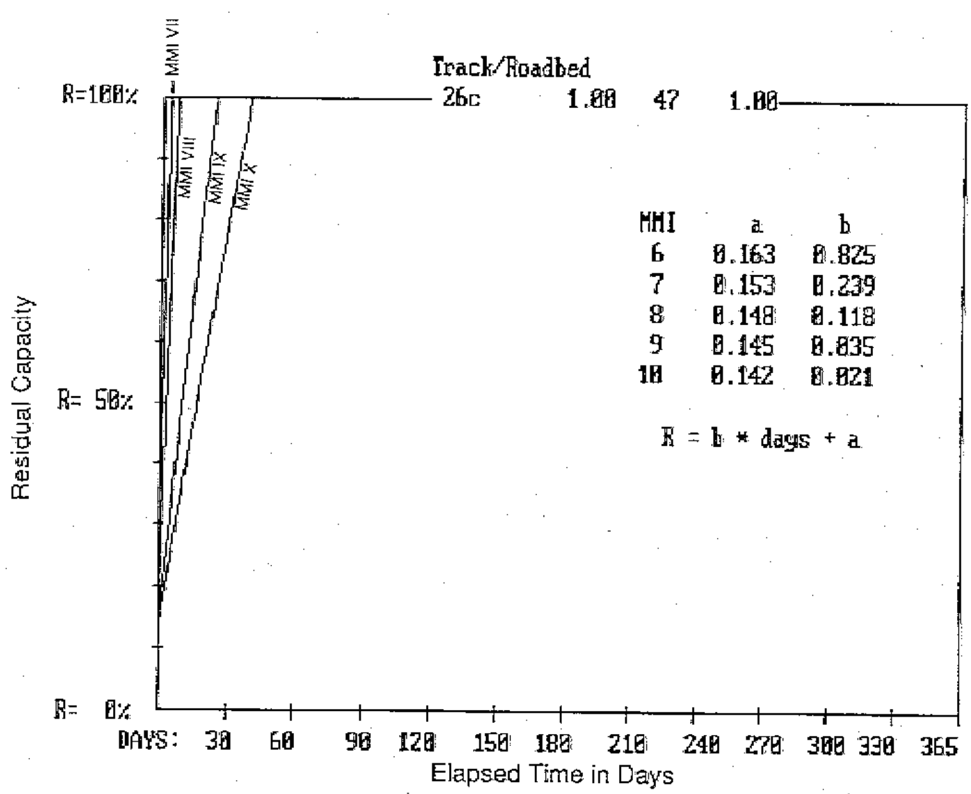

Figure B-26 Residual capacity for tracks/roadbeds (NEHRP Map Area: California 3-6, California 7, Non-California 7, Puget Sound, and all other areas).

building codes. All critical equipment should be well-anchored. Provisions should be made for backup emergency power for control and building equipment essential for continued operations.

1. Direct Damage

Basis: Damage curves for the railway system terminal station are based on ATC-13 data for FC 10, medium-rise reinforced masonry shear wall buildings; FC 68, mechanical equipment; and FC 47, railways (seee Figure B-27). FC 10 was chosen to represent a generic building, based on review of damage curves for all buildings. Railway terminals were assumed to be a combination of 60% generic buildings, 20% mechanical equipment, and 20% railways.

Standard construction is assumed to represent typical California railway system terminals under present conditions (i.e., a composite of older and more modern terminals). It is assumed that there is no regional variation in construction quality of roadbed/embankments within the station and that only minimal variation exists for mechanical equipment.

Present Conditions: In the absence of data to the type of construction material, age, etc., the following factors were used to modify the mean curves for each of the three facility classes listed above, under present conditions:

	MMI Intensity Shift		
NEHRP Map Area	*FC 10*	*FC 47*	*FC 68*
California 7	0	0	0
California 3-6	+1	0	0
Non-California 7	+1	0	0
Puget Sound 5	+1	0	0
All other areas	+2	0	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in one or two beneficial intensity

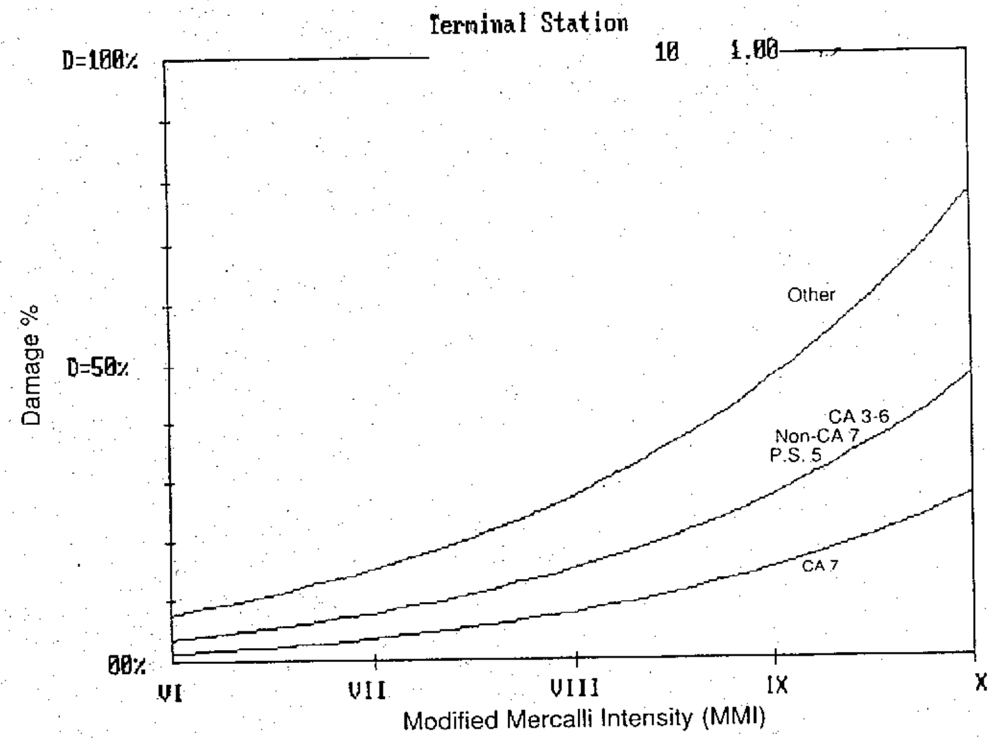

Figure B-27 Damage percent by intensity for railway terminal stations.

shifts (i.e., -1 or -2), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 26d, terminal stations for railway systems, are assumed to apply to all terminal stations. By combining these data with the damage curves derived using the data for FC 10, 47, and 68, the time-to-restoration curves shown in Figures B-28 through B-30 were derived.

B.3 Air Transportation

B.3.1 Terminals

1. General

Description: In general, air transportation terminals include terminal buildings, control towers, hangars, and other miscellaneous structures (including parking garages and crash houses). These structures may be constructed of virtually any building material, although control towers are typically reinforced concrete shear wall buildings and hangars are either steel or wood long-span structures. Equipment at air terminals ranges from sophisticated control, gate, and x-ray equipment to typical electrical and mechanical equipment found in commercial buildings. Airplane refueling is accomplished by either on-site or off-site fuel tanks and underground pipelines.

Typical Seismic Damage: Damage may include generic building and equipment damage. Building damage may range from broken windows and cracks in walls and frames to partial and total collapse. Unanchored or improperly anchored equipment may slide or topple, experiencing damage or causing attached piping and conduit to fail. The source of this damage can be ground shaking or soil failure, as many airports are located in low-lying alluvial regions. Gate equipment may become misaligned and inoperable. Fuel tanks and fuel lines may rupture or experience damage, reducing or eliminating refueling capacity. Tank damage may include wall buckling, settlement, ruptured piping, or loss of contents, or even collapse. Such collapses could lead to fires and

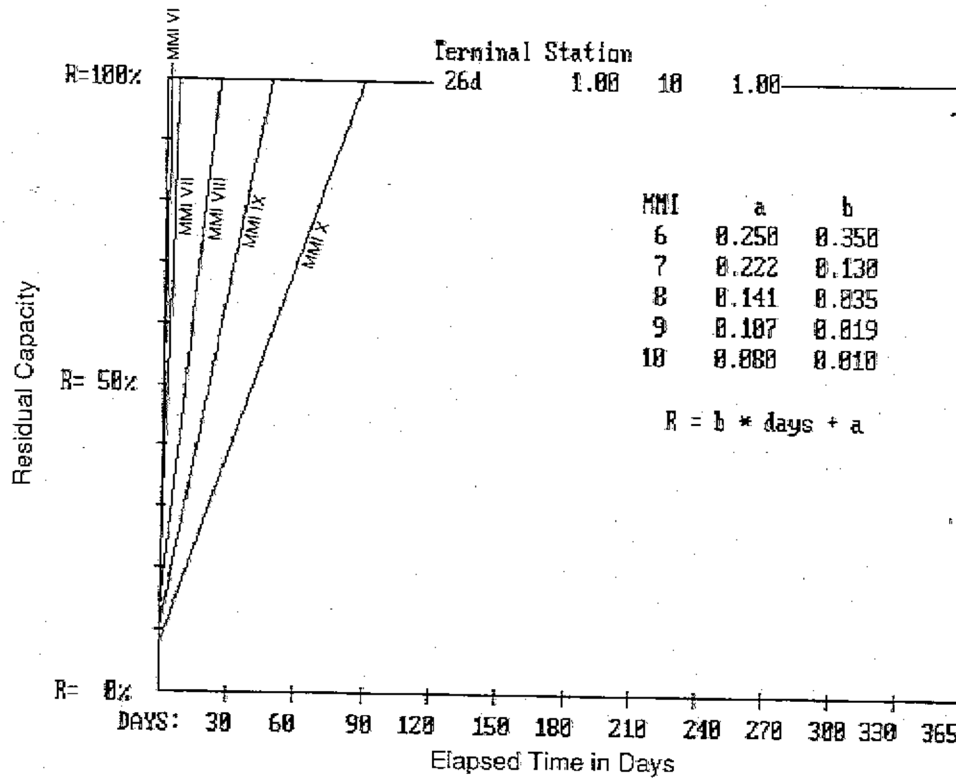

Figure B-28 Residual capacity for railway terminal stations (NEHRP California 7).

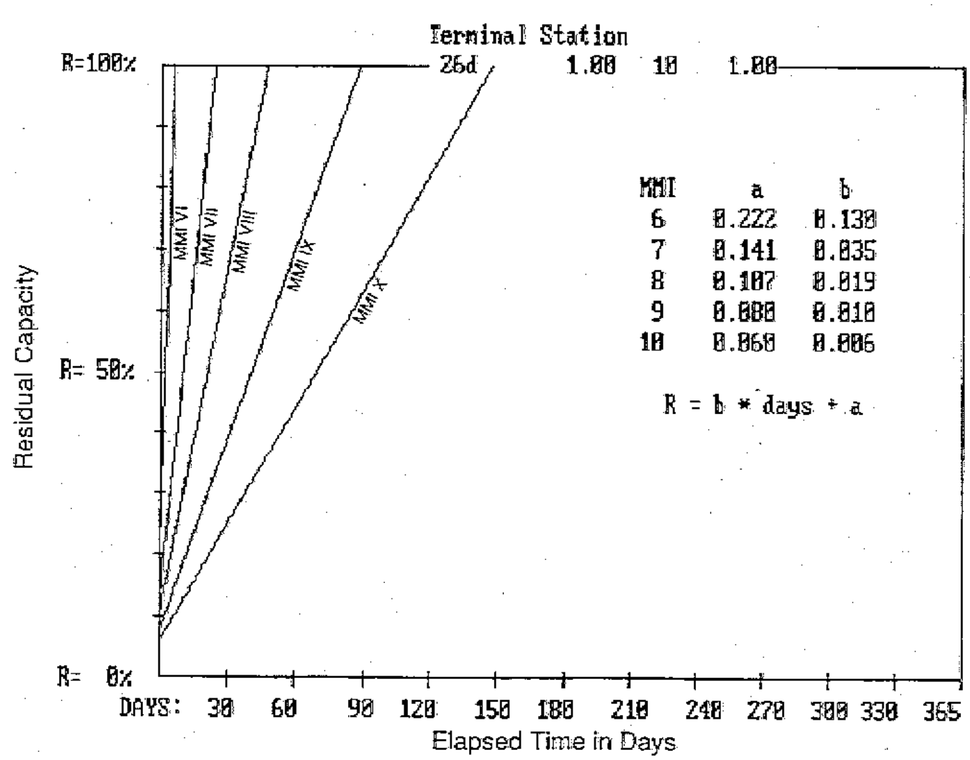

Figure B-29 Residual capacity for railway terminal stations (NEHRP Map Area 3-6, Non-California 7, and Puget Sound 5).

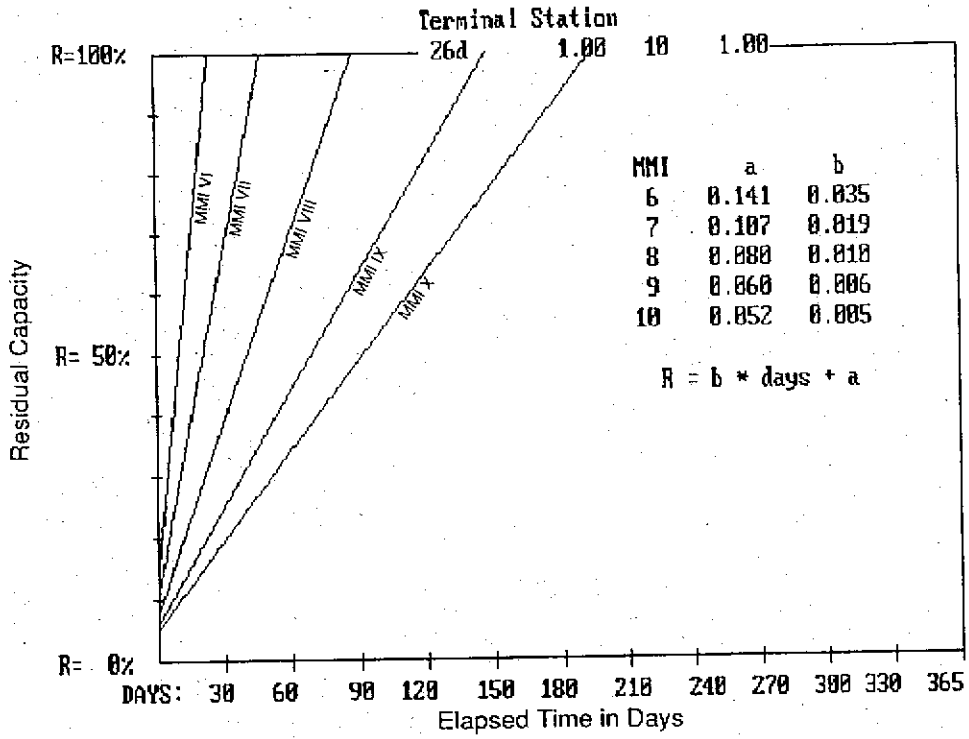

Figure B-30 Residual capacity for railway terminal stations (All other areas).

explosions. Damage to ground access and egress routes may seriously affect operations. Airports in low-lying areas may be subject to damage due to flooding or tsunamis.

Seismically Resistant Design: Building design should be performed in accordance with seismic provisions of building codes. Control-tower design should receive special attention based on its importance and the fact that the geometry of the tower makes it prone to earthquake damage. Enhanced design criteria (e.g., a higher importance factor) may be appropriate for control towers. All critical equipment should be anchored. Provisions should be made for backup emergency power for control equipment and landing lights.

2. Direct Damage

Basis: Damage curves for air transportation system terminals are based on ATC-13 data for FC 10, mid-rise reinforced masonry shear wall buildings; FC 43, on-ground liquid storage tanks; and FC 91, long-span structures (see Figure B-31). FC 10 was chosen to represent a generic building, based on review of damage curves for all buildings. Air transportation system terminals are assumed to be a combination of 40% generic buildings, 40% long-span structures, and 20% on-ground liquid storage tanks.

Standard construction is assumed to represent typical California air terminals under present conditions (i.e., a composite of older and more modern terminals). Only minimal regional variation in construction quality of long-span structures is assumed, as design wind and seismic loads may be comparable.

Present Conditions: In the absence of data on the type of construction, age, etc., the following factors were used to modify the mean curves for each of the three facility classes listed above, under present conditions:

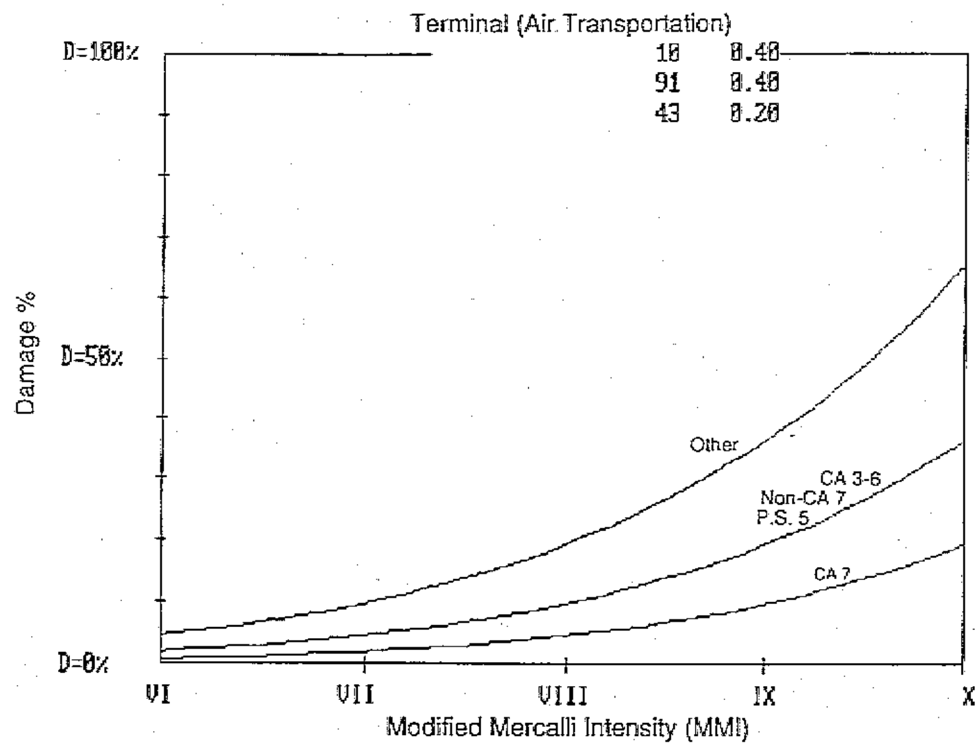

Figure B-31 Damage percent by intensity for airport terminals.

NEHRP Map Area	MMI Intensity Shift FC 10	FC 43	FC 91
California 7	0	0	0
California 3-6	+1	+1	+1
Non-California 7	+1	+1	+1
Puget Sound 5	+1	+1	+1
All other areas	+2	+2	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in one or two beneficial intensity shifts (i.e., -1 or -2), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 27a, air transportation terminals, are assumed to apply to all terminals. By combining these data with the damage curves derived using the data for FC 10, 43, and 91, the time-to-restoration curves shown in Figures B-32 through B-34 were derived.

B.3.2 Runways and Taxiways

1. General

Description: In general, runways and taxiways in the air transportation system include runways, taxiways, aprons, and landing lights. Runways and taxiways comprise pavements, grades, and subgrades. Pavement types include portland cement concrete and asphaltic concrete.

Typical Seismic Damage: Runway damage is a direct function of the strength characteristics of the underlying soils. Airports tend to be located in low-lying alluvial areas or along water margins subject to soil failures. Hydraulic fills are especially prone to failure during ground shaking. Runways can be damaged by liquefaction, compaction, faulting, flooding, and tsunamis. Damage may include misalignment, uplift, cracking, or buckling of pavement.

Seismically Resistant Design: Seismic design practices include providing proper gradation and compaction of soils or imported fills, grades, and subgrades.

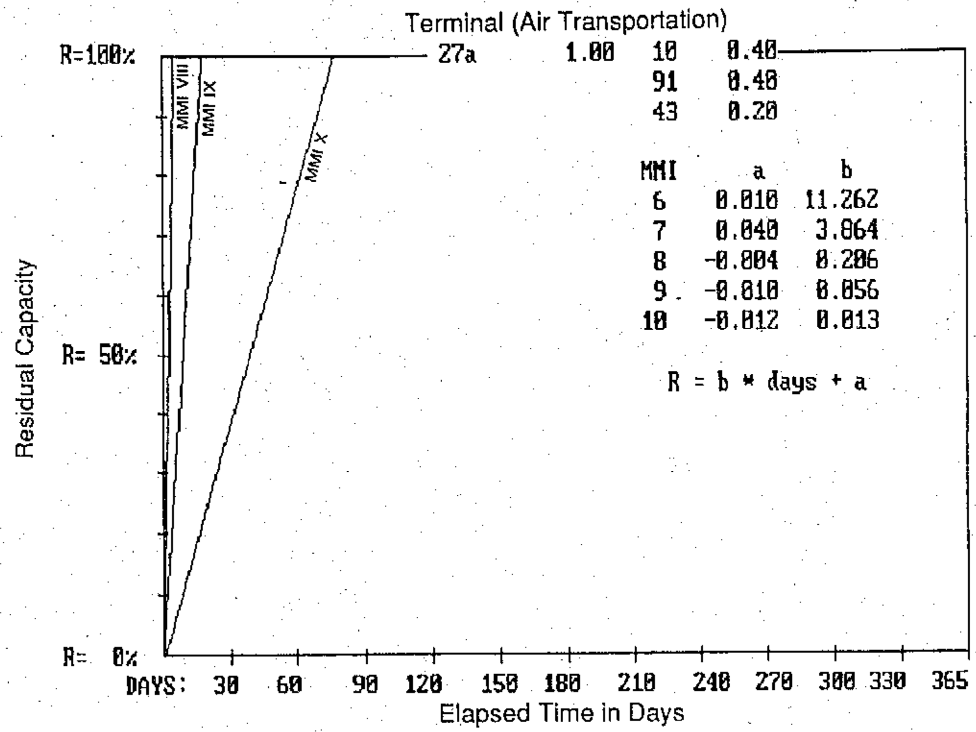

Figure B-32 Residual capacity for airport terinals (NEHRP California 7).

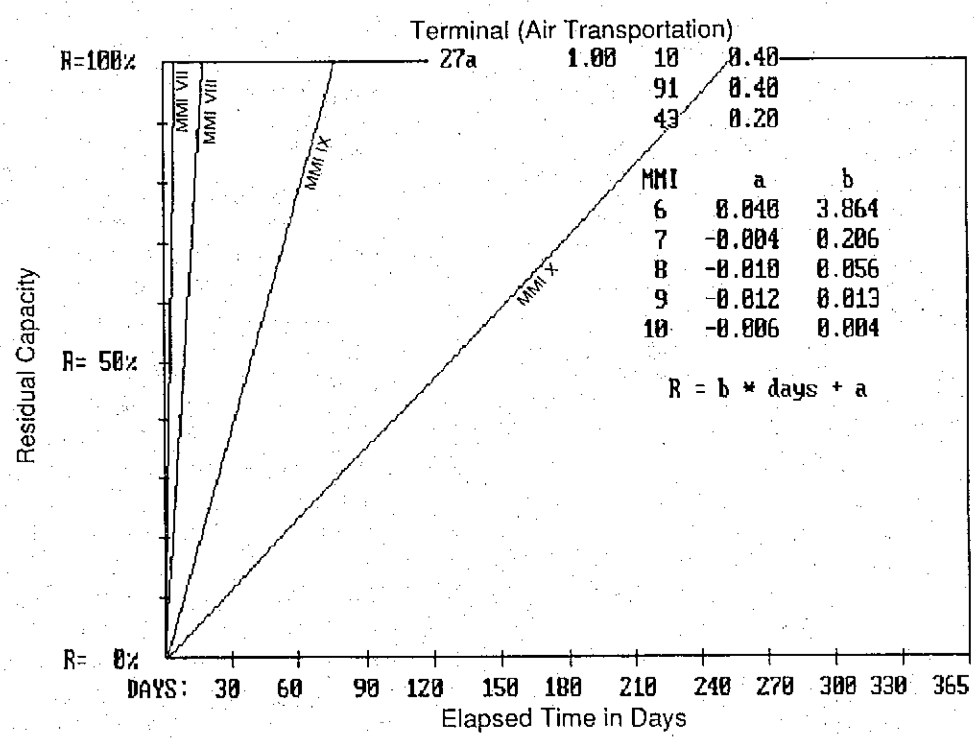

Figure B-33 Residual capacity for airport terminals (NEHRP Map Area 3-6, Non-California 7, and Puget Sound 5).

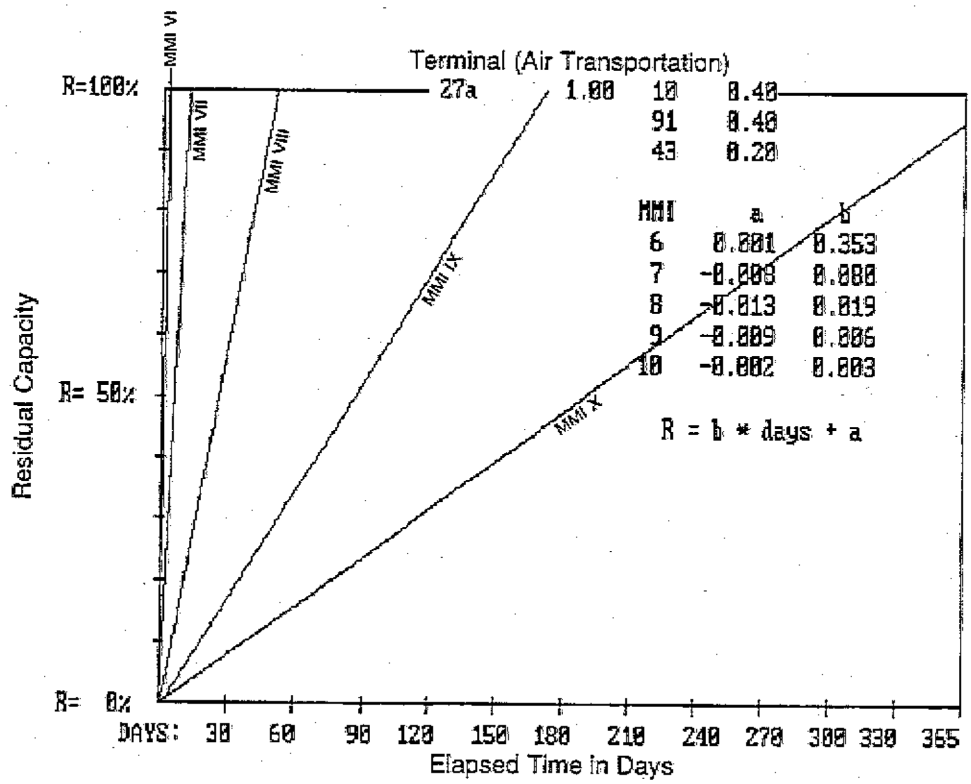

Figure B-34 Residual capacity for airport terminals (All other areas).

2. Direct Damage

Basis: Damage curves for air transportation system runways and taxiways are based on ATC-13 data for FC 49, runways (see Figure B-35). Standard construction is assumed to represent typical California runways and taxiways under present conditions (i.e., a composite of older and more modern runways).

Present Conditions: In the absence of data on the type of soils, material, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	MMI Intensity Shift
California 7	0
California 3-6	0
Non-California 7	0
Puget Sound 5	0
All other areas	0

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 27b, runways and taxiways, are assumed to apply for all runways and taxiways. By combining these data with the damage curves for FC 49, the time-to-restoration curves shown in Figure B-36 were derived.

B.4 Sea/Water Transportation

B.4.1 Ports/Cargo Handling Equipment

1. General

Description: In general, ports/cargo handling equipment comprise buildings (predominantly warehouses), waterfront structures, cargo handling equipment, paved aprons, conveyors, scales, tanks, silos, pipelines, railroad terminals, and support services. Building type varies, with steel frame being a common construction type. Waterfront structures include quay walls,

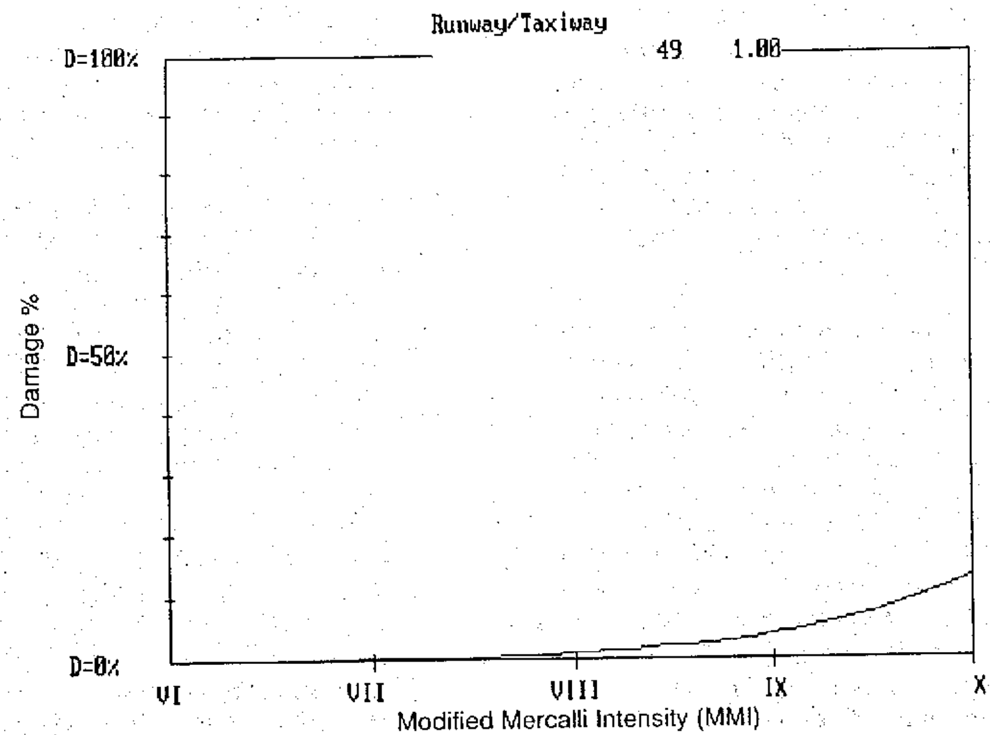

Figure B-35 Damage percent by intensity for runways/taxiways.

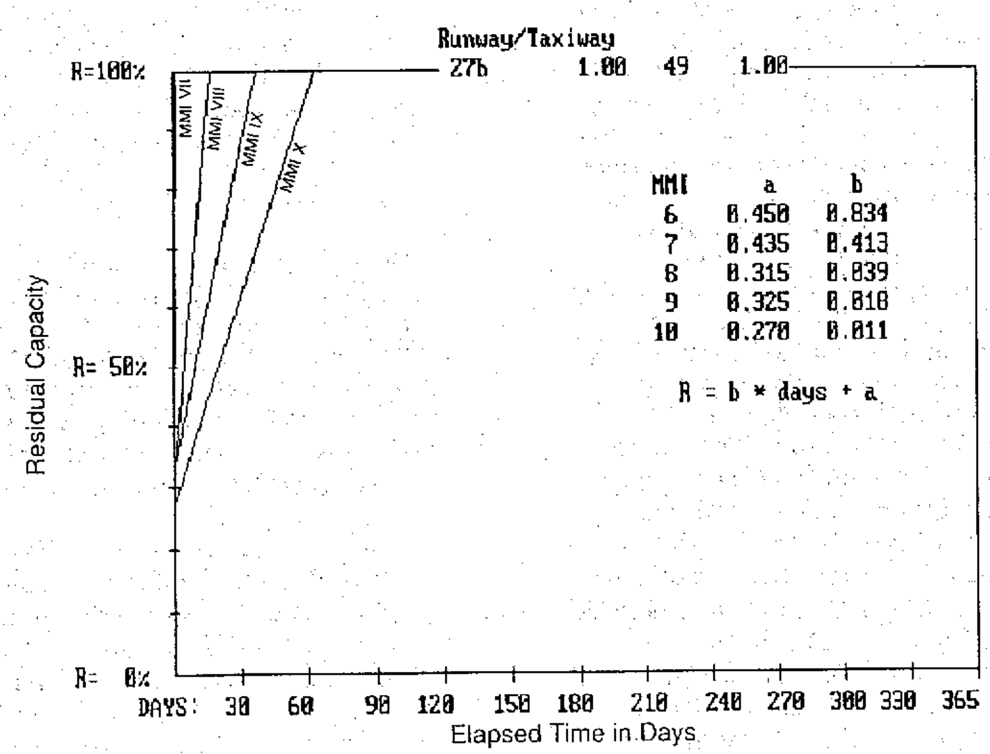

Figure B-36 Residual capacity for runways/taxiways (NEHRP Map Area: California 3-6, California 7, Non-California 7, Puget Sound 5, and all other areas).

sheet-pile bulkheads, and pile-supported piers. Quay walls are essentially waterfront masonry or caisson walls with earth fills behind them. Piers are commonly wood or concrete construction and often include batter piles to resist lateral transverse loads. Cargo handling equipment for loading and unloading ships includes cranes for containers, bulk loaders for bulk goods, and pumps for fuels. Additional handling equipment is used for transporting goods throughout port areas.

Typical Seismic Damage: By far the most significant source of earthquake-induced damage to port and harbor facilities has been pore-water pressure buildup in the saturated cohesionless soils that prevail at these facilities. This pressure buildup can lead to application of excessive lateral pressures to quay walls by backfill materials, liquefaction, and massive submarine sliding. Buildings in port areas are subject to generic damage due to shaking, as well as damage caused by loss of bearing or lateral movement of foundation soils. Past earthquakes have caused substantial lateral sliding, deformation, and tilting of quay walls and sheet-pile bulkheads. Block-type quay walls are vulnerable to earthquake-induced sliding between layers of blocks. This damage has often been accompanied by extensive settlement and cracking of paved aprons. The principal failure mode of sheet-pile bulkheads has been insufficient anchor resistance, primarily because the anchors were installed at shallow depths, where backfill is most susceptible to a loss of strength due to pore-water pressure buildup and liquefaction. Insufficient distance between the anchor and the bulkhead wall can also lead to failure. Pile-supported docks typically perform well, unless soil failures such as major submarine landslides occur. In such cases, piers have undergone extensive sliding and buckling and yielding of pile supports. Batter piles have damaged pier pile caps and decking because of their large lateral stiffness. Cranes can be derailed or overturn by shaking or soil failures. Toppling cranes can damage adjacent structures or other facilities. Misaligned crane rails can damage wheel assemblies and immobilize cranes. Tanks containing fuel may rupture and spill their contents into the water, presenting fire hazards. Pipelines from storage tanks to docks may be ruptured where they cross areas of structurally poor ground in the vicinity of docks. Failure of access roads and railway tracks can severely limit port operations. Port facilities, especially on the West Coast, are also subject to tsunami hazard.

Seismically Resistant Design: At locations where earthquakes occur relatively frequently it is the current Seismically resistant design practice to use seismic factors included in local building codes for the design of port structures. However, past earthquakes have indicated that seismic coefficients used for design are of secondary importance compared to the potential for liquefaction of the site soil materials. Quay wall and sheet-pile bulkhead performance could be enhanced by replacing weak soils with dense soils, or designing these structures to withstand the combination of earthquake-induced dynamic water pressures and pressures due to liquefied fills. Pier behavior in earthquakes has been good primarily because they are designed for large horizontal berthing and live loads, and because they are not subject to the lateral soil pressures of the type applied to quay walls and bulkheads. However, effects on bearing capacity, and lateral resistance of piles due to liquefaction and induced slope instability should also be considered.

2. Direct Damage

Basis: Damage curves for ports/cargo handling equipment in the sea/water transportation system are based on ATC-13 data for FC 53, cranes, and FC 63, waterfront structures (see figure B-37). Ports/cargo handling equipment were assumed to be a combination of 60% waterfront structures and 40% cranes.

Standard construction is assumed to represent typical California ports/cargo handling equipment under present conditions (i.e., a composite of older and more modern ports/cargo handling equipment). Only minimal regional variation in construction quality is assumed, as seismic design is performed only for selected port

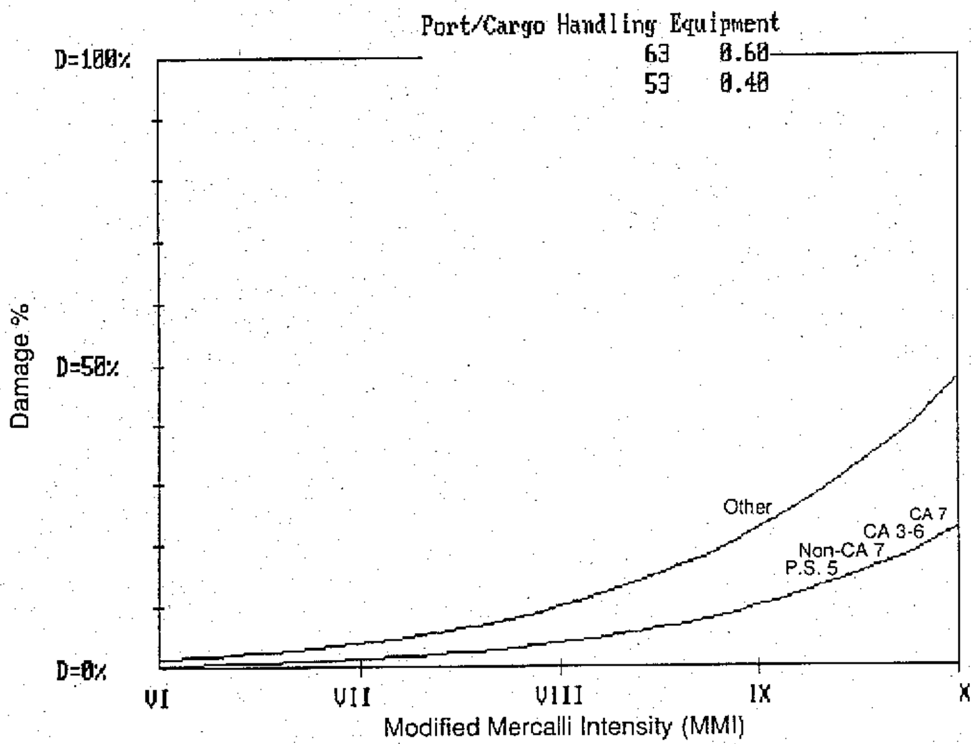

Figure B-37 Damage percent by intensity for ports/cargo handling equipment.

structures, and soil performance is the most critical determinant in port performance.

Present Conditions: In the absence of data on the type of material, age, etc., the following factors were used to modify the mean curve for the two facility classes listed above, under present conditions:

NEHRP Map Area	MMI Intensity Shift FC 53	FC 63
California 7	0	0
California 3-6	0	0
Non-California 7	0	0
Puget Sound 5	0	0
All other areas	+1	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 28a, ports, and SF 28b, cargo handling equipment, were assumed to apply to all ports/cargo handling equipment. Ports/cargo handling facilities were assumed to be a combination of 60% ports and 40% cargo handling facilities. By combining these data with the damage curves derived using the data for FC 53 and 63, the time-to-restoration curves shown in Figures B-38 and B-39 were derived.

B.4.2 Inland Waterways

1. General

Description: In general, inland waterways of the sea/water transportation system can be natural (rivers and bays) or human-made (canals). The sides and/or bottoms of inland waterways may be unlined or lined with concrete. Portions of the waterway may be contained through the use of quay walls, retaining walls, riprap, or levees.

Typical Seismic Damage: Damage to inland waterways will be greatest near ruptured faults. Channels or inland waterways may be blocked by earthquake-induced slumping.

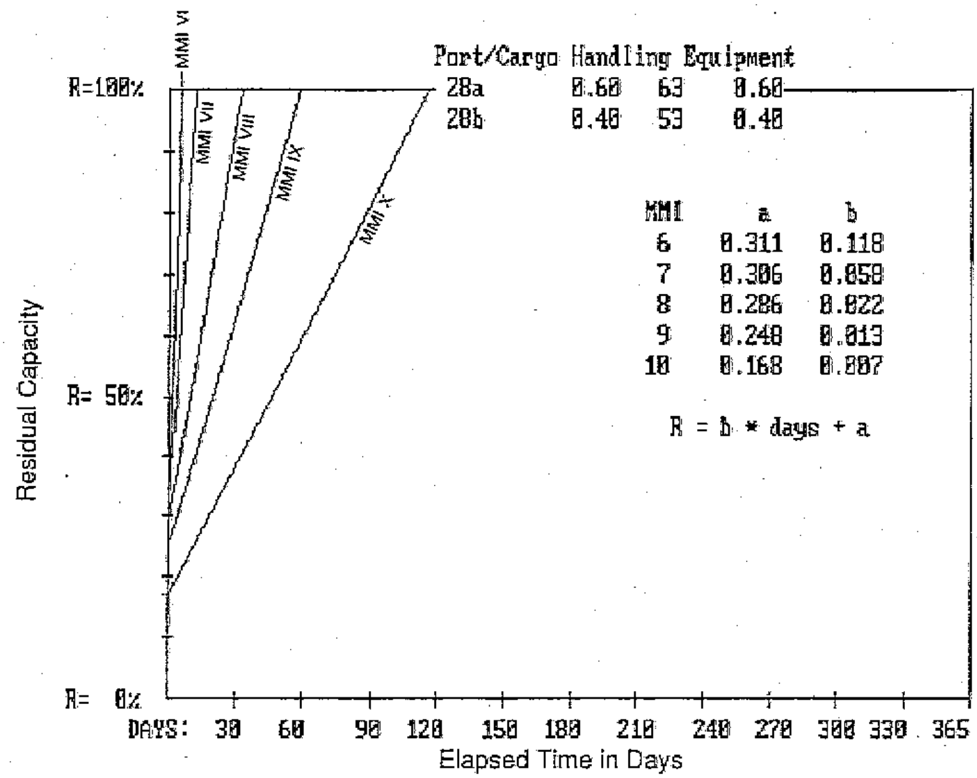

Figure B-38 Residual capacity for ports/cargo handling equipment (NEHRP Map Area: California 3-6, California 7, Non-California 7, and Puget Sound 5).

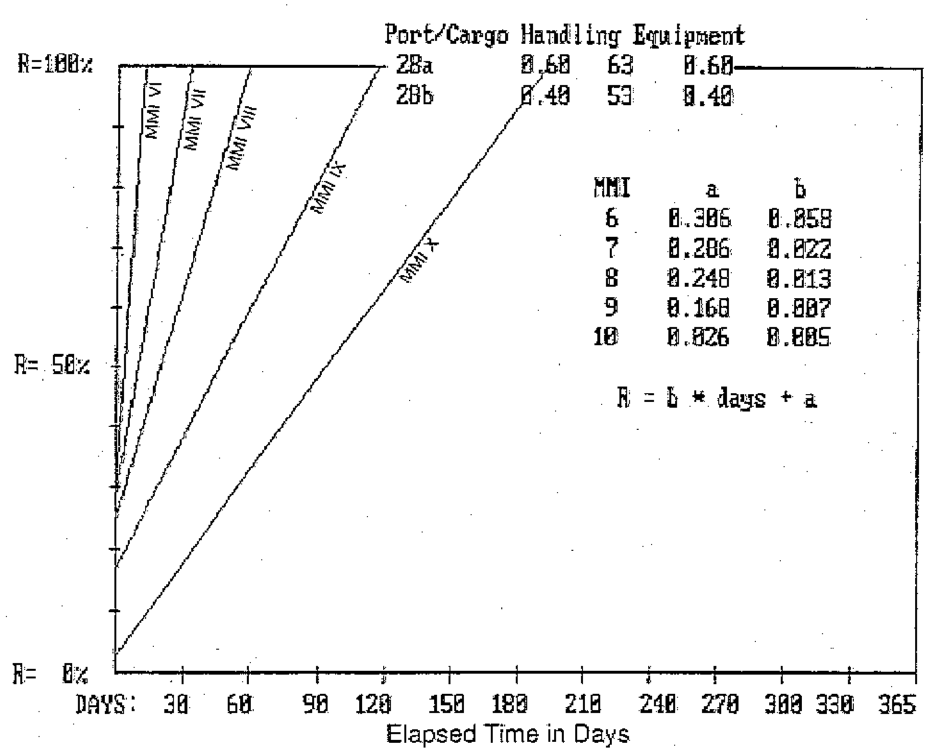

Figure B-39 Residual capacity for ports/cargo handling equipment (All other areas).

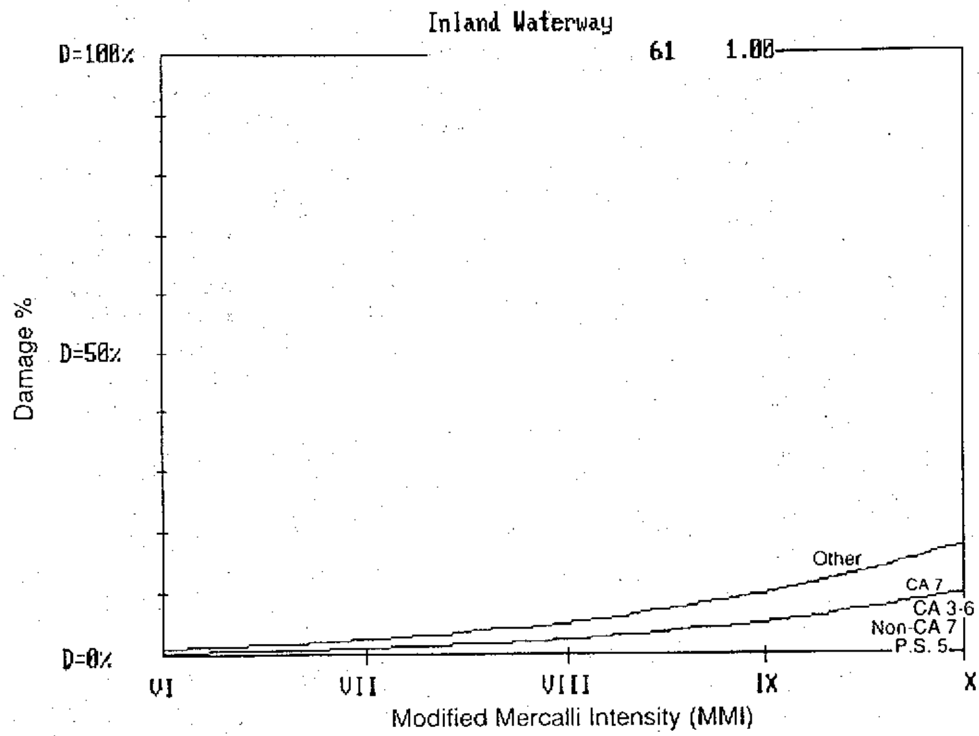

Figure B-40 Damage percent by intensity for inland waterways.

Quay walls, retaining walls, or levees can be damaged or collapse. Deep channels dredged in soft mud are subject to earthquake-induced slides that can limit the draft of ships that can pass. Channels lined with unreinforced concrete are susceptible to damage due to differential ground displacement. Loss of lining containment can lead to erosion of soil beneath lining. Waterways can be blocked by fallen bridges and are made impassable by spilled fuel or chemicals from tanks or facilities adjacent to the waterway.

Seismically Resistant Design: Seismically resistant design practices include providing walls of waterways with slopes appropriate for the embankment materials used, and/or designing quay walls and retaining walls to restrain soils in the event of soil failure.

2. Direct Damage

Basis: Damage curves for inland waterways in the sea/water transportation system are based on ATC-13 data for FC 61, canals (see Figure B-40).

Standard construction is assumed to present typical California inland waterways under present conditions (i.e., a composite of natural as well as new and old human-made waterways). It is assumed that the regional variation in construction quality is minimal.

Present Conditions: In the absence of data on the type of lining, age, etc., use the following factors to modify the mean curve, under present conditions:

NEHRP Map Area	MMI Intensity Shift
California 7	0
California 3-6	0
Non-California 7	0
Puget Sound 5	0
All other areas	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 35b, levees

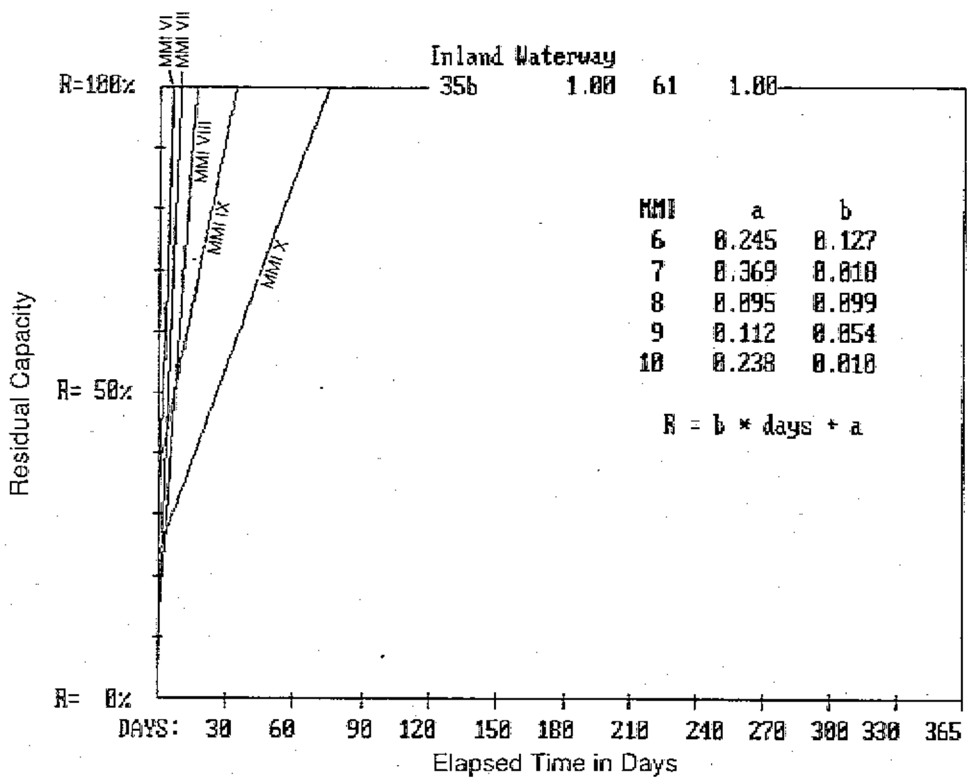

Figure B-41 Residual capacity for inland waterways (NEHRP Map Area: California 3-6, California 7, Non-California 7, and Puget Sound 5).

in flood control systems, are assumed to apply to all inland waterways. By combining these data with the damage curves for FC 61, the time-to-restoration curves shown in Figures B-41 and B-42 were derived.

B.5 Electrical

B.5.1 Fossil-fuel Power Plants

1. General

Description: In general, fossil-fuel power plants can be fueled by either coal or oil. Structures at fossil-fuel power plants are commonly medium-rise steel braced frames. A generation building typically comprises turbine, boiler, and fan areas. The turbine-generators are typically supported on reinforced concrete pedestals that are seismically isolated from the generation building. Boiler feed pumps are usually located below the turbine-generators. The boiler area typically includes the boilers (which are usually suspended from the support structures), steam drums, coal silos, conveyors, de-aerators, heaters, and associated equipment and piping. The fan area houses the air preheaters as well as the forced-draft fans and related duct work. Other components include instrumentation and control systems, water and fuel storage tanks, stacks, cooling towers, both underground and above ground piping, cable trays, switchgear and motor control centers, fuel handling and water treatment facilities, water intake and discharge, and cranes. Associated switchyards step up voltage and include transformers and circuit breakers.

Typical Seismic Damage: Damage to steel structures at power plants in past earthquakes has usually been limited to overstressed connections or buckled braces. Turbine pedestals may pound against the surrounding floor of the generation building and damage the turbine-generators. Boilers may sway and impact the support structure, causing damage to the expansion guides and possibly the internal tubes of the boiler. Structural damage to older timber cooling

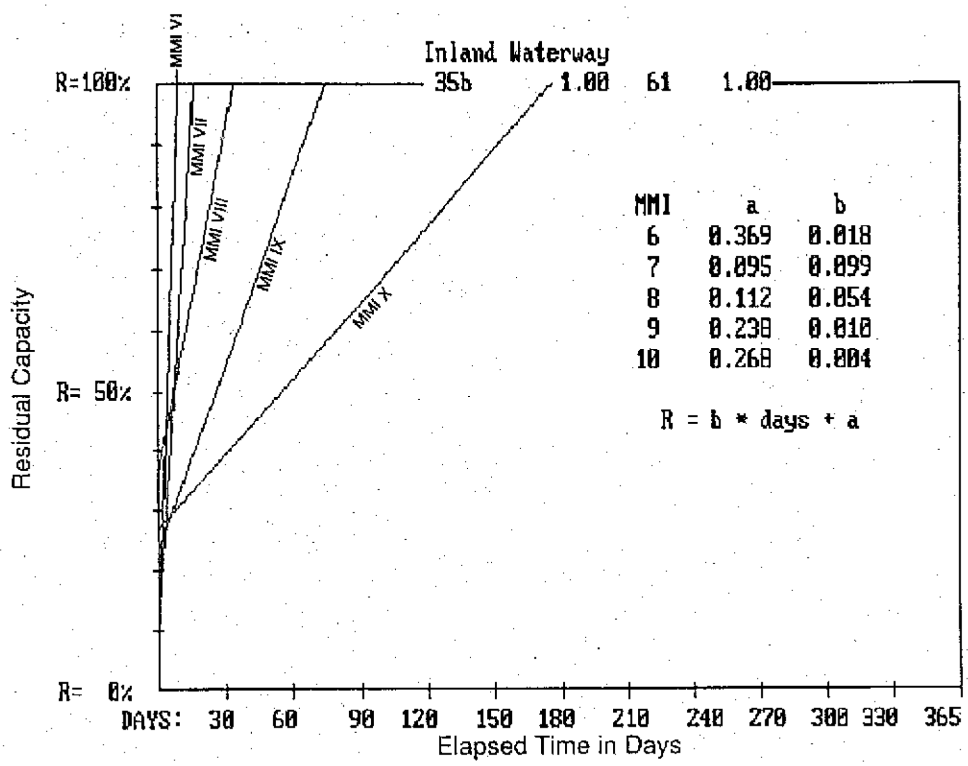

Figure B-42 Residual capacity for inland waterways (All other areas).

towers may occur due to deterioration and weakening of the structures with age. Fan blades and gearboxes in cooling towers have been damaged attributable to impact with fan housing. Water and fuel tanks may experience buckled walls, ruptured attached piping, stretched anchor bolts, or collapse. Piping attached to unanchored equipment or subjected to differential movement of anchor points or corrosion may lose its pressure integrity. Coal conveyors can become misaligned, and coal bins without proper seismic design may be severely damaged. Unrestrained batteries may topple from racks, and equipment supported on vibration isolators may fall off supports and rupture attached piping. In the switchyard, improperly anchored transformers may slide and topple, stretching and breaking attached electrical connections and/or ceramics.

Seismically Resistant Design: Seismically resistant design practices include, as a minimum, designing all structures to satisfy the seismic requirements of the applicable local or national building code. In addition, well-designed seismic ties should be provided between the boiler and the generation building to prevent pounding; all equipment should be anchored; sufficient clearance and restraints on piping runs should be provided to prevent interaction with equipment and other piping; and piping should be made flexible to accommodate relative movement of structures and equipment to which it is attached. Generous clearances between adjacent equipment should be provided to prevent interaction. Sufficient joints between the turbine pedestal and the generation building are required to prevent pounding. Maintenance programs for some systems, including wood timber cooling towers, piping transporting corrosive materials, and steel tanks, should be established so that these components are not in a weakened condition when an earthquake strikes. An emergency power source consisting of well-braced batteries and well-anchored emergency generators is necessary to permit restart without power from the outside grid. Heavy equipment and stacks should be anchored with long bolts anchored deep into the foundation to allow for ductile yielding of the full anchor bolt

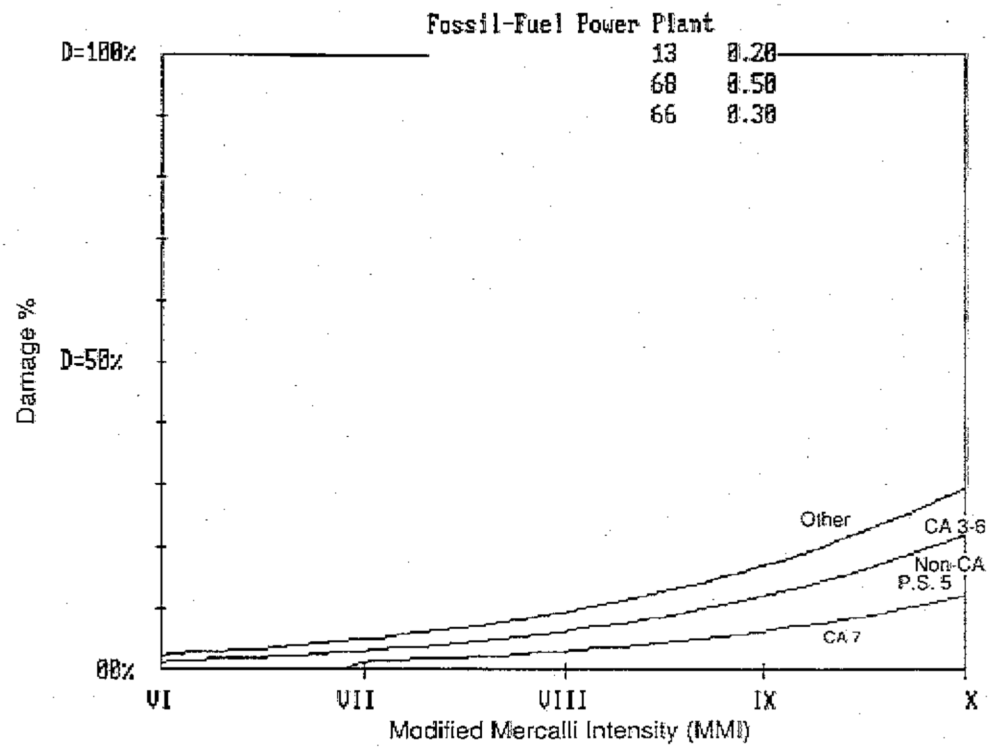

Figure B-43 Damage percent by intensity for fossil-fuel power plants.

length in extreme seismic load conditions. Expansion anchor installation procedures should be subject to strict quality control.

2. Direct Damage

Basis: Damage curves for fossil-fuel power plants in the electrical system are based on ATC-13 data for FC 13, medium-rise steel braced-frame buildings; FC 66, electrical equipment, and FC 68, mechanical equipment (see Figure B-43). Fossil-fuel power plants are assumed to be a combination of 20% mid-rise steel braced-frame structures, 30% electrical equipment, and 50% mechanical equipment. Over the years power plants have been designed using seismic provisions that equal or exceed those used for conventional construction. Consequently, the beneficial intensity shifts indicated below are assumed appropriate.

Standard construction is assumed to represent typical California fossil-fuel plants (and geothermal power plants) under present conditions (i.e., a composite of older and more modern plants). Only minimal regional variation in construction quality of mechanical equipment is assumed, as operational loads frequently govern over seismic requirements.

Present Conditions: In the absence of data on the construction type, age, etc., the following factors were used to modify the mean curves for each of the three facility classes listed above, under present conditions:

	MMI Intensity Shift		
NEHRP Map Area	FC 13	FC 66	FC 68
California 7	-1	-1	-1
California 3-6	0	0	0
Non-California 7	0	0	0
Puget Sound 5	0	0	0
All other areas	1	1	0

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

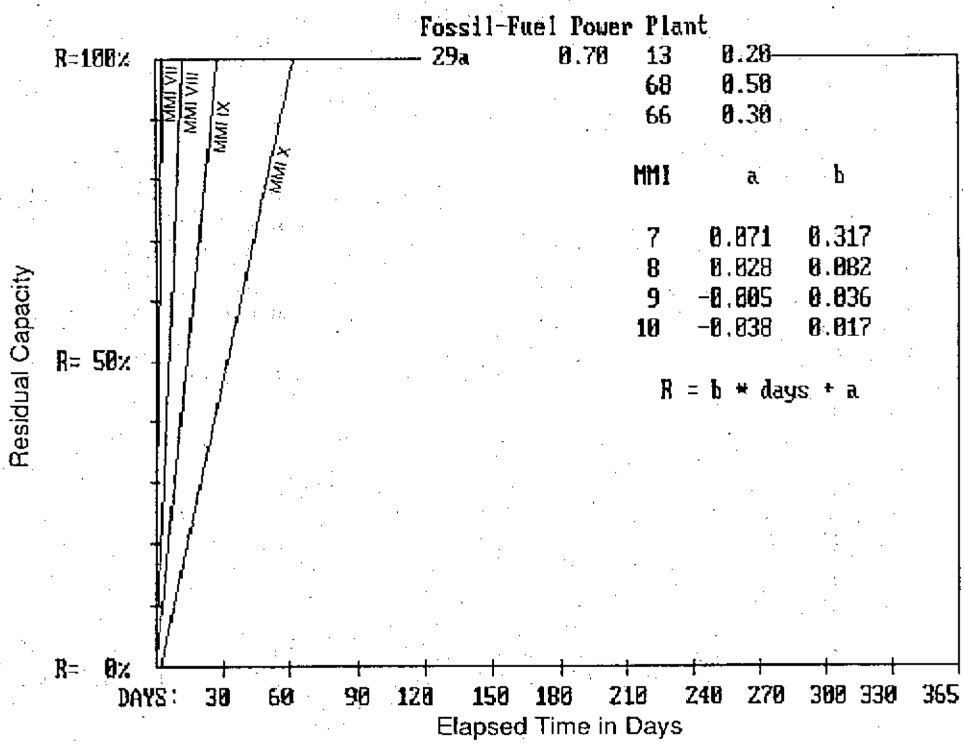

Figure B-44 Residual capacity for fossil-fuel power plants (NEHRP California 7).

Time-to-restoration: The time-to-restoration data assigned to SF 29a, electrical generating facilities, are assumed to apply to all fossil- fuel power plants. By combining these data with the damage curves derived using data for FC 13, 66, and 68, the time-to-restoration curves shown in Figures B-44 through B-46 were derived.

B.5.2 Hydroelectric Power Plants

1. General

Description: In general, hydroelectric power plants consist of a dam and associated equipment including water-driven turbines, a control house and control equipment, and a substation with transformers and other switching equipment. The dam may be earthfill, rockfill, or concrete and may include canals, penstocks, spillways, conduit, tunnels, and intake structures. Gantry cranes are frequently located on top of the concrete dams. Equipment inside the dam typically includes turbines, pumps, piping, switchgear, and emergency diesels.

Typical Seismic Damage: Hydroelectric powerhouses and dams are more likely to be seriously damaged by rock falls and landslides than by ground shaking. When slides do occur, turbines may be damaged if rocks or soils enter the intakes. Penstocks and canals can also be damaged by slides. Intakes have been damaged by the combination of inertial and hydrodynamic forces. Most engineered dams have performed well in past earthquakes, although dams constructed using fills of fine-grain cohesionless material have experienced failures. Equipment in power plants typically performs well in earthquakes unless unanchored. In such cases the equipment may slide or topple and experience substantial damage. Unrestrained batteries have toppled from racks. Piping may impact equipment and structures and damage insulation. Piping attached to unrestrained equipment may rupture due to equipment movement. The control house may experience generic building damage ranging from dropped ceiling tiles and cracks in walls and frames to partial and total collapse. Substation

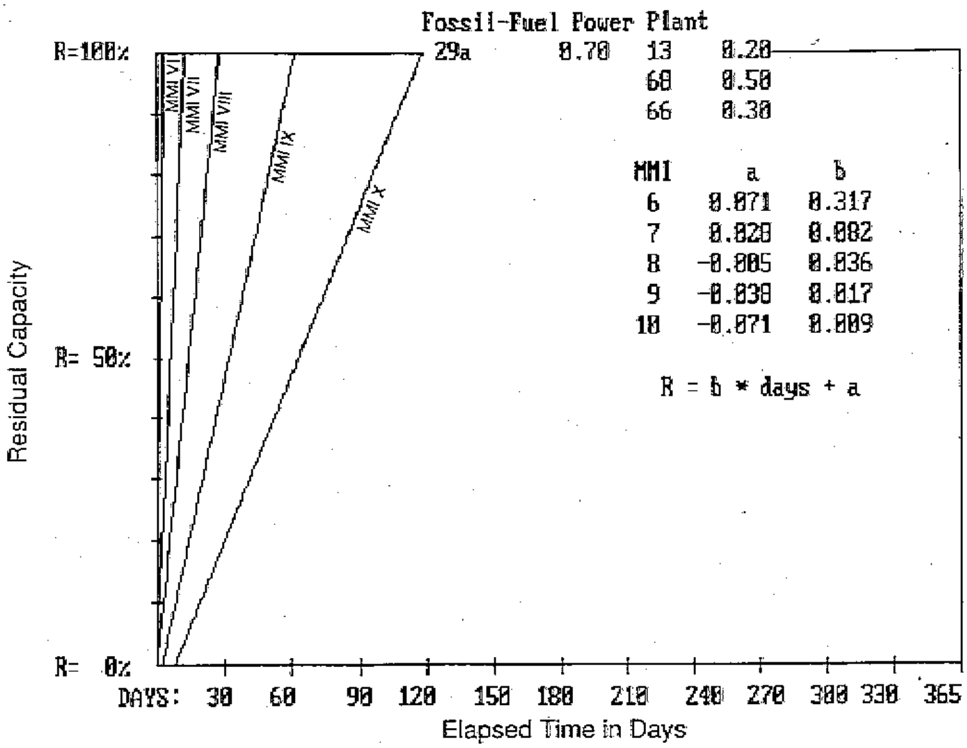

Figure B-45 Residual capacity for fossil-fuel power plants (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

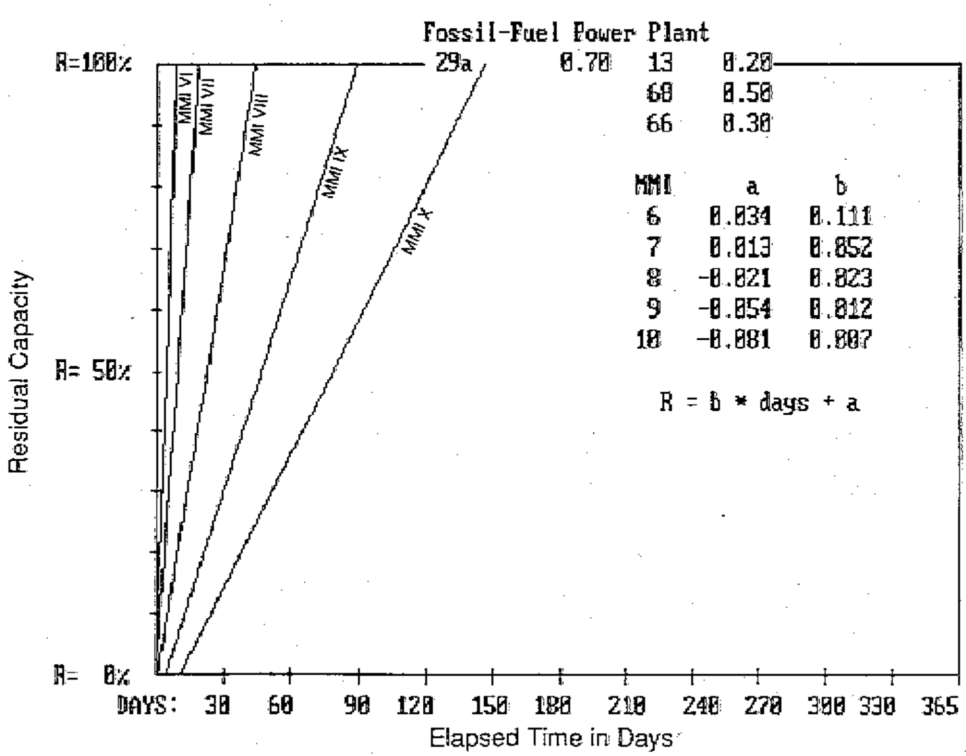

Figure B-46 Residual capacity for fossil-fuel power plants (All other areas).

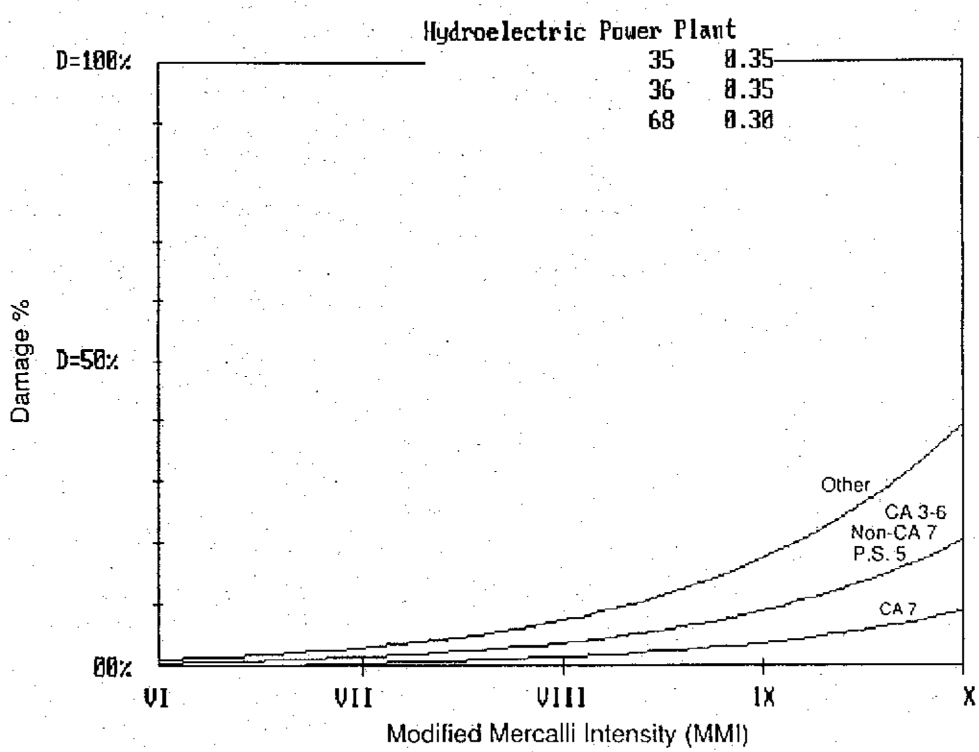

Figure B-47 Damage percent by intensity for hydroelectric power stations.

equipment, and ceramics in particular, are vulnerable to damage. Higher-voltage ceramics tend to experience the most damage.

Seismically Resistant Design: Seismically resistant design practices for earthfill dams include providing ample freeboard, mechanically compacting soils, and using wide cores and transition zones constructed of material resistant to cracking. Generally, reducing slopes of earthfill dams can reduce vulnerability. Thorough foundation exploration and treatment are important. Dynamic analyses can be used to determine the liquefaction or settlement potential of embankments and foundations, and the cracking potential of concrete dams and dam appurtenances. All buildings should be designed, as a minimum, to satisfy the seismic requirements of a national or local building code. All equipment should be anchored and generous clearances between adjacent equipment provided to prevent interaction. An emergency power source consisting of well-braced batteries and well-anchored emergency generators is necessary to ensure that control systems, lighting, and other critical systems function with turbine trip and loss of power from the outside grid.

2. Direct Damage

Basis: Damage curves for hydroelectric power plants in the electrical system are based on ATC-13 data for FC 35, concrete dams; FC 36, earthfill or rockfill dams; and FC 68, mechanical equipment (see Figure B-47). Hydroelectric power plants are assumed to be a combination of 35% concrete dams, 35% earthfill or rockfill dams, and 30% mechanical equipment. Over the years power plants have been designed using seismic provisions that equal or exceed those used for conventional construction. Consequently, the beneficial intensity shifts indicated below for mechanical equipment are assumed appropriate.

Standard construction is assumed to represent typical California hydroelectric power plants under present conditions (i.e., a composite of older and more modern plants). Only minimal regional variation in construction quality is assumed for mechanical equipment, as operational loads

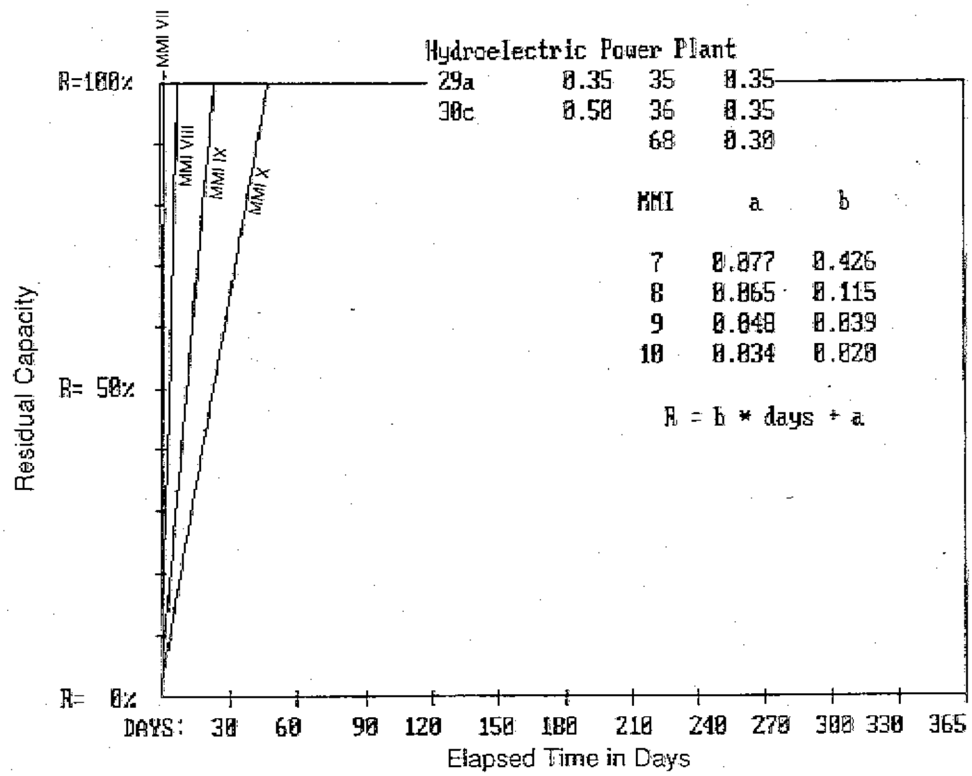

Figure B-48 Residual capacity for fossil-fuel power plants (NEHRP California 7).

frequently govern over seismic requirements.

Present Conditions: In the absence of data on the type of material, age, etc., the following factors were used to modify the mean curves for each of the three facility classes listed above, under present conditions:

	MMI Intensity Shift		
NEHRP Map Area	*FC 35*	*FC 36*	*FC 68*
California 7	0	0	-1
California 3-6	+1	+1	0
Non-California 7	+1	+1	0
Puget Sound 5	+1	+1	0
All other areas	+2	+2	0

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 29a, generating facilities, and SF 30c, storage reservoirs, are assumed to apply to all hydroelectric power plants. By combining these data with the damage curves derived using the data for FC 35, 36, and 68, the time-to-restoration curves shown in Figures B-48 through B-50 were derived.

B.5.3 Transmission Lines

1. General

Description: In general, transmission lines may be underground or above ground (supported by towers). Towers are usually steel and carry several circuits at high voltages (64 kV or higher). Each circuit consists of three conductors, one for each phase. Towers are provided with reinforced concrete footings and may be supported on piles. Most transmission systems are ac, but some long-distance lines are dc. The dc systems require convertor stations at each end of the line.

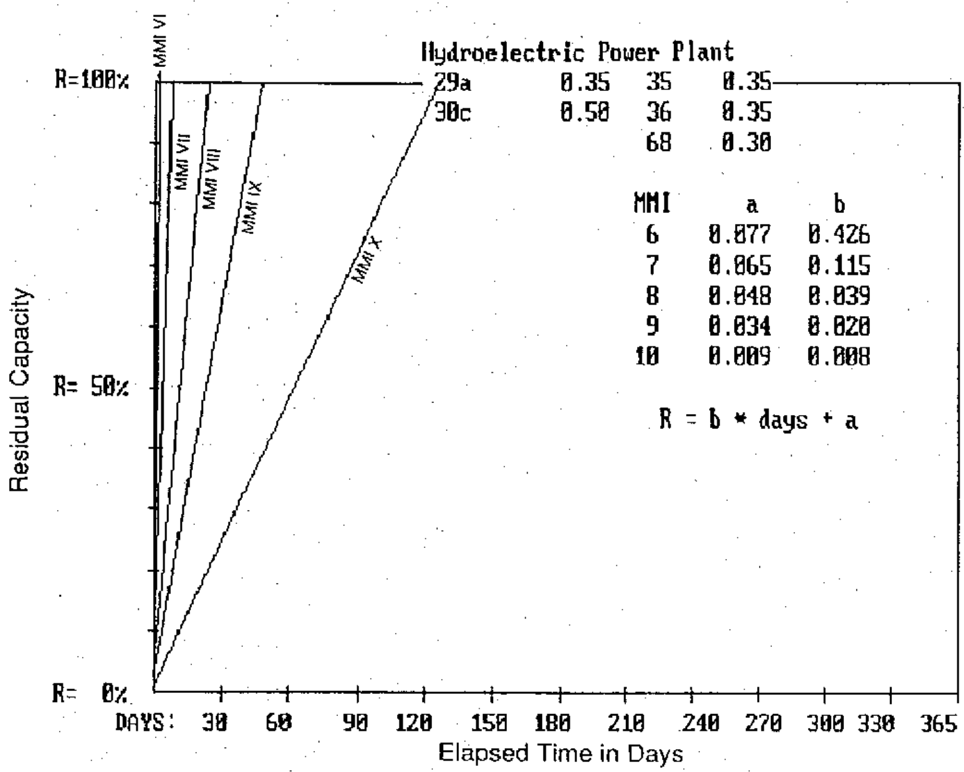

Figure B-49 Residual capacity for hydroelectric power stations (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

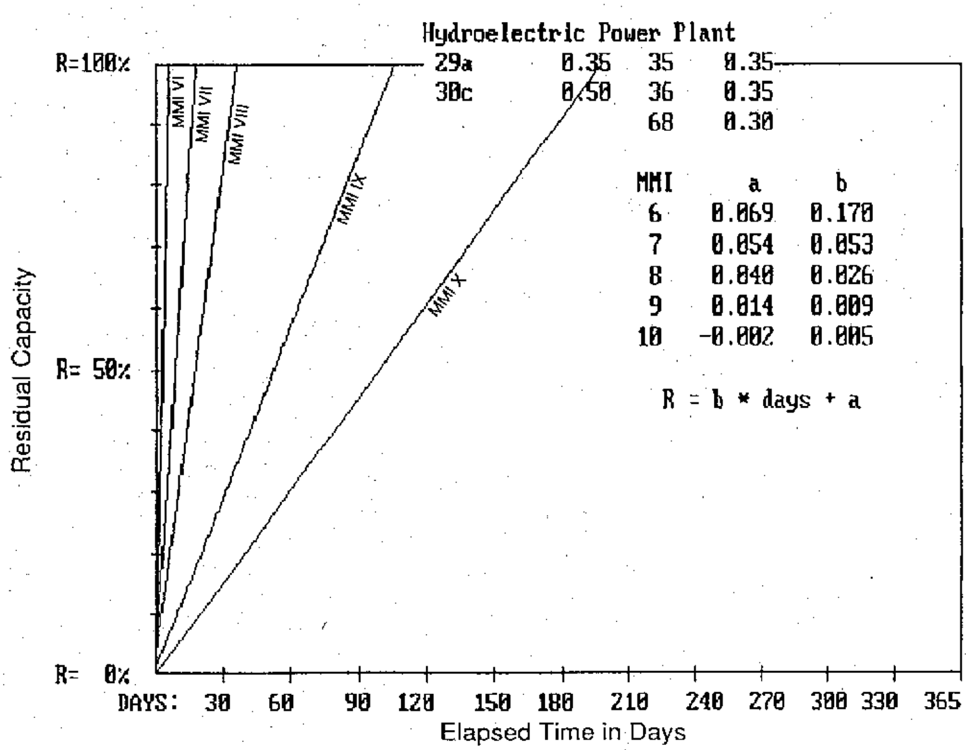

Figure B-50 Residual capacity for hydroelectric power stations (All other areas).

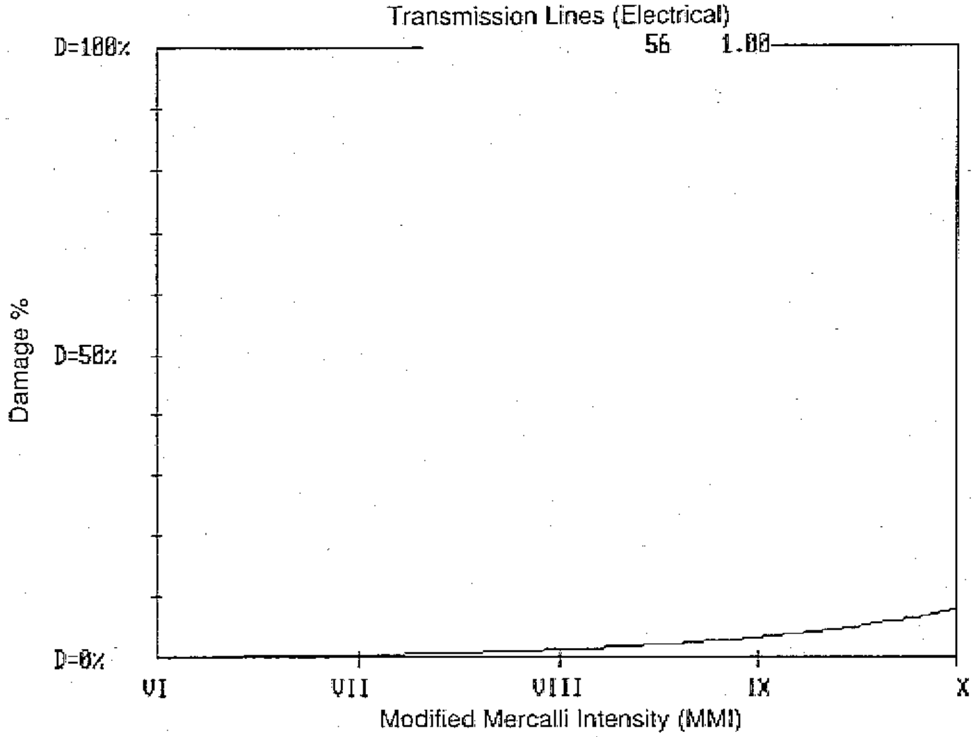

Figure B-51 Damage percent by intensity for electric transmission lines.

Typical Seismic Damage: Transmission towers and the lines they support are principally subject to damage through secondary effects such as landslides, and rock falls, liquefaction, and other ground failures. This is also true for the underground lines. It is possible that the conductors supported by towers can slap against each other and burn down. Ceramics used on transmission towers typically perform well in earthquakes because they are in compression rather than in tension or bending. Fault slippage is unlikely to damage underground lines (unless the line crosses the fault fracture) because transmission lines have a thick-wall, welded-steel pipe jacket.

Seismically Resistant Design: Seismic loads do not generally have much influence on the design of transmission lines and towers. The towers are designed to withstand heavy wind and ice loads, as well as loads due to broken wires. The primary Seismically resistant concern is siting towers and conductors in locations where soils are stable, or providing special foundations designed to survive effects of soil failure.

1. Direct Damage

Basis: Damage curves for transmission lines in the electrical system are based on ATC-13 data for FC 56, major electrical transmission line towers (over 100 feet tall, see Figure B-51). Standard construction is assumed to represent typical California transmission lines and towers under present conditions (i.e., a composite of older and more modern towers). It is assumed that no regional variation in construction quality exists, as seismic loads are relatively unimportant in the design of transmission towers.

Present Conditions: In the absence of data on the type of tower, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	*MMI Intensity Shift*
California 7	0
California 3-6	0
Non-California 7	0
Puget Sound 5	0
All other areas	0

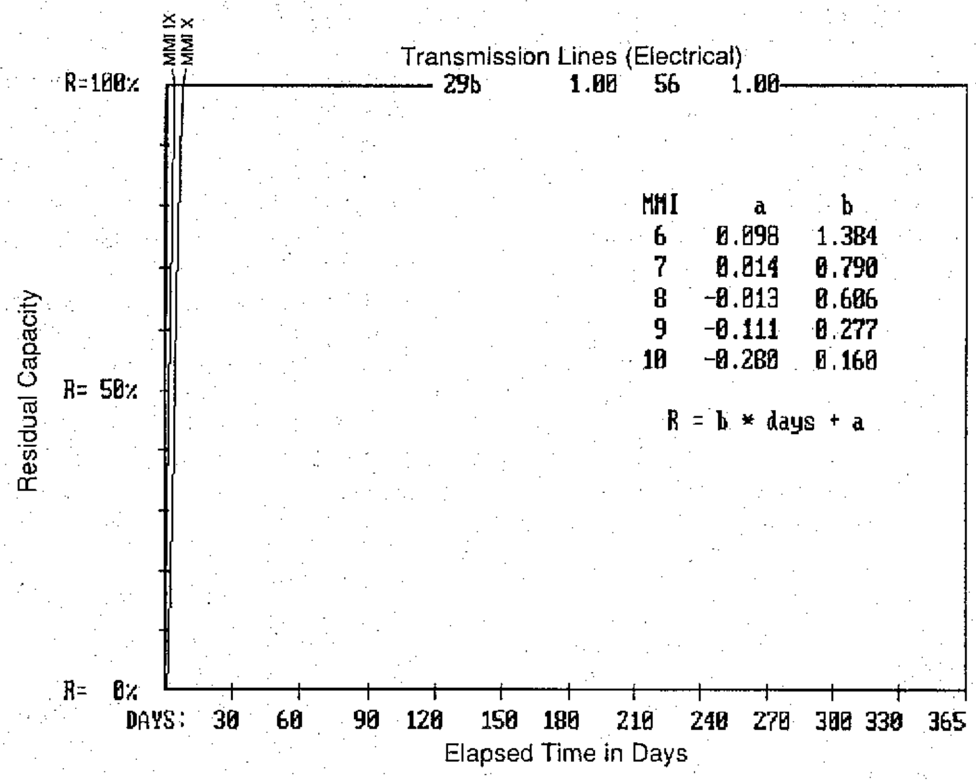

Figure B-52 Residual capacity for electric transmission lines (NEHRP Map Area: California 3-6, California 7, Non-California 7, and Puget Sound 5, and all other areas).

Upgraded Conditions: It is not cost-effective or practical to upgrade existing transmission towers or lines unless supporting or adjacent soils are known to be unstable. Therefore, no intensity shifts for retrofitting are recommended.

Time-to-restoration: The time-to-restoration data assigned to SF 29b, transmission lines for the electrical system, are assumed to apply to all transmission lines and towers. By combining these data with the damage curves for FC 56, the time-to-restoration curves shown in Figure B-52 were derived.

B.5.4 Transmission Substations

1. General

Description: Transmission substations in the electrical system generally receive power at high voltages (220 kV or more) and step it down to lower voltages for distribution. The substations generally consist of one or more control buildings, steel towers, conductors, ground wires, underground cables, and extensive electrical equipment including banks of circuit breakers, switches, wave traps, buses, capacitors, voltage regulators, and massive transformers. Circuit breakers (oil or gas) protect transformers against power surges due to short circuits. Switches prevent long-term interruption of the circuits. Wave traps enable transmission of supervisory signals through power lines. Buses provide transmission linkage of the many and varied components within the substation. Capacitors are used to keep the three phases of a transmission circuit in proper relation to each other. Transformers and voltage regulators serve to maintain the predetermined voltage, or to step down or step up from one voltage to another. Porcelain lightning arresters are used to protect the system from voltage spikes caused by lightning. Long, cantilevered porcelain components (e.g., bushings and lightning arresters) are common on many electrical equipment items.

Typical Seismic Damage: Control buildings are subject to generic building damage ranging from dropped suspended ceilings and cracks in walls and frames to partial and total collapse. Unanchored or improperly anchored control equipment may slide or topple, experiencing damage or causing attached piping and conduit to fail. In the yard, steel towers are typically damaged only by soil failures. Porcelain bushings, insulators, and lightning arresters are brittle and vulnerable to shaking and are frequently damaged. Transformers are large, heavy pieces of equipment that are frequently unanchored or inadequately anchored. Transformers may shift, tear the attached conduit, break bushings, damage radiators, and spill oil. Transformers in older substations that are mounted on rails frequently have fallen off their rails unless strongly anchored. Other top-heavy pieces of electrical equipment can topple or slide when inadequately anchored, damaging connections. Frequently, inadequate slack in conductors or rigid bus bars result in porcelain damage resulting from differential motion.

Seismically Resistant Design: Porcelain is used extensively in ways that make it susceptible to damage (bending and tension). Recent developments including gas-insulated substations and installation details that base isolate, reinforce, or add damping, may reduce the problem in the future. Seismically resistant design practice includes the use of damping devices for porcelain; proper anchorage for equipment (avoid the use of friction clips); provision of conductor slack between equipment in the substation; use of breakaway connectors to reduce loads on porcelain bushings and insulators; and replacement of single cantilever-type insulator supports with those having multiple supports. Transformer radiators that cantilever from the body of transformer can be braced. Adequate spacing between equipment can reduce the likelihood of secondary damage resulting from adjacent equipment falling. Control buildings and enclosed control equipment should be designed to satisfy the seismic requirements of the local or national building code, as a minimum.

2. Direct Damage

Basis: Damage curves for transmission substations for the electrical system are based on ATC-13 data for FC 66, electrical equipment (see Figure B-53). High-voltage porcelain insulators, bushings, and supports are vulnerable to damage, even when the porcelain components have been designed and qualified to enhanced seismic criteria. Consequently, the detrimental intensity shift indicated below is assumed appropriate.

Standard construction is assumed to represent typical California transmission substations under present conditions (i.e., a composite of older non-seismically designed substations as well as more modern substations designed to enhanced seismic requirements).

Present Conditions: In the absence of data on the type of equipment, substation voltage, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	*MMI Intensity Shift*
California 7	+1
California 3-6	+2
Non-California 7	+2
Puget Sound 5	+2
All other areas	+3

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 29c, transmission substations, are assumed to apply to all transmission substations in California. For transmission substations in other areas, response planning is not as complete, and the restoration time is assumed to be 1.5 times longer. By combining these data with the modified damage curves for FC 66, the time-to-restoration curves shown in Figures B-54 through B-56 were derived.

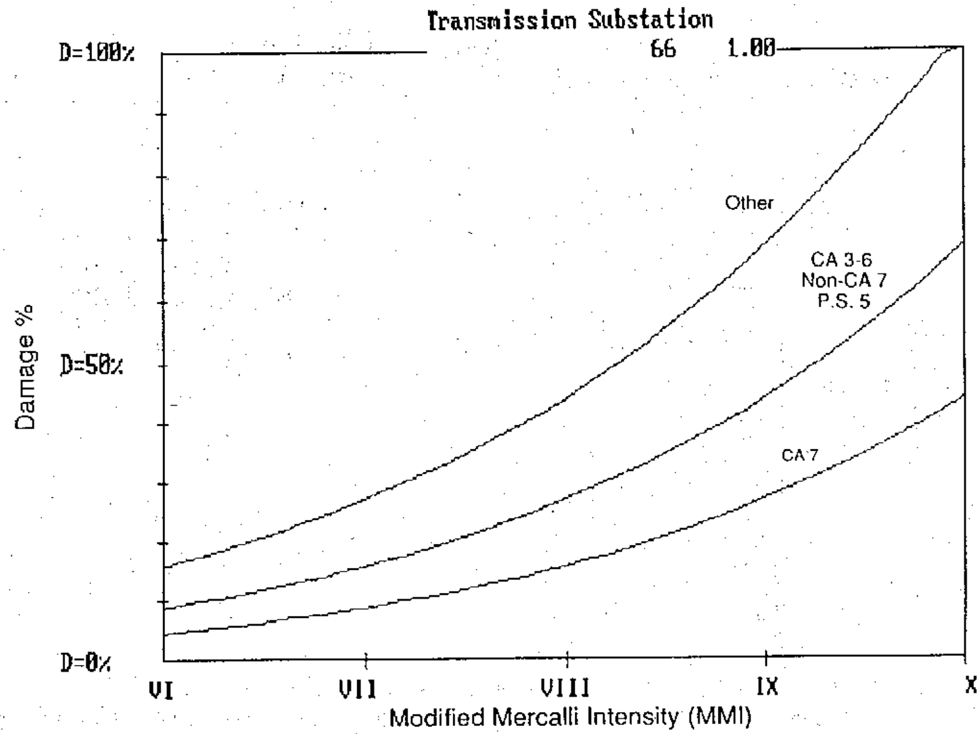

Figure B-53 Damage percent by intensity for electric transmission substations.

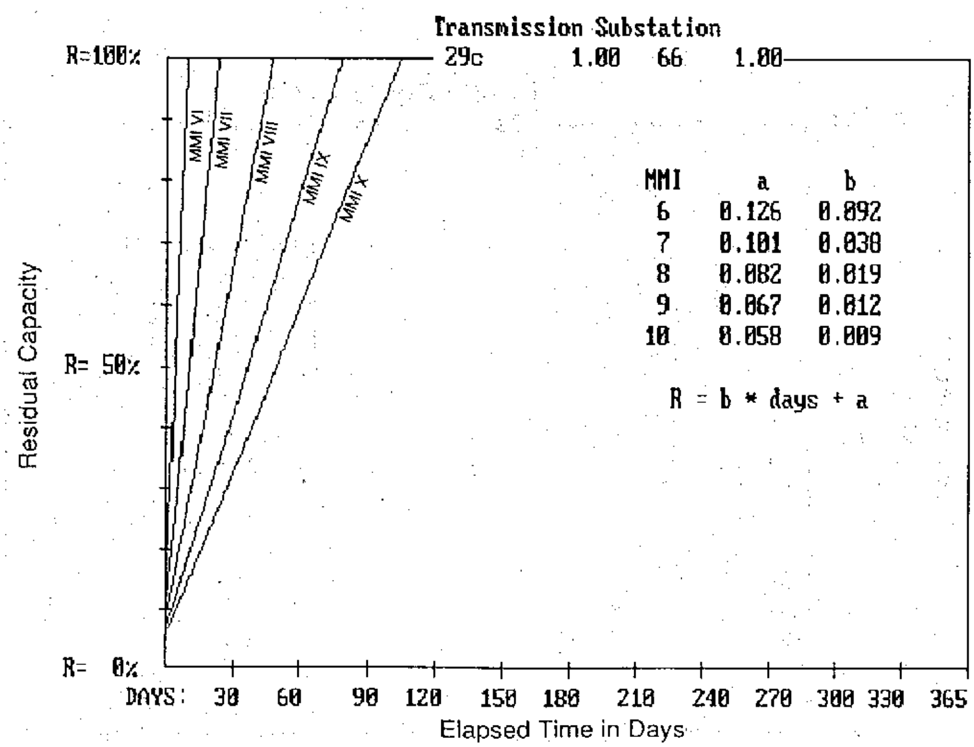

Figure B-54 Residual capacity for electric transmission substations (NEHRP California 7).

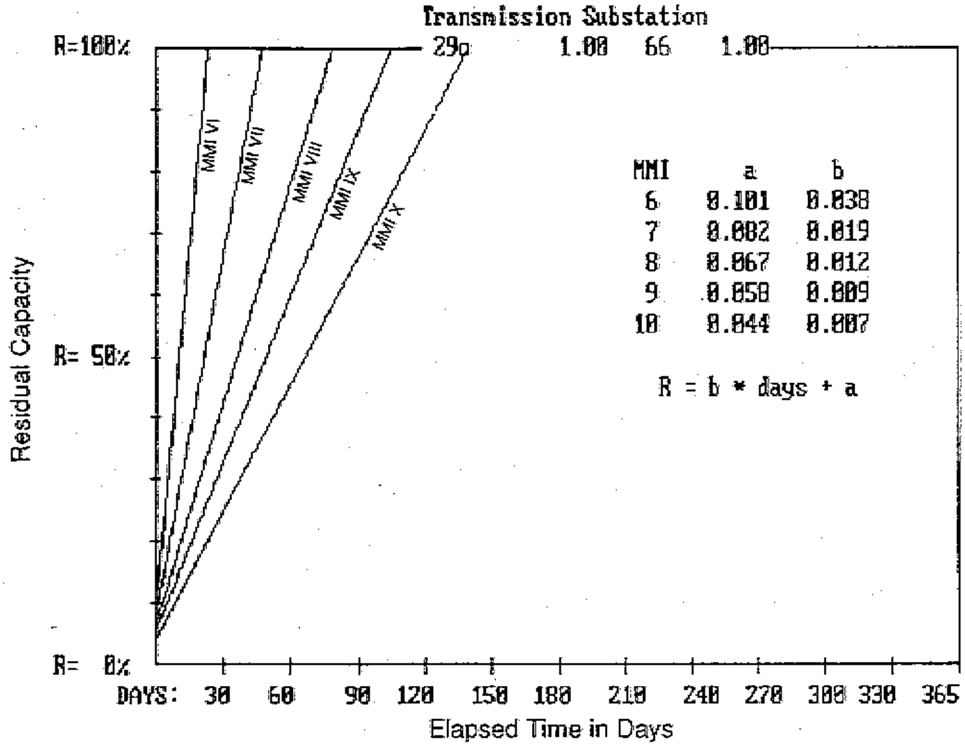

Figure B-55 Residual capacity for electric transmission substations (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

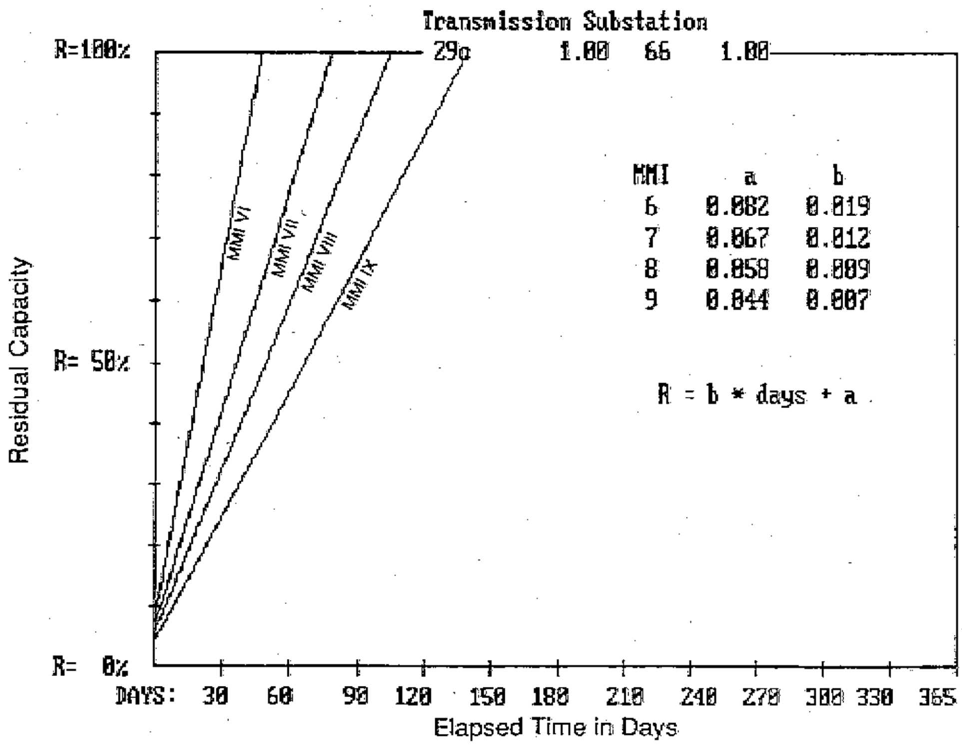

Figure B-56 Residual capacity for electric transmission substations (All other areas).

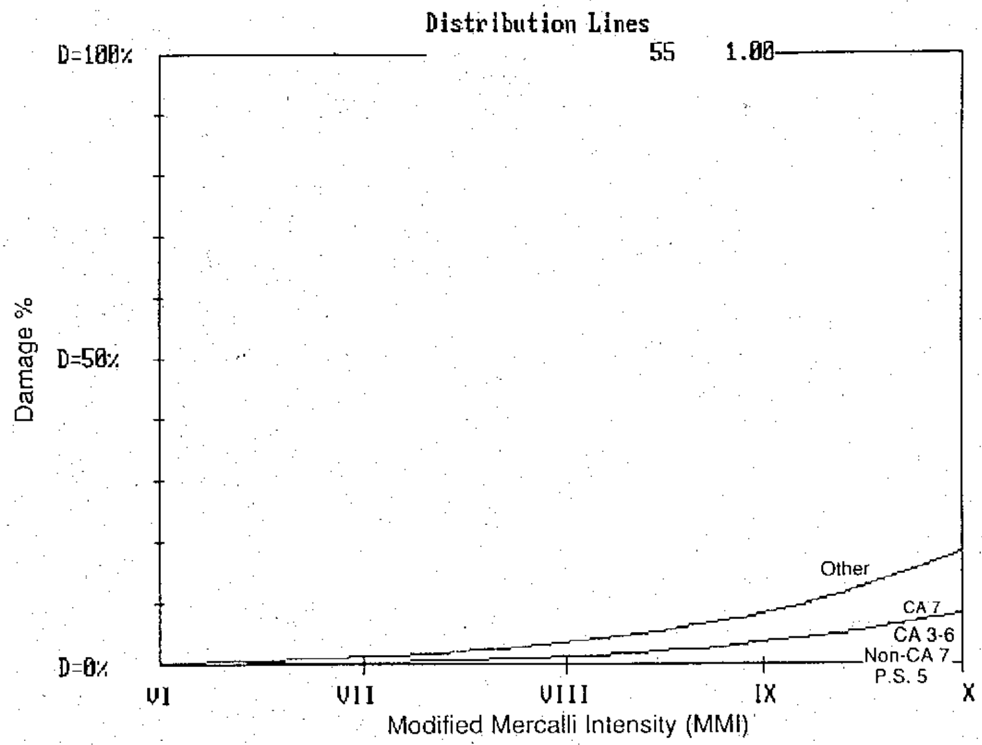

Figure B-57 Damage percent by intensity for electric distribution lines.

B.5.5 Distribution Lines

1. General

Description: In general, distribution lines may be underground or above ground supported by towers or poles. Towers are usually steel, and poles are usually treated wood. Towers are provided with concrete footings, and poles may have footings or may be embedded directly into the ground. Transformers on poles may be supported on platforms or anchored directly to poles. Distribution lines typically operate at lower voltages (64 kV or less).

Typical Seismic Damage: Unanchored pole-mounted transformers may be knocked down and some will burn. Towers and poles are generally undamaged except by secondary effects such as landslides, liquefaction, and other ground failures. Conductor lines swinging together can cause burnouts and/or start fires. Settlement of soils with respect to manholes can sometimes cause underground line routed through the manhole to fail.

Seismically Resistant Design: Seismic loads do not generally have much influence on the design of distribution lines and towers. The towers are typically designed to withstand wind loads. The primary concern is siting towers and poles where soils are stable to prevent foundation failures.

2. Direct Damage

Basis: Damage curves for distribution lines in the electrical system are based on ATC-13 data for FC 55, conventional electrical transmission line towers (less than 100 feet tall, see Figure B-57). In general, less conservative design criteria are used for distribution lines than for lines in the transmission system.

Standard construction is assumed to represent typical California distribution lines, towers, and poles, under present conditions (i.e., a composite of older and more modern lines and towers). Only minimal regional variation in the construction quality is assumed.

Present Conditions: In the absence of data on the type of tower/pole or conductor, age,

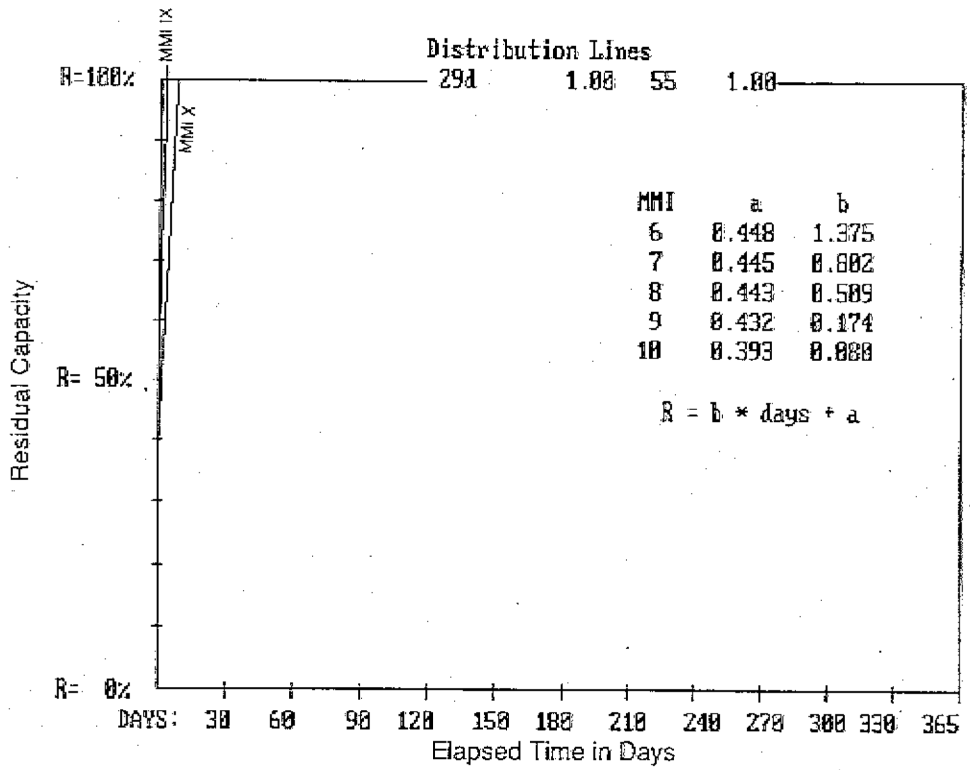

Figure B-58 Residual capacity for electric distribution lines (NEHRP Map Area: California 3-6, California 7, Non-California 7, and Puget Sound 5).

etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	*MMI Intensity Shift*
California 7	0
California 3-6	0
Non-California 7	0
Puget Sound 5	0
All other areas	+1

Upgraded Conditions: It is not cost-effective or practical to upgrade existing transmission towers, unless supporting or adjacent soils are known to be unstable. Therefore, no intensity shifts for upgrading are recommended.

Time-to-restoration: The time-to-restoration data assigned to SF 29d, distribution lines, are assumed to apply to all distribution lines. By combining these data with the damage curves for FC 55, the time-to-restoration curves shown in Fiugres B-58 and B-59 were derived.

B.5.6 Distribution Substations

1. General

Description: Distribution substations in the electrical system generally receive power at low voltages (64 kV or less) and step it down to lower voltages for distribution to users. The substations generally consist of one small control building, steel towers, conductors, ground wires, and electrical equipment including circuit breakers, switches, wave traps, buses, capacitors, voltage regulators, and transformers.

Typical Seismic Damage: Control buildings are subject to generic building damage ranging from cracks in walls and frames to partial and total collapse. Unanchored or improperly anchored control equipment may slide or topple, experiencing damage or causing attached conduit to fail. In the yard, steel towers are typically damaged only by soil failures. Porcelain bushings, insulators, and lightning arresters are brittle and vulnerable to shaking and are frequently

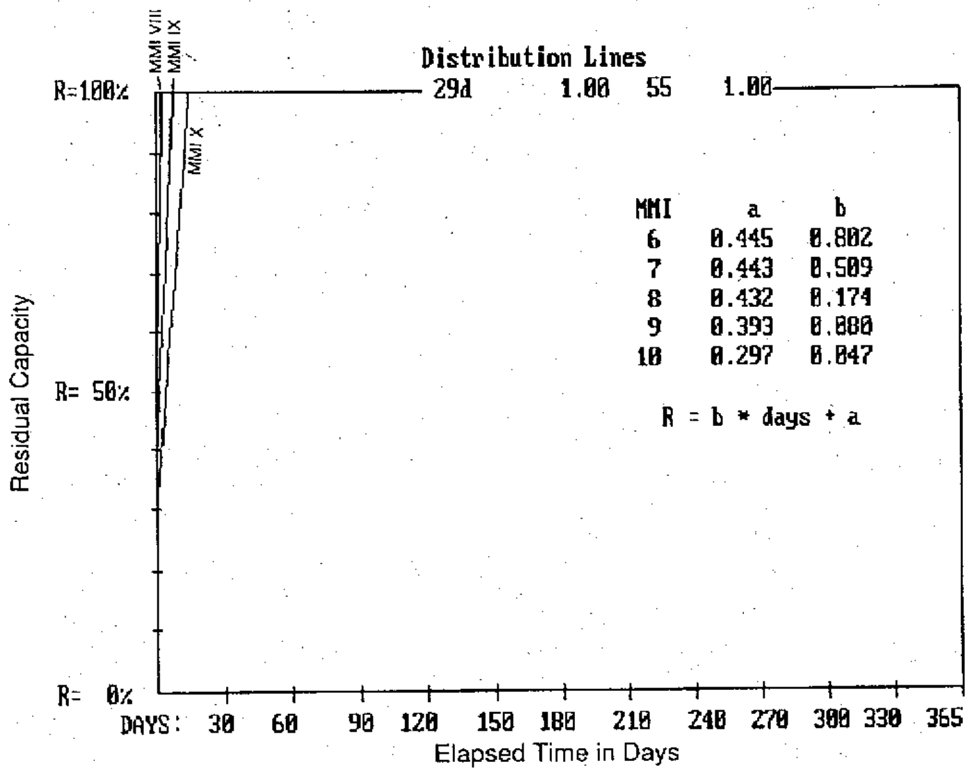

Figure B-59 Residual capacity for electric distribution lines (All other areas).

damaged. Transformers are large, heavy pieces of equipment that are frequently unanchored or inadequately anchored. Transformers may shift, tear the attached conduit, break bushings, damage radiators, and spill oil. Transformers in older substations that are mounted on rails frequently have fallen off their rails unless strongly anchored. Other top-heavy pieces of electrical equipment can topple or slide when inadequately anchored, damaging connections. Frequently, inadequate slack in conductors or rigid bus bars result in porcelain damage resulting from differential motion.

Seismically Resistant Design: Porcelain in distribution substation is susceptible to damage but is less vulnerable than porcelain in transmission substations by virtue of its shorter cantilever lengths. Seismically resistant design practices include the use of installation details that base isolate, reinforce, or add damping devices to the porcelain. Proper anchorage details should be used for all yard equipment. Breakaway connectors for porcelain; replacement of single cantilever-type insulator supports with those having multiple supports; and provision of adequate slack in conductors and bus bars connecting components that may experience differential movement will significantly reduce seismic vulnerability.

2. Direct Damage

Basis: Damage curves for distribution substations for the electrical system are based on ATC-13 data for FC 66, electrical equipment (see Figure B-60). It is believed that this facility class best approximates the expected performance of distribution substations.

Standard construction is assumed to represent typical California distribution substations under present conditions (i.e., a composite of older non-seismically designed substations as well as more modern substations designed to enhanced seismic requirements).

Present Conditions: In the absence of data on the type of equipment, substation

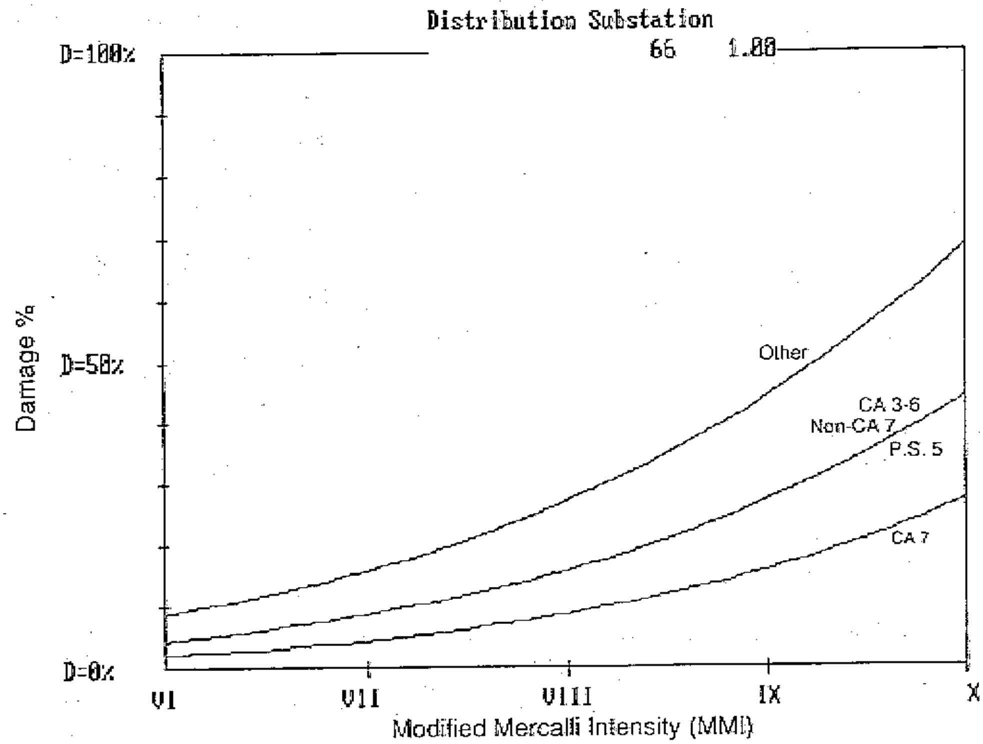

Figure B-60 Damage percent by intensity for electric distribution substations.

voltage, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	MMI Intensity Shift
California 7	0
California 3-6	+1
Non-California 7	+1
Puget Sound 5	+1
All other areas	+2

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 29e, distribution substations, are assumed to apply to all distribution substations in California. For distribution substations in other areas, response planning is not as complete and restoration time is assumed be 1.5 times longer. By combining these data with the damage curves for FC 66, the time-to-restoration curves shown in Figures B-61 through B-63 were derived.

B.6 Water Supply

B.6.1 Transmission Aqueducts

1. General

Description: In general, various types of transmission aqueducts can be used for transporting water, depending on topography, head availability, construction practices, and environmental and economic considerations. Open channels are used to convey water under conditions of atmospheric pressure. Flumes are open channels supported above ground. Channels may be lined or unlined. Lining materials include concrete, bituminous materials, butyl rubber, vinyl, synthetic fabrics, or other products to reduce the resistance to flow, minimize seepage, and lower maintenance costs. Flumes are usually constructed of concrete, steel, or timber. Pipelines are built where topographic conditions preclude the

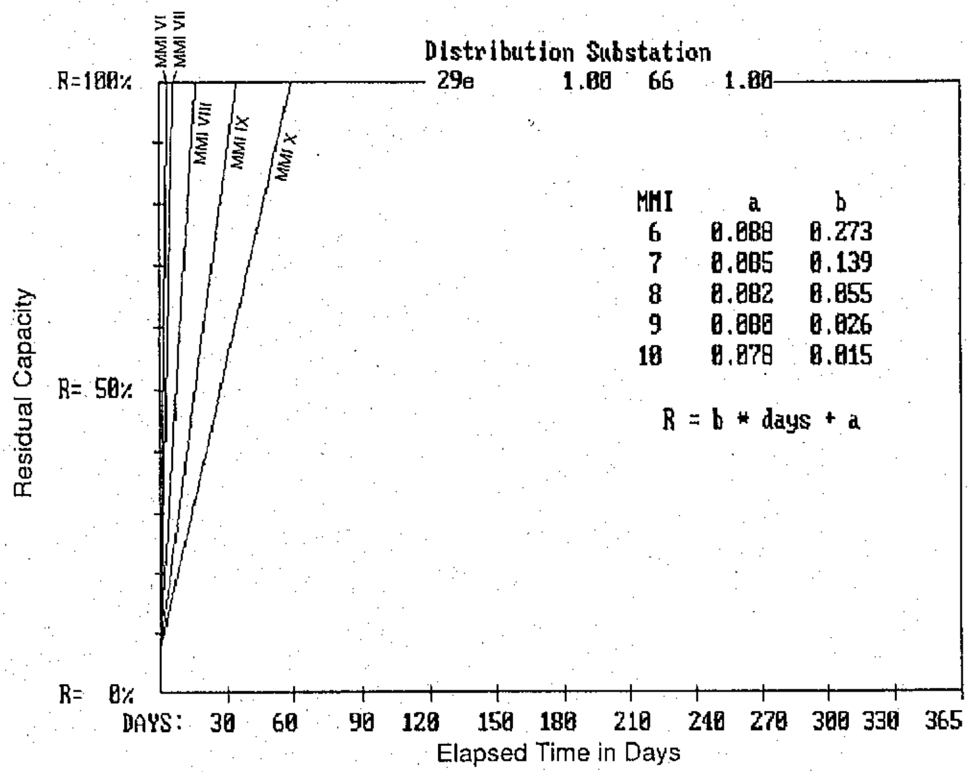

Figure B-61 Residual capacity for electric distribution substations (NEHRP California 7).

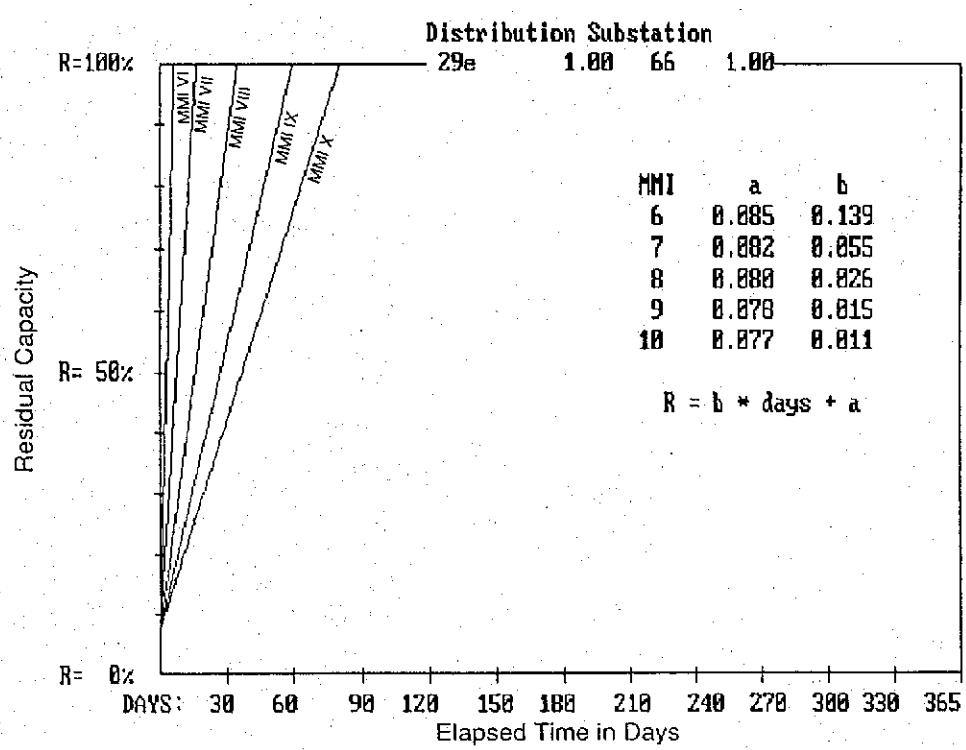

Figure B-62 Residual capacity for electric distribution substations (NEHRP Map Area 3-6, Non-California 7, and Puget Sound 5).

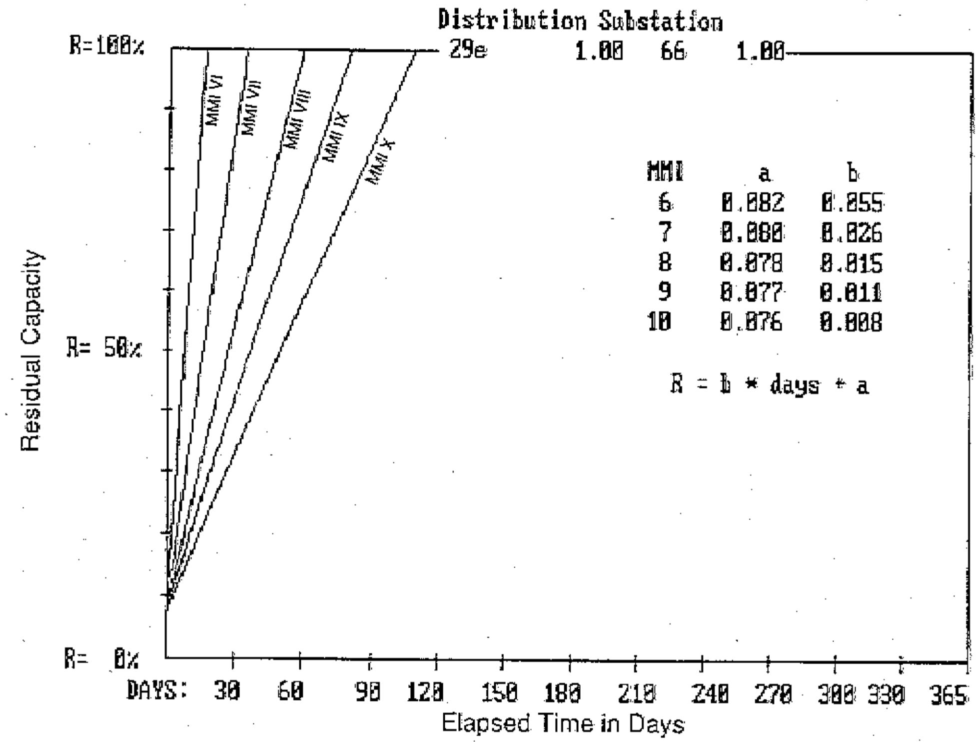

Figure B-63 Residual capacity for electric distribution substations (All other areas).

use of canals. Pipelines may be laid above- or below ground, or may be partly buried. Most modern pressure conduit are built of concrete, steel, ductile iron, or asbestos cement. Tunnels are used where it is not practical to lay a pipeline, such as mountain or river crossings. They may be operated under pressure or act as open channels. Linings may be unreinforced concrete, reinforced concrete, steel, or brick.

Typical Seismic Damage: Channels are most susceptible to damage from surface faulting and soil failures such as differential settlement, liquefaction, or landsliding. Unreinforced linings are more susceptible to damage than are reinforced linings. Small fractures in the lining can result in a transmission aqueduct being taken out of service, as water leaking through the lining could erode supporting embankments or surrounding soils and cause significant damage. Regional uplift could result in long-term loss of function by changing the hydraulic flow characteristics of the aqueduct.

Seismically Resistant Design: Seismically resistant design practices include providing reinforced concrete linings for channels and tunnels. Channels should have slopes appropriate for embankment materials to prevent slumping. Tunnels should be strengthened at intersections, bends, and changes in shape and construction materials. Aqueducts should be sited to eliminate or minimize fault crossings. Aqueducts that cross faults can be routed through pipe buried in shallow loose fill or installed above ground near the fault, to allow lateral and longitudinal slippage.

1. Direct Damage

Basis: Damage curves for transmission aqueducts of the water supply system are based on ATC-13 data for FC 38, tunnels passing through alluvium, and FC 61, canals (see Figure B-64). Aqueducts are assumed to be a combination of 50% tunnels and 50% canals. Tunnels passing through alluvium are less vulnerable than cut-and-cover tunnels and more vulnerable than

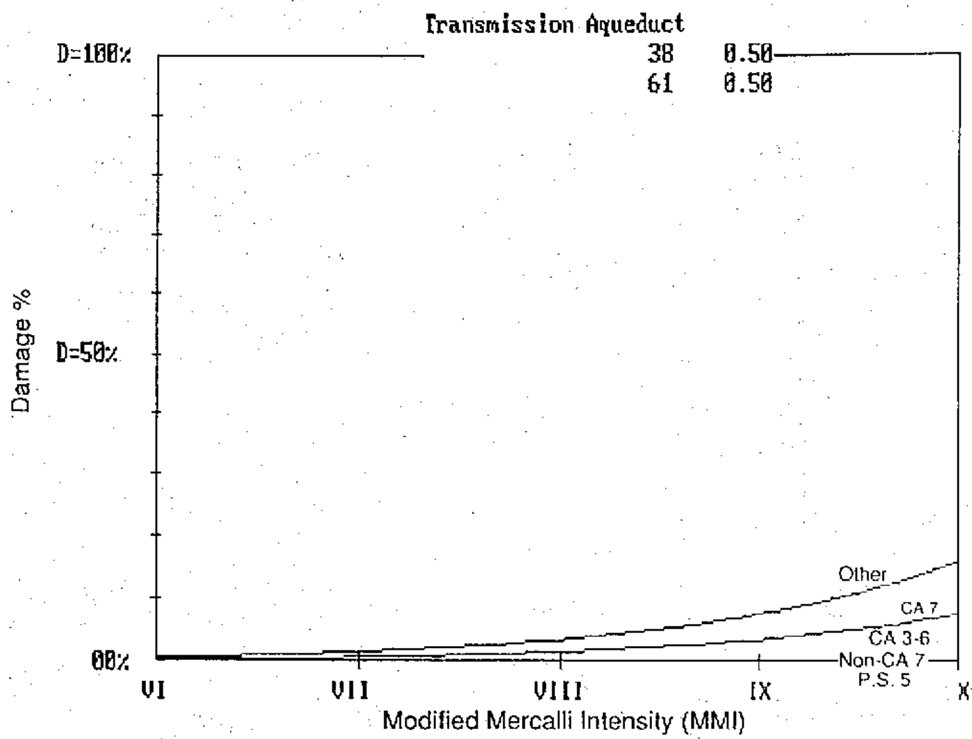

Figure B-64 Damage percent by intensity for transmission aqueducts.

tunnels passing through rock; they were chosen as representative of all tunnels.

Standard construction is assumed to represent typical California aqueducts under present conditions (i.e., a composite of older and more modern aqueducts). Only minimal regional variation in construction quality of aqueducts is assumed.

Present Conditions: In the absence of data on the type of construction, age, etc., the following factors were used to modify the mean curves for the two facility classes listed above, under present conditions:

NEHRP Map Area	*MMI Intensity Shift* *FC 38*	*FC 61*
California 7	0	0
California 3-6	0	0
Non-California 7	0	0
Puget Sound 5	0	0
All other areas	+1	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 30a, transmission aqueducts, are assumed to apply to all transmission aqueducts. By combining these data with the damage curves derived using the data from FC 38 and 61, the time-to-restoration curves shown in Figures B-65 and B-66 were derived.

B.6.2 Pumping Stations

1. General

Description: Pumping equipment forms an important part of the water supply system transportation and distribution facilities. In general, pumping stations include larger stations adjacent to reservoirs and rivers, and smaller stations distributed throughout the water system intended to raise head. Large pumping stations typically include intake structures. Pumping stations typically

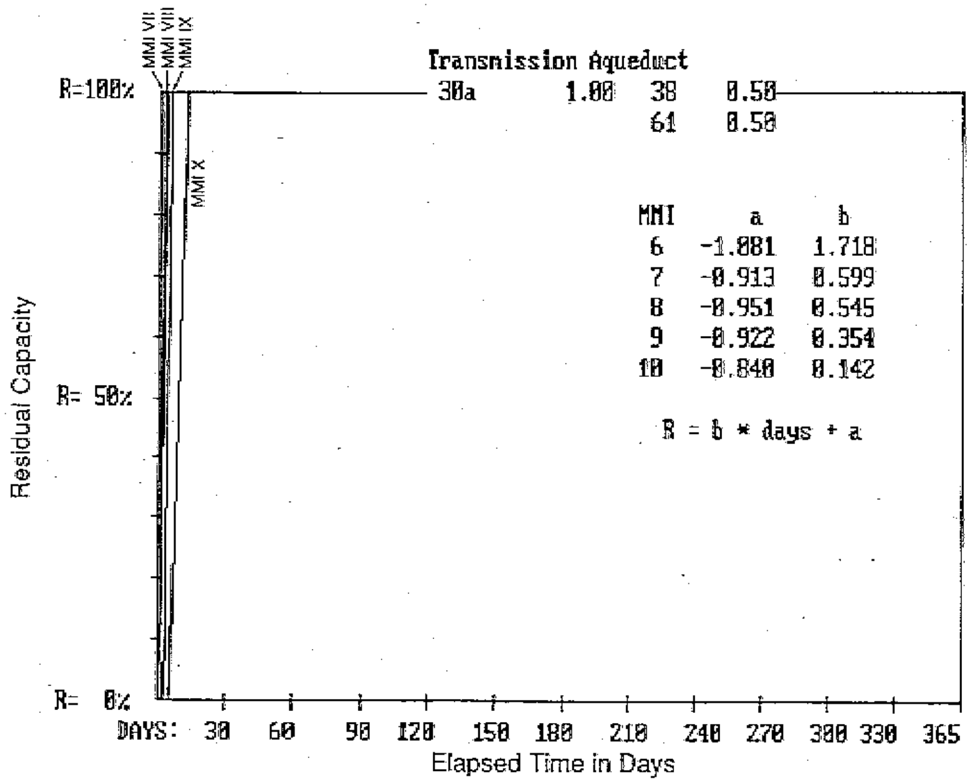

Figure B-65 Residual capacity for transmission aqueducts (NEHRP Map Area: California 3-6, Californa 7, Non-California 7, and Puget Sound 5).

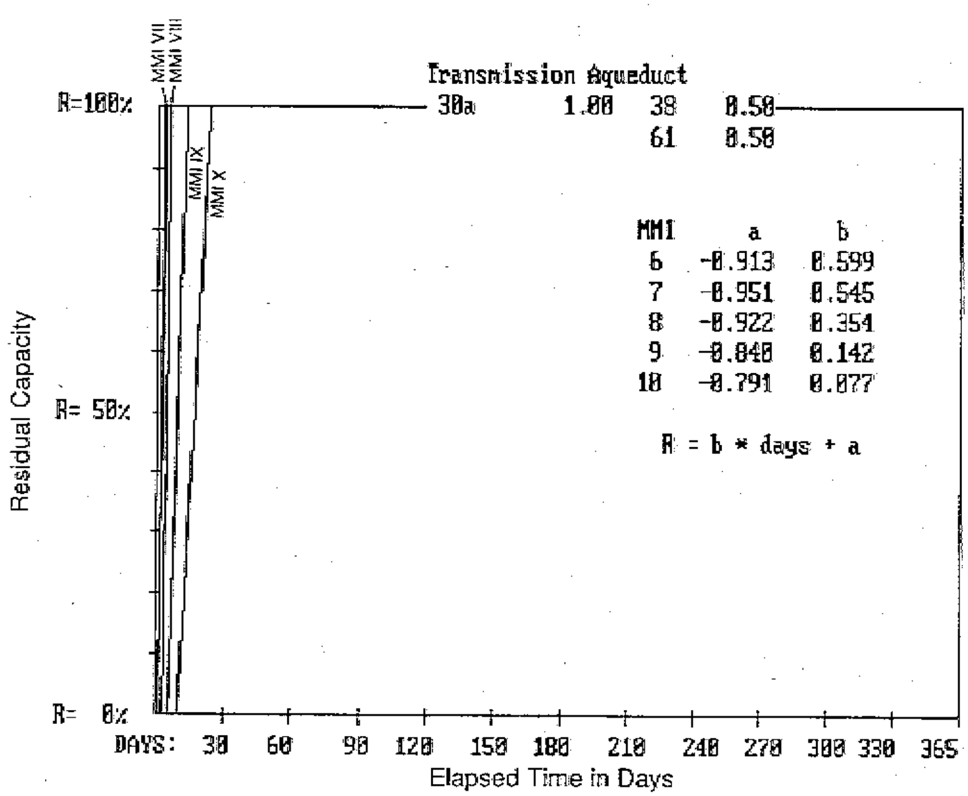

Figure B-66 Residual capacity for transmission aqueducts (All other areas).

comprise shear-wall-type buildings, intake structures, pump and motor units, pipes, valves, and associated electrical and control equipment. Requirements vary from small units used to pump only a few gallons per minute to large units capable of handling several hundred cubic feet per second. Vertical turbine (most common) and displacement pumps are the two primary types used. Horizontal centrifugal pumps, air-lift and jet pumps, and hydraulic rams are also used in special applications. Centrifugal pumps have impellers, which impart energy to the water. Displacement pumps are commonly the reciprocating-type where a piston draws water into a closed chamber and then expels it under pressure. Pumps may be in series or in parallel. Often an emergency power supply comprising a standby diesel generator, battery rack, and diesel fuel tank is included in primary pumping stations to operate in emergency situations when electric power fails.

Typical Seismic Damage: Pumping stations will suffer damage closely related to the performance of the soils on which they are constructed. Intake structures are typically tower-type structures that are vulnerable to inertial effects, and settlement and landslides at bottoms of reservoirs and rivers. Toppling of these towers allows coarse sediment to enter the distribution system, plugging pipelines and causing extensive damage to pump bearings and seals. Piping attached to heavy pump structures is susceptible to damage caused by differential settlement. Unanchored electrical and control equipment may be severely damaged. Pumps with long shafts may suffer misalignment, and shafts may be cracked or sheared by ground movement. Pipe hangers may be damaged by relative settlement of building and associated equipment. Damage to substation transformers can result in the loss of power.

Seismically Resistant Design: Seismically resistant design practice includes avoiding unstable soils in siting the pumping stations, or providing foundations for structures and equipment capable of resisting expected soil failures without damage. Design of intake structures should consider inertial forces developed from self-mass and surrounding water, and these structures should be built on stable soil. Also, pumps and heavy equipment should be provided with positive means (anchorage) of resisting lateral forces; base isolators should be used only when adequate snubbers are provided. Buildings enclosing plant equipment should be designed with seismic provisions of local or national building codes. The casings of wells should be separated from the pump house by at least 1 inch to allow for relative movement and settlement. Pumps that are hung from the motor at the top of the well by a non-flexible drive shaft inside the pump column are not recommended. Submersible motor-driven, vertical turbine pumps do not require the long drive shaft, and the need for a perfectly straight well casing is therefore eliminated. Horizontal pumps and their motors should be mounted on a single foundation to prevent differential movement. Provisions for emergency power should be made for pump stations critical to systems operation.

1. Direct Damage

Basis: Damage curves for pumping stations for the water system are based on ATC-13 data for FC 10, medium-rise reinforced masonry shear wall buildings; FC 66, electrical equipment, and FC 68, mechanical equipment (see Figure B-67). FC 10 was chosen to represent a generic building, based on review of damage curves for all buildings. Pumping stations are assumed to be a combination of 30% generic buildings, 20% electrical equipment, and 50% mechanical equipment.

Standard construction is assumed to represent typical California pumping stations for water systems under present conditions (i.e., a composite of older and more modern stations). Only minimal regional variation in construction quality of mechanical equipment is assumed, as operational loads frequently govern over seismic requirements.

Present Conditions: In the absence of data on the type of pumps, age, etc., the following factors were used to modify the mean curves for each of the three facility

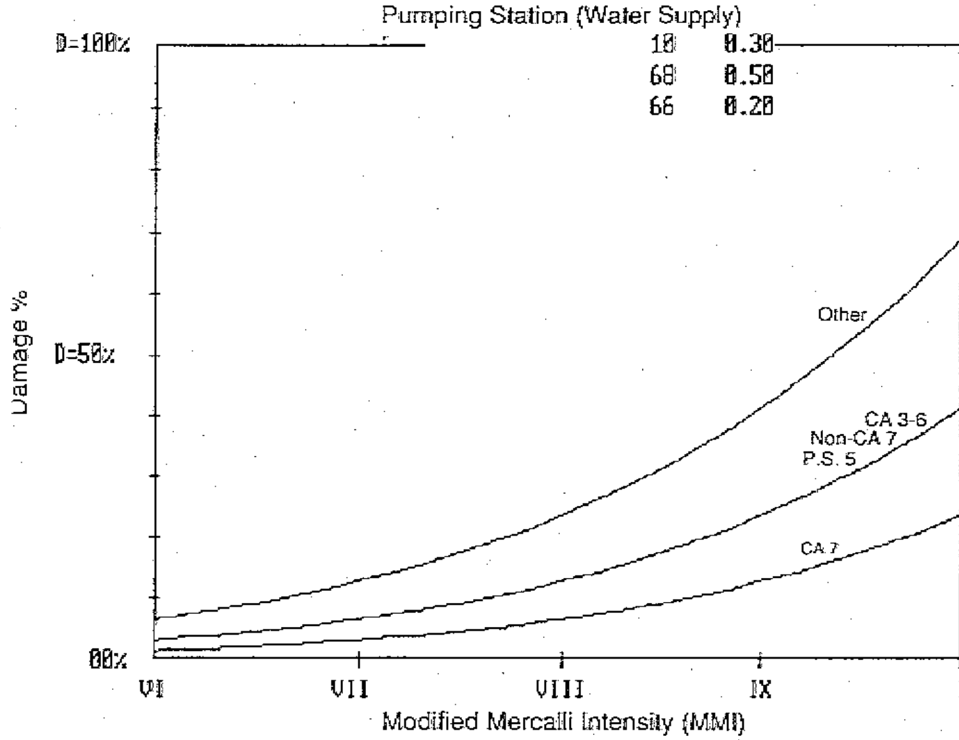

Figure B-67 Damage percent by intensity for water supply pumping stations.

classes listed above, under present conditions:

NEHRP Map Area	MMI Intensity Shift FC 10	FC 66	FC 68
California 7	0	0	0
California 3-6	+1	+1	0
Non-California 7	+1	+1	0
Puget Sound 5	+1	+1	0
All other areas	+2	+2	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in one or two beneficial intensity shifts (i.e., -1 or -2), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 30b, pumping stations for water systems, are assumed to apply to all pumping stations. By combining these data with the damage curves derived using the data for FC 10, 66, and 68, the time-to-restoration curves shown in Figures B-68 through B-70 were derived.

B.6.3 Storage Reservoirs

1. General

Description: In general, storage reservoirs for the water system comprise earthfill, rockfill, or concrete dams with gates, spillways, conduit, tunnels, and intake structures. Earthfill dams include an impervious core, typically a clay material, transition zones, drains, and sand filters adjacent to the core. Grout is frequently provided under the impervious core in the foundation material, and in the abutments to prevent water penetration through cracks and fissures in bedrock or flow through permeable native soils. Rockfill dams typically have concrete linings to prevent water penetration. Concrete dam types include gravity and arch. Roadways and/or gantry cranes are commonly located at the crest of the dam.

Typical Seismic Damage: Most engineered, mechanically compacted earthfill dams have performed well in earthquakes. Additionally, earthfill dams constructed predominantly

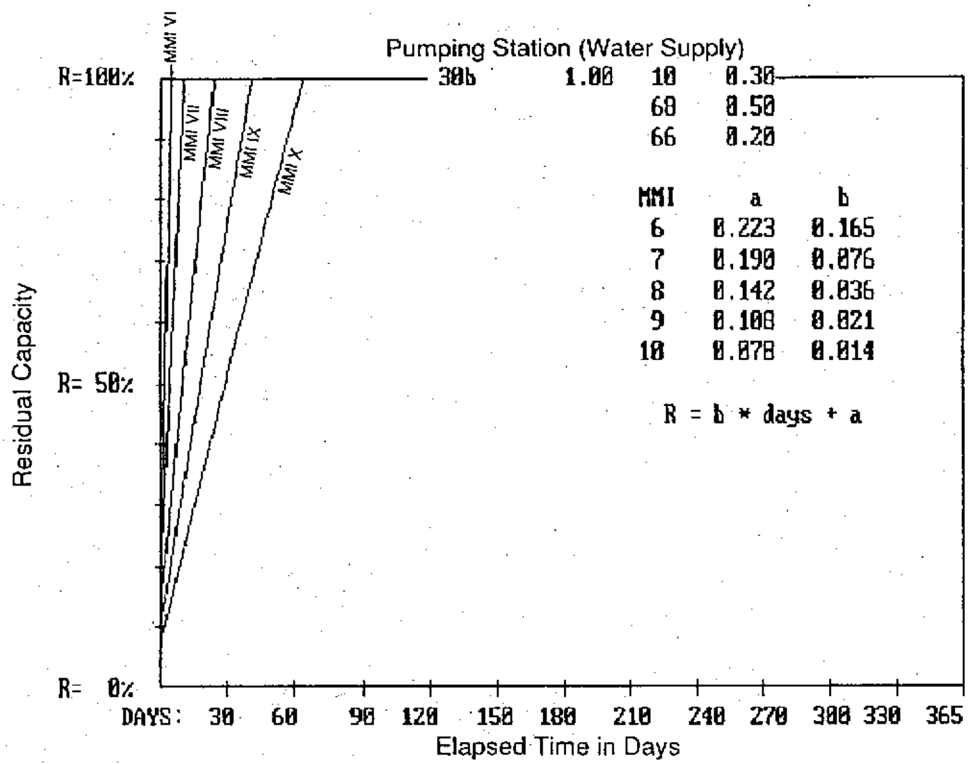

Figure B-68 Residual capacity for water supply pumping stations (NEHRP California 7).

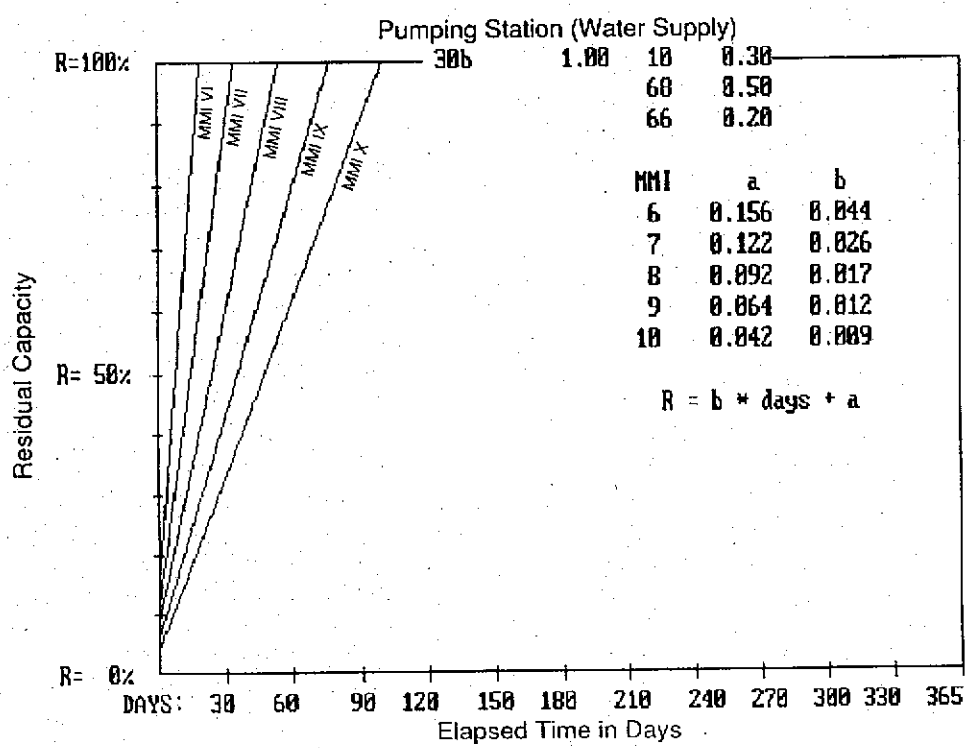

Figure B-69 Residual capacity for water supply pumping stations (NEHRP Map Area 3-6, Non-California 7, and Puget Sound 5).

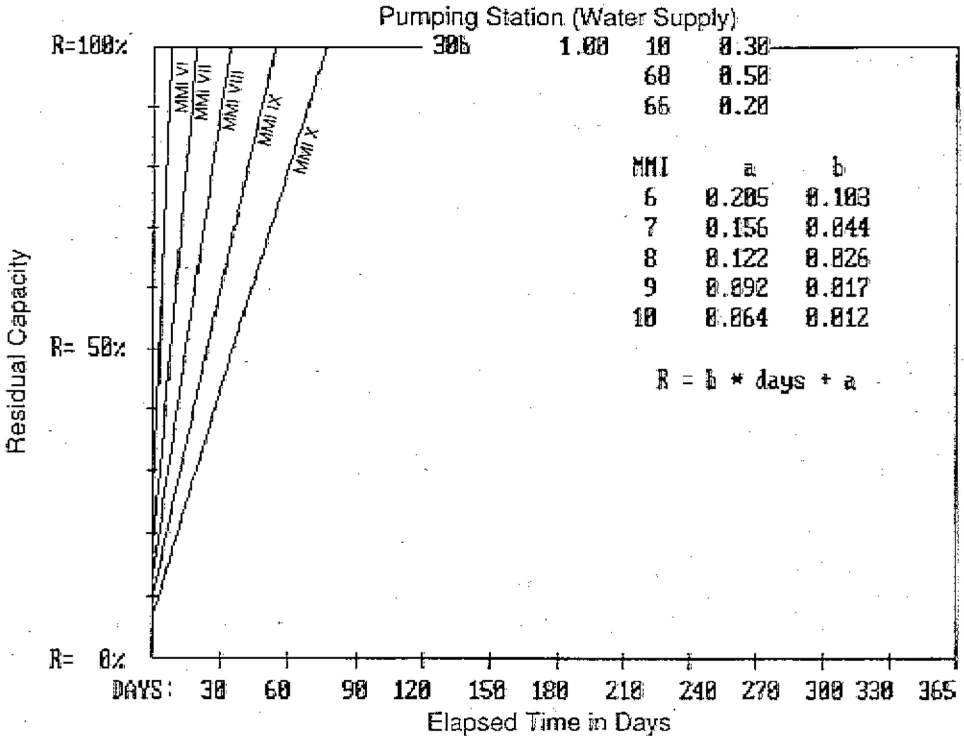

Figure B-70 Residual capacity for water supply pumping stations (All other areas).

with clayey soils have performed well. Dams constructed of hydraulic fill using saturated, poorly compacted, fine-grain cohesionless material; dams constructed on natural cohesionless deposits that are not as dense as the embankments; and dams with unusually steep embankments have experienced failures in past earthquakes. Dam embankments may respond to soil failures by cracking (usually at the crest or near the crest and abutments), spreading or settling, or by slope stability failures or zonal separations. Liquefaction may occur in saturated zones of cohesionless materials that are loose or marginally compacted, such as hydraulic fills. Both soil and rock foundations may be damaged by fault rupture, resulting in loss of continuity or integrity of internal design features, (drains, imperious zones, etc.) and water-release features (conduit and tunnels). Earthquake-induced landslides may block water outlet features or spillways, or cause waves that overtop the dam and cause erosion. Where cracks are opened in the embankment or foundation, the danger of piping exists if cracks remain open. Rockfill dams have performed well, with some damage to material near the crest of the dam.

Settlement of rockfill dams is also a possibility. Concrete dams have also performed well with little damage known. Cracking of dams and foundation failures are possible.

Seismically Resistant Design: Seismically resistant design practices for earthfill dams include providing ample freeboard to allow for settlement and other movements, and using wide cores and transition zones constructed of material resistant to cracking. Current design typically used dynamic analyses for all but small dams on stable foundations. These analyses are used to determine the liquefaction or strain potential of embankments and foundations, and to estimate the settlement of embankments. Conservative crest details include providing transition and shell zones that extend to the crest to control any seepage that develops through cracks, and providing camber for static and dynamic settlement. Conservative zoning consists of providing confined clay cores, wide cohesionless transitions, and free draining shells. Reduction of embankment slopes and elimination of embankment saturation through linings can reduce susceptibility to

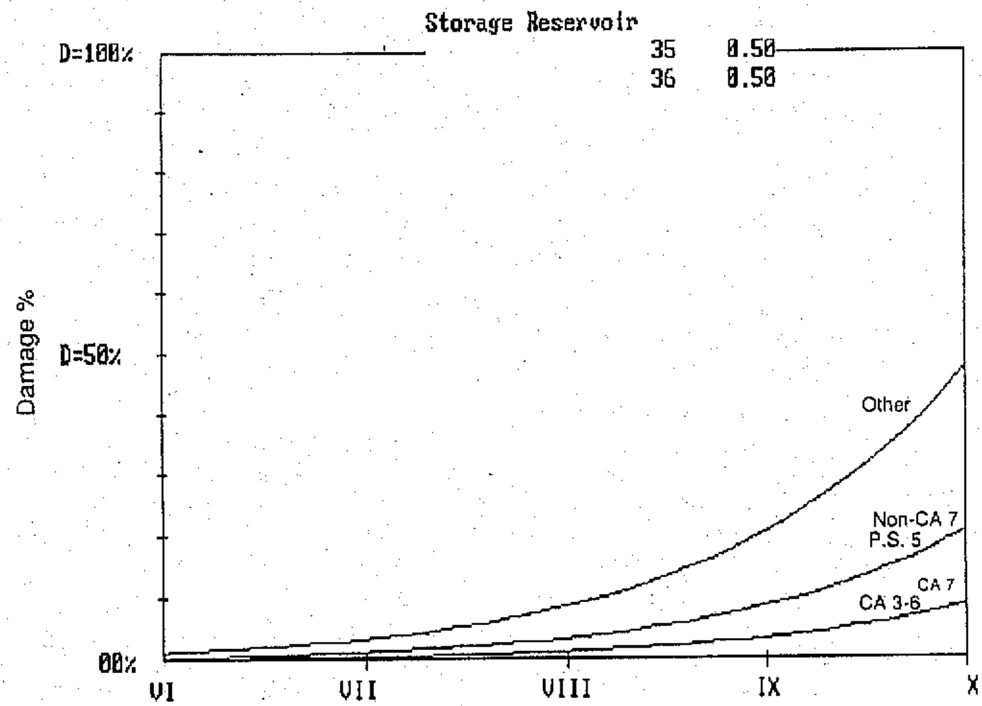

Figure B-71 Damage percent by intensity for storage reservoirs.

embankment failures. Seismically resistant design of concrete dams includes thorough foundation exploration and treatment, and selection of a good geometrical configuration. Dynamic analyses similar to those used for earthfill dams may be used to check designs, and to determine stresses and cracking potential of dams and dam appurtenances. Effective quality control is necessary in the design and construction of all dams. Stabilization of existing dams can be achieved by buttressing, draining, or reduction in reservoir storage. Potentially liquefiable soils have been densified by blasting, vibratory probing, adding backfill, and driving compaction piles.

1. Direct Damage

Basis: Damage curves for storage reservoirs in the water supply system are based on ATC-13 data for FC 35, concrete dams, and FC 36, earthfill or rockfill dams (see Figure B-71). Storage reservoirs are assumed to be a combination of 50% concrete dams and 50% earthfill or rockfill dams. If inventory data identify dams as concrete, or earthfill or rockfill, then the appropriate damage curves will need to be developed (see ATC-13).

Standard construction is assumed to represent typical California reservoirs (i.e., a composite of older and more modern reservoirs).

Present Conditions: In the absence of data on the type of construction, age, etc., the following factors were used to modify the mean curves for each of the two facility classes listed above, under present conditions:

	MMI Intensity Shift	
NEHRP Map Area	FC 35	FC 36
California 7	0	0
California 3-6	0	0
Non-California 7	+1	+1
Puget Sound 5	+1	+1
All other areas	+2	+2

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades

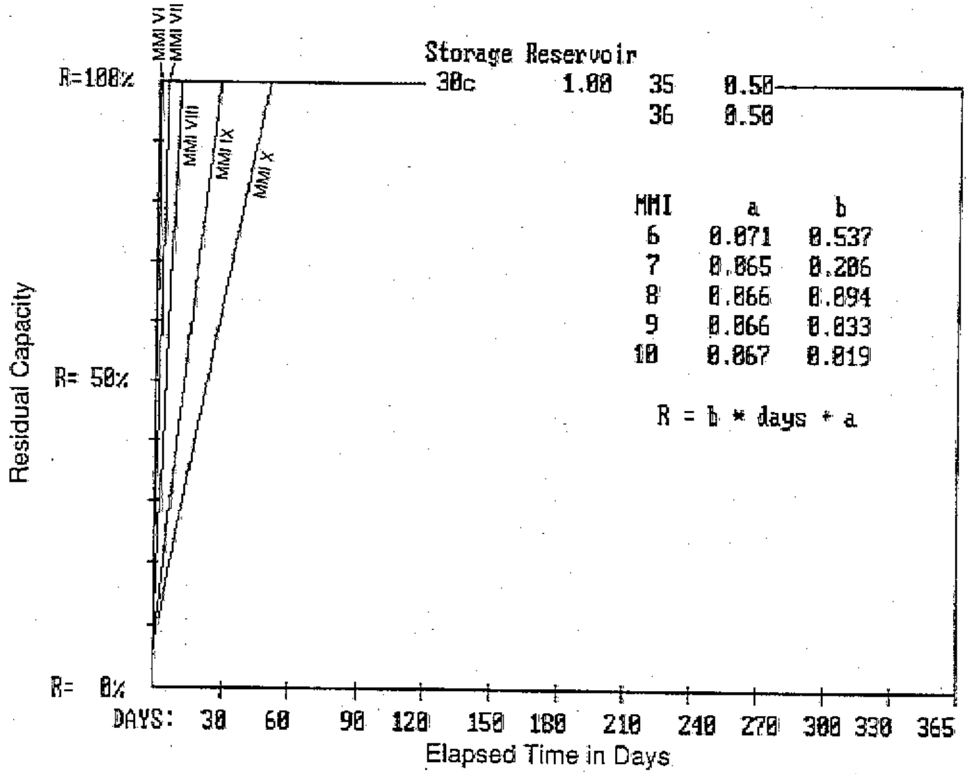

Figure B-72 Residual capacity for storage reservoirs (NEHRP California 7).

result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 30c, storage reservoirs for water supply systems, are assumed to apply to all storage reservoirs. By combining these data with the damage curves derived using the damage data for FC 35 and 36, the time-to-restoration curves shown in Figures B-72 through B-74 were derived.

B.6.4 Treatment Plants

1. General

Description: Water treatment plants are complex facilities. In general, the typical water sources for a treatment plant are shallow or deep wells, rivers, natural lakes, and impounding reservoirs. Treatment processes used depend on the raw-water source and the quality of finished water desired. Water from wells typically requires the least treatment, and water from rivers requires the most. Types of water treatment plants include aeration, split treatment, or chemical treatment plants. Flexibility and room for growth are typically provided to handle changing quality of water. Consequently, plants commonly contain components of different vintages and construction types. Current pre-treatment processes are screening, pre-sedimentation or desilting, chemical addition, and aeration. Components in the treatment process include pre-sedimentation basins, aerators, detention tanks, flocculators, clarifiers, backwash tanks, conduit and channels, coal-sand or sand filters, mixing tanks, settling tanks, clear wells, and chemical tanks. Processes used for flocculation include paddle (most common in modern facilities), diffused air, baffles (common in older facilities), transverse or parallel shaft mixers, vertical turbine mixers, and walking-beam-type mixers. Sedimentation basin construction may vary from excavation in the ground to a structure of concrete or steel construction. Most modern sedimentation basins are circular concrete tanks (open or covered), equipped with

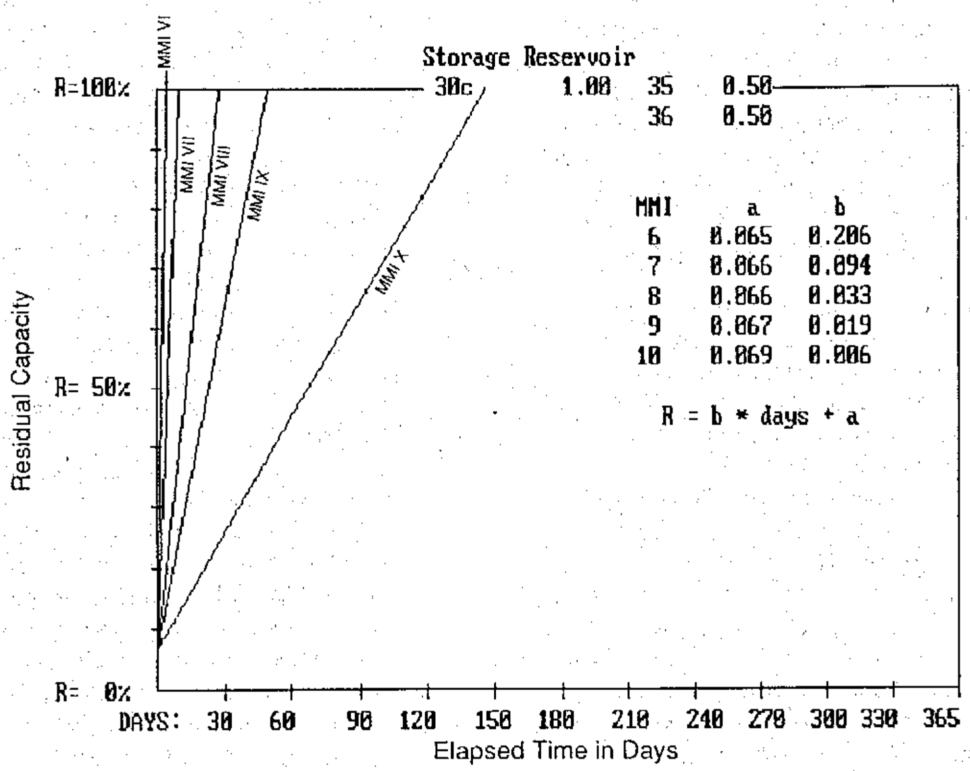

Figure B-73 Residual capacity for storage reservoirs (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

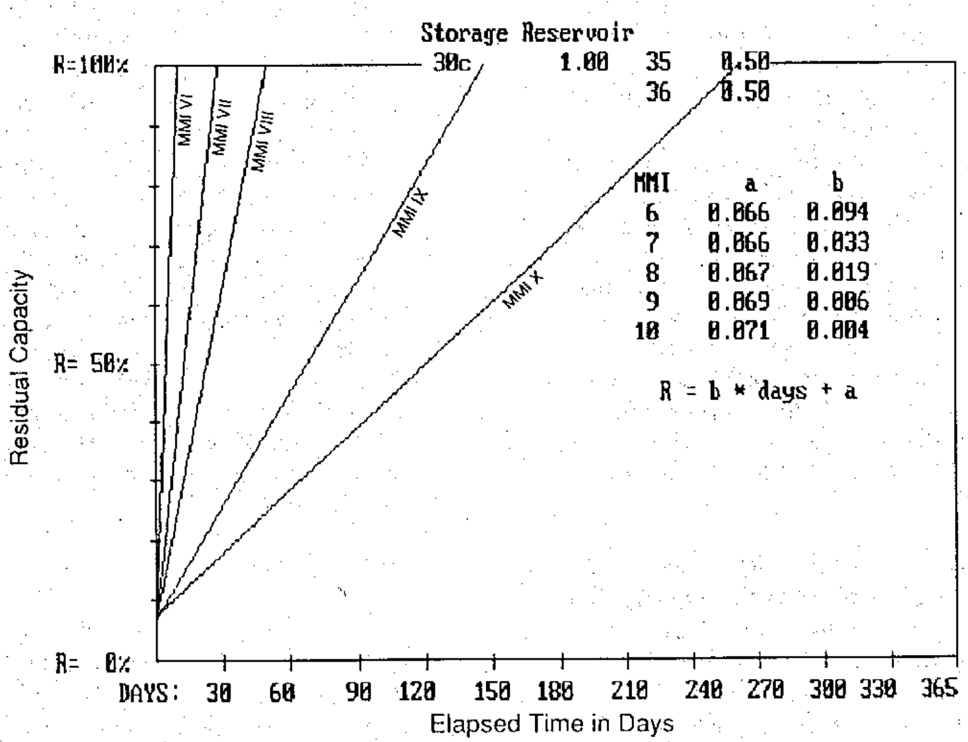

Figure B-74 Residual capacity for storage reservoirs (All other areas).

mechanical scrapers for sludge removal. Depths typically vary from 8 to 12 feet and diameters from 30 to 150 feet. Sludge processing components include holding tanks and clarifier thickeners. Control equipment, pumps, piping, valves, and other equipment are typically housed in a control building. Yard equipment generally includes transformers and switchyard equipment.

Typical Seismic Damage: Structures and equipment in water treatment plants are vulnerable to settling of foundations, especially when founded on fill. Differential settlement of adjacent structures and components supported on different foundations is a particular problem. Pipes are vulnerable at locations where they connect to or penetrate treatment structures. Equipment such as pumps can be damaged by loads imposed by piping when differential settlement occurs. Channels and large conduit connecting processing units are subject to seismic damage from several mechanisms, including differential movement from inertial loading, differential settlement, and increased lateral earth pressures. Liquefaction may cause some underground structures in areas of high groundwater to float. Concrete basins and tanks are subject to cracking and collapse of walls and roofs. Pounding damage or permanent movement may result in the opening of expansion joints in basins. Within basins, sloshing and wave action, as well as shaking, can damage anchor bolts and support members for reactors and rakes. Building damage may range from dropped suspended ceilings and cracks in walls and frames to partial and total collapse. Unanchored or improperly anchored equipment may slide or topple, experiencing damage or causing attached piping and conduit to fail. Damage to substation transformers can result in loss of power supply.

Seismically Resistant Design: Seismically resistant design includes providing capability to bypass plant treatment and to provide emergency chlorination in the event of damage caused by an earthquake. An emergency power system for the chlorine injection, controls, and radios is a minimum and if gravity flow is not possible, sufficient emergency power to provide pumping capacity must be available. Slopes adjacent to the plant should be studied to ascertain their stability, and mitigating measures should be taken if necessary. Damage to channels and conduit can be mitigated by providing wall penetrations that allow for differential settlement. Similarly, flexibility should be provided in connections and piping where they span across expansion joints or between structures on different foundation types. Equipment damage can be reduced by using cast-in-place bolts rather than expansion anchors and using equipment with a low center of gravity. Equipment and piping should be protected from falling debris. Building design should satisfy the seismic requirements of the local building code, as a minimum. Heavy equipment such as sludge-processing equipment should be located as low as possible in the building. Horizontal tanks on saddles should be restrained to saddles to prevent slippage and rupture of attached piping. Design of equipment immersed in water (e.g., paddles, rakes, baffles) should consider both inertial effects and those due to sloshing of water. Design of such equipment should also consider ease of replacement. Vertical turbine pumps hanging in tanks should be avoided if possible--or designed for seismic loads, as a minimum. Chlorine cylinders should be strapped in place on snubbed chlorine scales. Standard safety and shutdown systems for gas and chemical systems should be installed and properly maintained. Routine checks are recommended to ensure that valves are operable, and that stockpiles of spare parts and tools are available. Basins or structures founded on separate foundation materials should have separate foundations and should be separated by a flexible joint. All critical piping (exclusive of corrosive chemical systems) should be welded steel.

2. Direct Damage

Basis: Damage curves for treatment plants in the water supply system (see Figure B-75) are based on ATC-13 data for FC 10, medium-rise reinforced masonry shear wall buildings; FC 41, underground liquid storage tanks, and FC 68, mechanical equipment.

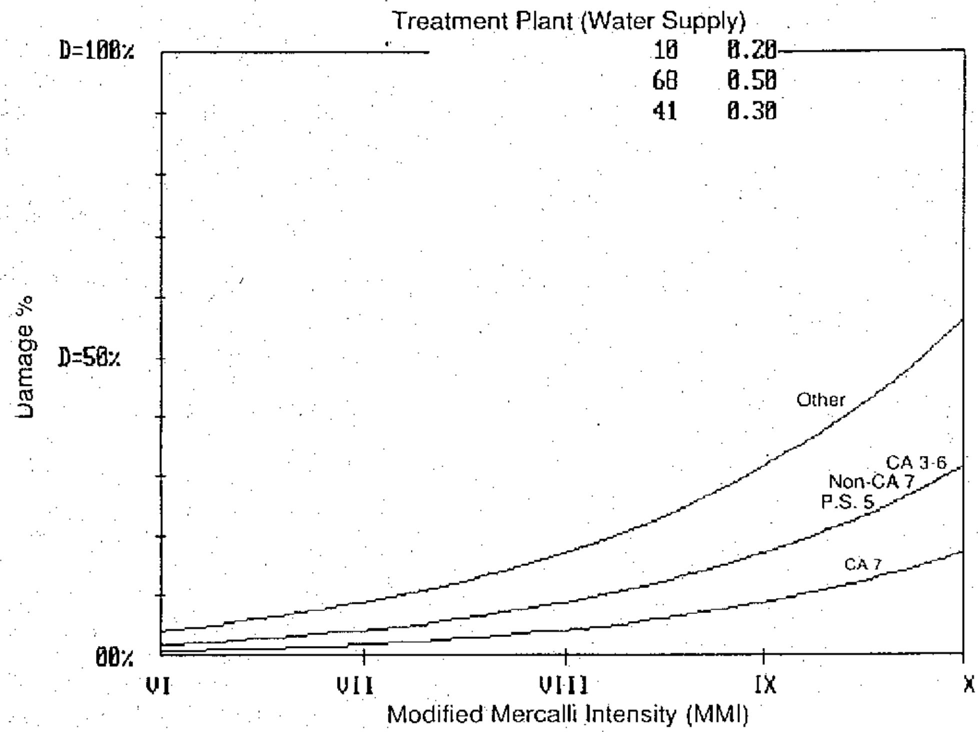

Figure B-75 Damage percent by intensity for water supply treatment plants.

FC 10 was chosen to represent a generic building, based on review of damage curves for all buildings. Water treatment plants are assumed to a combination of 20% generic buildings, 30% underground storage tanks, and 50% mechanical equipment.

Standard construction is assumed to represent typical California treatment plants under present conditions (i.e., a composite of older and more modern treatment plants). It is assumed that minimal regional variation exists in construction quality of underground storage tanks and mechanical equipment. Seismic loads have little impact on underground storage tank design, and operational loads often govern over seismic requirements in the design of mechanical equipment.

Present Conditions: In the absence of data on the type of material, age, etc., use the following factors to modify the mean curves for each of the three facility classes listed above, under present conditions:

	MMI Intensity Shift		
NEHRP Map Area	FC 10	FC 41	FC 68
California 7	0	0	0
California 3-6	+1	0	0
Non-California 7	+1	0	0
Puget Sound 5	+1	0	0
All other areas	+2	+1	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 30d, treatment plants in the water supply system, are assumed to apply to all treatment plants. By combining these data with the damage curves derived using the data for FC 10, 41, and 68, the time-to-restoration curves shown in Figures B-76 through B-78 were derived.

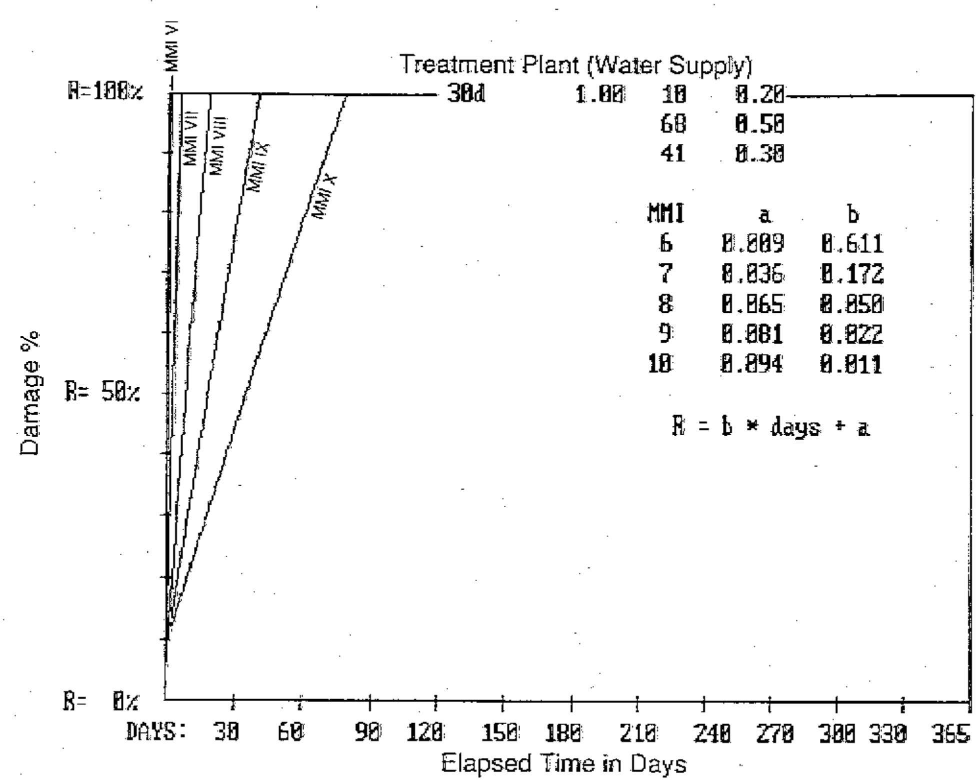

Figure B-76 Residual capacity for water supply treatment plants (NEHRP California 7).

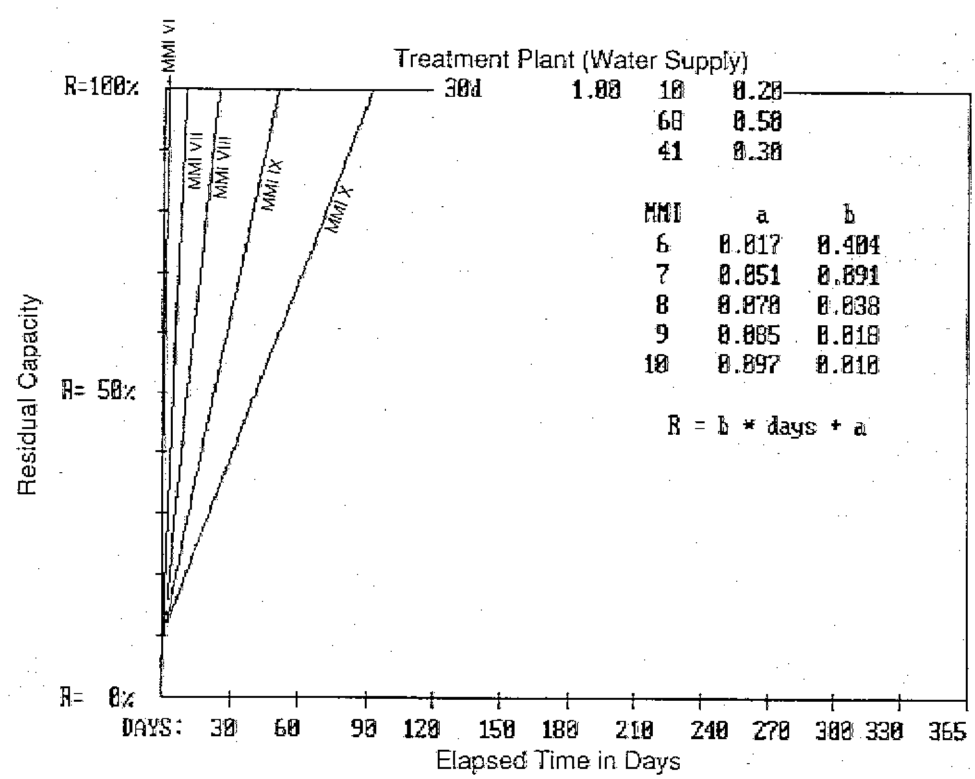

Figure B-77 Residual capacity for water supply treatment plants (NEHRP Map Area 3-6, Non-California 7, and Puget Sound 5).

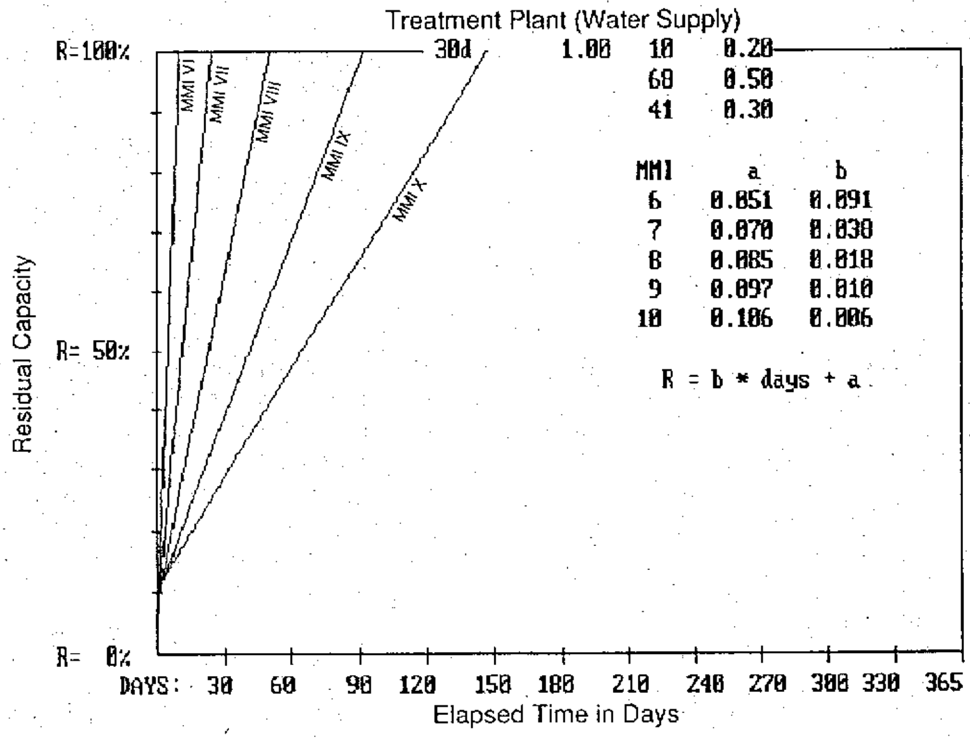

Figure B-78 Residual capacity for water supply treatment plants (All other areas).

B.6.5 Terminal Reservoirs/Tanks

1. General

Description: In general, terminal reservoirs may be underground, on-ground, or elevated storage tanks or impounding reservoirs. Underground storage tanks are typically reinforced or prestressed concrete wall construction with either concrete or wood roofs. They may be either circular or rectangular. On-ground water supply storage tanks are typically vertical anchored and/or unanchored tanks supported at ground level. Construction materials include welded, bolted, or riveted steel; reinforced or prestressed concrete; or wood. Tank foundations may consist of sand or gravel, or a concrete ring wall supporting the shell. Elevated storage tanks consist of tanks supported by single or multiple columns. Most elevated tanks are steel and are generally cylindrical or ellipsoidal in shape. Multiple-column tanks typically have diagonal braces, for lateral loads. Elevated tanks are more common in areas of flat terrain. There is large variation in tank sizes (i.e., height and diameter), so volumes range from thousands to millions of gallons. Impounding reservoirs may be lined or unlined, and with or without roofs.

Typical Seismic Damage: Failure modes for underground tanks include damage to concrete columns that support roofs, sloshing damage to roofs, and cracking of walls. In cases of liquefaction, empty tanks can become buoyant and float upward, rupturing attached piping. Impounding reservoirs perform similarly to underground tanks. At-ground tanks are subject to a variety of damage mechanisms, including, for steel tanks: (1) failure of weld between base plate and wall, (2) buckling of tank wall (elephant foot), (3) rupture of attached rigid piping resulting from sliding or rocking of tank, (4) implosion of tank caused by rapid loss of contents and negative internal pressure, (5) differential settlement, (6) anchorage failure or tearing of tank wall, (7) failure of roof-to-shell connection, (8) failure of shell at bolts or rivets, and (9) total collapse. Concrete tank failure modes include: (1) failure of columns supporting roofs, (2) spalling and cracking, and (3) sliding at construction joints. Wood tanks have not performed well in past earthquakes and generally fail in a catastrophic manner.

Elevated tanks typically fail as a result of inadequate bracing or struts, although column buckling or anchorage or connection failure (clevises and gusset plates) are common causes. If elevated tank damage exceeds minor bracing or connection failure, damage is usually catastrophic. Piping and other appurtenances attached to tanks can also fail because of tank or pipe motion, causing loss of contents.

Seismically Resistant Design: General Seismically resistant design practices for underground tanks include designing walls for a combination of earth pressures and seismic loads; densifying the backfill used behind the walls to reduce liquefaction potential; designing columns supporting the roof for seismic loads; tying the roof and walls together; providing adequate freeboard to prevent sloshing against the roof; and recognizing the potential for flotation and providing restraint. Control of buoyant forces can be achieved by tying the tank to piles designed to resist uplift, increasing the mass of the tank (e.g., provide overburden on the roof), or providing a positive drainage system. An annular space that permits relative movement should be provided where piping penetrates the wall. Seismically resistant design practices for at-ground tanks include the use of flexible piping, pressure relief valves, and well-compacted foundations and reinforced concrete ring walls that prevent differential settlement. Adequate freeboard to prevent sloshing against the roof should be maintained. Good practices for steel tanks include providing positive attachment between the roof and shell, stiffening the bottom plate and its connection to the shell, protecting the base plate against corrosion, and avoiding abrupt changes in thickness between adjacent courses. Properly detailed ductile anchor bolts may be feasible on smaller steel tanks. For concrete tanks, keying and detailing to prevent sliding is good practice. Columns supporting roofs should be detailed to prevent brittle failures. In areas where freeze-thaw cycles are a problem, minimum strength requirements that ensure durability should be met. For wood tanks, Seismically resistant design practices include increasing hoop capacity, and anchoring or strapping the tank to the foundation. Maintaining a height-to-diameter ratio of between 0.3 and 0.7 for tanks supported on-ground controls seismic loading. Because the damage to elevated tanks typically involves the supporting structure rather than the supported vessel, the primary Seismically resistant design practices for elevated tanks are design of the braces for adequate lateral loads, providing adequate anchorage at the column bases, connecting the tank to the frames that support it for load transfer, and providing flexibility in the attached piping to accommodate expected motions. The bracing system should be designed to yield prior to connection failure. Rods used for bracing should have upset threads with large deformable washers under retaining nuts to absorb energy.

2. Direct Damage

Basis: Damage curves for water supply terminal reservoirs are based on ATC-13 data for FC 43, on-ground liquid storage tanks (see Figure B-79). On-ground storage tanks are less vulnerable than elevated tanks, and more vulnerable than underground tanks, and were chosen as representative of existing terminal reservoirs. If inventory data identify tanks as underground or elevated, then use FC 41 or 45, respectively, in lieu of FC 43.

Standard construction is assumed to represent typical California terminal reservoirs under present conditions [i.e., a composite of older, non-seismically designed tanks as well as more modern tanks designed to seismic requirements (e.g., AWWA D100, Appendix A)].

Present Conditions: In the absence of data as to type of material, age etc., use the following factors to modify the mean curves, under present conditions:

NEHRP Map Area	*MMI Intensity Shift*
California 7	0
California 3-6	+1
Non-California 7	+1
Puget Sound 5	+1
All other areas	+2

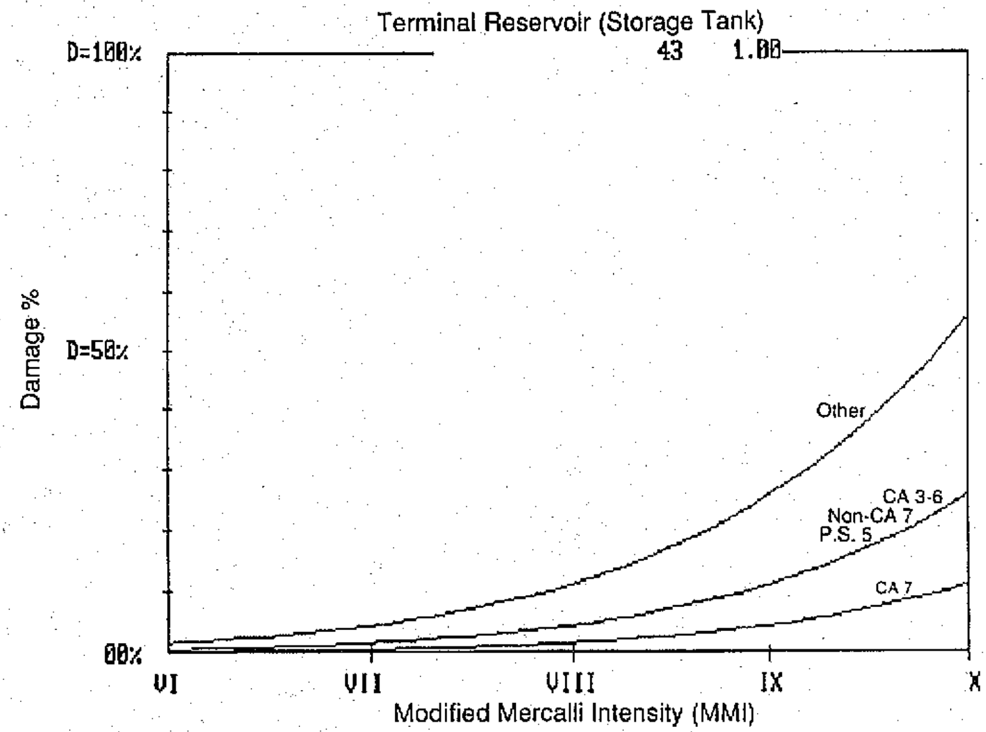

Figure B-79 Damage percent by intensity for water supply terminal reservoirs/storage tanks.

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in one or two beneficial intensity shifts (i.e., -1 or -2), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 30e, terminal reservoirs for water supply, are assumed to apply to all tanks. By combining these data with the damage curves for FC 43, the time-to-restoration curves shown in Figures B-80 through B-82 are derived.

B.6.6 Trunk Lines

1. General

Description: In general, trunk lines may be underground, on-ground, or supported on elevated frames above ground. However, most trunk lines in the water supply system are located underground. Pipe materials include cast iron, welded steel, riveted steel, concrete-lined steel, asbestos cement, and plastic. Newer trunk lines (typically 20 inches or more in diameter) are usually welded steel or reinforced concrete and may carry water at high pressures (several hundred psi). Joints in steel pipes may be welded or bell-and-spigot types. Except in areas of freezing, backfill measured from the pipe crown is typically between 2.5 and 4.5 feet. In addition to the pipes themselves, trunk lines include a number of other components. Pipelines may require gate valves, check valves, air-inlet release valves, drains, surge control equipment, expansion joints, insulation joints, and manholes. Check valves are normally located on the upstream side of pumping equipment and at the beginning of each rise in the pipeline to prevent back flow. Gate valves are used to permit portions of pipe or check valves to be isolated. Air-release valves are needed at the high points in the line to release trapped gases and to vent the lines to prevent vacuum formation. Drains are located at low points to permit removal of sediment and allow the conduit to be emptied. Surge tanks or quick-opening valves provide relief for problems of hydraulic surge.

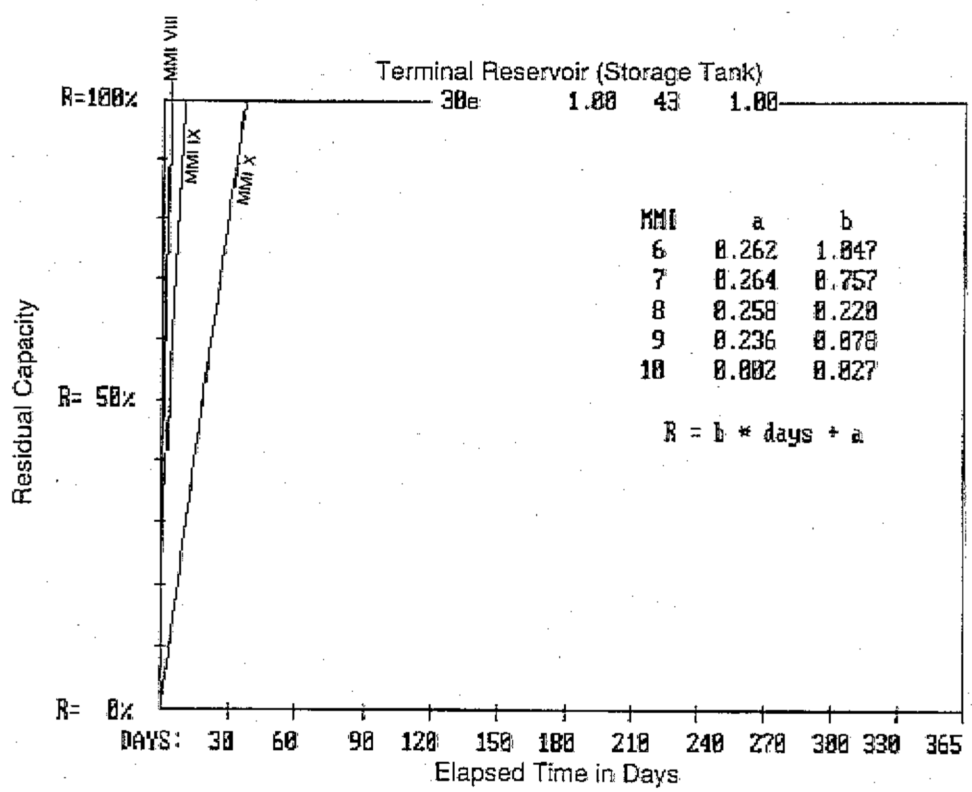

Figure B-80 Residual capacity for water supply terminal reservoirs/storage tanks (NEHRP California 7).

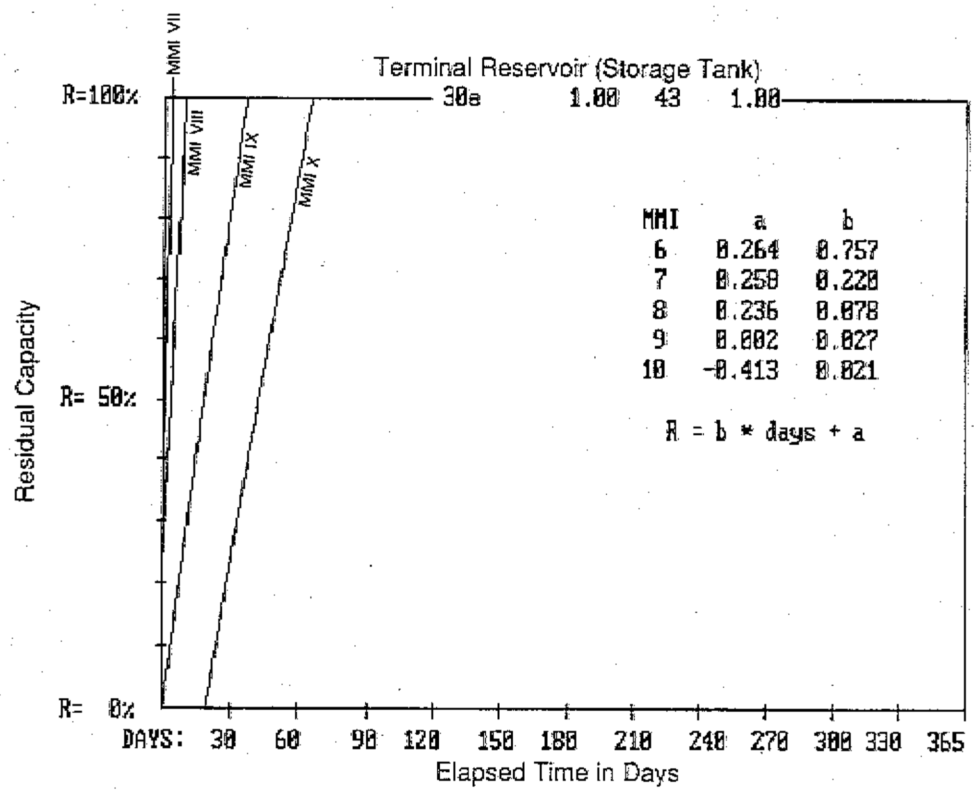

Figure B-81 Residual capacity for water supply terminal reservoirs/storage tanks (NEHRP Map Area 3-6, Non-California 7, and Puget Sound 5).

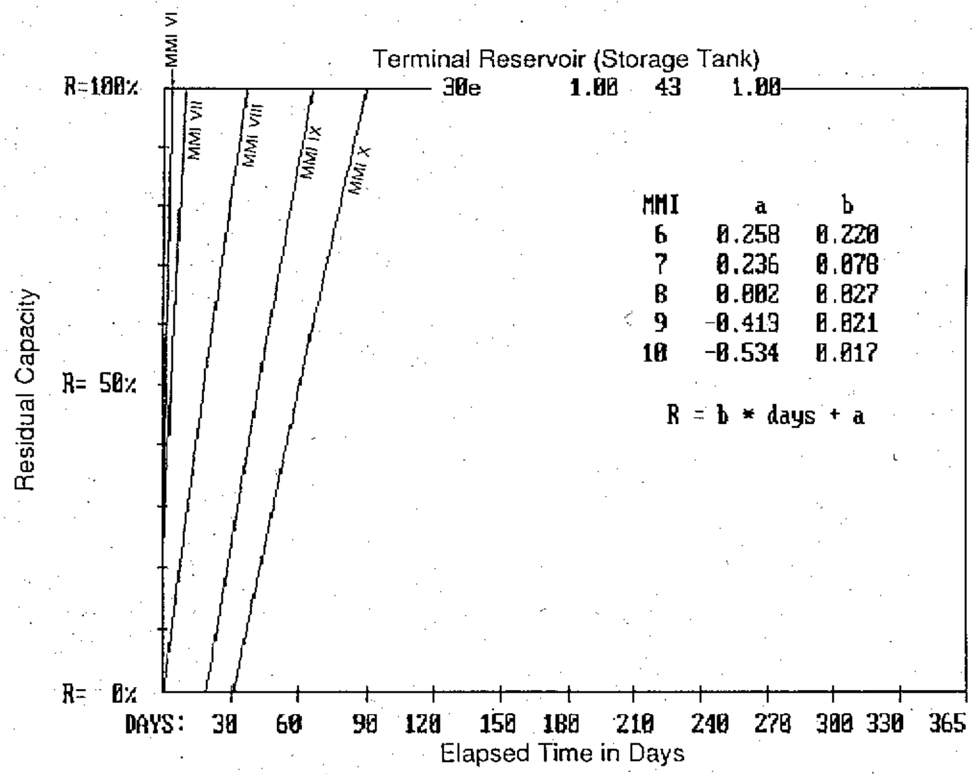

Figure B-82 Residual capacity for water supply terminal reservoirs/storage tanks (All other areas).

Typical Seismic Damage: The performance of pipelines is strongly dependent on whether or not the supporting or surrounding soil fails. Failure of a piping system resulting from inertial loads only is rare; more typically differential settlement or severe ground failure (e.g., landslide, liquefaction, faulting) causes damage. Regional uplift can alter the hydraulic characteristics of a transmission system rendering it nonfunctional. Pipe damage is most common in soft alluvial soils or at interfaces between soft and firm soils. Types of pipe damage include bending or crushing of the pipe, shearing of the pipe, compressional buckling, soil deposits in the pipe, circumferential and longitudinal cracks, and joint failure. It has frequently been observed that pipelines with rigid joints fail more frequently than those with flexible joints. Damage has been substantial at locations of local restraint such as penetrations to heavy subsurface structures (including manholes), tees, and elbows. Water hammer induced by ground motions can cause damage by temporarily increasing pressure in pipelines.

Seismically Resistant Design: Seismically resistant design practices for trunk lines include the use of ductile pipe materials, such as steel, ductile iron, copper, or plastic. The performance of welded steel pipelines is dependent upon the quality of welds, with more modern pipes generally having superior welds. Use of flexible joints (e.g., bell-and-spigot with rubber gaskets, mechanical joints, expansion joints, rubber or metallic bellows, and ball joints) and placement of pipes in dense native or compact soil not subject to liquefaction, slides, or surface rupture will mitigate much of the potential damage. Special precautions should be taken to reduce earthquake effects at pumping plants, tanks, bay or river crossings, and fault crossings. Shut-off valves should be installed near active fault zones so that flow can be stopped if the pipeline crossing is damaged. Trunk lines at fault crossings should be located in a sacrificial tunnel or culvert, or lubricated, wrapped in sheathing, or buried in shallow loose fill, installed or above ground near the fault to allow lateral and longitudinal slippage. Anchors such as thrust blocks or bends

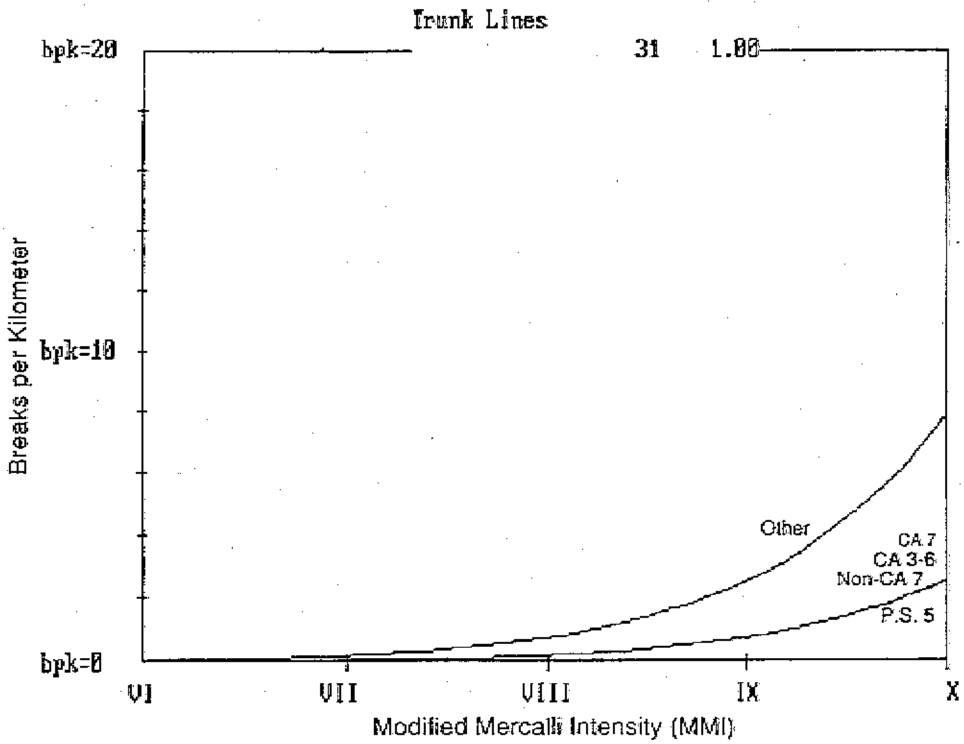

Figure B-83 Damage percent by intensity for water supply trunk lines.

should be excluded within a distance of 300 feet of a fault zone and strengthened pipe should be used within the zone. Valve spacing near fault zones or in areas of expected soil failure should be reduced. Proper maintenance and cathodic protection to limit corrosion, which weakens pipes, is important for mitigating damage. Supports for on- or above ground piping should provide restraint in all three orthogonal directions by using ring girders, and spacing between adjacent trunk lines should be sufficient to prevent pounding. Use of pressure relief valves can mitigate damage caused by water hammer. Redundancy should be built into the system whenever possible; several smaller pipes should be used in lieu of one large pipe. Any equipment attached to piping should be properly anchored.

2. Direct Damage

Basis: Damage curves for trunk lines in the water supply system are based on ATC-13 data for FC 31, underground pipelines (see Figure B-83). Distribution pipelines (between 4 and 20 inches in diameter) are generally more susceptible to damage because of their construction type, and it is assumed that their behavior can be approximated using these data through the use of one detrimental intensity shift (i.e., +1).

Standard construction is assumed to represent typical California trunk lines under present conditions (i.e., a composite of older and more modern trunk lines). Only minimal regional variation in the construction quality is assumed.

Present Conditions: In the absence of data on the type of material, diameter, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	MMI Intensity Shift
California 7	0
California 3-6	0
Non-California 7	0
Puget Sound 5	0
All other areas	+1

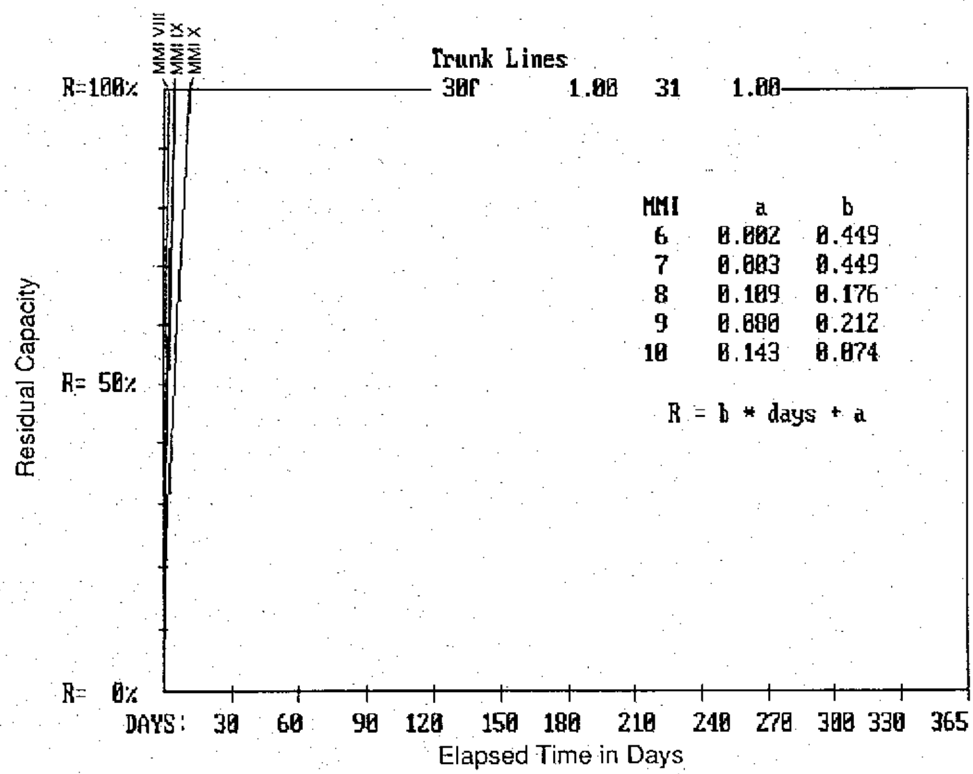

Figure B-84 Residual capacity for water supply trunk lines (NEHRP Map Area: California 3-6, California 7, Non-California 7, and Puget Sound 5).

Upgraded Conditions: It is not cost-effective or practical to upgrade existing trunk lines in the water supply system, except perhaps at fault crossings or in areas of extremely unstable soils. Therefore, no intensity shifts for retrofitting are recommended.

Typical Seismic Damage: The time-to-restoration data assigned to SF 30f, trunk lines, are assumed to apply to all trunk lines in the water supply system. By combining these data with the damage curves for FC 31, the time-to-restoration curves shown in Figures B-84 and B-85 were derived. Distribution line restoration will take longer based on prioritization of work. It is assumed that restoration of distribution lines will take approximately twice as long as restoration of trunk lines.

B.6.7 Wells

1. General

Description: The collection of groundwater is accomplished primarily through the construction of wells or infiltration galleries. A well system is generally composed of three elements: the well housing structure, the motor/pump, and the discharge piping. The well system may or may not be located in a well house. The well contains an open section (typically a perforated casing or slotted metal screen) through which flow enters and a casing through which the flow is transported to the ground surface. Vertical turbine pumps are often used for deep wells.

Typical Seismic Damage: Well casings will move with the surrounding soils. This movement can result in damage to pumps and/or discharge lines without flexible couplings. Additional problems include fluctuation in production (disruption of aquifer), bad sanding conditions due to local soil disturbance (mostly in older wells with

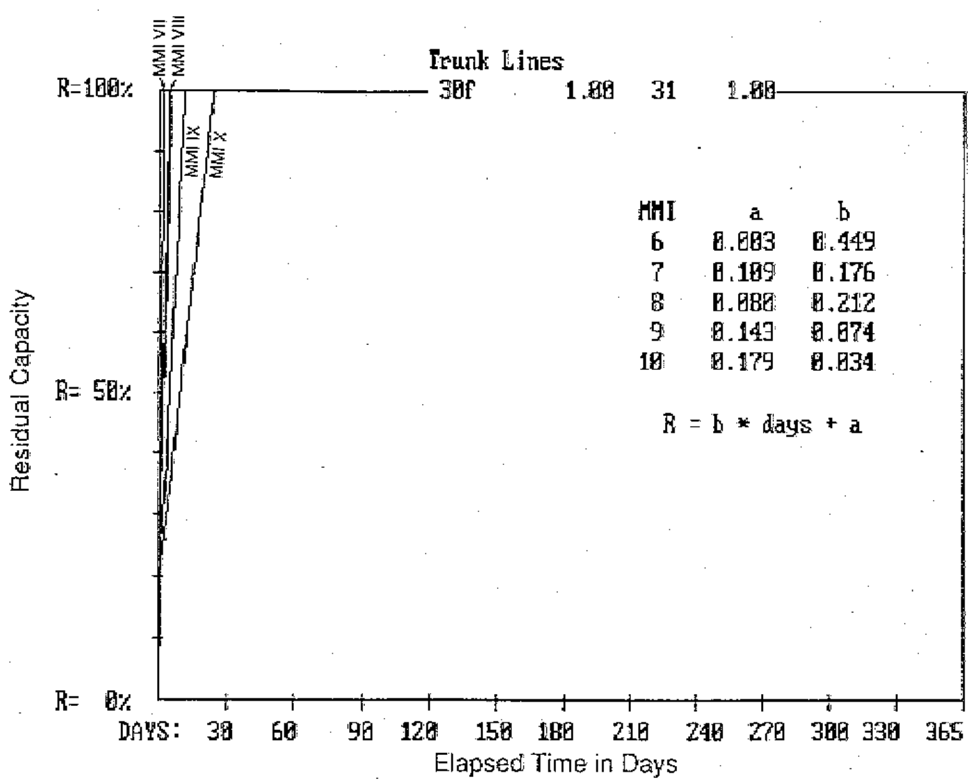

Figure B-85 Residual capacity for water supply trunk lines (All other areas).

insufficient screen design), kinked tubing, and collapse of the casing. The well shaft can be crushed or sheared off by ground displacement across the shaft or by ground vibration. Wells may be contaminated by inflow from nearby sewers, septic tanks, and cesspools that are damaged by the earthquake. Damage to substation transformers can result in loss of power supply.

Seismically Resistant Design: As seismic design practices may include providing double casing at depths below where horizontal movement is expected. Submersible pumps/motors have a greater probability of remaining in service than do pumps connected to motors at the surface with drive shafts. Because the well casing will respond differently than the slab of the surrounding well house, a flexible separation joint should be provided between the casing and the slab. Effects of differential movement and settlement can be mitigated by providing a flexible joint between the pump discharge header and the discharge piping. Other electrical and mechanical equipment should be provided with adequate seismic anchorage. The well-housing structure should be designed with seismic provisions of local or national building codes.

2. Direct Damage

Basis: Damage curves for wells in the water supply system (see Figure B-86) are based on ATC-13 data for FC 68, mechanical equipment. It is believed that this facility class best approximates the expected performance of wells, which typically comprise a vertical pump in a shaft.

Standard construction is assumed to represent typical California wells under present conditions (i.e., a composite of older and more modern wells). Only minimal regional variation in the construction quality is assumed.

Present Conditions: In the absence of data on the type of pump, etc., the following factors were used to modify the mean curves, under present conditions:

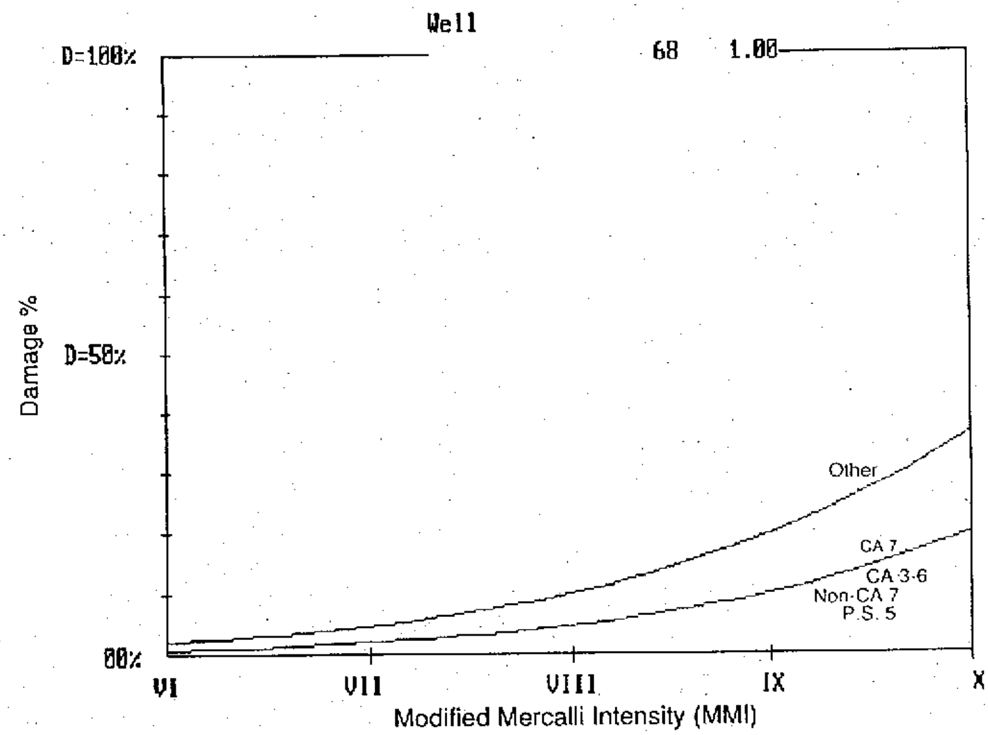

Figure B-86 Damage percent by intensity for wells.

NEHRP Map Area	MMI Intensity Shift
California 7	0
California 3-6	0
Non-California 7	0
Puget Sound 5	0
All other areas	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 30b, pumping stations in the water supply system, are assumed to apply to all wells. By combining these data with the damage curves for FC 68, the time-to-restoration curves shown in Figures B-87 and B-88 were derived.

B.7 Sanitary Sewer

B.7.1 Mains

1. General

Description: In general, mains in the sanitary sewer system are underground pipelines that normally follow valleys or natural streambeds. Valves and manholes are also included in system. Pipe materials commonly consist of cast iron, vitrified clay concrete, asbestos cement pipe, brick, and bituminized fiber. Pipe diameters are generally greater than 4 inches. Joint materials include welded bell-and spigot, rubber gasket, lead caulking, cement caulking, and plastic compression rings. Bolted flange couplings are also sometimes used. Manholes are typically provided at changes in direction or pipe size, or where flow is received from collecting sewers. Wastewater pipelines are usually designed as open channels except where lift stations are required to overcome topographic barriers. Sometimes the sanitary sewer

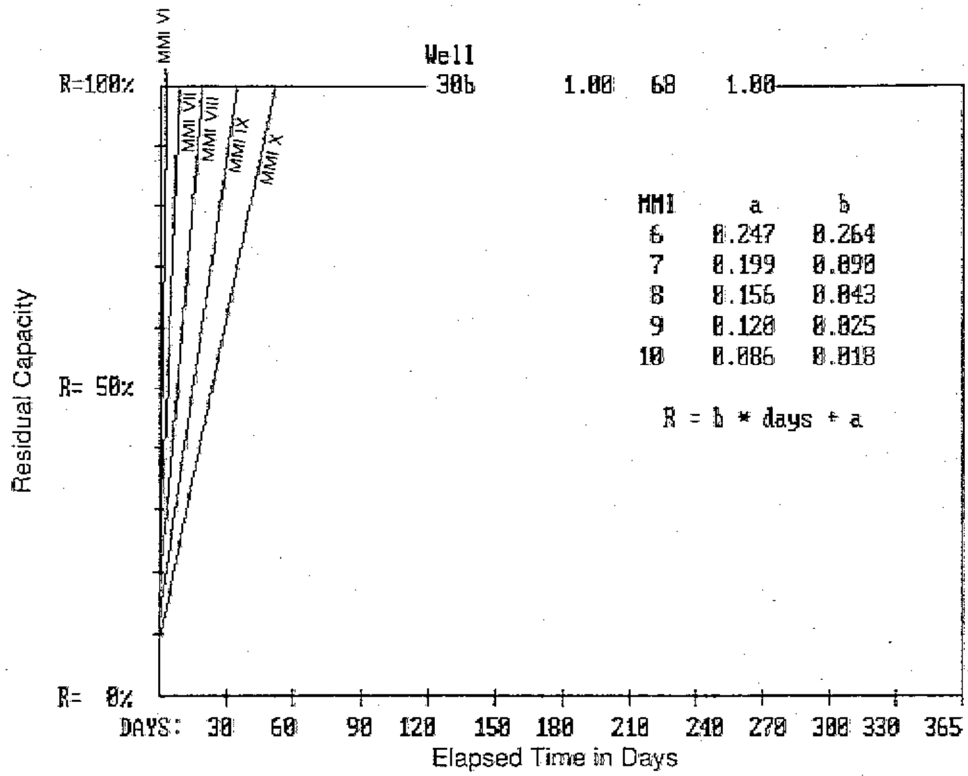

Figure B-87 Residual capacity for wells (NEHRP Map Area: California 3-6, California 7, Non-California 7, and Puget Sound 5).

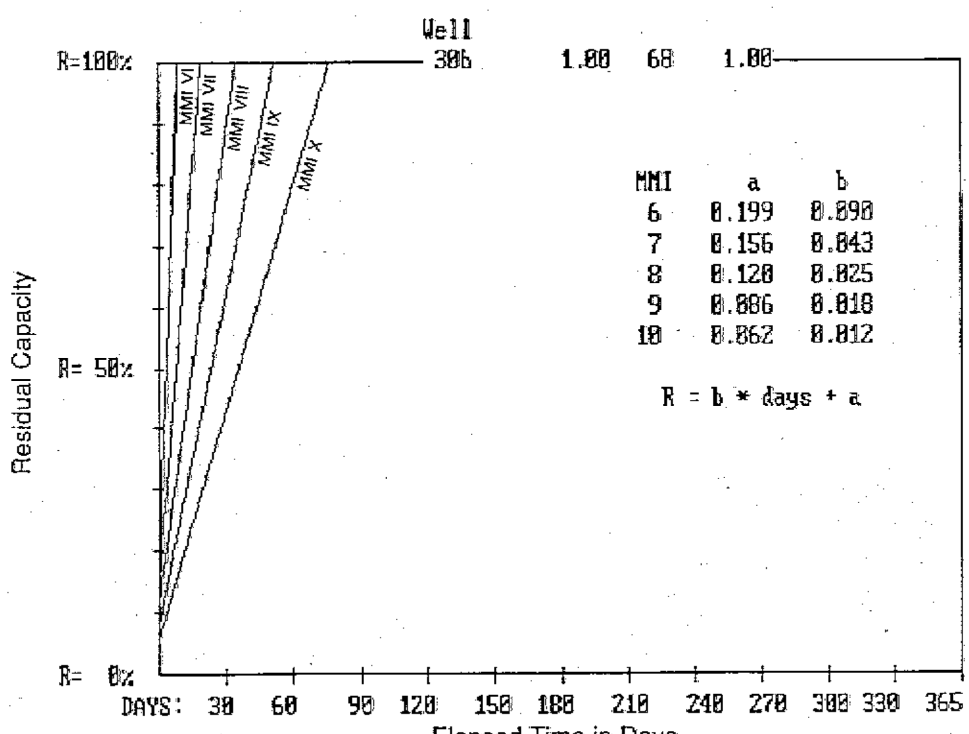

Figure B-88 Residual capacity for wells (All other areas).

system flow is combined with the storm water system prior to treatment.

Typical Seismic Damage: The performance of pipelines is strongly dependent on whether or not the surrounding soil fails (e.g., landslide, liquefaction, or fault rupture). Pipe damage is most common in soft alluvial soils or at interfaces between soft and firm soils. Failure of piping caused by inertial loads is uncommon. Potential types of damage include pipe crushing and cracking caused by shearing and compression; joint breaking because of excessive deflection or compression; joints pulling open in tension; and changes in sewer grade, causing reduced flow capacity. Tension and compression failures at joints because of soil movement have been common. Flexible joints have suffered significantly less damage than rigid joints. Welded bell-and-spigot joints have performed poorly when subjected to longitudinal stress. Cast-iron pipes with rubber gaskets or lead-caulked joints have accommodated movements better than those caulked with cement, but may still pull apart with major soil movements.

Seismically Resistant Design: Seismically resistant design practices for mains in the sewer system include the use of flexible joints (e.g., butt-welded and double-welded joints, restrained-articulated joints, and restrained bell-and-spigot joints with ring gaskets on a short length of pipe section), and avoiding longitudinally stiff couplings such as cement or lead-caulked, plain bell-and-spigot, and bolted flange. Placement of mains in dense native or compact soil not subject to liquefaction, slides, or surface rupture will mitigate much of the potential damage. Special precautions should be taken to reduce earthquake effects at fault crossings. Main lines at fault crossings can be located in a sacrificial tunnel or culvert, or lubricated, wrapped in sheathing, buried in shallow loose fill, or installed above ground near the fault to allow lateral and longitudinal slippage. Anchors such as bends should be excluded within a distance of 300 feet of a fault zone and strengthened pipe should be used within the zone. Isolation valves should be placed near fault zones or in areas of expected soil failure. Proper maintenance to limit corrosion of metal pipes, which weakens pipes, is important to mitigate damage. Any equipment attached to piping should be properly anchored.

2. Direct Damage

Basis: Damage curves for mains in the sanitary sewer system are based on ATC-13 data for FC 31, underground pipelines (see Figure B-89). In general, mains in the sanitary sewer system are more vulnerable than those used in other systems because of the construction materials used. Unlike the water supply system, larger pipes generally operate at lower pressures and thus are of similar construction quality to the smaller pipes. Consequently, the above damage curves may be used for all pipelines in the sanitary sewer system.

Standard construction is assumed to represent typical California mains in the sanitary sewer system under present conditions (i.e., a composite of older and more modern mains). Only minimal regional variation in the construction quality is assumed.

Present Conditions: In the absence of data on the type of material, diameter, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	MMI Intensity Shift
California 7	+1
California 3-6	+1
Non-California 7	+1
Puget Sound 5	+1
All other areas	+2

Upgraded Conditions: It is not cost-effective or practical to upgrade existing mains in the sewer system, except perhaps at fault crossings or in areas of extremely unstable soils. Therefore, no intensity shifts for retrofitting are recommended.

Time-to-restoration: The time-to-restoration data assigned to SF 31a, effluent and main sewer lines, are assumed to apply to all distribution lines. By combining these data with the damage curves for FC 31, the time-to-restoration curves shown in Figures

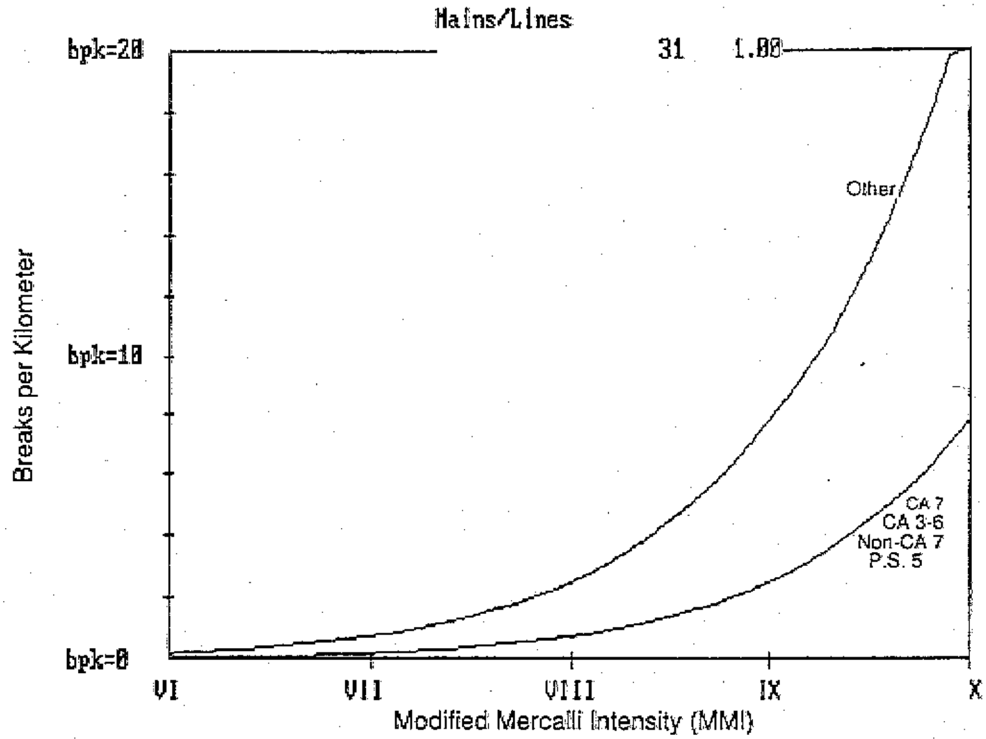

Figure B-89 Damage percent by intensity for sanitary sewer mains/lines.

B-90 and B-91 were derived. Collector pipe restoration will take longer because of its relatively lower priority. It is assumed that restoration of collector lines will take approximately twice as long as restoration of the mains.

B.7.2 Pumping Stations

1. General

Description: Pumping stations or lift stations are typically used to transport accumulated wastewater from a low point in the collection system to a treatment plant. Pumping stations consist primarily of a wet well, which intercepts incoming flows and permits equalization of pump loadings, and a bank of pumps, which lift the wastewater from the wet well. The centrifugal pump finds widest use at pumping stations. Lift stations are commonly located in small, shear-wall-type buildings.

Typical Seismic Damage: Pumping stations will suffer damage closely related to the soil materials on which they are constructed. Because of their function, these stations are typically located in low-lying areas of soft alluvium where soil failures may occur. Buildings housing stations may experience generic building damage ranging from cracking of walls and frames to collapse, and unanchored electrical and mechanical control equipment may topple and slide, experiencing damage and tearing piping and conduit connections. Piping attached to heavy pump/motor equipment structures is susceptible to damage caused by differential settlement. Pumps/motors may also experience damage as a result of differential settlement. Damage to substation transformers can result in a loss of power supply.

Seismically Resistant Design: Seismically resistant design practice includes avoiding unstable soils whenever possible and addressing problems of expected differential settlement and liquefaction in the design of foundations. Flexibility of pipelines should be provided when pipes are attached to two separate structures on different foundations. Annular space should be provided at pipe

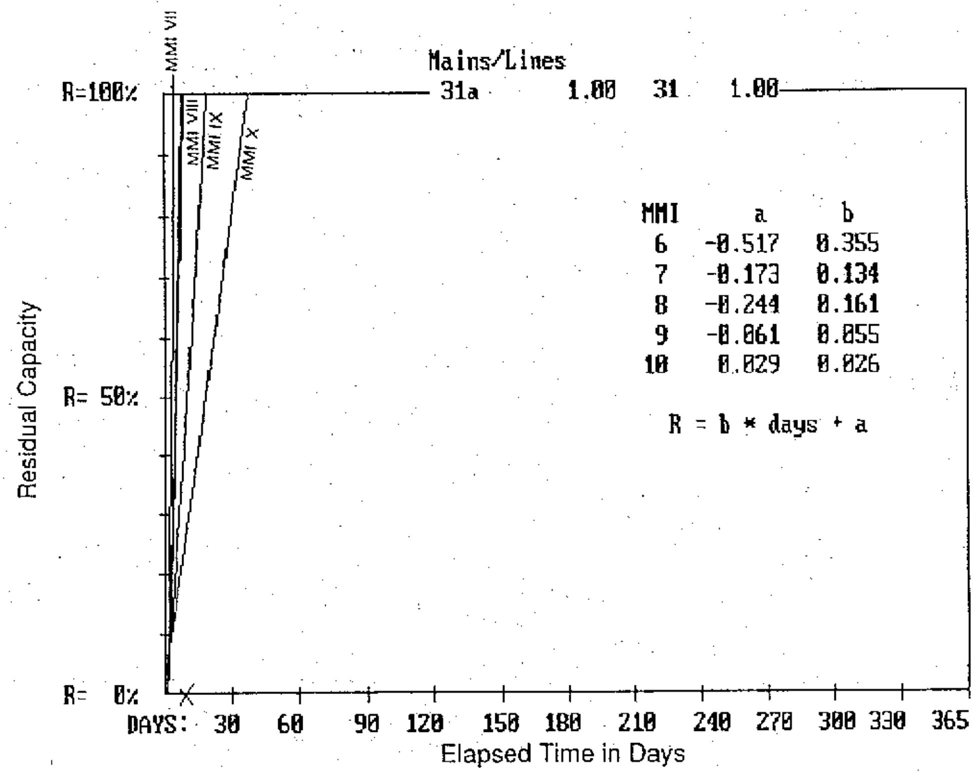

Figure B-90 Residual capacity for sanitary sewer mains/lines (NEHRP Map Area: California 3-6, California 7, Non-California 7, and Puget Sound 5).

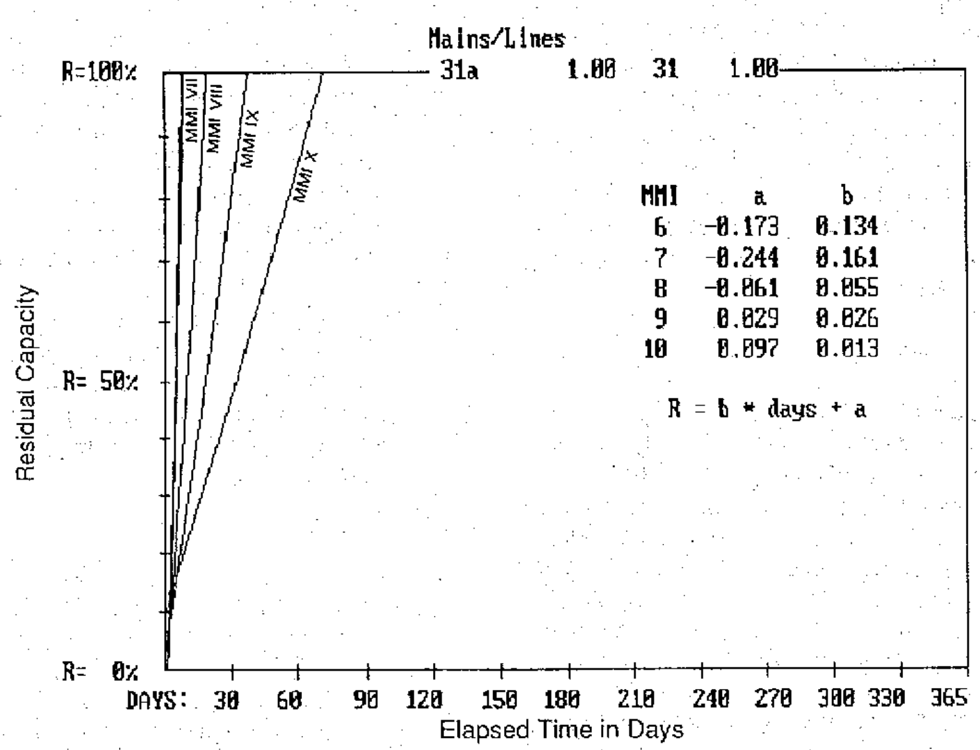

Figure B-91 Residual capacity for sanitary sewer mains/lines (All other areas).

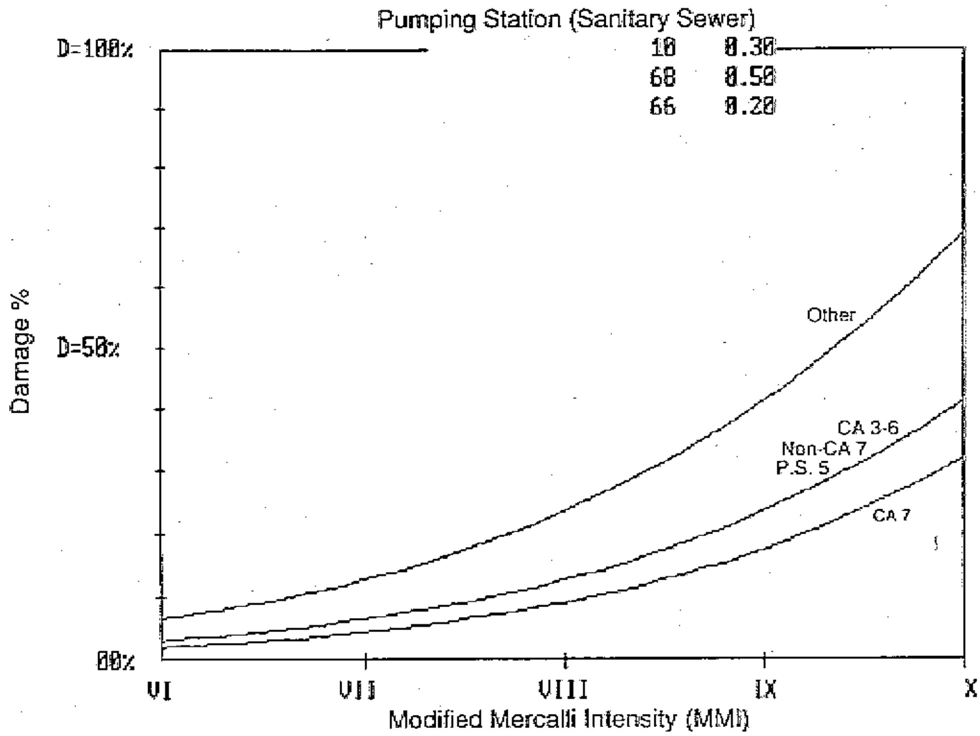

Figure B-92 Damage percent by intensity for sanitary sewer pumping stations.

penetrations in massive structures to prevent pipe damage in the event of differential settlement. All mechanical and electrical equipment should be anchored and equipment on isolators properly snubbed. Buildings housing equipment should be designed in accordance with seismic provisions of a local or national building code. Provisions for emergency power should be made for pumping stations critical to systems operation.

2. Direct Damage

Basis: Damage curves for pumping stations for the sanitary sewer system (see Figure B-92) are based on ATC-13 data for FC 10, medium-rise reinforced masonry shear wall buildings; FC 66, electrical equipment, and FC 68, mechanical equipment (see attached figure). FC 10 was chosen to represent a generic building, based on review of damage curves for all buildings. Pumping stations are assumed to be a combination of 30% generic buildings, 20% electrical equipment, and 50% mechanical equipment. Pumping plants in the sewage system are assumed to be located in poor soil areas. Consequently, the detrimental intensity shift indicated below for mechanical and electrical equipment is assumed appropriate.

Standard construction is assumed to represent typical California pumping stations for sanitary sewer systems under present conditions (i.e., a composite of older and more modern stations). Only minimal regional variation in construction quality of mechanical equipment is assumed.

Present Conditions: In the absence of data on the type of pumps, age, etc., the following factors were used to modify the mean curves for each of the three facility classes listed above, under present conditions:

	MMI Intensity Shift		
NEHRP Map Area	*FC 10*	*FC 66*	*FC 68*
California 7	0	0	+1
California 3-6	+1	+1	+1
Non-California 7	+1	+1	+1
Puget Sound 5	+1	+1	+1
All other areas	+2	+2	+2

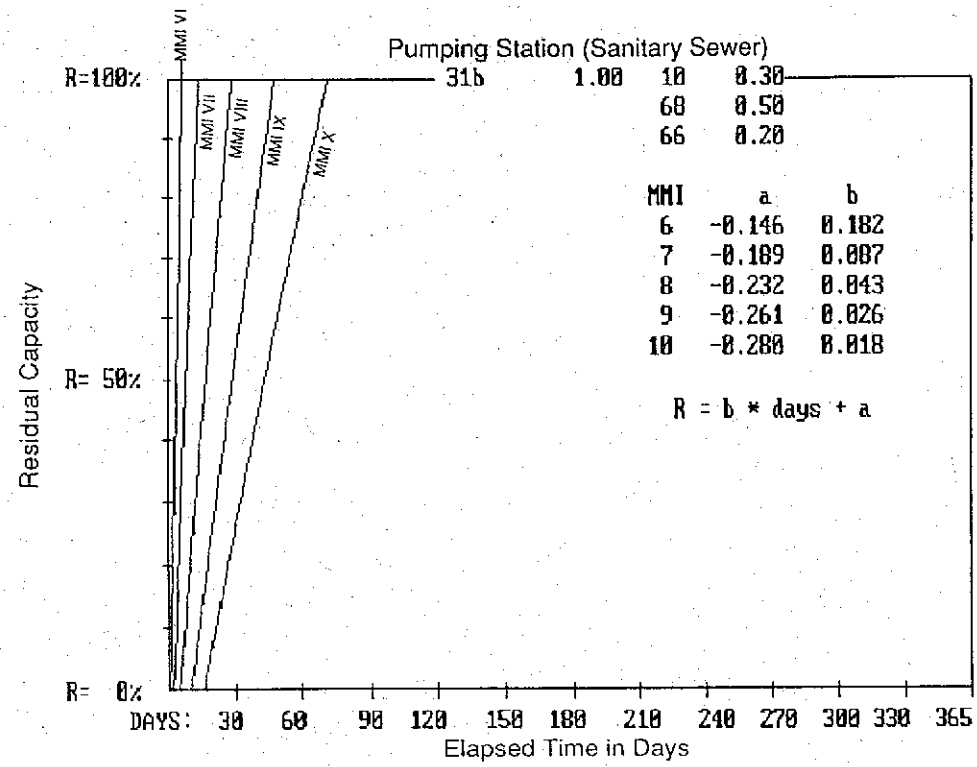

Figure B-93 Residual capacity for sanitary sewer pumping stations (NEHRP California 7).

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 31b, booster pumping and main sewer pumping stations, are assumed to apply to all pumping stations in the sanitary sewer system. By combining these data with the damage curves derived using the data for FC 10, 66, and 68, the time-to-restoration curves shown in Figures B-93 through B-95 were derived.

B.7.3 Treatment Plants

1. General

Description: Treatment plants in the sanitary sewer system are complex facilities which include a number of buildings (commonly reinforced concrete) and underground or on-ground reinforced concrete tank structures or basins. Common components at a treatment plant include trickling filters, clarifiers, chlorine tanks, re-circulation and wastewater pumping stations, chlorine storage and handling, tanks, and pipelines. Concrete channels are frequently used to convey the wastewater from one location to another within the complex. Within the buildings are mechanical, electrical, and control equipment, as well as piping and valves. Conventional wastewater treatment consists of preliminary processes (pumping, screening, and grit removal), primary settling to remove heavy solids and floatable materials, and secondary biological aeration to metabolize and flocculate colloidal and dissolved organics. Waste sludge may be stored in a tank and concentrated in a thickener. Raw sludge can be disposed of by anaerobic digestion and vacuum filtration, with centrifugation and wet combustion also currently used. Additional preliminary treatments (flotation, flocculation, and chemical treatment) may be required for industrial wastes. Preliminary treatment units vary but generally include screens to protect pumps and prevent solids from fouling grit-removal units and flumes. Primary treatment typically comprises sedimentation, which removes up to half of the suspended solids. Secondary treatment

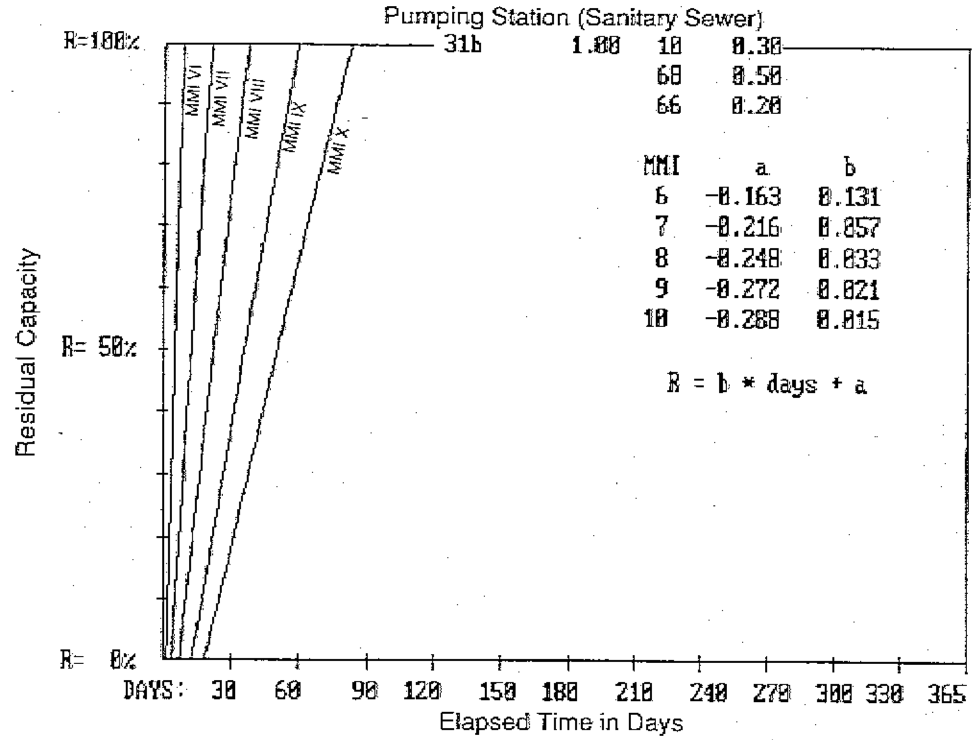

Figure B-94 Residual capacity for sanitary sewer pumping stations (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

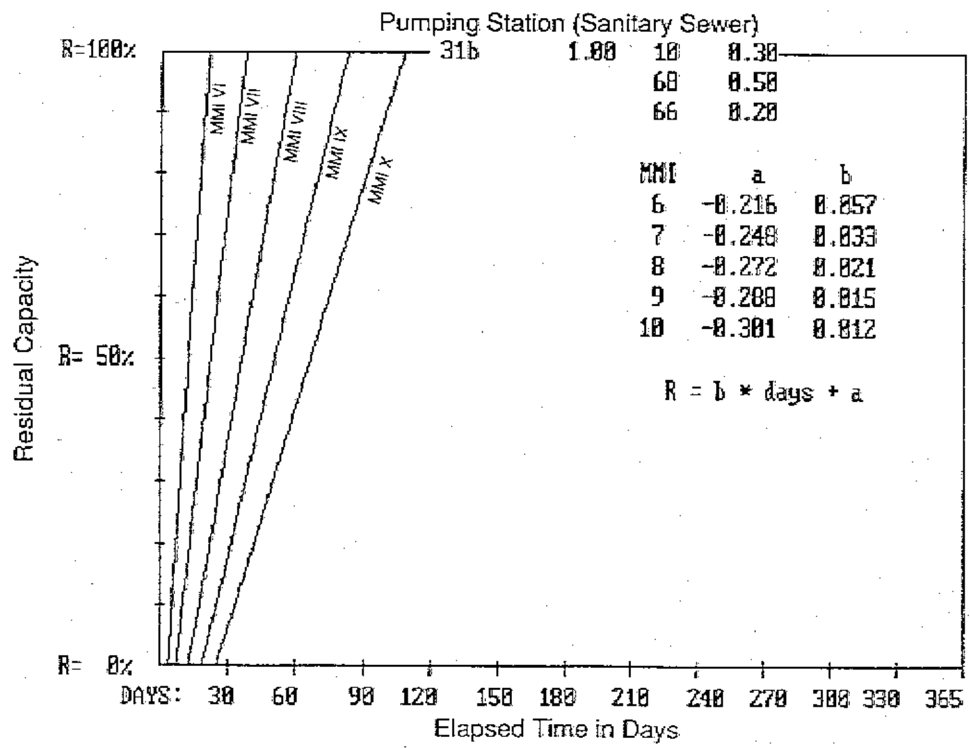

Figure B-95 Residual capacity for sanitary sewer pumping stations (All other areas).

removes remaining organic matter using activated-sludge processes, trickling filters, or biological towers. Chlorination of effluents is commonly required.

Typical Seismic Damage: Sanitary sewer treatment plants are commonly located in low-lying areas on soft alluvium. Consequently, soil failure (e.g., liquefaction or settlement) is common. Many of the heavy structures are supported on foundations that include piles. Differential settlements between these structures and structures not supported on piles will result in damage to pipes or conduit, especially at structure penetrations. Liquefaction may cause some underground structures to float in areas of high groundwater. Pumps and other equipment can be damaged by loads imposed by piping when differential settlement occurs. Generic building damage ranging from cracked walls and frames to collapse may occur. Unanchored equipment may slide or topple, rupturing attached piping and conduit. Damage to substation transformers can result in a loss of power supply. Damage as the result of sloshing or wave action is likely in basins that contain rotating equipment or other moving devices. Basin walls may crack or collapse. Pounding damage or permanent movement may result in the opening of expansion joints in basins.

Seismically Resistant Design: Seismically resistant design practice includes siting treatment plants in areas of stable soil, or designing foundations and systems to perform adequately in the event of expected soil failure. Each structure should be supported on one foundation type only if adjacent structures have different foundation types; structures should be adequately separated; and piping and other systems spanning between structures should be provided with adequate flexibility to accommodate relative motions. Piping should be provided with annular space where it penetrates heavy structures to accommodate settlement. Buildings should be designed in accordance with the seismic requirements of a local or national building code. Walls for all basins should be designed for a combination of soil and hydrodynamic pressures, taking into consideration the possibility of soil failure. All backfills should be compacted properly to avoid liquefaction. If buoyant loading is possible, foundations should be designed to resist such loading. All equipment should be properly anchored, and equipment on base isolators properly snubbed. Arms, rakes, and other equipment in basins should be designed for hydrodynamic forces associated with sloshing. Embankment stability and considerations for buried piping should be taken into account for sewage outfalls. Outfall diffusers are also subjected to hydrodynamic forces, which should be included in design consideration.

2. Direct Damage

Basis: Damage curves for treatment plants in the sanitary system are based on ATC-13 data for FC 10, medium-rise reinforced masonry shear wall buildings; FC 41, underground liquid storage tanks; and FC 68, mechanical equipment (see Figure B-96). FC 10 was chosen to represent a generic building, based on review of damage curves for all buildings. Sanitary sewer treatment plants are assumed to a combination of 20% generic buildings, 30% underground storage tanks, and 50% mechanical equipment. Treatment plants in the sewage system are assumed to be located in poor soil areas. Consequently, the detrimental intensity shift indicated below for mechanical equipment is assumed appropriate.

Standard construction is assumed to represent typical California treatment plants under present conditions (i.e., a composite of older and more modern treatment plants). It is assumed that minimal regional variation exists in construction quality of underground storage tanks and mechanical equipment. Seismic loads have little impact on underground storage tank design, and operational loads often govern over seismic requirements in the design of mechanical equipment.

Present Conditions: In the absence of data on the type of construction, age, etc., the following factors were used to modify the mean curves for each of the three facility classes listed above, under present conditions:

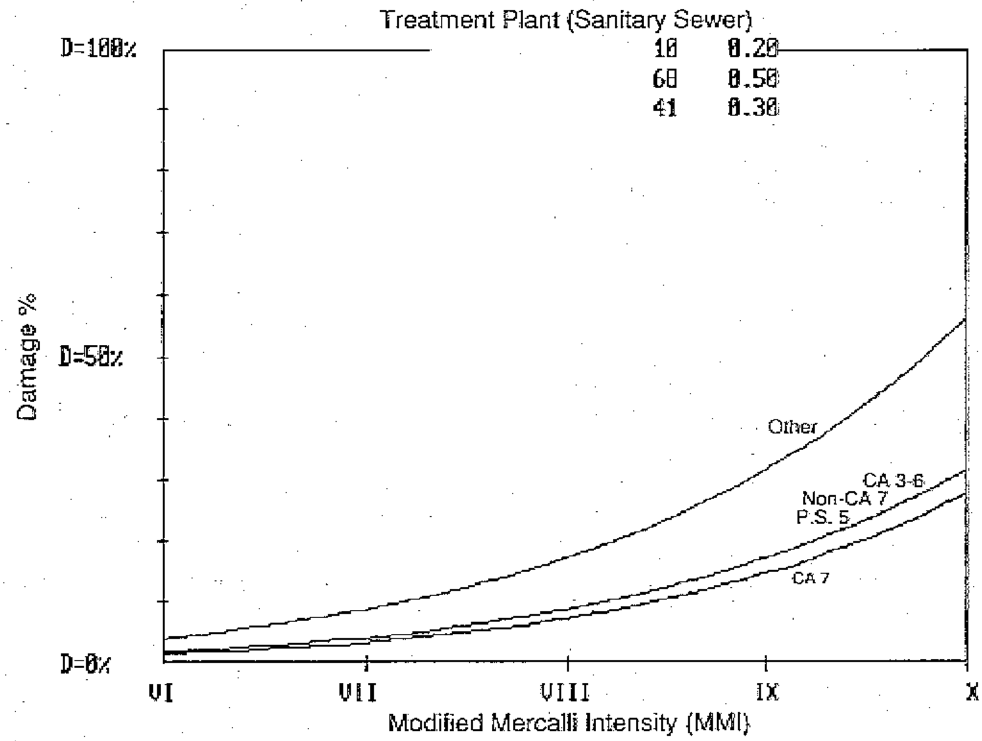

Figure B-96 Damage percent by intensity for sanitary sewer treatment plants.

	MMI Intensity Shift		
NEHRP Map Area	*FC 18*	*FC 41*	*FC 68*
California 7	0	+1	+1
California 3-6	+1	+1	+1
Non-California 7	+1	+1	+1
Puget Sound 5	+1	+1	+1
All other areas	+2	+2	+2

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit, relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 31c, treatment plants in the sanitary sewer system, are assumed to apply to all treatment plants. By combining these data with the damage curves derived using data for FC 10, 41, and 68, the time-to-restoration curves shown in Figures B-97 through B-99 were derived.

B.8 Natural Gas

B.8.1 Transmission Lines

1. General

Description: In general, transmission lines in the natural-gas system are located underground, except where they cross rivers or gorges, or where they emerge for connection to compressor or pumping stations. They are virtually always welded steel and operate at high pressures. Transmission pipelines range between 2 and 25 inches in diameter, but most are larger than 12 inches. Shut-off valves, which automatically function when line pressure drops below a certain threshold pressure, are frequently included.

Typical Seismic Damage: The performance of pipelines is strongly dependent on whether or not the supporting soil fails. Routes are often selected along the edges of river channels to avoid urban buildup and street crossings and to simplify the acquisition of real estate. Such routes have high liquefaction potential. Failures in the past have typically occurred at sharp vertical

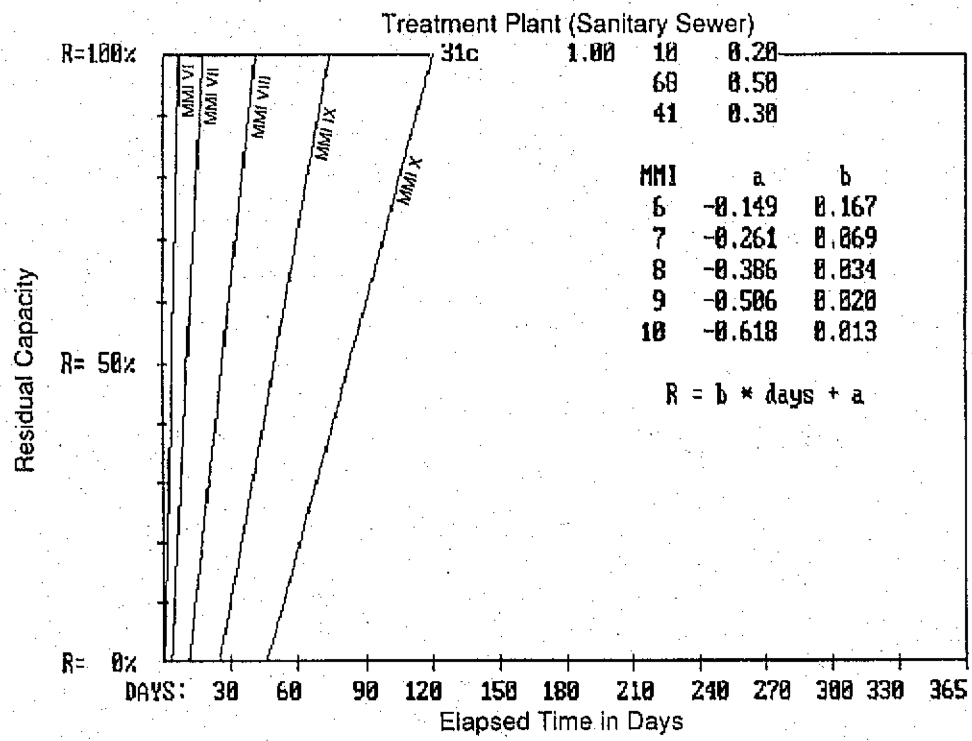

Figure B-97 Residual capacity for sanitary sewer treatment plants (NEHRP California 7).

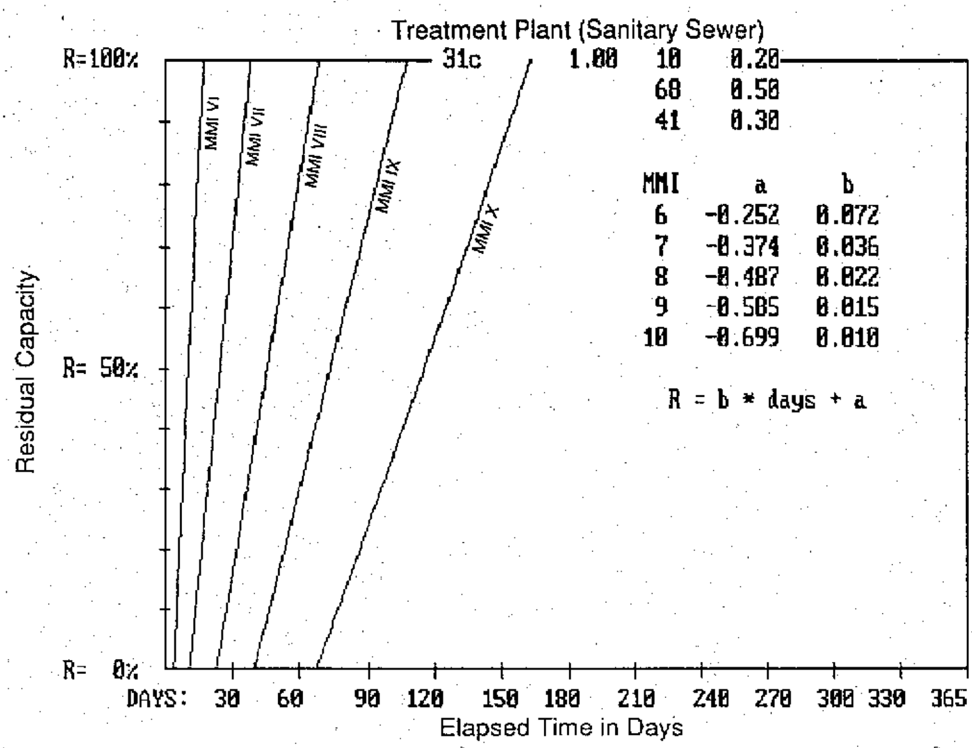

Figure B-98 Residual capacity for sanitary sewer treatment plants (NEHRP Map Area 3-6, Non-California 7, and Puget Sound 5).

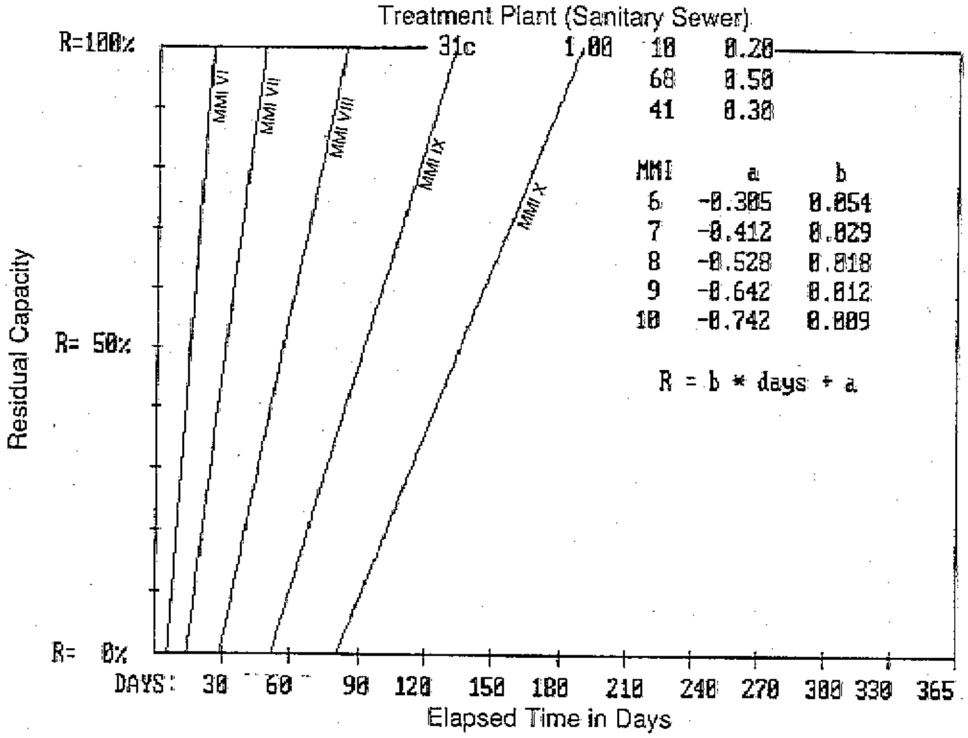

Figure B-99 Residual capacity for sanitary sewer treatment plants (All other areas).

or lateral dislocations or ruptures of the ground. Pipes may buckle under compressive forces, especially where they cross ruptured faults. Damage has also occurred as a result of axial elongations caused by relative movement of two horizontally adjacent soil layers. Damage may occur because of displacements of unanchored compressors or pumps or other above ground structures. Several past failures have been attributed to corrosion combined with surges in line pressure during the earthquake. Failures of above ground lines have been caused by support failure, failure of pipeline attachment to support structure, and relatively large support movement. Rupture of pipes and loss of contents could lead to fire and explosions.

Seismically Resistant Design: Modern high-pressure gas lines provided with proper full penetration welds and heavy walls are very ductile and have considerable resistance to earthquake damage. Welded steel pipeline performance depends on the integrity of the welds--modern butt-welded pipelines perform well, whereas gas lines constructed before and during the early 1930s using oxyacetylene and electric-arc welds do not.

Special precautions should be taken to reduce earthquake effects at bay, river, and fault crossings. Transmission lines at fault crossings should be buried in shallow loose fill or installed above ground near the fault to allow lateral and longitudinal slippage. Anchors such as thrust blocks or bends should be excluded within a distance of 300 feet of a fault zone, and strengthened pipe should be used within the zone. Valve spacing near fault zones or in areas of expected soil failure should be reduced. Automatic shut-off valves should not rely on electricity to operate. Proper maintenance to limit corrosion, which weakens pipes, is important to mitigate damage.

1. Direct Damage

Basis: Damage curves for transmission lines in the natural-gas system are based on ATC-13 data for FC 31, underground pipelines (see Figure B-100). Transmission pipelines are typically large-diameter, welded steel pipes that are expected to perform in earthquakes in a manner superior to that of typical underground pipelines, as indicated by the beneficial intensity shift below.

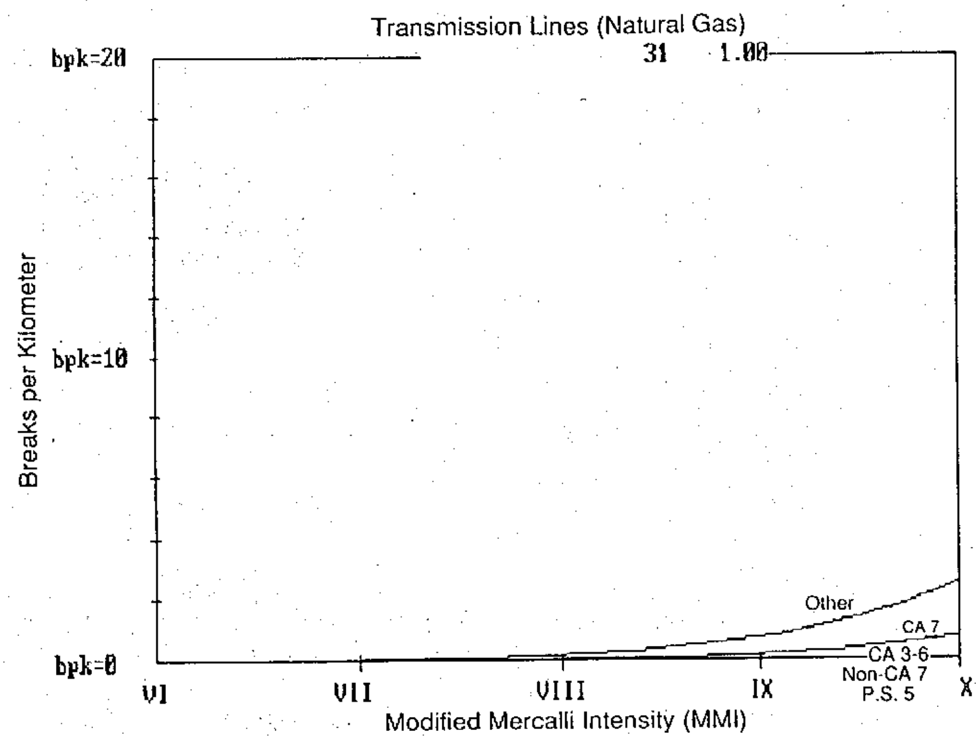

Figure B-100 Damage percent by intensity for natural gas transmission lines.

Standard construction is assumed to represent typical California natural-gas transmission lines under present conditions (i.e., a composite of older and more modern transmission lines). Only minimal regional variation in the construction quality is assumed.

Present Conditions: In the absence of data on the type of material, diameter, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	MMI Intensity Shift
California 7	-1
California 3-6	-1
Non-California 7	-1
Puget Sound 5	-1
All other areas	0

Upgraded Conditions: It is not cost-effective or practical to upgrade existing natural-gas transmission lines, except perhaps at fault crossings or in areas of extremely unstable soils. Therefore, no intensity shifts for retrofitting are recommended.

Time-to-restoration: The time-to-restoration data assigned to SF 32a, transmission lines, are assumed to apply to all transmission lines in the natural-gas system. By combining these data with the damage curves for FC 31, the time-to-restoration curves shown in Figures B-101 and B-102 were derived.

B.8.2 Compressor Stations

1. General

Description: In general, compressor stations include a variety of electrical and mechanical equipment, as well as structures and buildings. A typical plant yard may contain electrical equipment, heat exchangers, horizontal gas-storage tanks on plinths, compressors, fans, air-operated valves, pumps, cooling towers, steel stacks and columns, and piping. The control equipment is usually located in a control building. Cryogenic systems may also exist

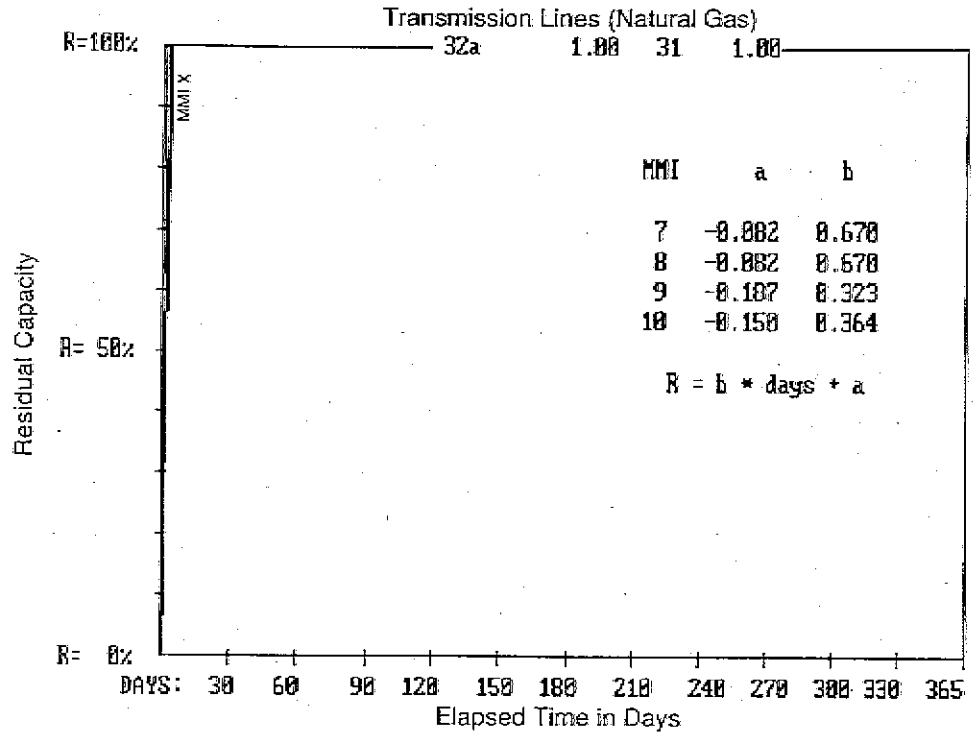

Figure B-101 Residual capacity for natural gas transmission lines (NEHRP Map Area: California 3-6, California 7, Non-California 7, and Puget Sound 5).

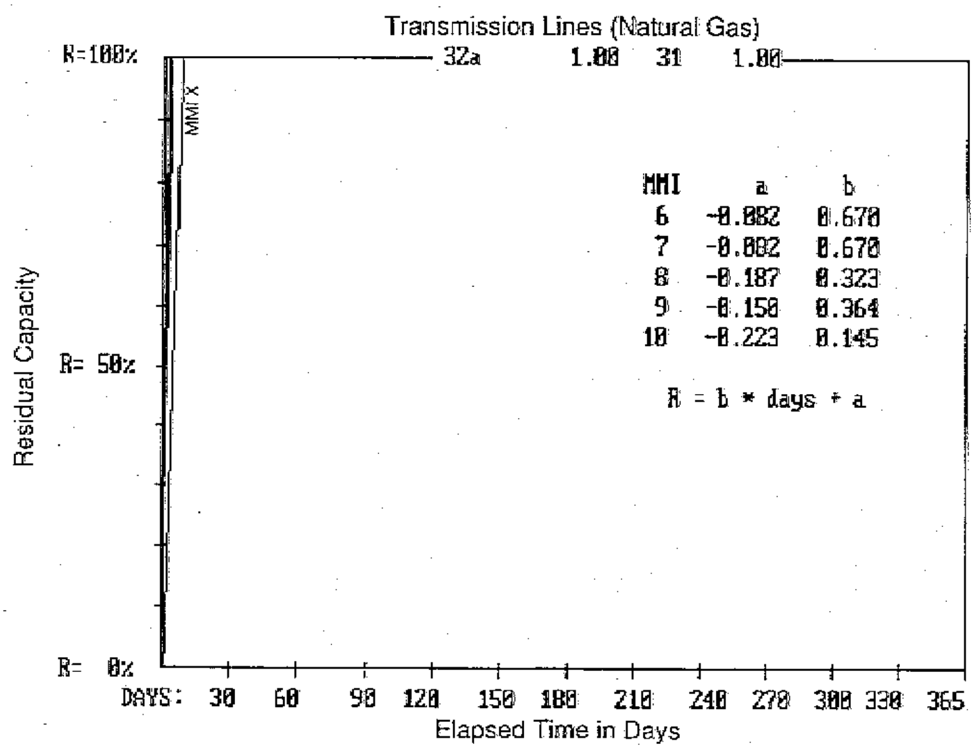

Figure B-102 Residual capacity for natural gas transmission lines (All other areas).

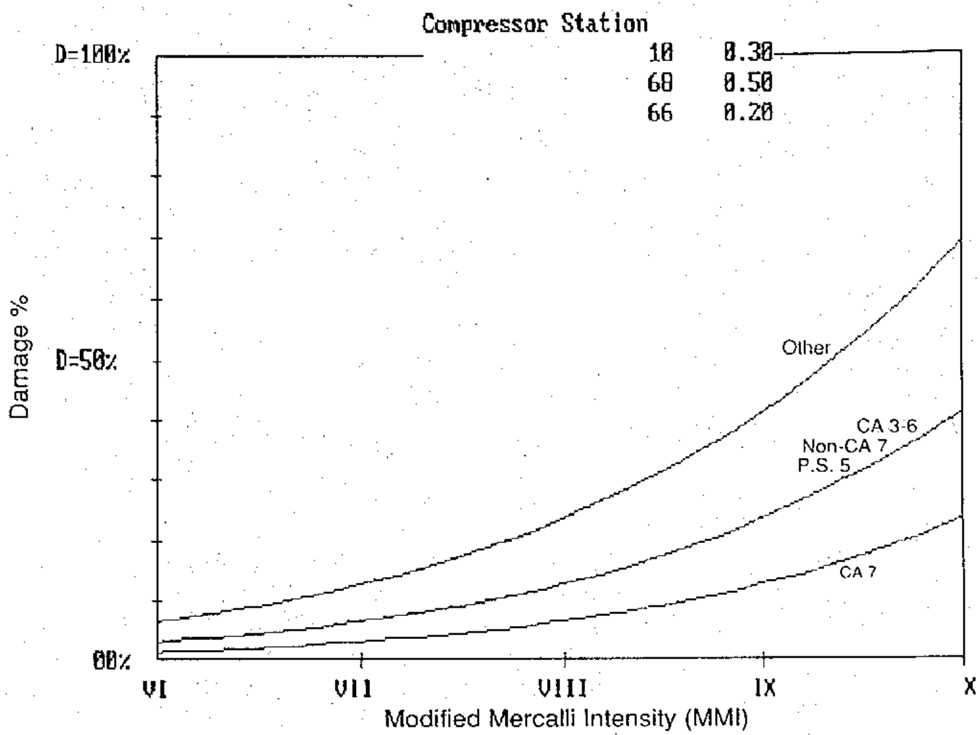

Figure B-103 Damage percent by intensity for compressor stations.

on the site. Compressors are typically used to boost pressures in long distance transmission lines.

Typical Seismic Damage: Damage experienced at the site may include sliding and toppling of unanchored equipment, stretching of anchor bolts on stacks and columns, damage to old timber cooling towers, and sliding of unrestrained horizontal tanks on plinths. Piping may rupture because of movement of attached unanchored equipment. Generic building damage ranging from cracking of frames and walls to partial or total collapse may be experienced by the control building and other buildings.

Seismically Resistant Design: Seismically resistant design practices include designing the buildings and structures in accordance with the seismic requirements of a local or national building code. In addition, all equipment should be well anchored and equipment on isolators properly snubbed. Inspection and maintenance of timber cooling towers and piping can mitigate damage. Anchor bolts on stacks should be designed to yield over a long length to dissipate energy.

2. Direct Damage

Basis: Damage curves for compressor stations in the natural-gas system are based on ATC-13 data for FC 10, medium-rise reinforced masonry shear wall buildings; FC 66, electrical equipment; and FC 68, mechanical equipment (see Figure B-103). Compressor stations are assumed to be a combination of 30% generic buildings, 20% electrical equipment, and 50% mechanical equipment.

Standard construction is assumed to represent typical California compressor stations under present conditions (i.e., a composite of older and more modern stations). Only minimal regional variation in construction quality of mechanical equipment is assumed.

Present Conditions: In the absence of data on the type of material, age, etc., the following factors were used to modify the mean curves for each of the three facility

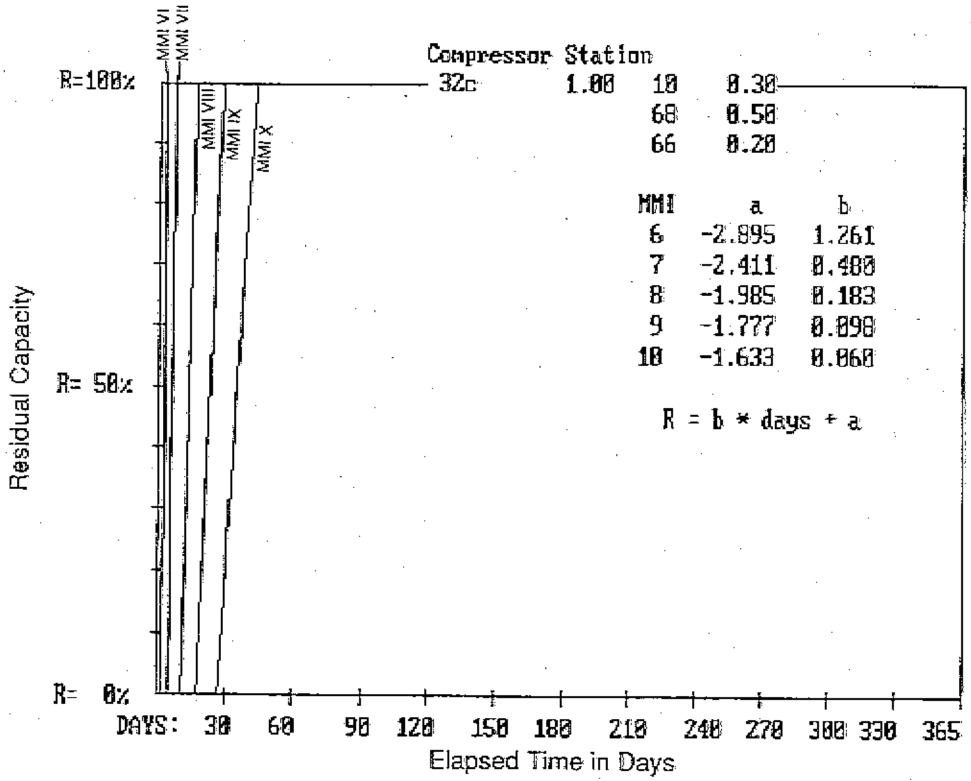

Figure B-104 Residual capacity for compressor stations (NEHRP California 7).

classes listed above, under present conditions:

NEHRP Map Area	MMI Intensity Shift FC 10	FC 66	FC 68
California 7	0	0	0
California 3-6	+1	+1	0
Non-California7	+1	+1	0
Puget Sound 5	+1	+1	0
All other areas	+2	+1	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 32c, compressor stations, high-pressure holders, and mixer/switching terminals, are assumed to apply to all compressor stations in the natural-gas system. By combining these data with the damage curves derived using the data for FC 10, 66, and 68, the time-to-restoration curves shown in Figures B-104 through B-106 were derived.

B.8.3 Distribution Mains

1. General

Description: In general, the distribution mains in the natural-gas system are located underground, except where they cross rivers or gorges or where they emerge for connection to compressor or pumping stations. They typically are between 2 and 20 inches in diameter and may be composed of steel, cast iron, ductile iron, or plastic. Approximately 80% of all new distribution piping is made of plastic. Shut-off valves, which automatically function when line pressure drops below a certain threshold pressure, are frequently used.

Typical Seismic Damage: The performance of pipelines is strongly dependent on whether or not the supporting soil fails. Routes are often selected along the edges of river channels to avoid urban buildup and street crossings and to simplify the

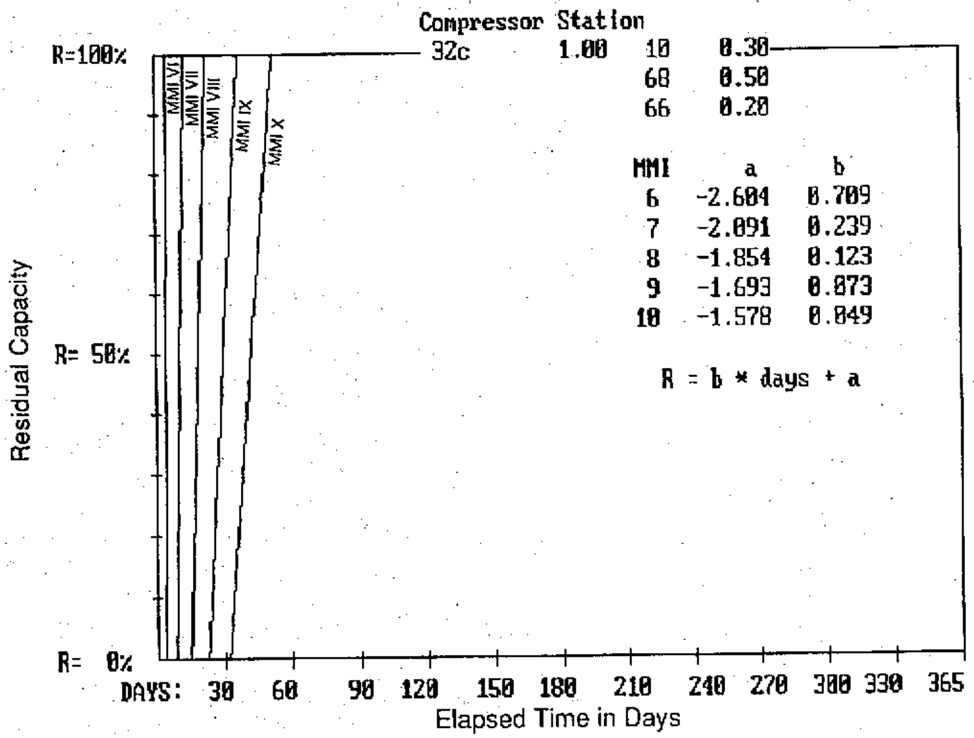

Figure B-105 Residual capacity for compressor stations (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

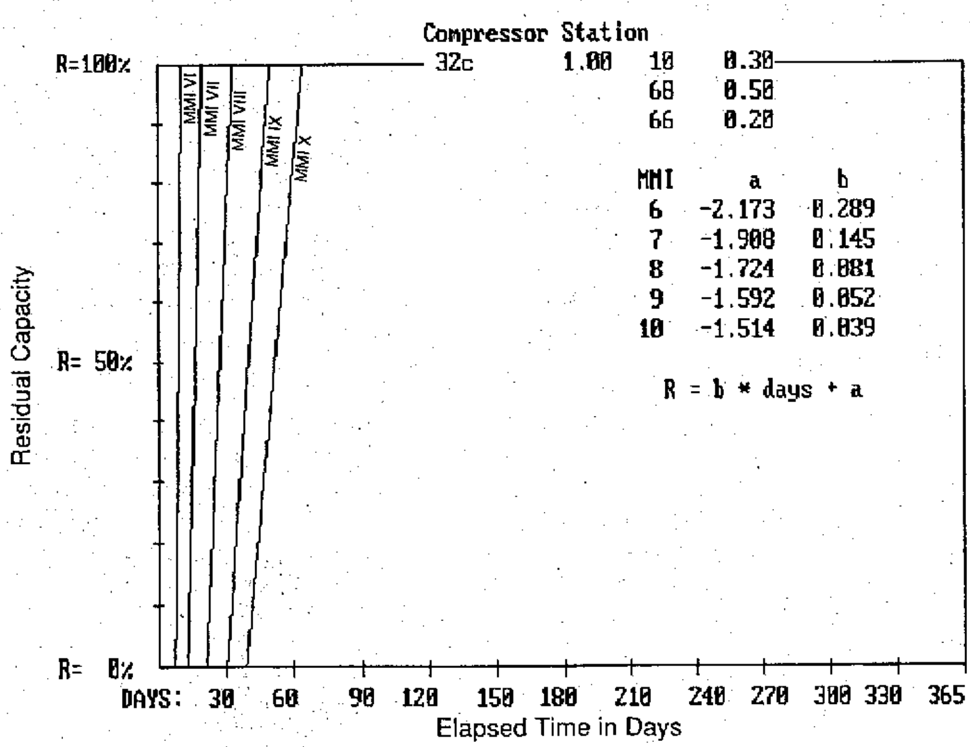

Figure B-106 Residual capacity for compressor stations (All other areas).

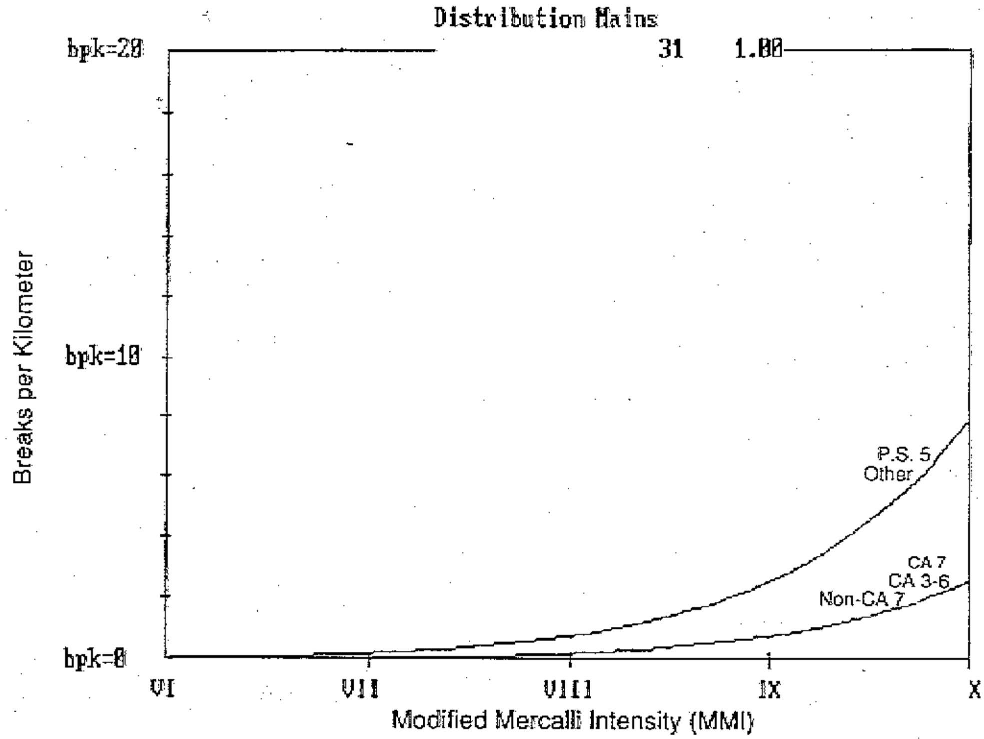

Figure B-107 Damage percent by intensity for natural gas distribution mains.

acquisition of real estate. Such routes have high liquefaction potential. Pipe damage is most common in soft alluvial soils, at interfaces between soft and firm soils, at locations of fault ruptures, or at sharp vertical or lateral dislocations or ruptures of the ground. Pipes may buckle under compressive forces, especially where they cross ruptured faults. Damage may occur as a result of displacements of unanchored compressors or pumps or other above ground structures. Several past failures have been attributed to corrosion combined with surges in line pressure during the earthquake. Rupture of pipes and loss of contents could lead to fire, explosions, or both.

Seismically Resistant Design: Seismically resistant design provisions for distribution piping are typically minimal. Consequently, large urban distribution systems should have suitable valving installed so that large areas can be broken down into zones. Special precautions should be taken to reduce earthquake effects at bay, river, and fault crossings. Distribution mains at fault crossings should be buried in shallow loose fill or installed above ground near the fault to allow lateral and longitudinal slippage. Anchors such as thrust blocks or bends should be excluded within a distance of 300 feet of a fault zone and strengthened pipe should be used within the zone. Valve spacing near fault zones or in areas of expected soil failure should be reduced. Automatic shut-off valves, which operate when pressure reduces, should not rely on electricity to operate. Proper maintenance to limit corrosion, which weakens pipes, is important for mitigating damage.

2. Direct Damage

Basis: Damage curves for distribution mains in the natural-gas system are based on ATC-13 data for FC 31, underground pipelines (see Figure B-107). Standard construction is assumed to represent typical California distribution mains under present conditions (i.e., a composite of older and more modern mains). Minimal regional variation in construction quality is assumed.

Present Conditions: In the absence of data on the type of material, diameter, age, etc., the following factors were used to modify the mean curves, under present conditions:

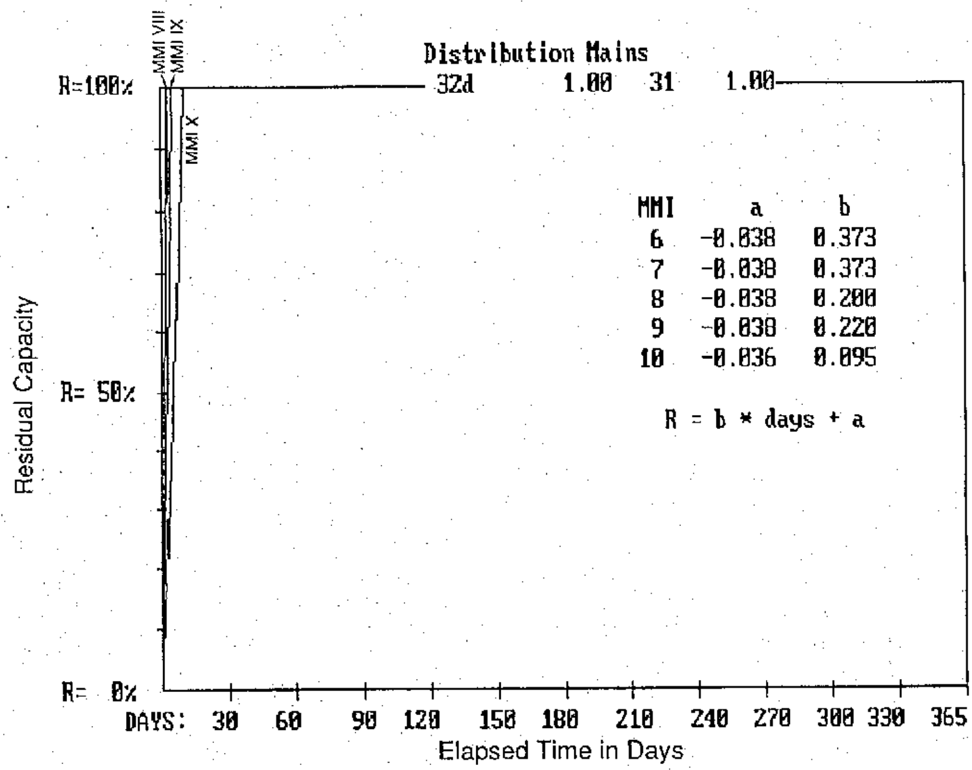

Figure B-108 Residual capacity for natural gas distribution mains (NEHRP Map Area: California 3-6, California 7, and Non-California 7).

NEHRP Map Area	MMI Intensity Shift
California 7	0
California 3-6	0
Non-California 7	0
Puget Sound 5	+1
All other areas	+1

Upgraded Conditions: It is not cost-effective or practical to upgrade existing natural-gas distribution mains, except perhaps at fault crossings or in areas of extremely unstable soils. Therefore, no intensity shifts for retrofitting are recommended.

Time-to-restoration: The time-to-restoration data assigned to SF 32d, distribution feeder mains, are assumed to apply to all distribution mains in the natural-gas system. By combining these data with the damage curves for FC 31, the time-to-restoration curves shown in Figures B-108 and B-109 were derived.

B.9 Petroleum Fuels

B.9.1 Oil Fields

1. General

Description: In general, oil fields in the petroleum fuels system may includes pressure vessels, demineralizers, filters, vertical tanks, horizontal water and oil pumps, large heat exchangers, air compressors, extensive piping, and air-operated valves. Additionally they may include their own water treatment plant, which demineralizes and filters water before it is injected as steam into oil wells in the area. Control houses with control equipment may monitor production and flow in and out of the field.

Typical Seismic Damage: Building damage may range from cracks in walls and frames to partial and total collapse. Unanchored or improperly anchored equipment may slide or topple, experiencing damage or causing attached piping and conduit to fail. Well

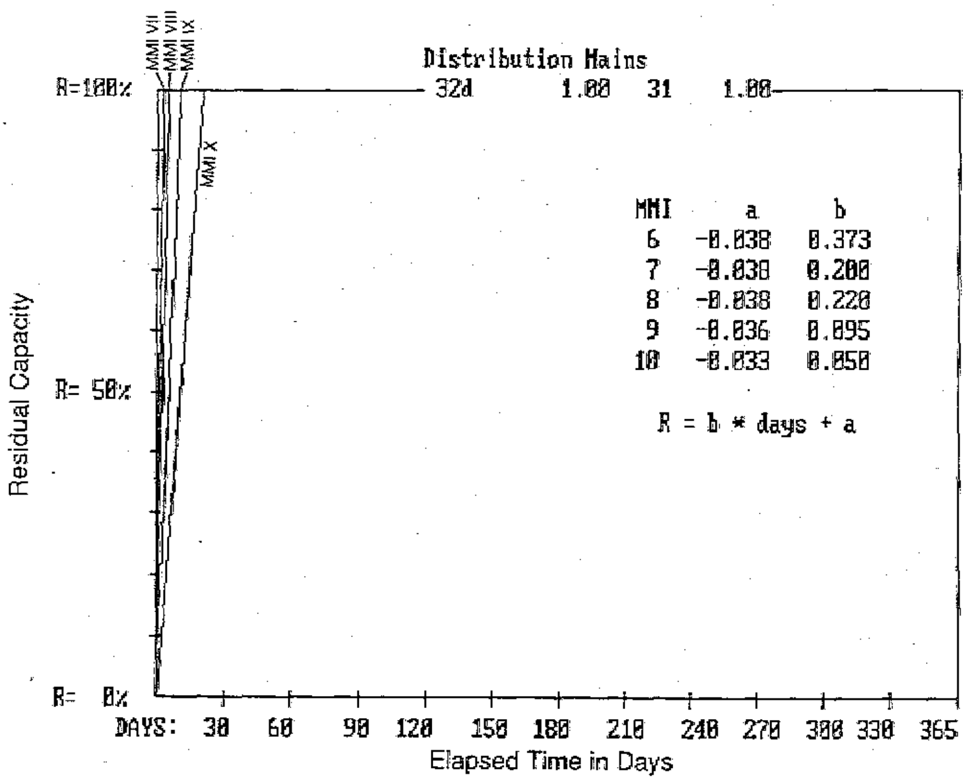

Figure B-109 Residual capacity for natural gas distribution mains (Puget Sound 5 and all other areas).

casings will move with the surrounding soils and may result in damage to the oil pumps. Reduction or increase in production may occur after an earthquake as a result of geological changes in the oil field.

Seismically Resistant Design: Buildings should be designed in accordance with the seismic provisions of a local or national building code. All equipment should be well anchored.

2. Direct Damage

Basis: Damage curves for oil fields in the petroleum fuels system (see Figure B-110) are based on ATC-13 data for FC 68, mechanical equipment. It is believed that this facility class best approximates the expected performance of oil fields.

Standard construction is assumed to represent typical California oil fields under present conditions (i.e., a composite of older and more modern fields). Only minimal regional variation in the construction quality is assumed, as shown in the intensity shift factors below.

Present Conditions: In the absence of data on the type of equipment, age, etc., the following factors were used to modify the mean curve, under present conditions:

NEHRP Map Area	*MMI Intensity Shift*
California 7	0
California 3-6	0
Non-California 7	0
Puget Sound 5	0
All other areas	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 18a, is assumed to apply to all oil fields. By combining these data with the damage

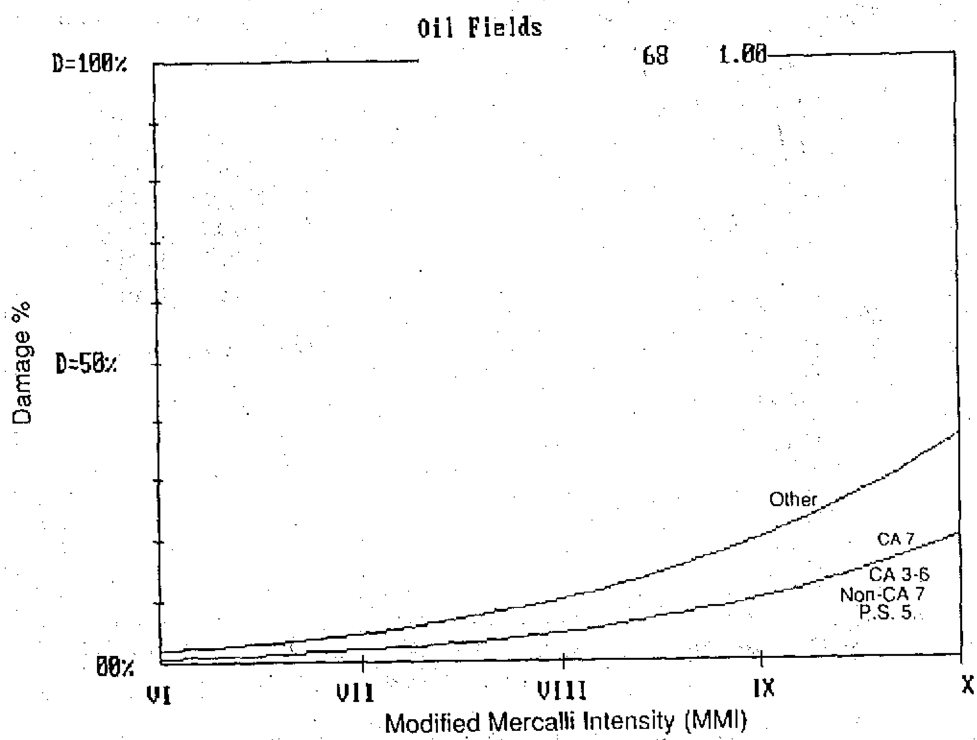

Figure B-110 Damage percent by intensity for oil fields.

curves for FC 68, the time-to-restoration curves shown in Figures B-111 and B-112 were derived.

B.9.2 Refineries

1. General

Description: The typical oil refinery is a complex facility with many different types of buildings, structures, and equipment. Tank storage for the various products produced at the refinery can consist of unanchored vertical storage tanks supported on the ground, horizontal pressurized storage tanks supported on steel or concrete plinths, and spherical tanks supported on legs. Refineries also include a large number of steel stacks or columns anchored to concrete foundations. Throughout the refinery there are extensive runs of piping, both on the ground and elevated. Mechanical equipment throughout the refinery includes pumps, heat exchangers, furnaces, motors, and generators. Electrical equipment includes transformers, switchgear, and motor control centers. Control rooms house control equipment. Timber cooling towers, refueling stations, administrative buildings, and wharf loading facilities are also included in some refineries.

Typical Seismic Damage: A major concern after any earthquake that affects a refinery is fire. Loss of contents from any one of a large number of tanks could lead to a fire that could spread throughout the facility. Similarly, toxic release and air emissions are also serious concerns. The large cylindrical ground-mounted steel tanks are typically the most vulnerable components at the refinery and can suffer tank-wall buckling, bottom rupture, wall-to-bottom weld failure, roof damage, settlement, or pipe failure. Piping systems can experience flange separations, damage to supports, rupture at connections to unanchored equipment, and valve damage. Mechanical equipment with inadequate anchorage can slide or topple. Buildings and structures can experience generic structural damage ranging from cracks in walls and frames to partial or complete collapse. Control room panels may

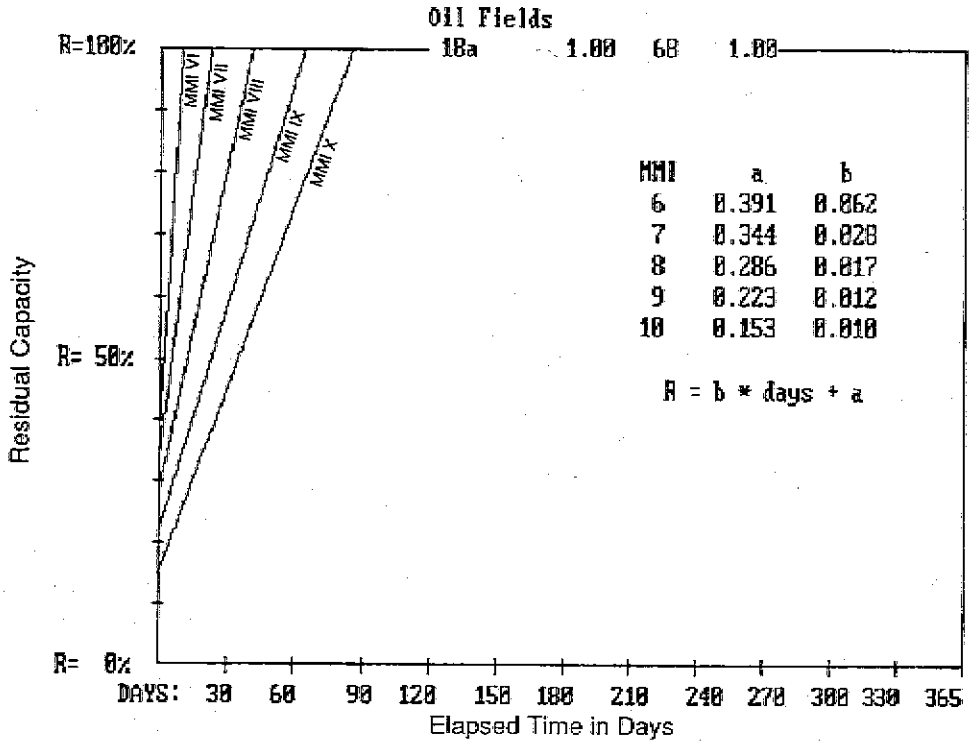

Figure B-111 Residual capacity for oil fields (NEHRP Map Area: California 3-6, California 7, Non-California 7, and Puget Sound 5).

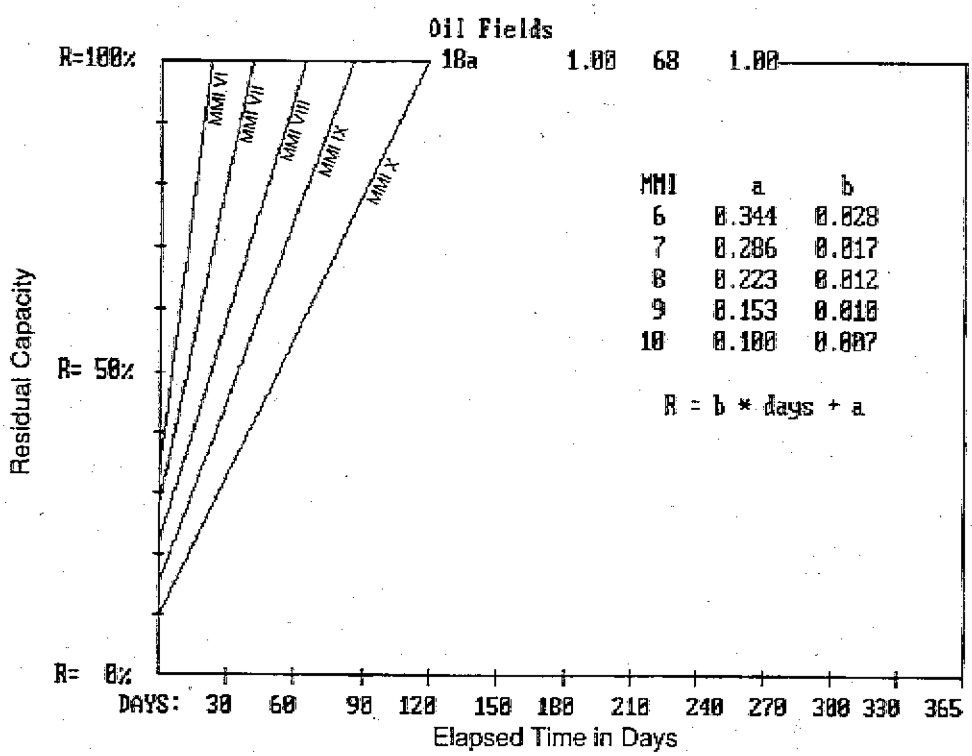

Figure B-112 Residual capacity for oil fields (All other areas).

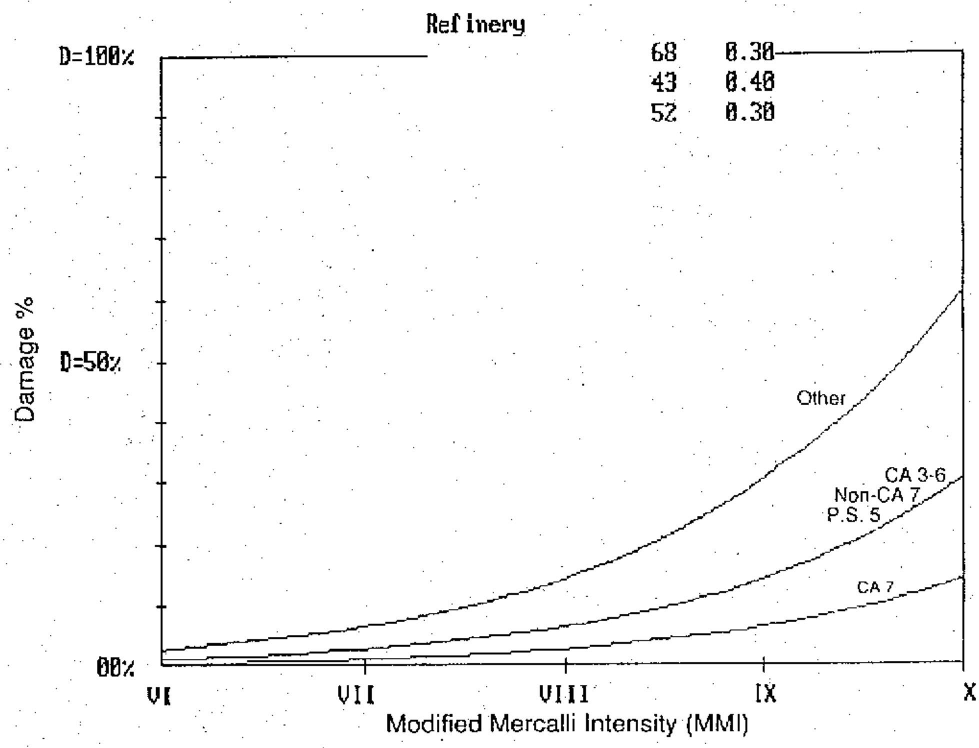

Figure B-113 Damage percent by intensity for oil refineries.

slide or topple, or experience relay problems. Stacks or columns may stretch anchor bolts. Horizontal tanks may slide on their plinths and rupture attached piping. Brick linings in boilers may break.

Seismically Resistant Design: Seismically resistant design practices include design of all buildings and structures (including tanks) for seismic requirements in a local or national code. Storage tanks should be provided with flexible piping, pressure relief valves, and well-compacted foundations resistant to differential settlement. Retention dikes with sufficient capacity to retain all of the oil contained in the enclosed tanks are necessary to mitigate the danger of catastrophic fire after an earthquake. Embankments for such dikes should be stable when subjected to ground shaking. Horizontal tanks on plinths should be restrained to prevent attached pipes from rupturing. Long anchor bolts that are properly embedded in foundations should be used for heavy equipment and stacks. Mechanical and electrical equipment should be anchored to prevent sliding and toppling. Maintenance and inspection programs for cooling towers and piping should be implemented. Supports for piping should be designed for seismic loads. An emergency power system should be provided for control and emergency equipment as a minimum.

2. Direct Damage

Basis: Damage curves for refineries in the petroleum fuels system are based on ATC-13 data for FC 43, on-ground liquid storage tanks; FC 52, steel chimneys; and FC 68, mechanical equipment (see Figure B-113). Refineries are assumed to be a combination of 40% on-ground storage tanks, 30% chimneys, and 30% mechanical equipment.

Standard construction is assumed to represent typical California refineries under present conditions (i.e., a composite of older and more modern refineries). Only minimal regional variation in the construction quality of mechanical equipment is assumed, as operational loads frequently govern over seismic requirements.

Present Conditions: In the absence of data on the type of construction, age, etc., the following factors were used to modify the mean curves for each of the three facility

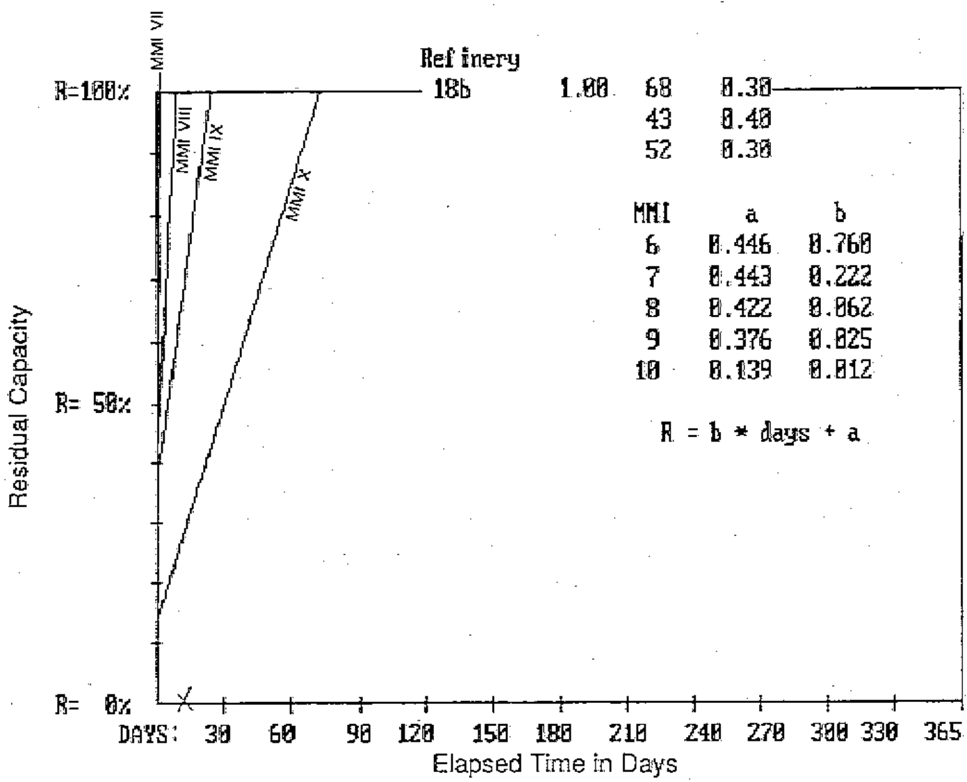

Figure B-114 Residual capacity for oil refineries (NEHRP California 7).

classes listed above, under present conditions:

	MMI Intensity Shift		
NEHRP Map Area	FC 43	FC 52	FC 68
California 7	0	0	0
California 3-6	+1	+1	0
Non-California 7	+1	+1	0
Puget Sound 5	+1	+1	0
All other areas	+2	+2	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in a beneficial intensity shift of one unit (i.e., -1), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 18b, refineries, are assumed to apply for all refineries in the petroleum fuels system. By combining these data with the damage curves derived using the data for FC 43, 52, and 68, the time-to-restoration curves shown in Figures B-114 through B-116 were derived.

B.9.3 Transmission Pipelines

1. General

Description: In general, transmission lines in the petroleum fuels system are located underground, except where they cross rivers or gorges, or where they emerge for connection to compressor or pumping stations. They are virtually always welded steel and operate at high pressures. Shut-off valves, which automatically function when line pressure drops below a certain threshold pressure, are frequently included.

Typical Seismic Damage: The performance of pipelines is strongly dependent on whether or not the supporting soil fails. Routes are often selected along the edges of river channels to avoid urban buildup and street crossings and to simplify the acquisition of real estate. Such routes have high liquefaction potentials. Failures in the past have typically occurred at sharp vertical

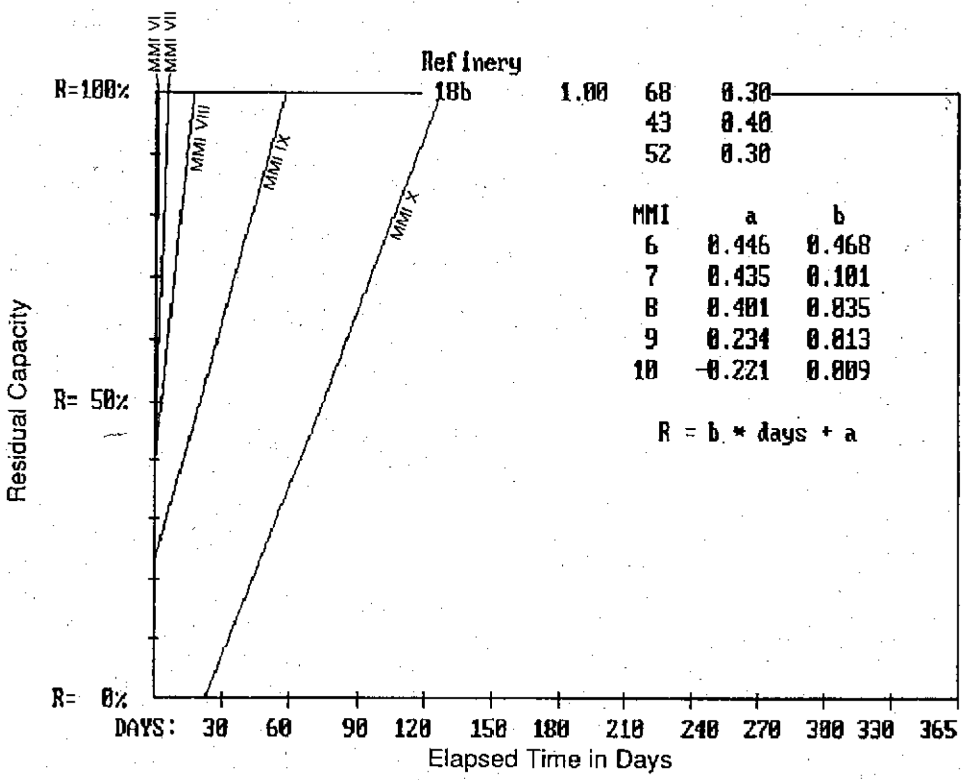

Figure B-115 Residual capacity for oil refineries (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

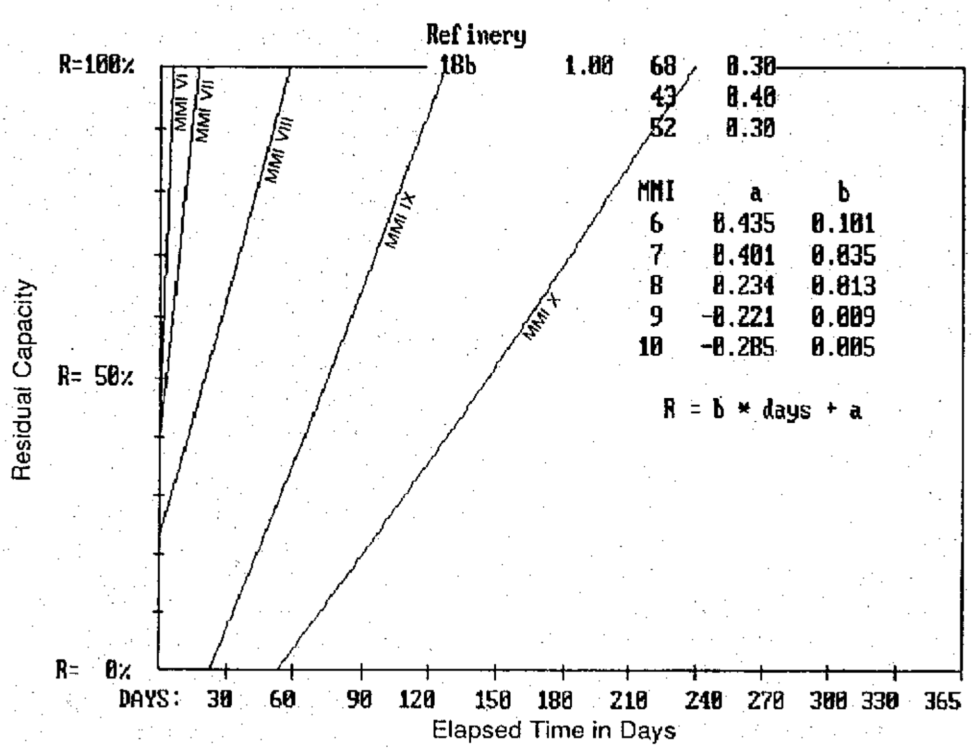

Figure B-116 Residual capacity for oil refineries (All other areas).

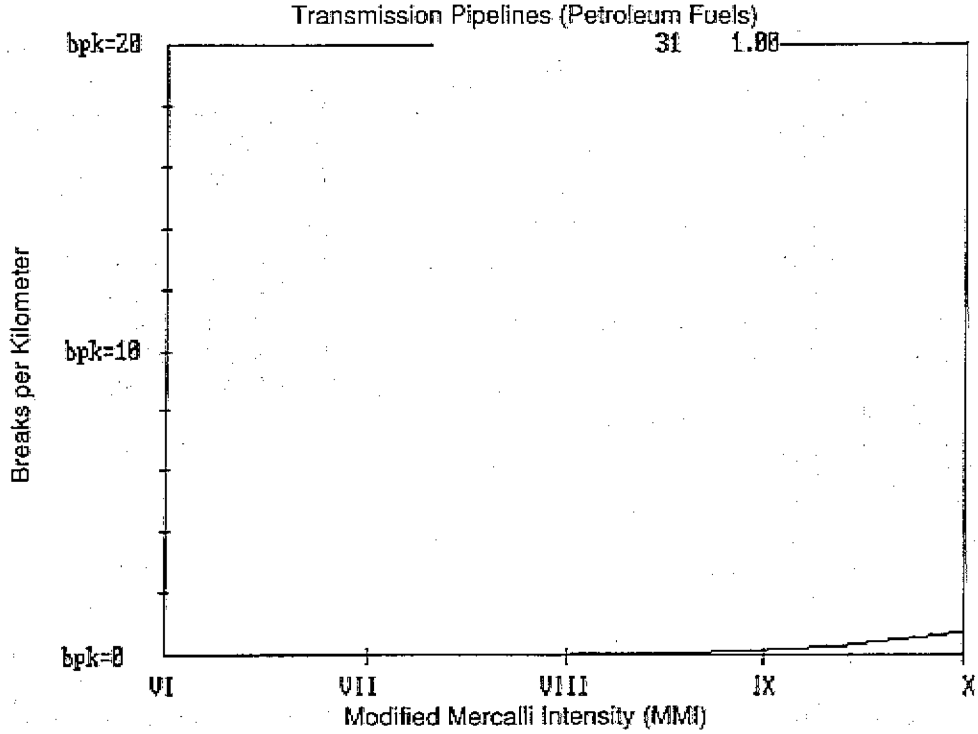

Figure B-117 Damage percent by intensity for petroleum fuels transmission pipelines.

or lateral dislocations or ruptures of the ground. Pipes may buckle under compressive forces, especially where they cross ruptured faults. Damage has also occurred because of axial elongations caused by relative movement of two horizontally adjacent soil layers. Damage may occur as the result of displacements of unanchored compressors or pumps or other above ground structures. Several past failures have been attributed to corrosion combined with surges in line pressure during the earthquake. Failures of above ground lines have resulted from support failure, failure of pipeline attachment to support structure, and relatively large support movement. Rupture of pipes and loss of contents could lead to ignition, fire, and/or explosions.

Seismically Resistant Design: Modern high-pressure petroleum fuel lines provided with proper full penetration welds, heavy walls, and strong couplings are very ductile and have considerable resistance to earthquake damage. Welded steel pipeline performance depends on the integrity of the welds--modern butt-welded pipelines perform well, whereas lines constructed before and during the early 1930s may not. Special precautions should be taken to reduce earthquake effects at bay, river, and fault crossings. Transmission lines at fault crossings should be buried in shallow loose fill or installed above ground near the fault to allow lateral and longitudinal slippage. Anchors such as thrust blocks or bends should be excluded within a distance of 300 feet of a fault zone, and strengthened pipe should be used within the zone. Valve spacing near fault zones or in areas of expected soil failure should be reduced. Automatic shut-off valves should not rely on electricity to operate. Proper maintenance to limit corrosion, which weakens pipes, is important for mitigating damage.

2. Direct Damage

Basis: Damage curves for transmission lines in the petroleum fuels system are based on ATC-13 data for FC 31, underground pipelines (see Figure B-117). Transmission pipelines are typically large-diameter welded steel pipes that are expected to perform in earthquakes in a manner superior to typical underground pipelines, as indicated by the beneficial intensity shift below.

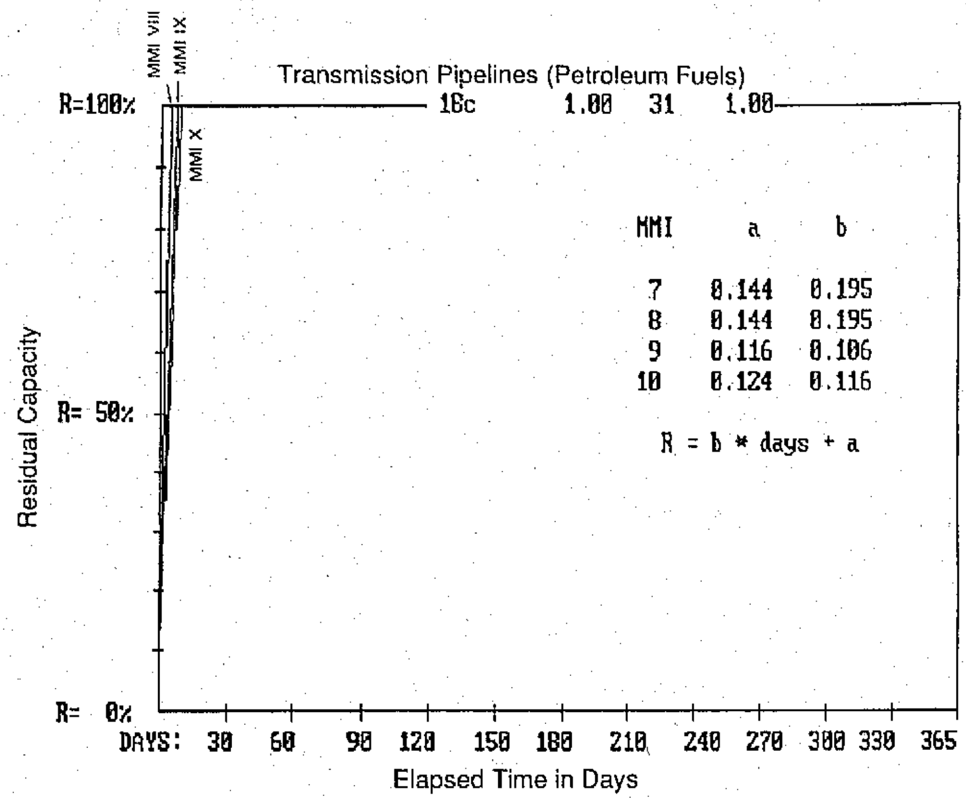

Figure B-118 Residual capacity for petroleum fuels transmission pipelines (NEHRP Map Area: California 3-6, California 7, Non-California 7, Puget Sound 5, and all other areas).

Standard construction is assumed to represent typical California petroleum fuels transmission lines under present conditions (i.e., a composite of older and more modern transmission lines). Only minimal regional variation in the construction quality is assumed.

Present Conditions: In the absence of data on the type of material, diameter, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	*MMI Intensity Shift*
California 7	-1
California 3-6	-1
Non-California 7	-1
Puget Sound 5	-1
All other areas	-1

Upgraded Conditions: It is not cost-effective or practical to upgrade existing petroleum fuels transmission pipelines, except perhaps at fault crossings or in areas of extremely unstable soils. Therefore, no intensity shifts for retrofitting are recommended.

Time-to-restoration: The time-to-restoration data assigned to SF 18c, transmission pipelines, are assumed to apply to all transmission pipelines in the petroleum fuels system. By combining these data with the damage curves for FC 31, the time-to-restoration curves shwon in Figure B-118 were derived.

B.9.4 Distribution Storage Tanks

1. General

Description: Most oil storage tanks are unanchored, cylindrical tanks supported directly on the ground. Older tanks have both fixed and floating roofs, while more modern tanks are almost exclusively floating-roofed. Diameters range from approximately 40 feet to more than 250 feet. Tank height is nearly always less than the diameter. Construction materials include welded, bolted, or riveted steel. Tank foundations may consist of sand or gravel, or a concrete ring wall supporting the shell.

Typical Seismic Damage: On-ground oil storage tanks are subject to a variety of damage mechanisms, including: (1) failure of weld between base plate and wall, (2) buckling of tank wall (elephant foot), (3) rupture of attached rigid piping because of sliding or rocking of tank, (4) implosion of tank resulting from rapid loss of contents and negative internal pressure, (5) differential settlement, (6) anchorage failure or tearing of tank wall, (7) failure of roof-to-shell connection or damage to roof seals for floating roofs (and loss of oil), (8) failure of shell at bolts or rivets because of tensile hoop stresses, and (9) total collapse. Torsional rotations of floating roofs may damage attachments such as guides, ladders, etc.

Seismically Resistant Design: Seismically resistant design practices for ground oil distribution storage tanks include the use of flexible piping, pressure relief valves, and well-compacted foundations and concrete ring walls that prevent differential settlement. Adequate freeboard to prevent sloshing against the roof should be maintained. Positive attachment between the roof and shell should be provided for fix-roofed tanks. The bottom plate and its connection to the shell should be stiffened to resist uplift forces, and the base plate should be protected against corrosion. Abrupt changes in thickness between adjacent courses should be avoided. Properly detailed ductile anchor bolts may be feasible on smaller steel tanks. Maintaining a height-to-diameter ratio of between 0.3 and 0.7 for tanks supported on the ground controls seismic loading. Retention dikes are needed to retain spilled oil and prevent it from reaching ignition sources. These dikes should have sufficient capacity to retain all oil that could spill within their confines. Also, all retention dike embankments should be stable in ground shaking.

2. Direct Damage

Basis: Damage curves for distribution storage tanks in the petroleum fuels system are based on ATC-13 data for FC 43, on-ground liquid storage tanks (see Figure B-119). Standard construction is assumed to represent typical California distribution storage tanks under present conditions (i.e., a composite of older, non-seismically designed tanks as well as more modern tanks designed to seismic requirements (e.g., API 650).

Present Conditions: In the absence of data on the type of material, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	MMI Intensity Shift
California 7	0
California 3-6	+1
Non-California 7	+1
Puget Sound 5	+1
All other areas	+2

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in one or two beneficial intensity shifts (i.e., -1 or -2), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 18d, distribution storage tanks, are assumed to apply to all tanks. By combining these data with the damage curves for FC 43, the time-to-restoration curves shown in Figures B-120 through B-121 were derived.

B.10 Emergency Service

B.10.1 Health Care

1. General

Description: Health care facilities (hospitals) are typically housed in one or more buildings. Construction type varies significantly. Smaller hospitals may contain only limited equipment associated with building services. Large hospitals may contain water treatment equipment, emergency power diesels, chillers, and boilers, as well as sophisticated equipment used for treating patients.

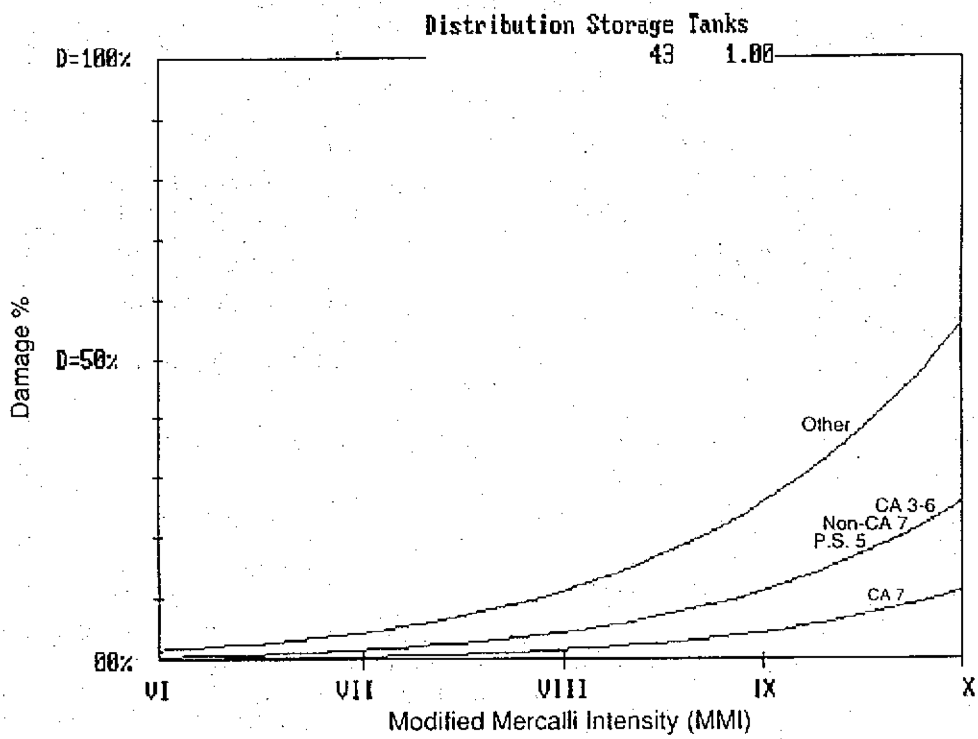

Figure B-119 Damage percent by intensity for petroleum fuelds distribution storage tanks.

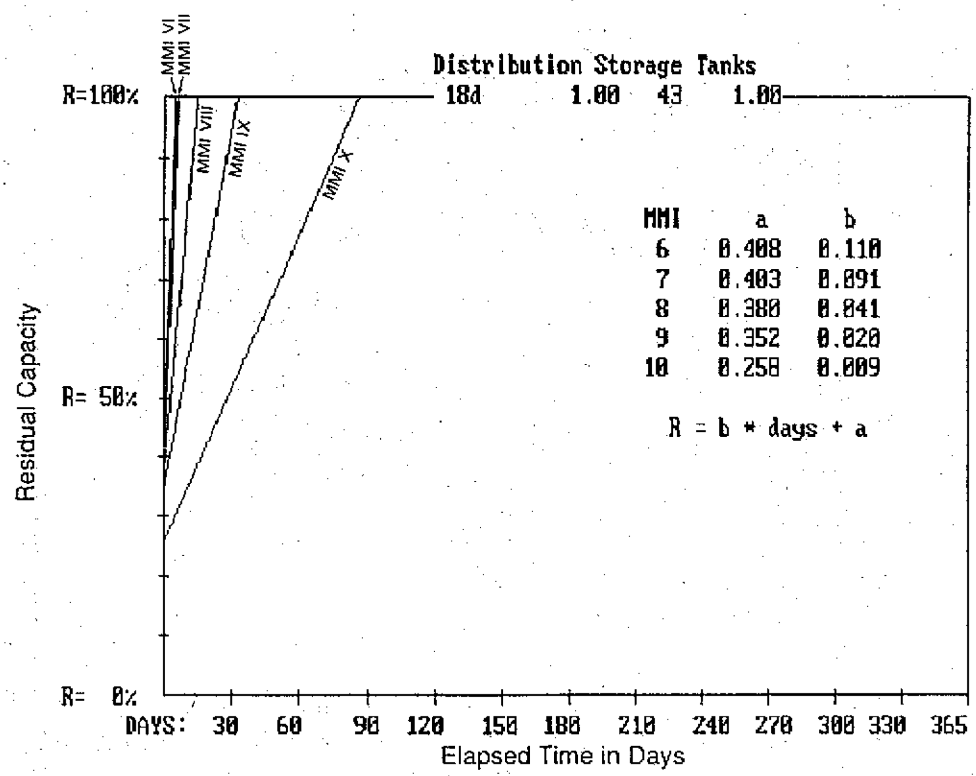

Figure B-120 Residual capacity for petroleum fuelds distribution storage tanks (NEHRP California 7).

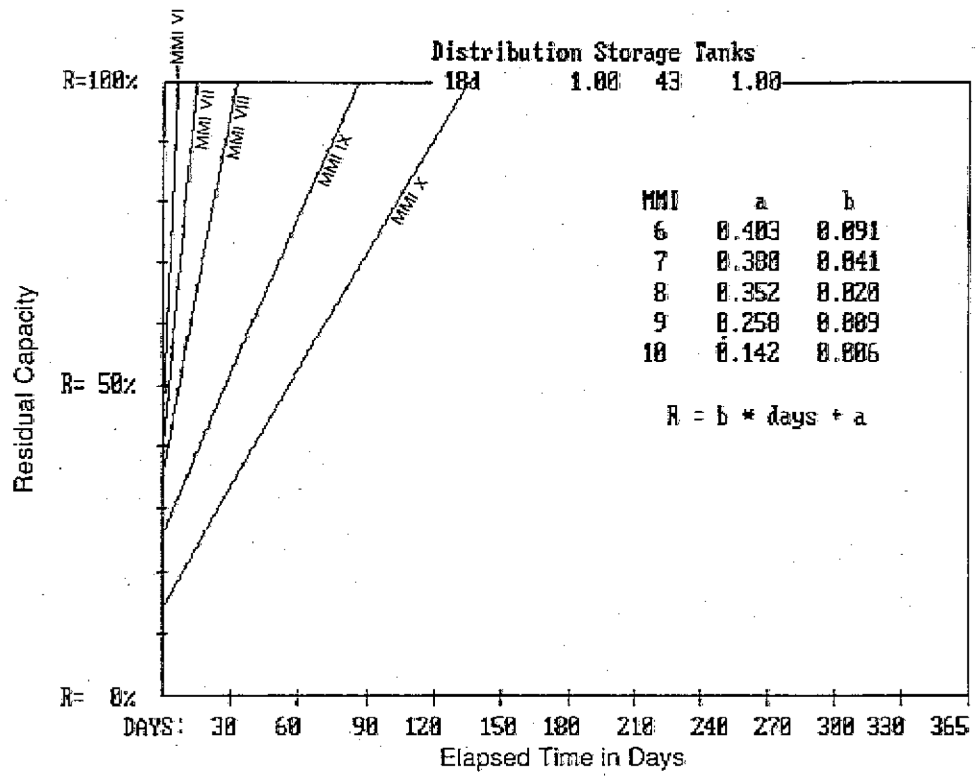

Figure B-121 Residual capacity for petroleum fuelds distribution storage tanks (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

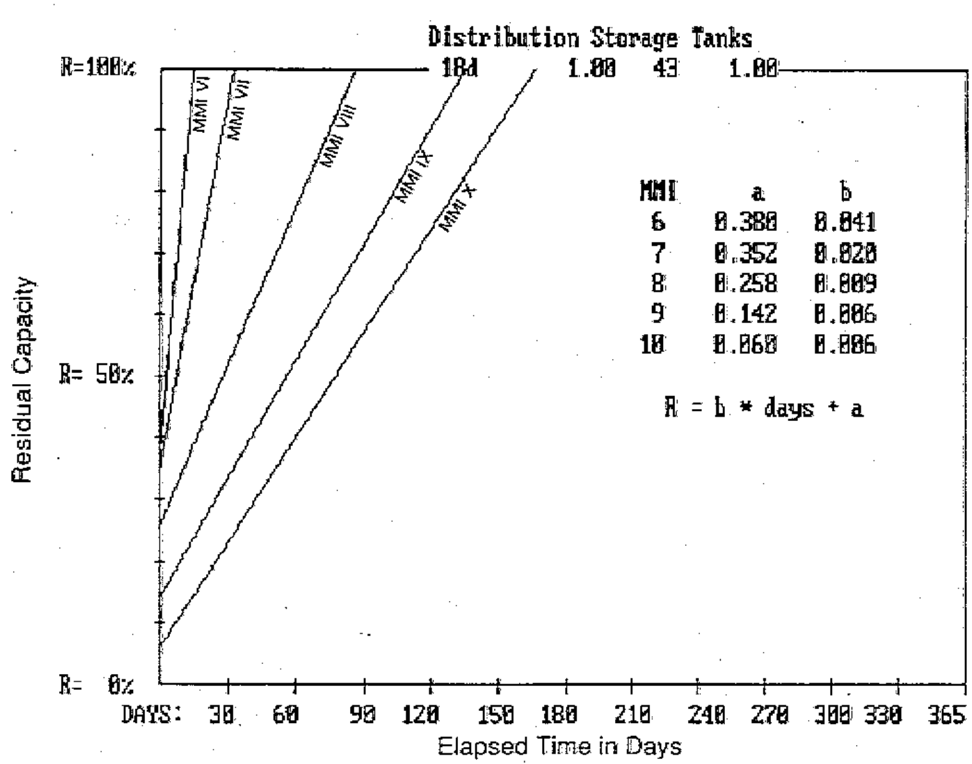

Figure B-122 Residual capacity for petroleum fuelds distribution storage tanks (All other areas).

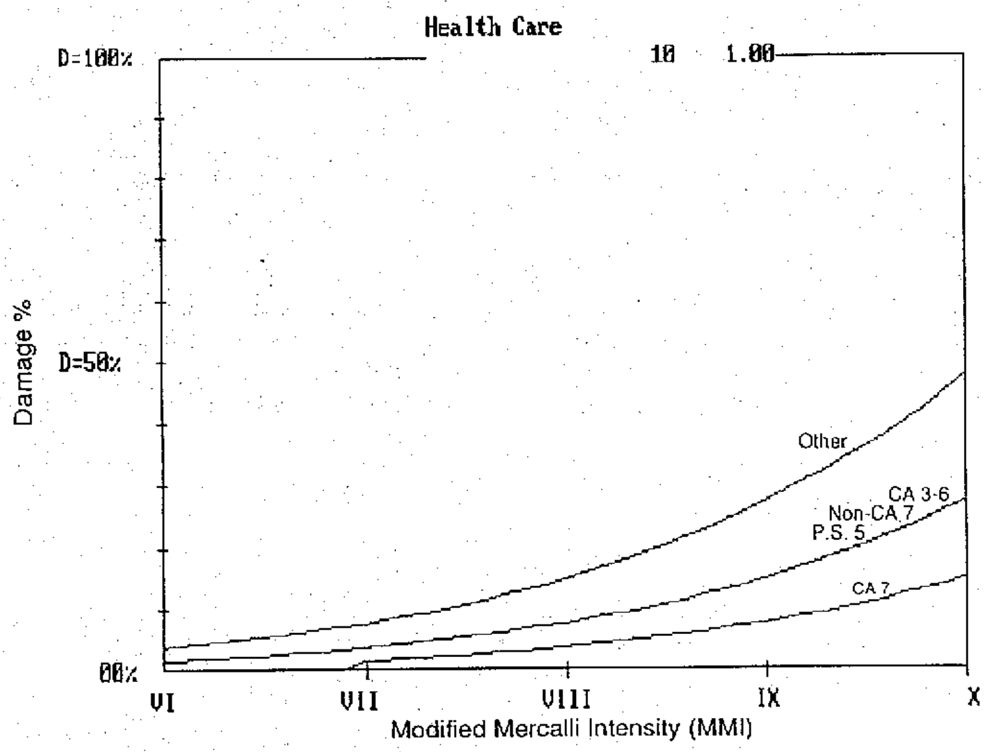

Figure B-123 Damage percent by intensity for health care facilities.

Typical Seismic Damage: Buildings may experience generic building damage ranging from cracks in walls and frames to partial and total collapse. Unanchored or improperly anchored equipment may slide or topple. Equipment supported on isolation mounts with no snubbers may fall off the mounts and rupture attached piping and conduits. Unrestrained batteries on racks may fall, rendering the emergency power systems inoperable. Suspended ceilings may fall and impede operations. Equipment necessary for treating patients may be damaged, especially if it is supported on carts or on wheels, or is top-heavy. Equipment that requires precise alignment is also susceptible to damage. In garages, structural damage may result in ambulances being unavailable when they are needed.

Seismically Resistant Design: As essential facilities, hospital should be designed to remain operational in the event of a major earthquake. Typically this involves using larger design forces and meeting more restrictive design requirements than those required by building codes for the building design. However, equipment and nonstructural items also require special attention if the hospital is to remain functional. All critical equipment should be anchored. Equipment on isolators should be snubbed. The emergency power system should be closely scrutinized, and the emergency diesel-generator system should be maintained and tested frequently. Equipment used to treat patients should be stored and restrained properly. Medicine in cabinets should be stored in a manner that prevents it from falling to the floor.

2. Direct Damage

Basis: Damage curves for health care facilities are based on ATC-13 data for FC 10, medium-rise reinforced masonry shear wall buildings (see Figure B-123). FC 10 was chosen to represent a generic building, based on review of damage curves for all buildings.

Standard construction is assumed to represent typical California health care facilities under present conditions (i.e., a

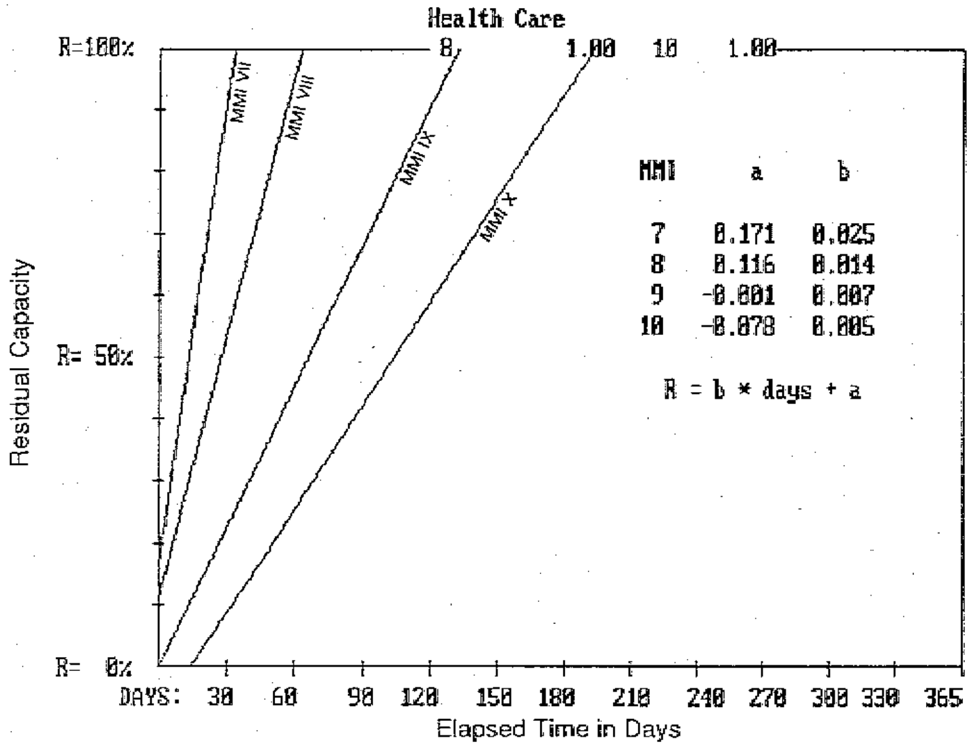

Figure B-124 Residual capacity for health care facilities (NEHRP California 7).

composite of older and more modern health care). It is assumed that such facilities were designed using enhanced seismic requirements and that the beneficial intensity shifts indicated below are appropriate.

Present Conditions: In the absence of data on the type of construction, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	MMI Intensity Shift
California 7	-1
California 3-6	0
Non-California 7	0
Puget Sound 5	0
All other areas	+1

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in one or two beneficial intensity shifts (i.e., -1 or -2), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 8, health care services, are assumed to apply to all health care facilities. By combining these data with the damage curves for FC 10, the time-to-restoration curves shown in Figures B-124 through B-126 were derived.

B.10.2 Emergency Response Services

1. General

Description: Emergency response services include fire and police stations. Both fire and police stations may be housed in low- to medium-rise structures of virtually any type of construction. In many urban areas these structures are old and were built prior to the adoption of earthquake design codes. Firehouses typically include garages to house engines, sleeping quarters, kitchens, utility rooms, and communications rooms. Some stations have hose towers used to dry hoses after use. Police stations typically include a dispatch center, detention area, and squad room.

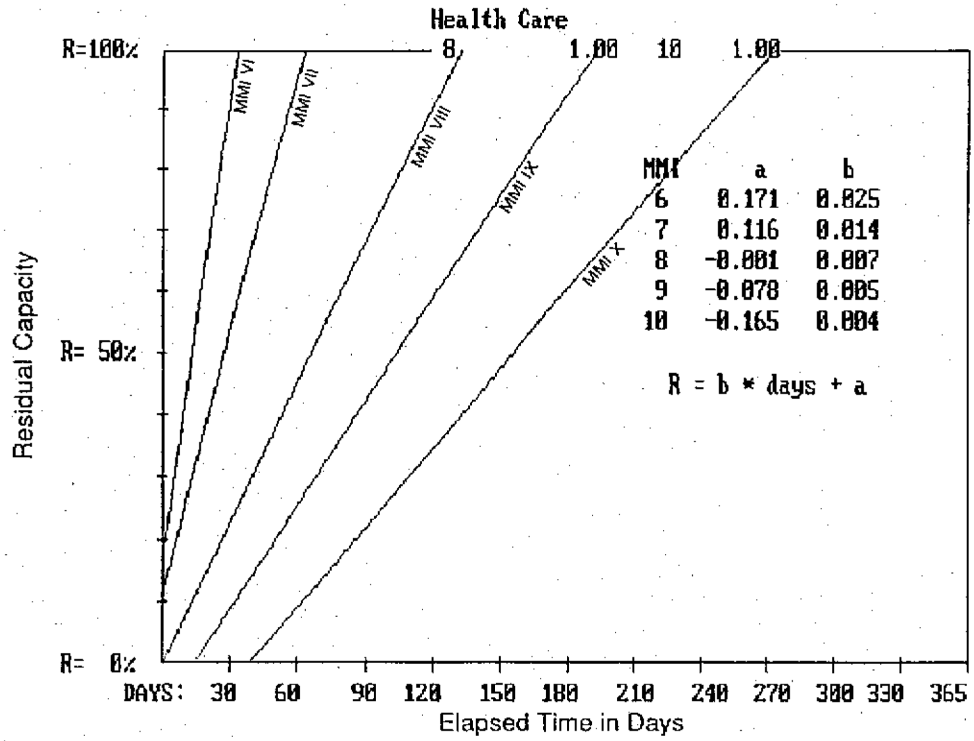

Figure B-125 Residual capacity for health care facilities (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

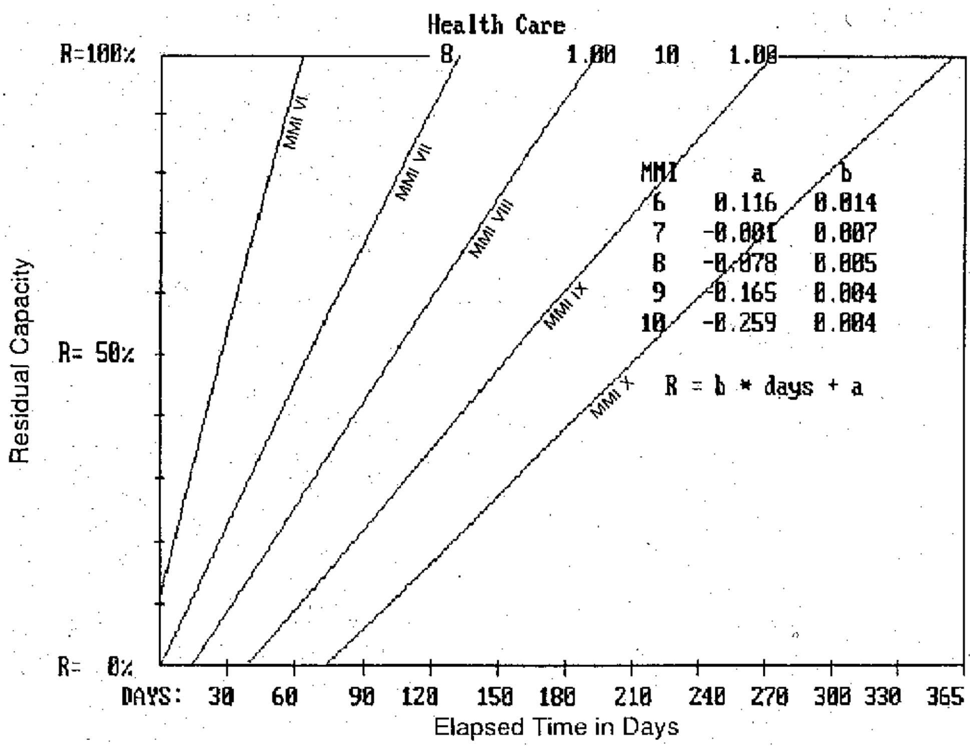

Figure B-126 Residual capacity for health care facilities (All other areas).

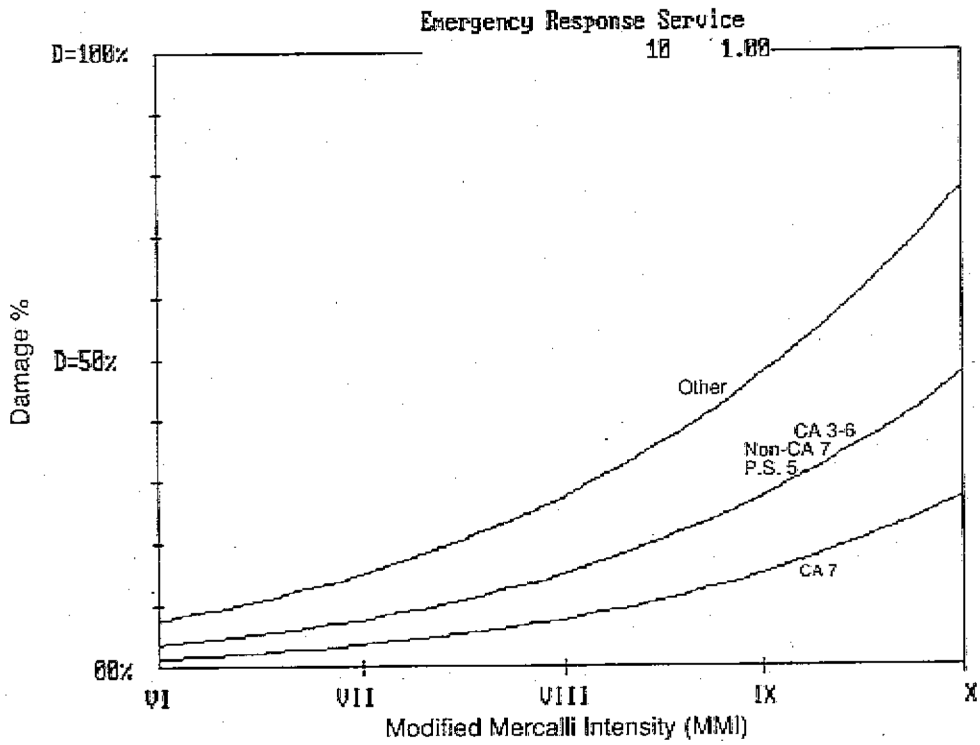

Figure B-127 Damage percent by intensity for emergency response service facilities.

Typical Seismic Damage: Buildings housing fire and police stations may experience generic building damage ranging from cracking of frames and walls to partial or total collapse. Fire stations may be more susceptible to damage than most buildings because of the presence of the large garage door openings and the hose towers, which interrupt the continuity of the roof diaphragm and frequently have discontinuous shear walls or frames. Significant damage to a fire station could lead to loss of use of engines housed within them. Unanchored communications equipment in both stations could severely hinder operations immediately after an earthquake.

Seismically Resistant Design: Both fire and police stations are critical buildings that should remain operational after a major earthquake. Accordingly, these facilities should be designed to meet the seismic requirements for critical buildings of a national or local building code. Geometric irregularities that will result in poor seismic performance should be avoided (e.g., separate hose towers should be provided). Communications equipment should be properly restrained and provided with backup emergency power. All equipment, especially boilers, should be well anchored. Engines and patrol cars should be stored in areas that are expected to escape serious damage.

2. Direct Damage

Basis: Damage curves for emergency response service are based on ATC-13 data for FC 10, medium-rise reinforced masonry shear wall buildings (see Figure B-127). FC 10 was chosen to represent a generic building, based on review of damage curves for all buildings. Although more modern facilities may be designed to enhanced seismic design criteria, many old police and fire stations are still in use. Consequently, no intensity shifts from typical FC 10 performance are assumed.

Standard construction is assumed to represent typical emergency response facilities under present conditions (i.e., a

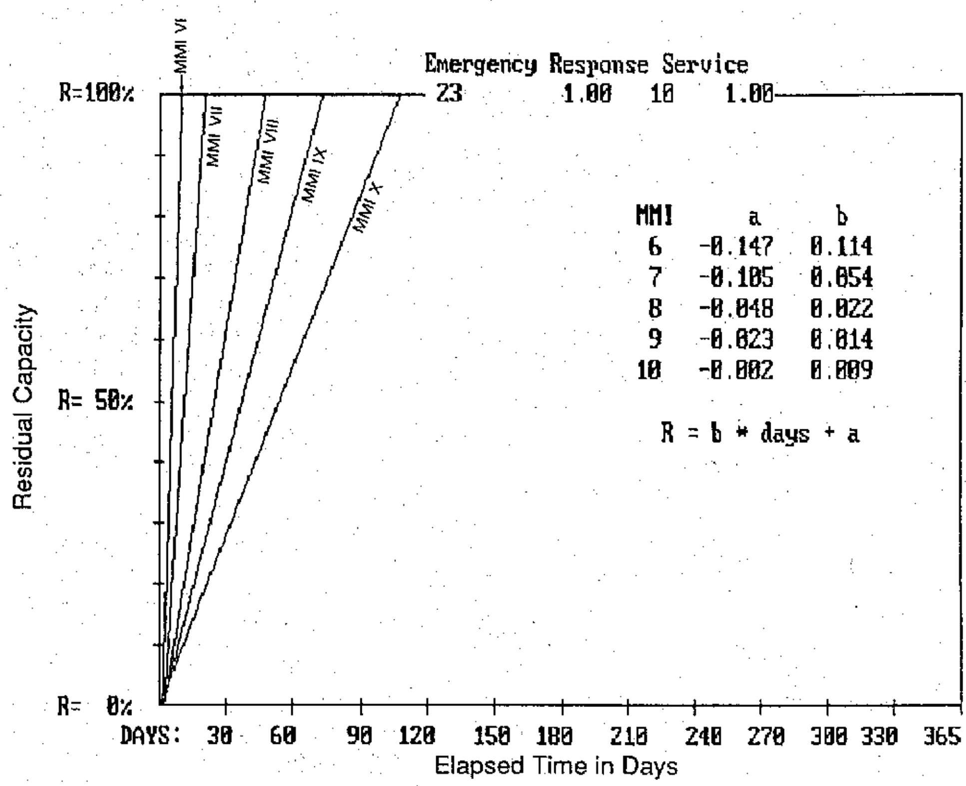

Figure B-128 Residual capacity for emergency response service facilities (NEHRP California 7).

composite of older and more modern police and fire stations).

Present Conditions: In the absence of data on the type of construction, age, etc., the following factors were used to modify the mean curves, under present conditions:

NEHRP Map Area	*MMI Intensity Shift*
California 7	0
California 3-6	+1
Non-California 7	+1
Puget Sound 5	+1
All other areas	+2

Upgraded Conditions: For areas where it appears cost-effective to improve facilities, assume on a preliminary basis that upgrades result in one or two beneficial intensity shifts (i.e., -1 or -2), relative to the above present conditions.

Time-to-restoration: The time-to-restoration data assigned to SF 23, emergency response services, are assumed to apply to all emergency response service facilities. By combining these data with the damage curves for FC 10, the time-to-restoration curves shown in Figures B-128 through B-130 were derived.

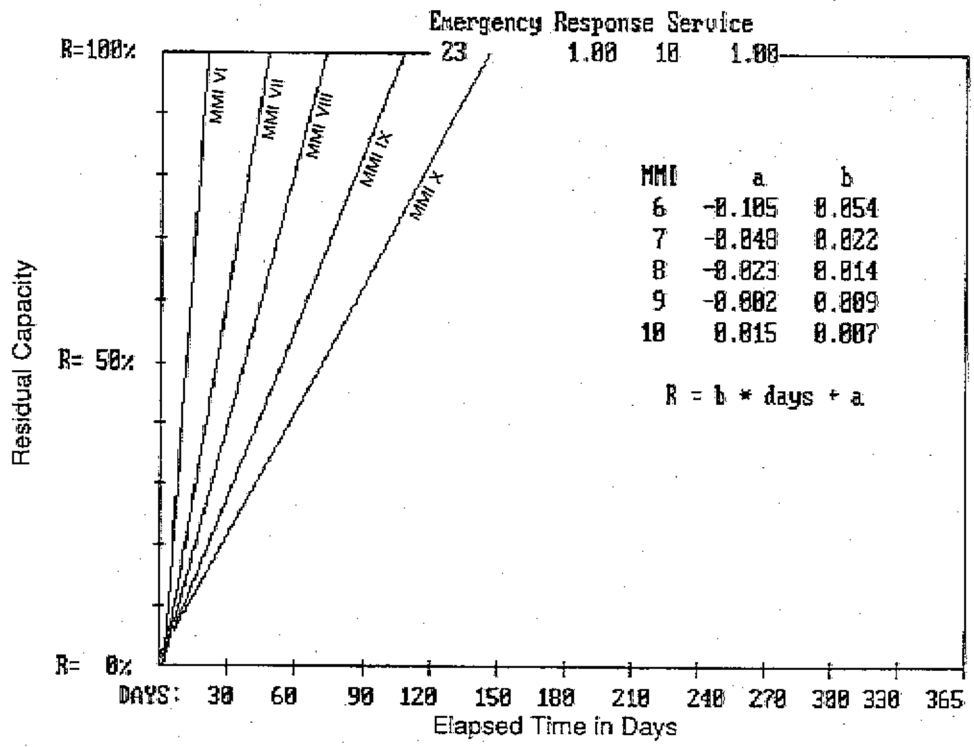

Figure B-129 Residual capacity for emergency response service facilities (NEHRP Map Area: California 3-6, Non-California 7, and Puget Sound 5).

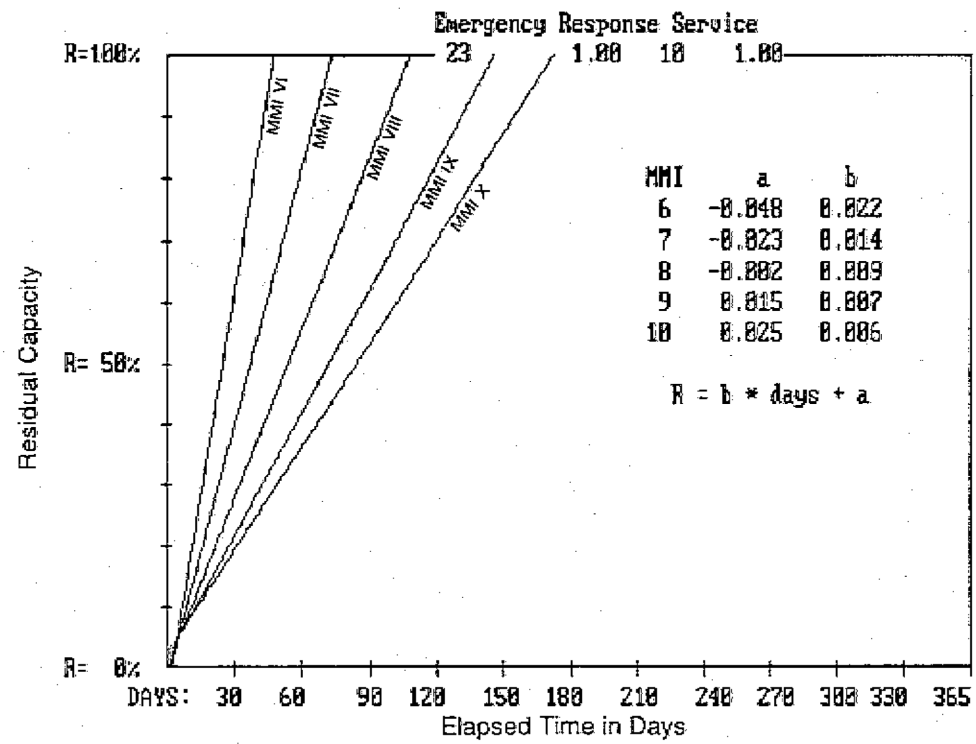

Figure B-130 Residual capacity for emergency response service facilities (All other areas).

Appendix C: Residual Capacity Plots for Each Lifeline and Scenario Earthquake

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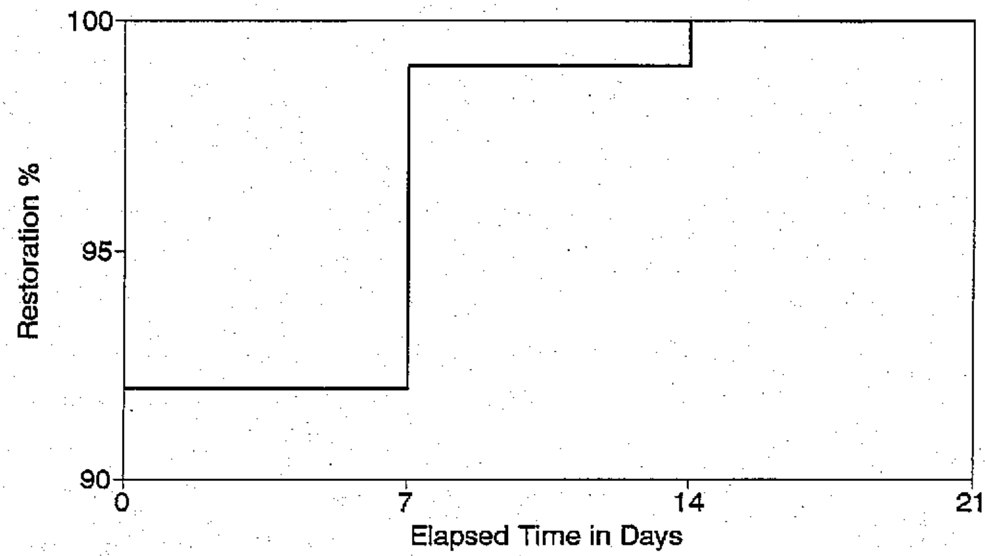


Figure C-1 Residual capacity of Illinois air transportation following New Madrid event (M=8).

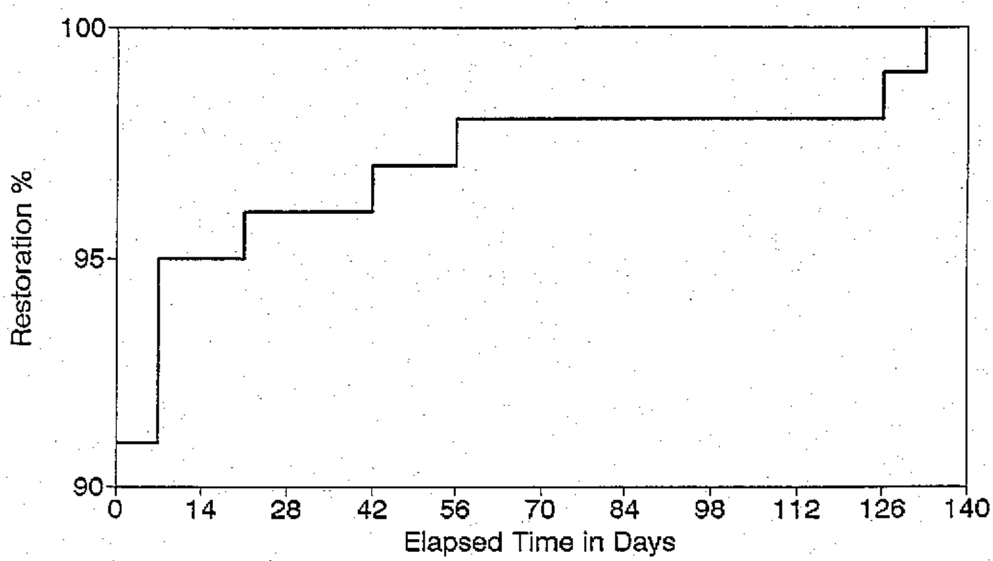


Figure C-2 Residual capacity of Missouri air transportation following New Madrid event (M=8).

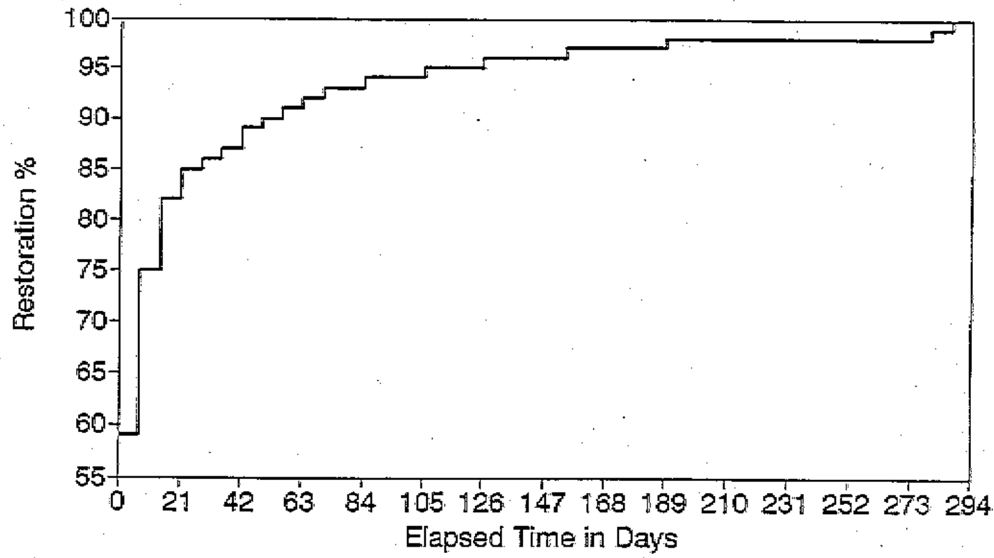


Figure C-3 Residual capacity of Arkansas air transportation following New Madrid event (M=8).

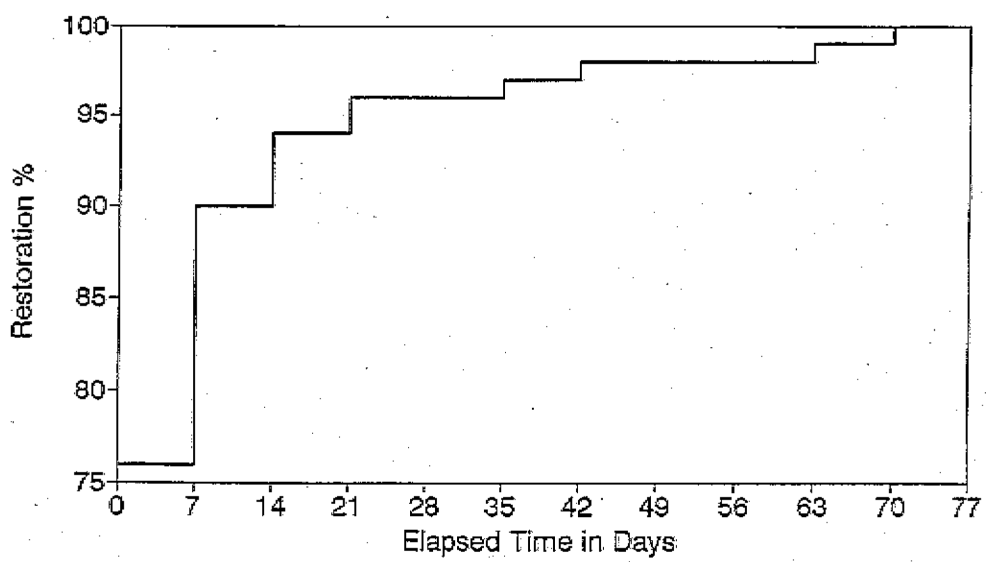


Figure C-4 Residual capacity of Tennessee air transportation following New Madrid event (M=8).

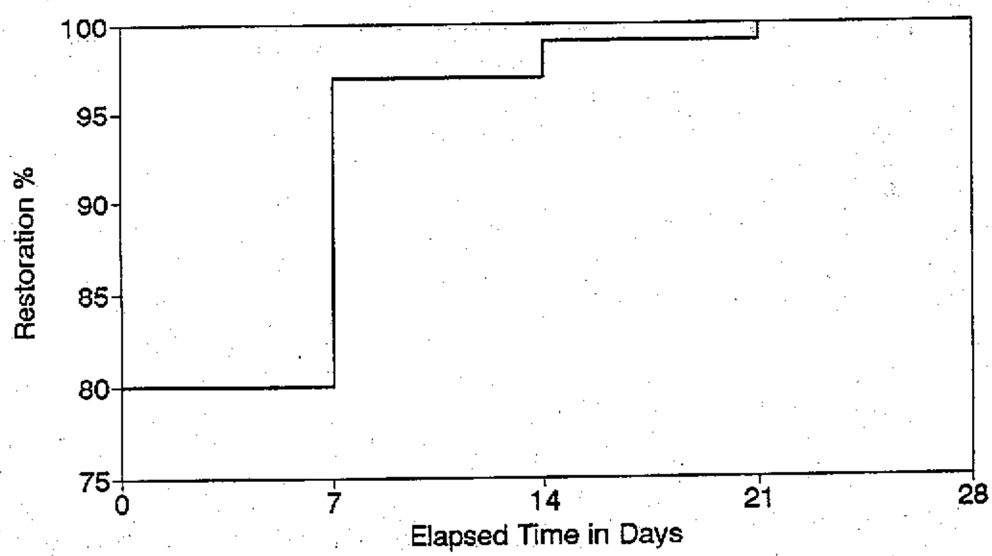


Figure C-5 Residual capacity of Kentucky air transportation following New Madrid event (M=8).

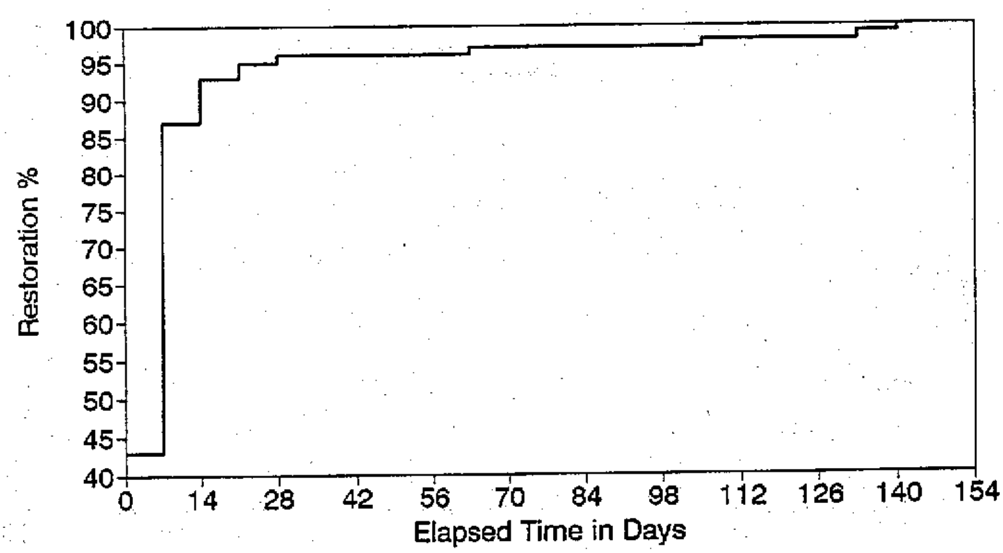


Figure C-6 Residual capacity of Mississippi air transportation following New Madrid event (M=8).

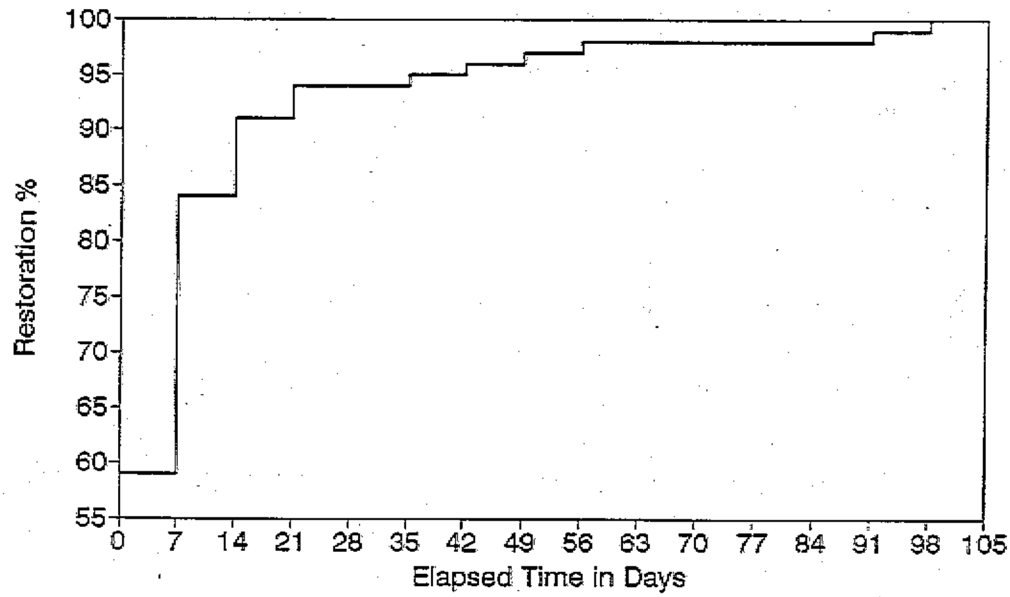


Figure C-7 Residual capacity of South Carolina air transportation following Charleston event (M=7.5).

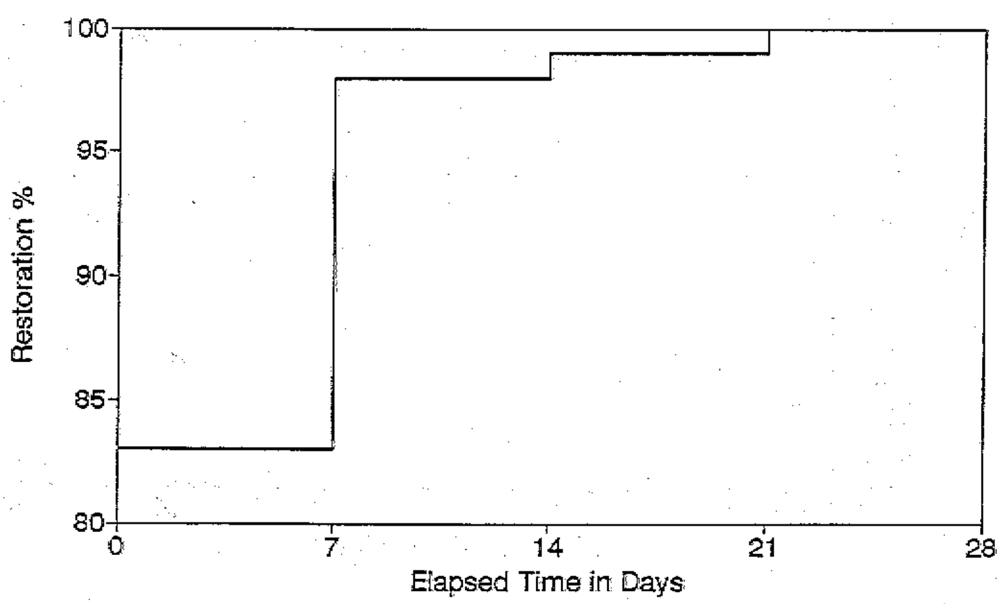


Figure C-8 Residual capacity of North Carolina air transportation following Charleston event (M=7.5).

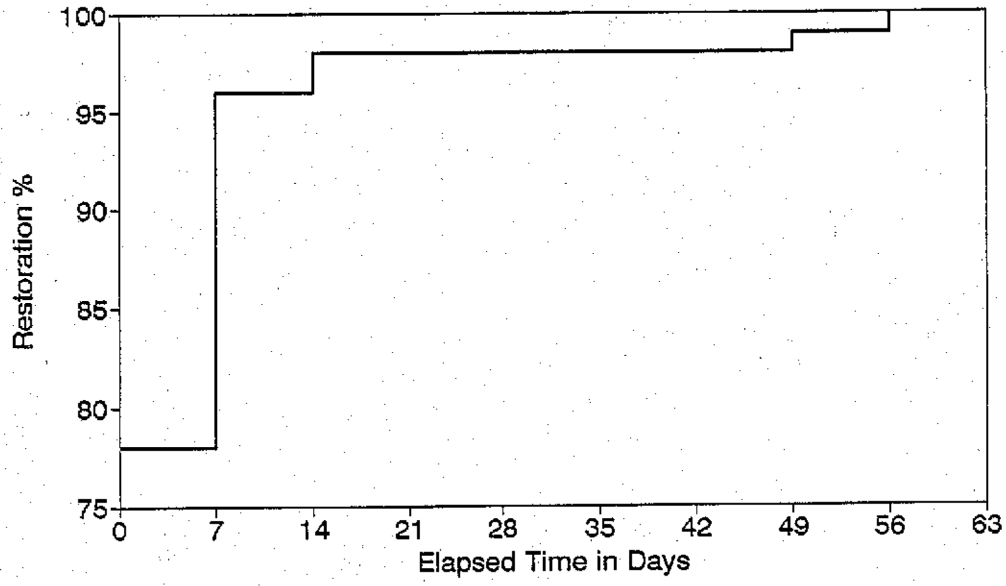


Figure C-9 Residual capacity of Georgia air transportation following Charleston event (M=7.5).

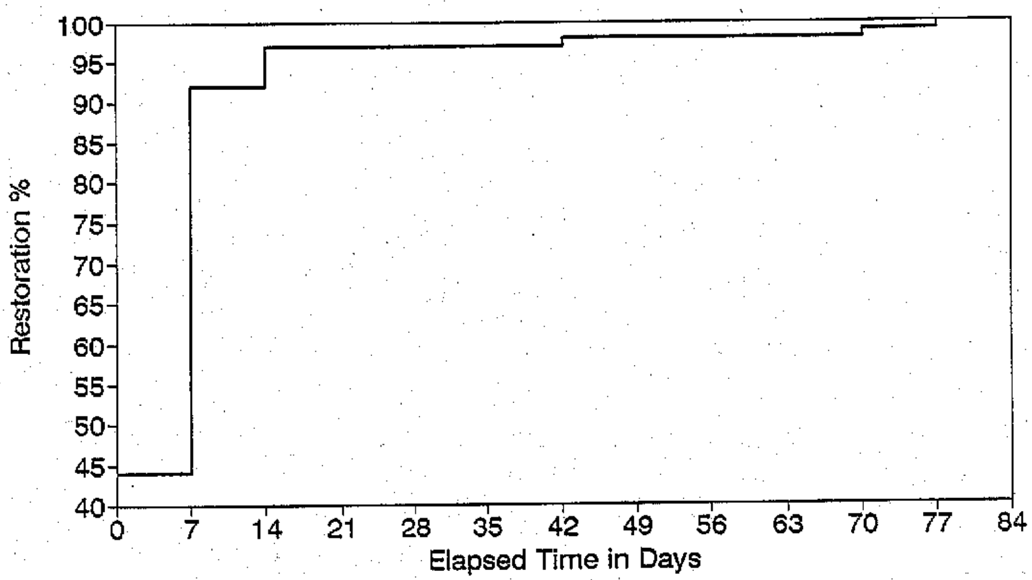


Figure C-10 Residual capacity of Massachusetts air transportation following Cape Ann event (M=7.0).

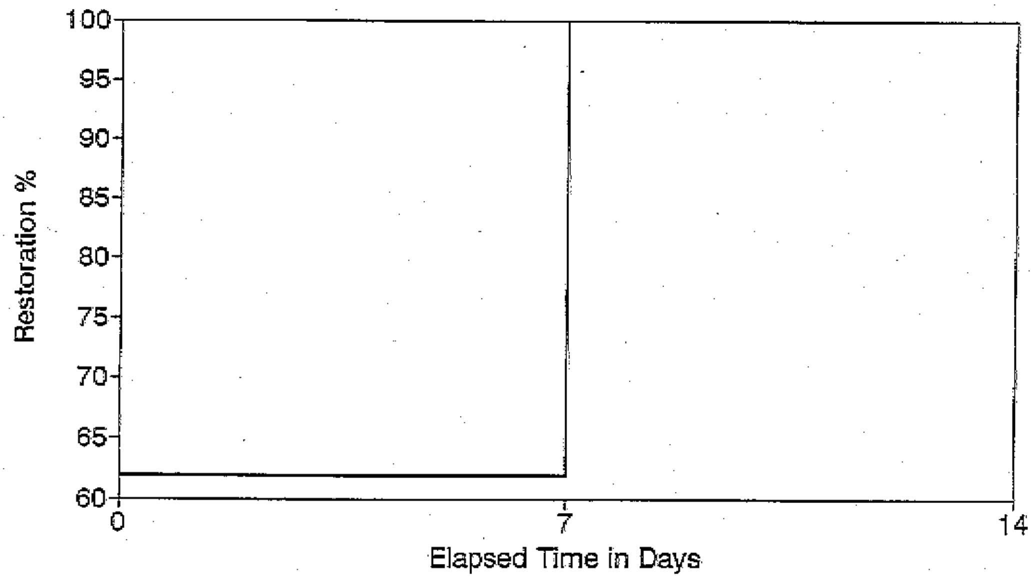


Figure C-11 Residual capacity of Connecticut air transportation following Cape Ann event (M=7.0).

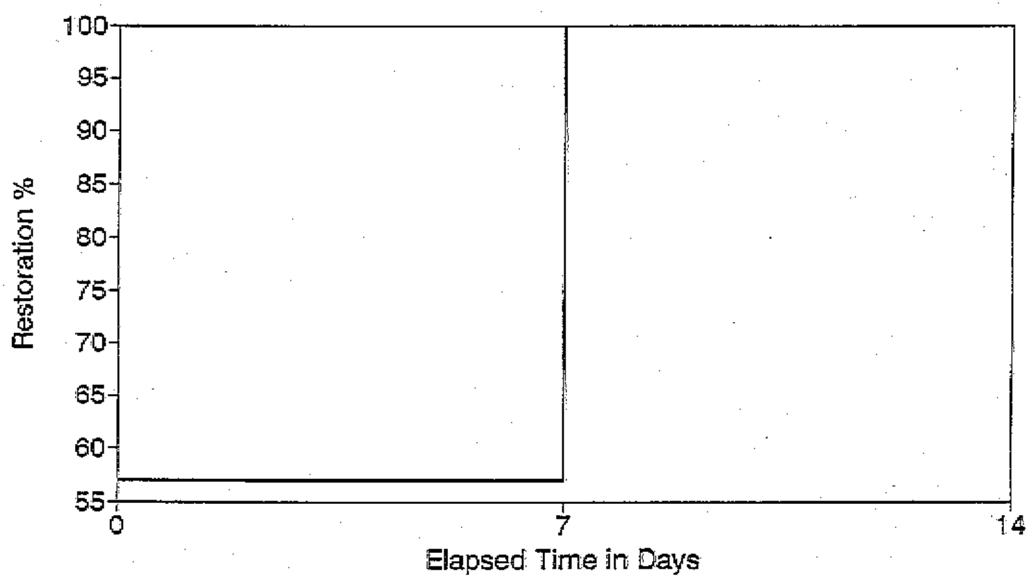


Figure C-12 Residual capacity of Delaware air transportation following Cape Ann event (M=7.0).

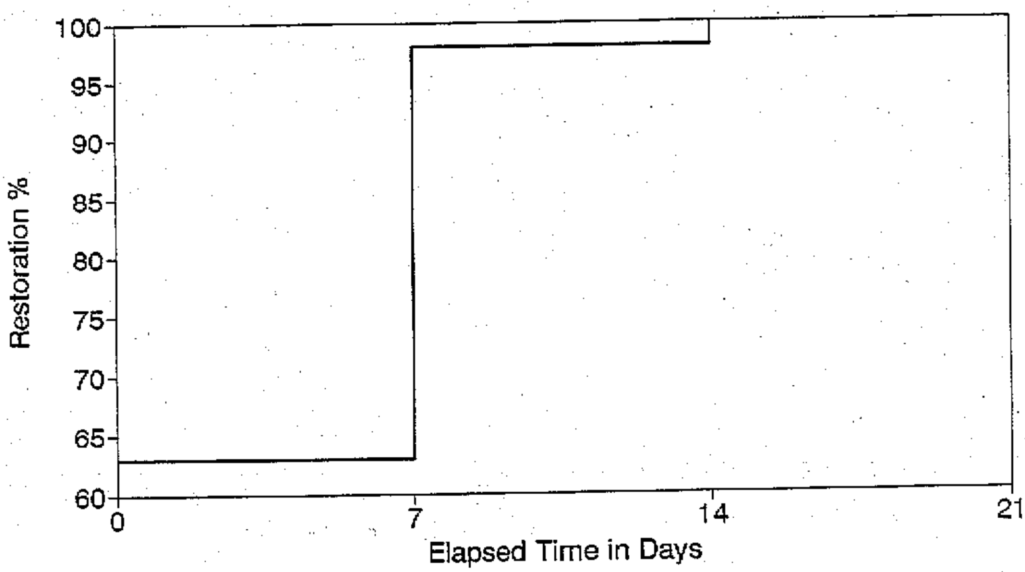


Figure C-13 Residual capacity of Rhode Island air transportation following Cape Ann event (M=7.0).

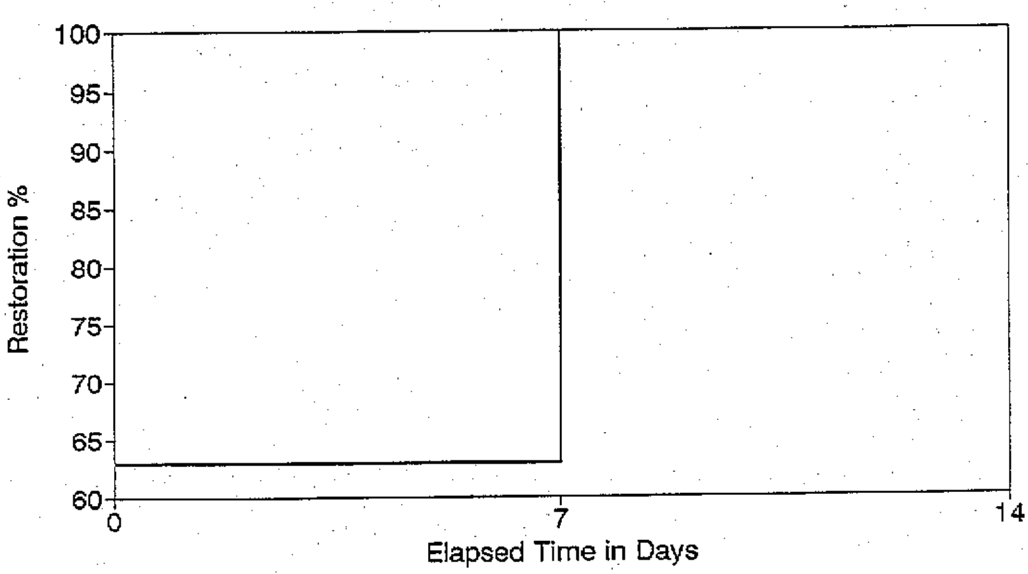


Figure C-14 Residual capacity of New Hampshire air transportation following Cape Ann event (M=7.0).

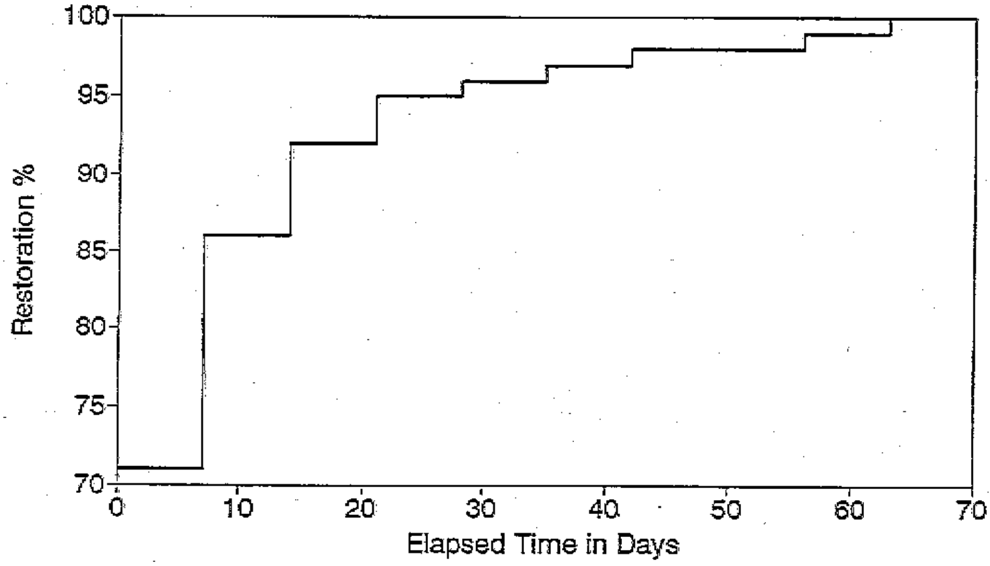


Figure C-15 Residual capacity of Utah air transportation following Wasatch Front event (M=7.5).

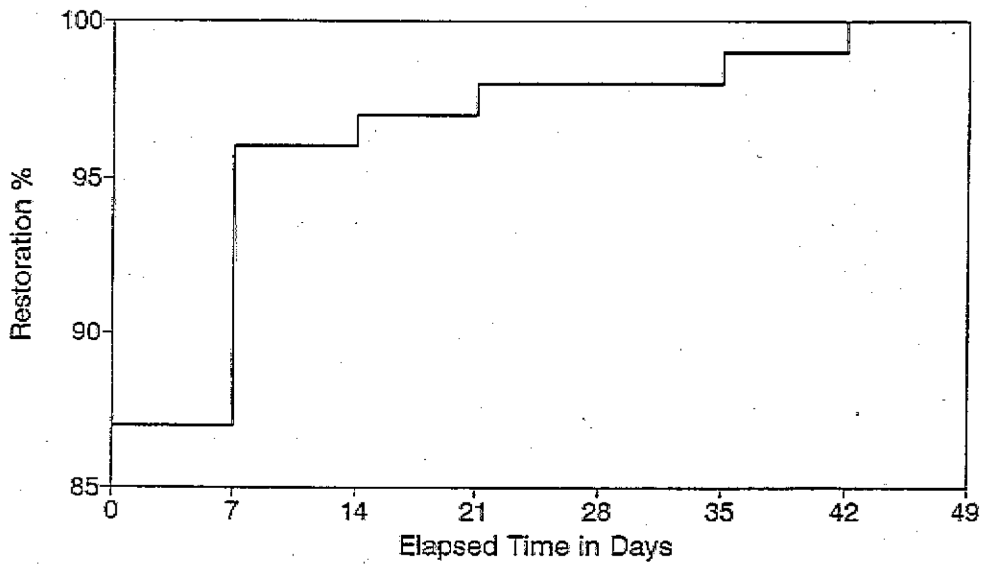


Figure C-16 Residual capacity of California air transportation following Hayward event (M=7.5).

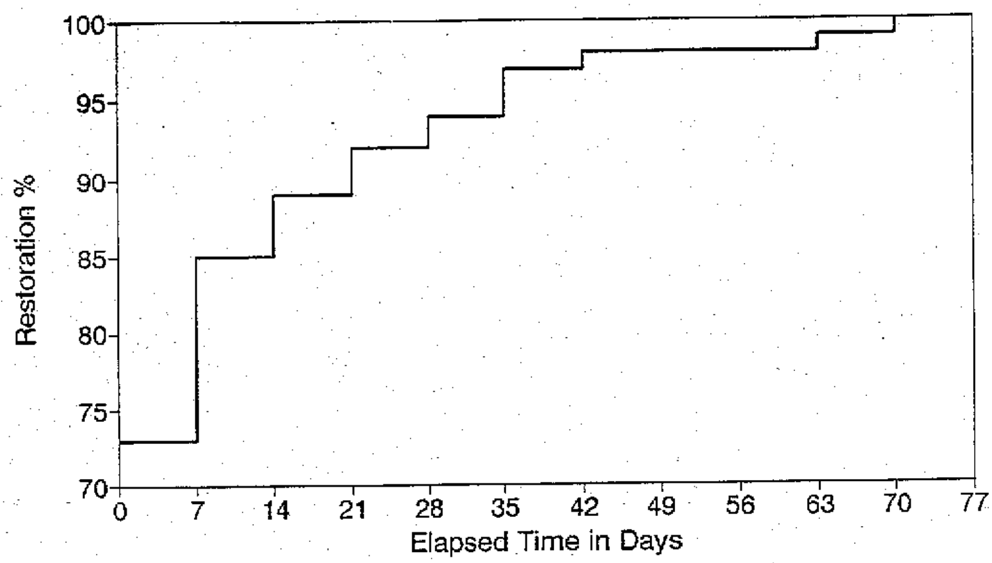


Figure C-17 Residual capacity of California air transportation following Fort Tejon event (M=8.0).

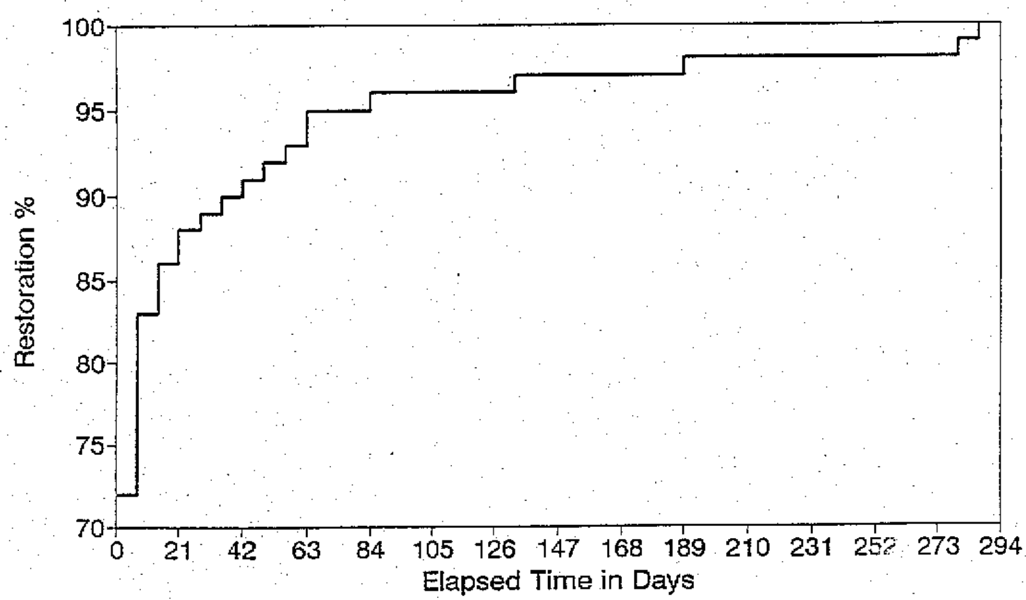


Figure C-18 Residual capacity of Washington air transportation following Puget Sound event (M=7.5).

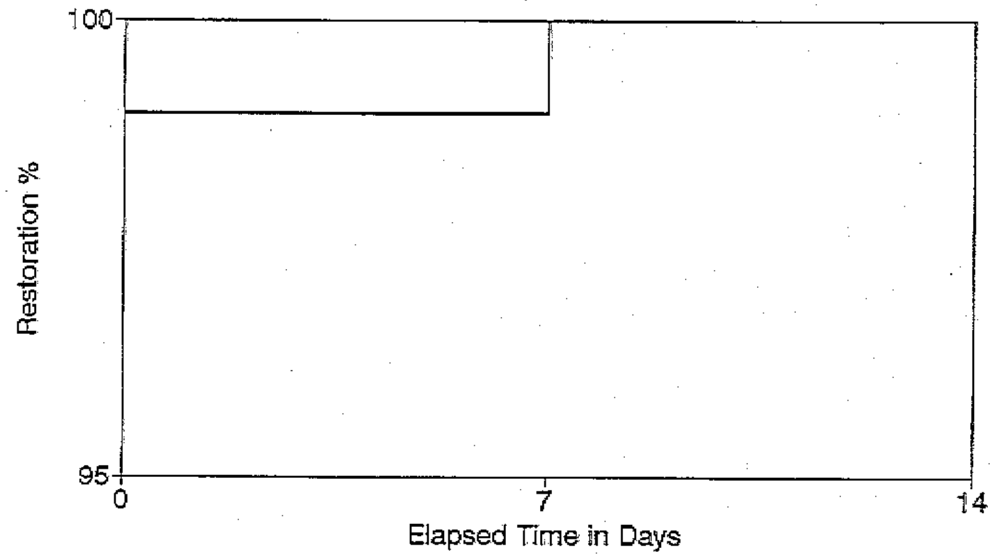


Figure C-19 Residual capacity of Illinois air transportation following New Madrid event (M=7.0).

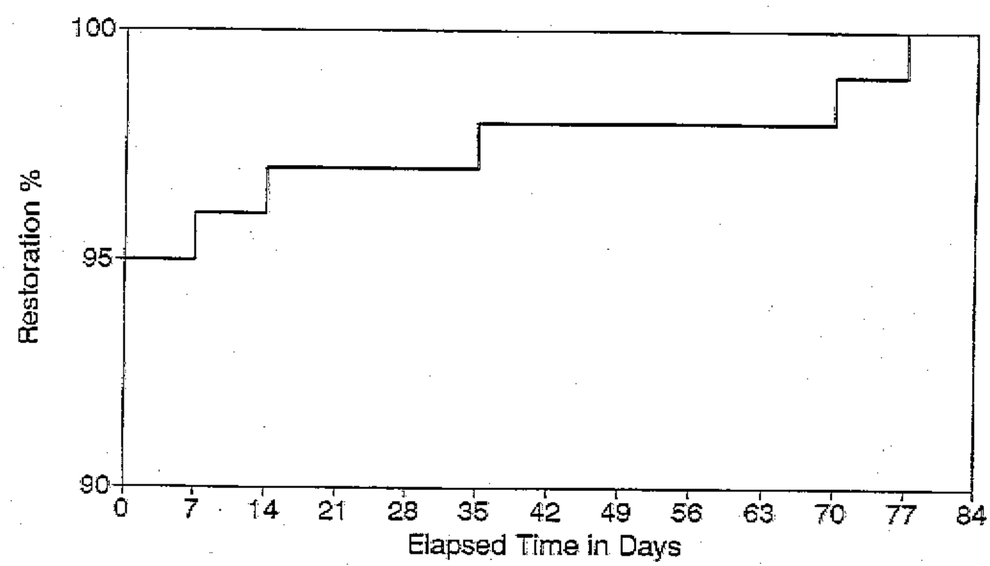


Figure C-20 Residual capacity of Missouri air transportation following New Madrid event (M=7.0).

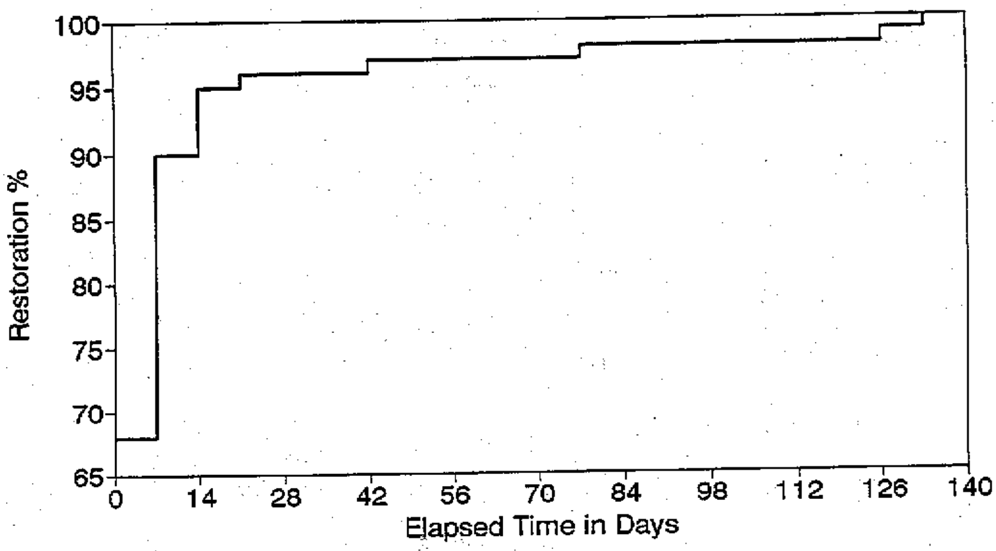


Figure C-21 Residual capacity of Arkansas air transportation following New Madrid event (M=7.0).

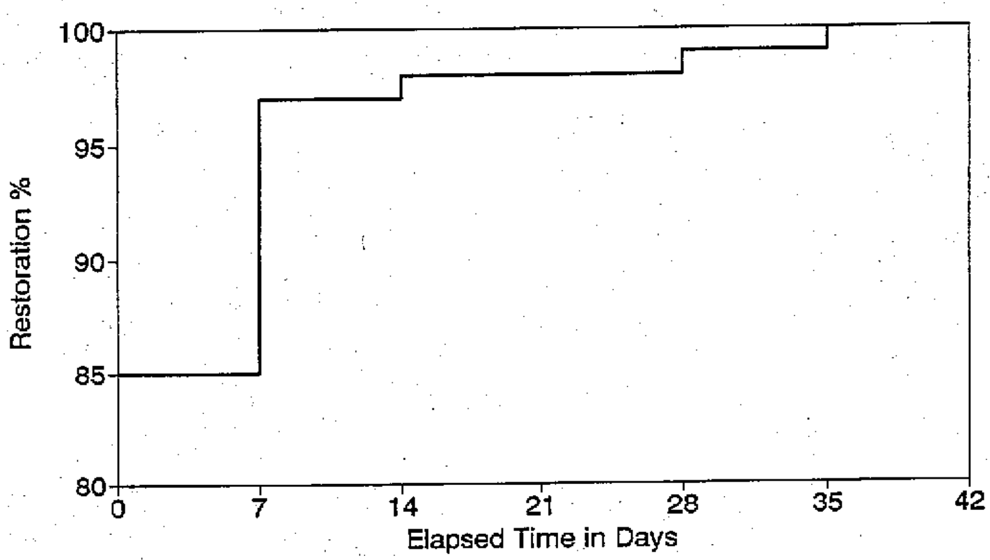


Figure C-22 Residual capacity of Tennessee air transportation following New Madrid event (M=7.0).

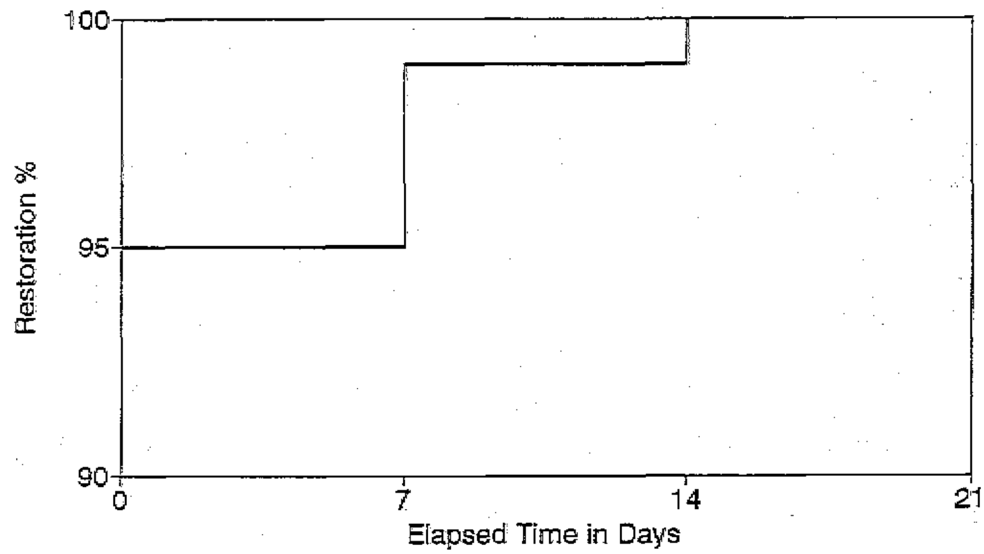


Figure C-23 Residual capacity of Kentucky air transportation following New Madrid event (M=7.0).

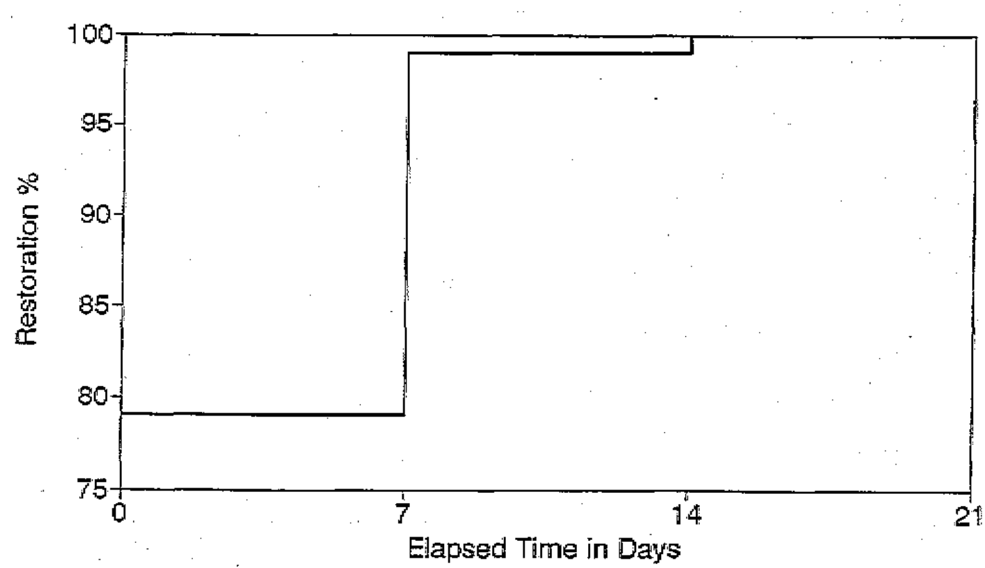


Figure C-24 Residual capacity of Mississippi air transportation following New Madrid event (M=7.0).

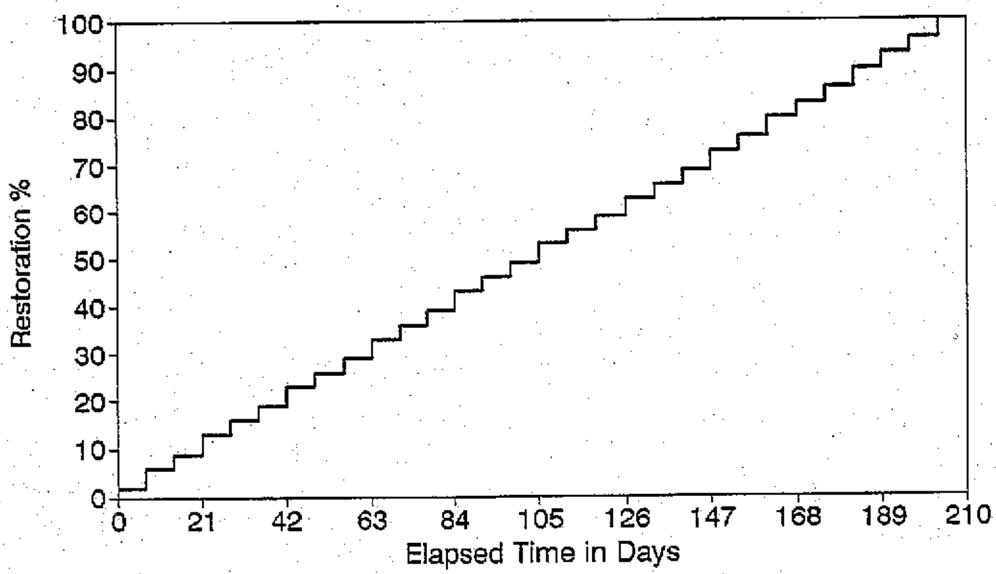


Figure C-25 Residual capacity of South Carolina ports following Charleston event (M=7.5).

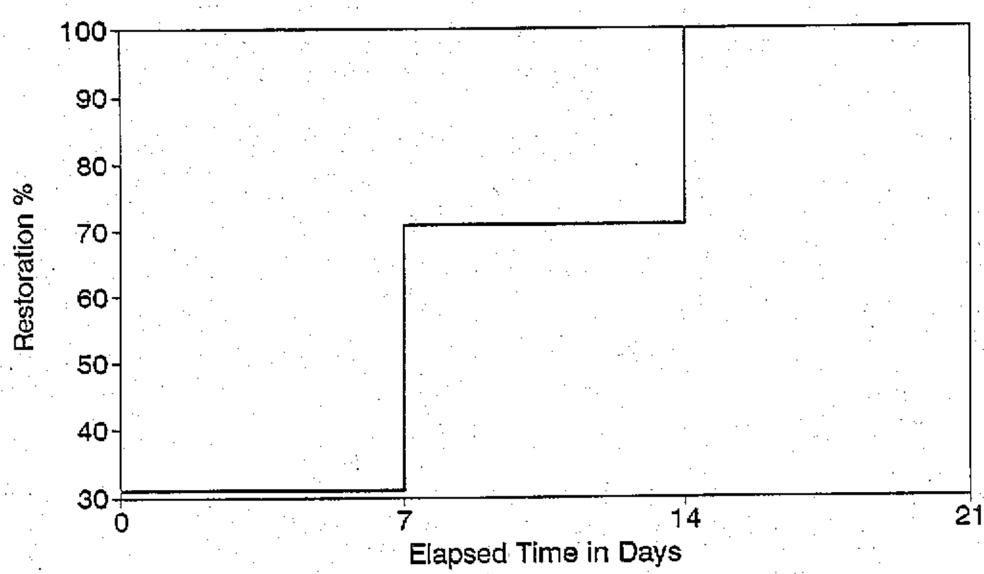


Figure C-26 Residual capacity of North Carolina ports following Charleston event (M=7.5).

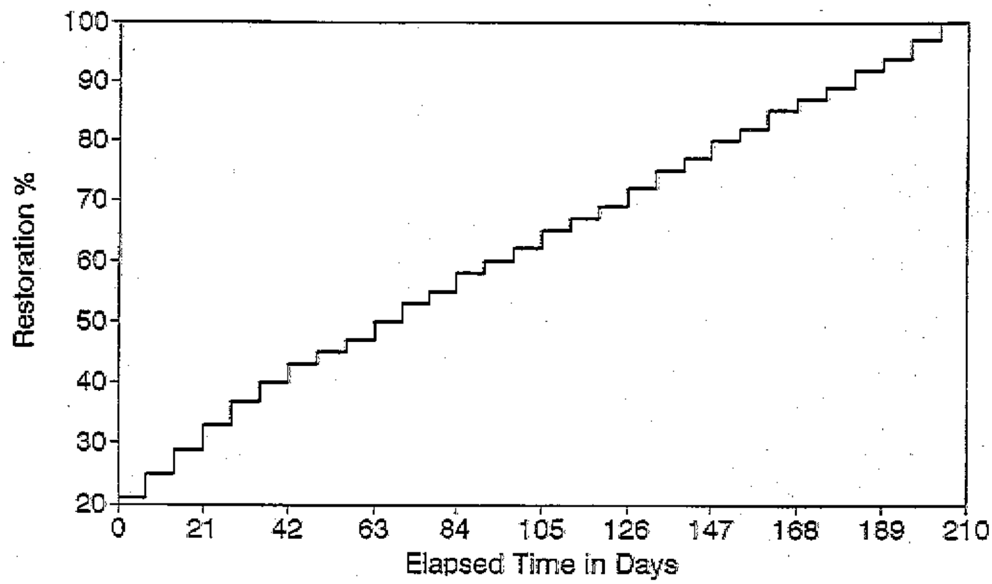


Figure C-27 Residual capacity of Georgia ports following Charleston event (M=7.5).

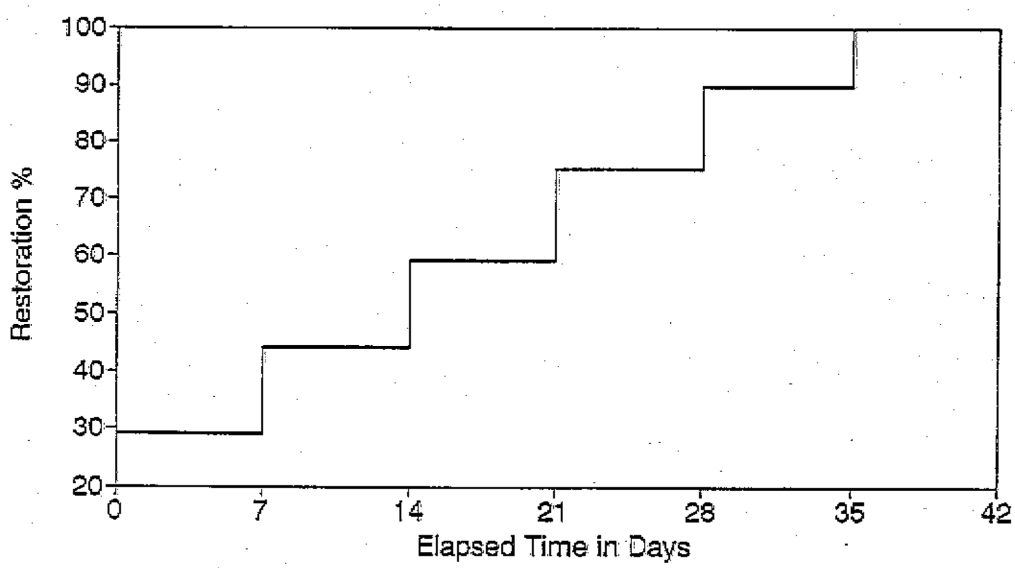


Figure C-28 Residual capacity of Massachusetts ports following Cape Ann event (M=7.0).

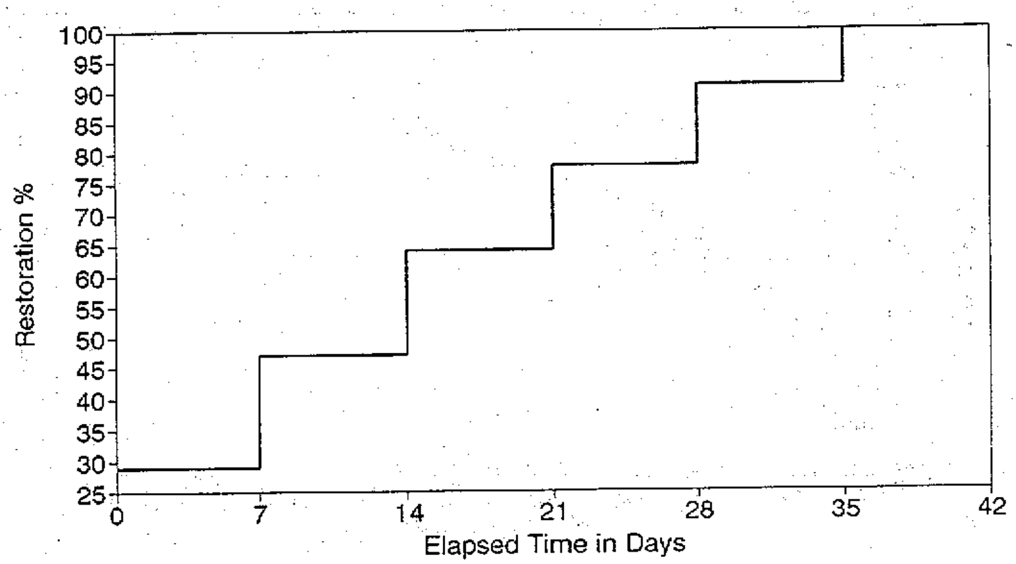


Figure C-29 Residual capacity of Rhode Island ports following Cape Ann event (M=7.0).

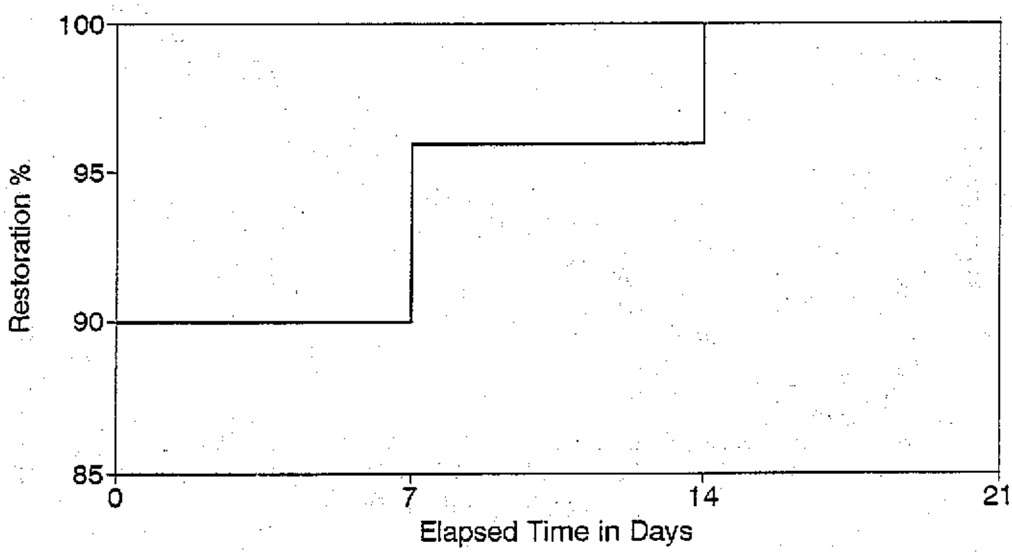


Figure C-30 Residual capacity of Connecticut ports following Cape Ann event (M=7.0).

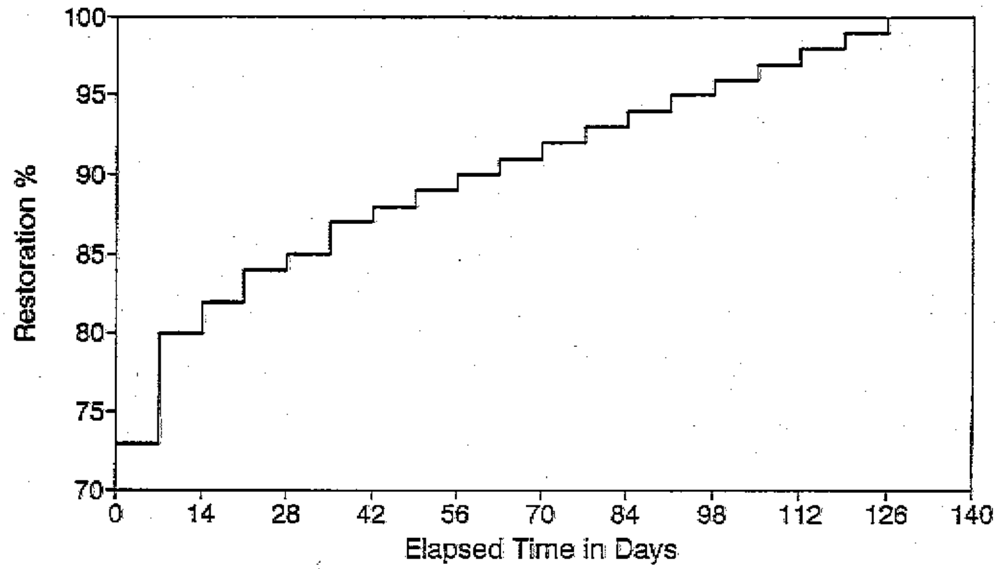


Figure C-31 Residual capacity of California ports following Hayward event (M=7.5).

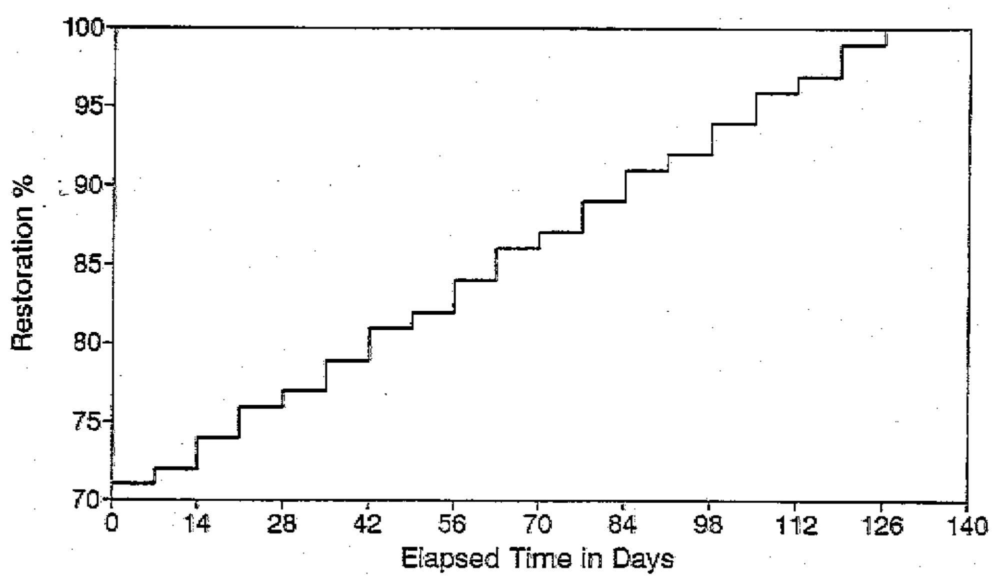


Figure C-32 Residual capacity of California ports following Fort Tejon event (M=8.0).

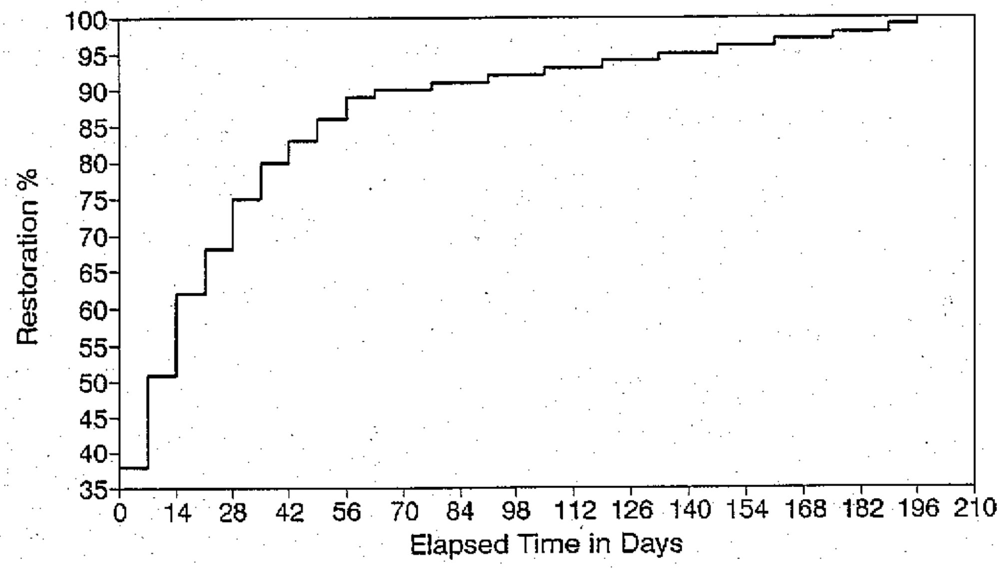


Figure C-33 Residual capacity of Washington ports following Puget Sound event (M=7.5).

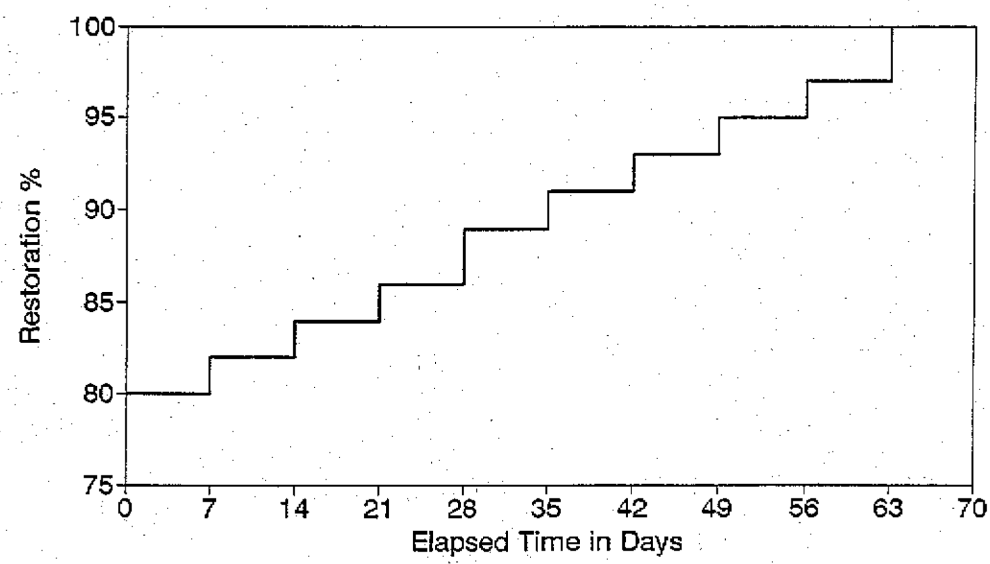


Figure C-34 Residual capacity of Illinois medical care centers following New Madrid event (M=8.0).

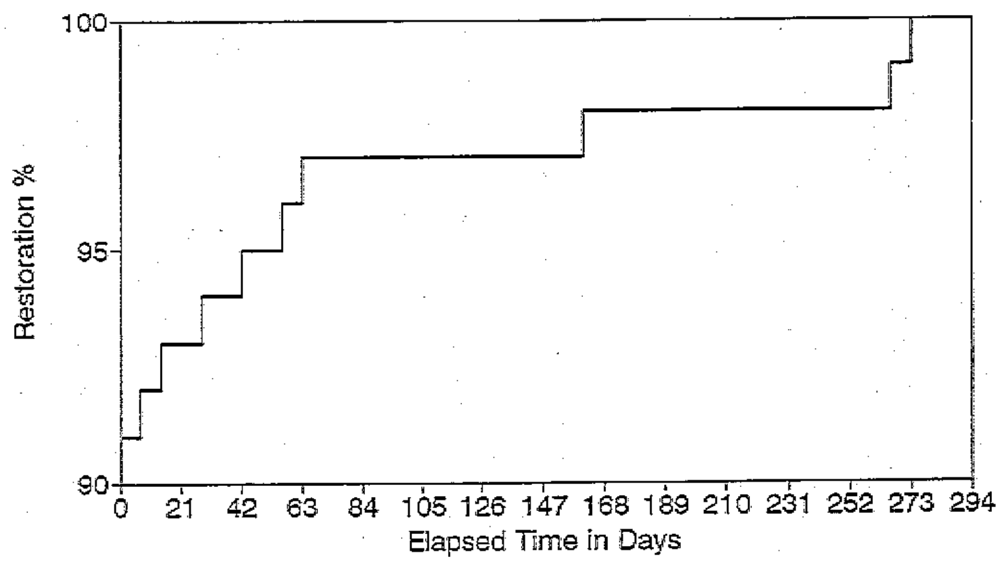


Figure C-35 Residual capacity of Missouri medical care centers following New Madrid event (M=8.0).

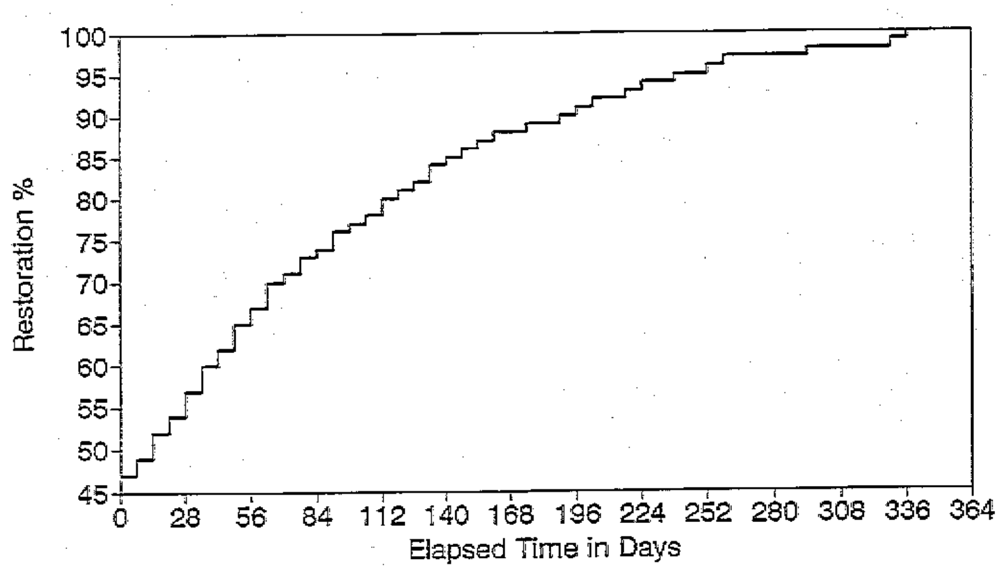


Figure C-36 Residual capacity of Arkansas medical care centers following New Madrid event (M=8.0).

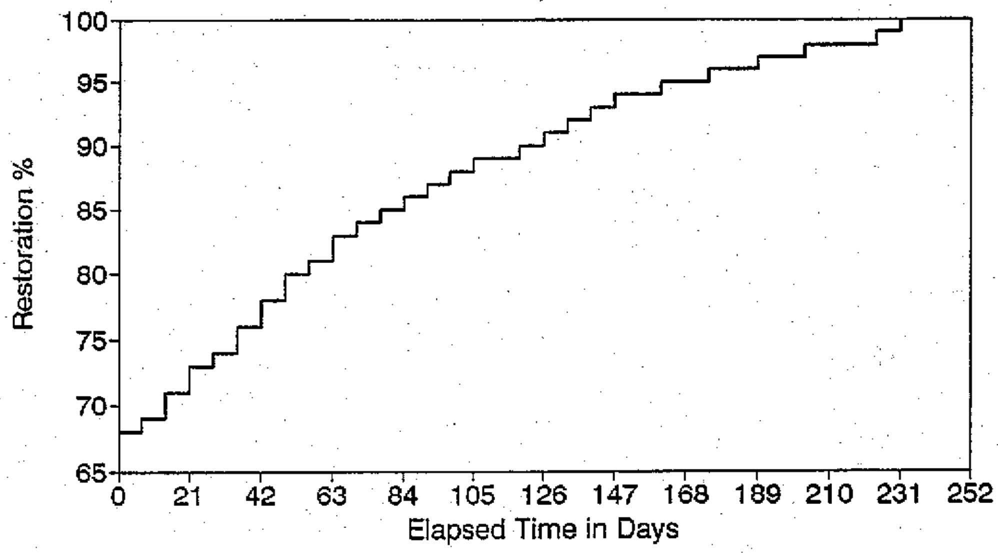


Figure C-37 Residual capacity of Tennessee medical care centers following New Madrid event (M=8.0).

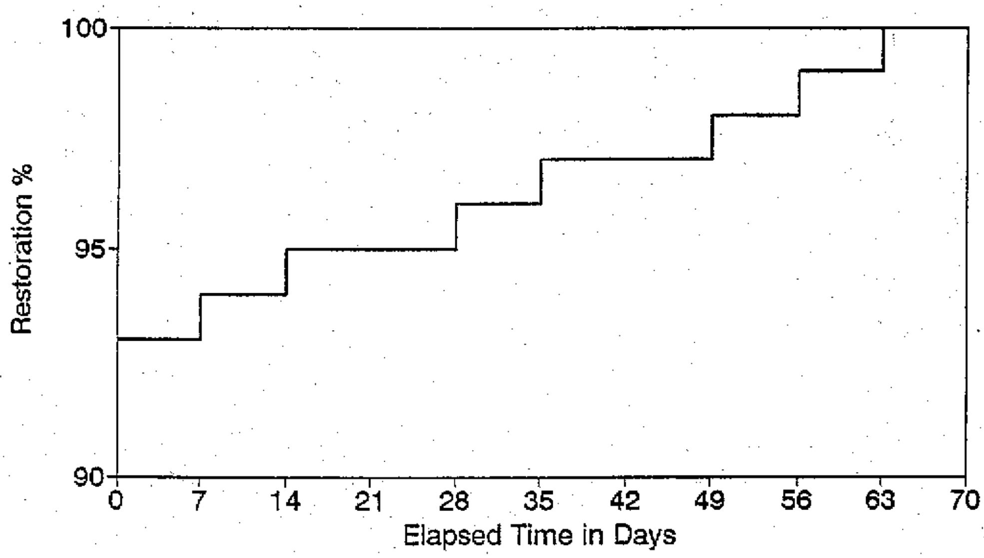


Figure C-38 Residual capacity of Indiana medical care centers following New Madrid event (M=8.0).

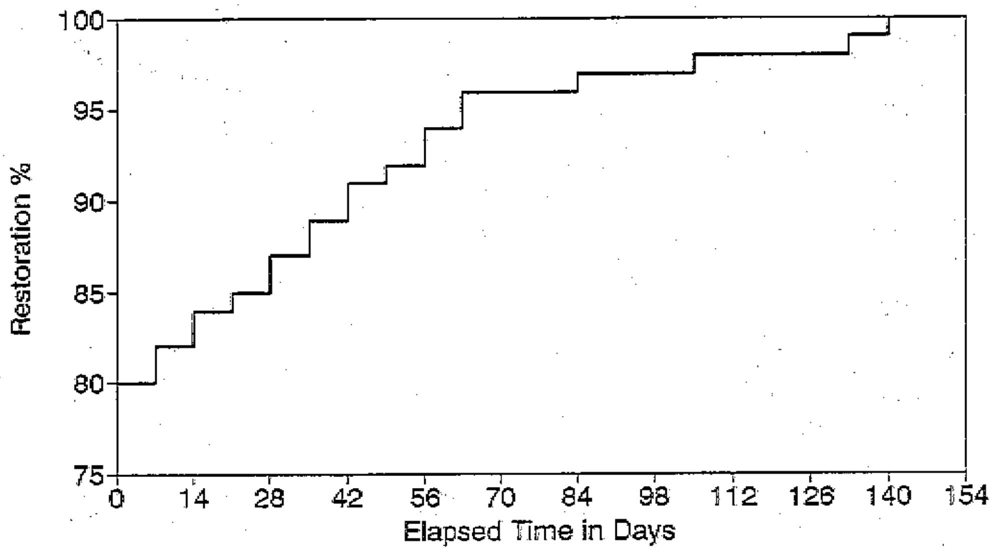


Figure C-39 Residual capacity of Kentucky medical care centers following New Madrid event (M=8.0).

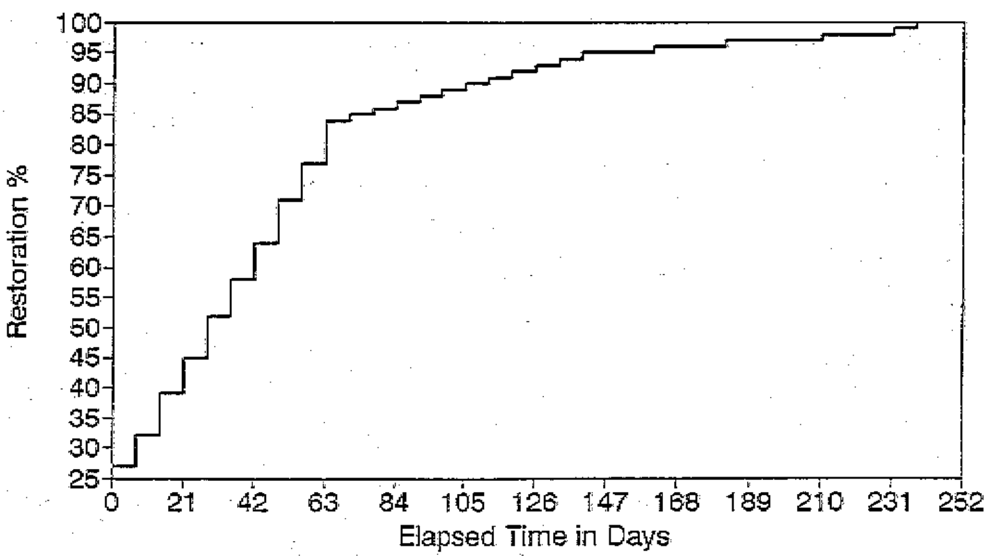


Figure C-40 Residual capacity of Mississippi medical care centers following New Madrid event (M=8.0).

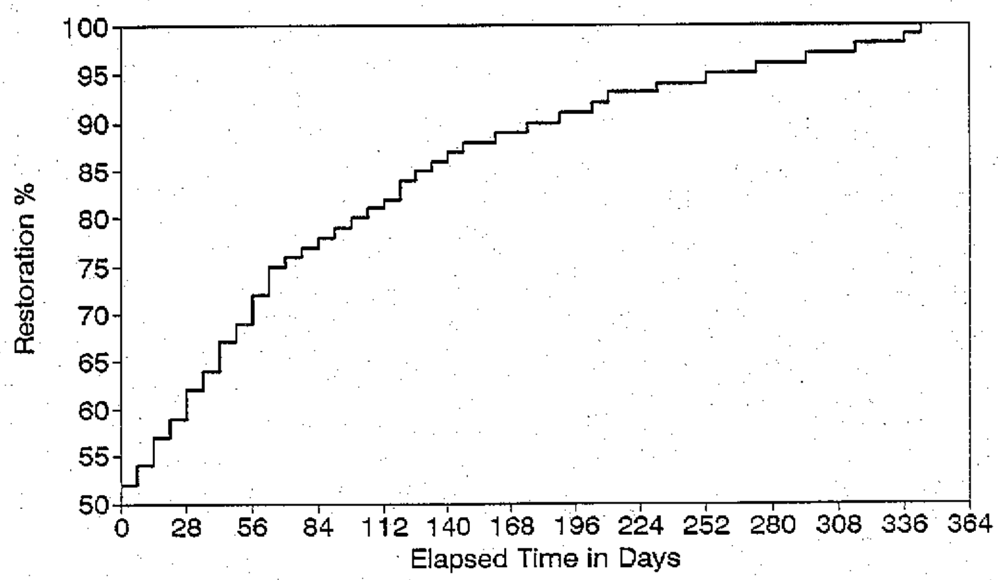


Figure C-41 Residual capacity of South Carolina medical care centers following Charleston event (M=7.5).

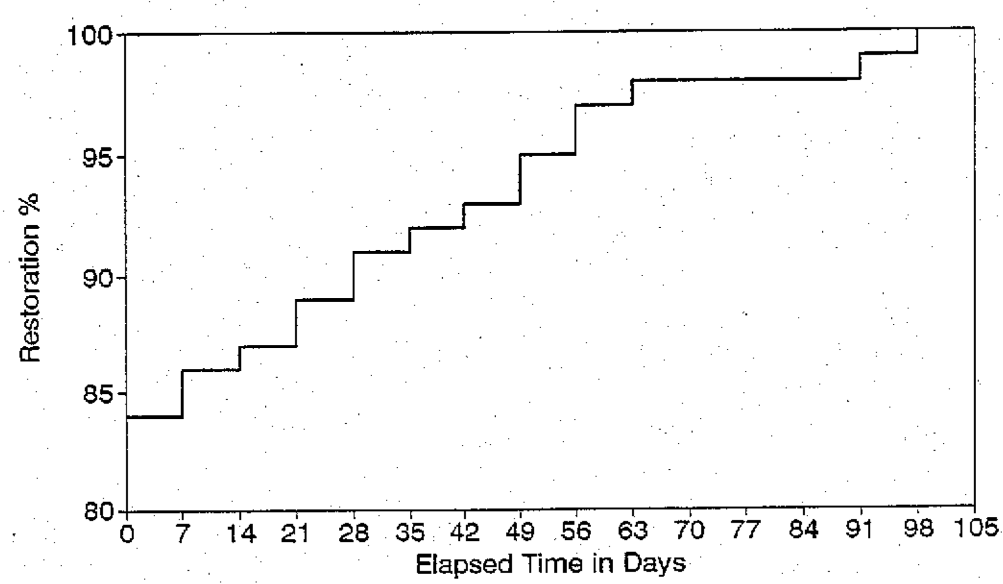


Figure C-42 Residual capacity of North Carolina medical care centers following Charleston event (M=7.5).

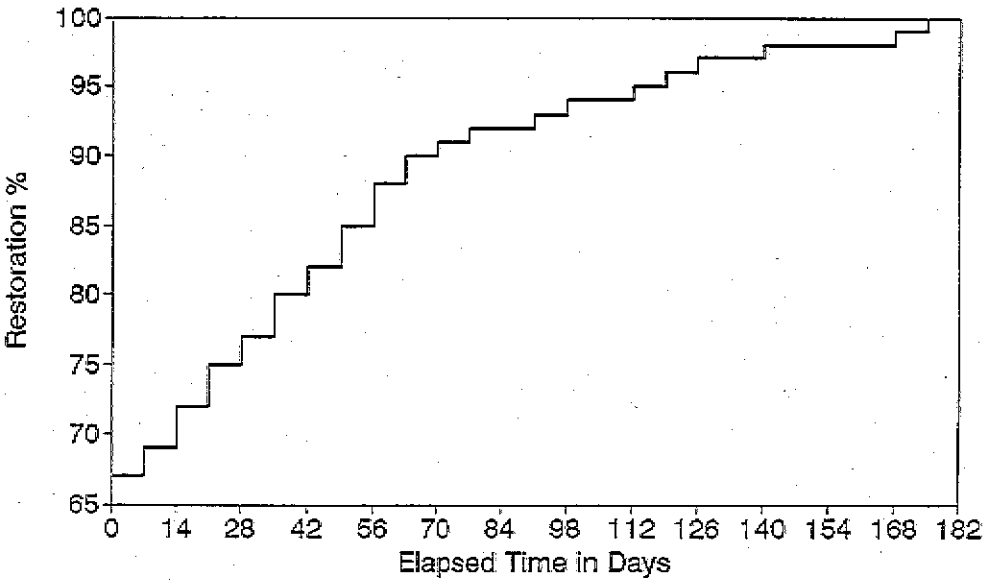


Figure C-43 Residual capacity of Georgia medical care centers following Charleston event (M=7.5).

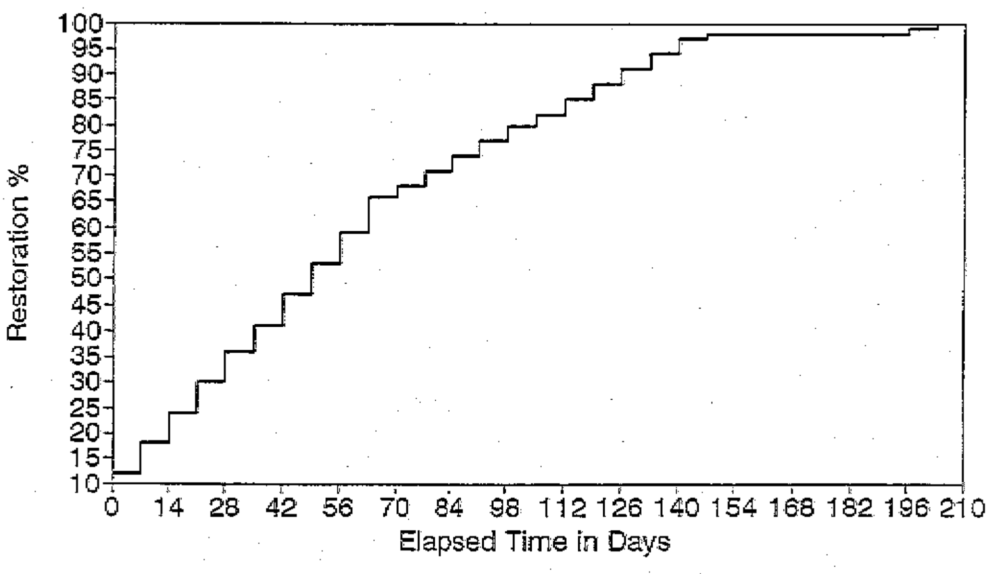


Figure C-44 Residual capacity of Massachusetts medical care centers following Cape Ann event (M=7.0).

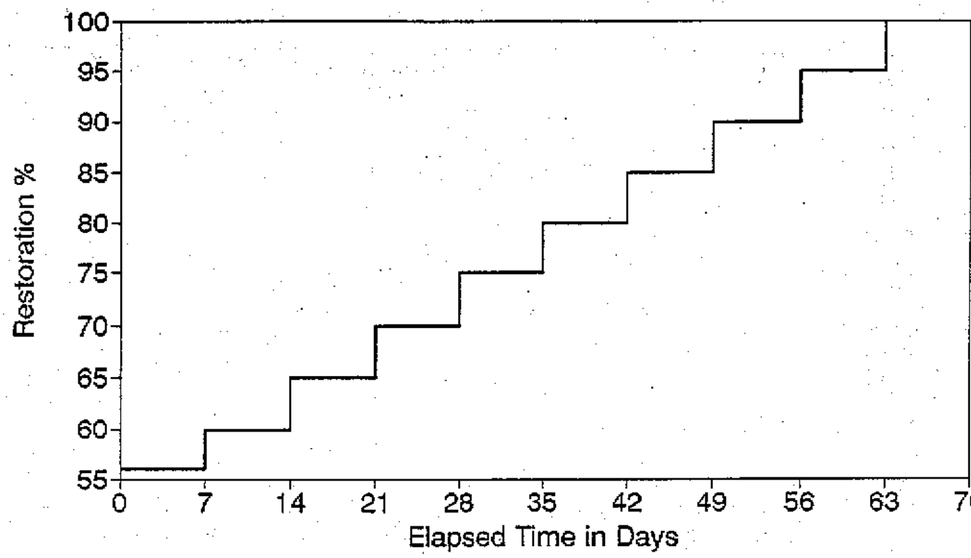


Figure C-45 Residual capacity of Connecticut medical care centers following Cape Ann event (M=7.0).

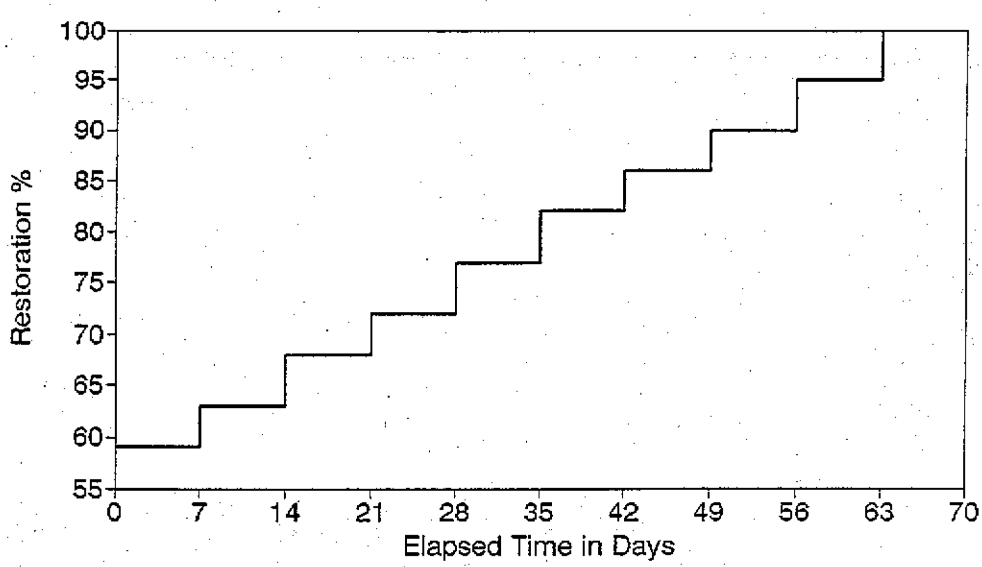


Figure C-46 Residual capacity of Delaware medical care centers following Cape Ann event (M=7.0).

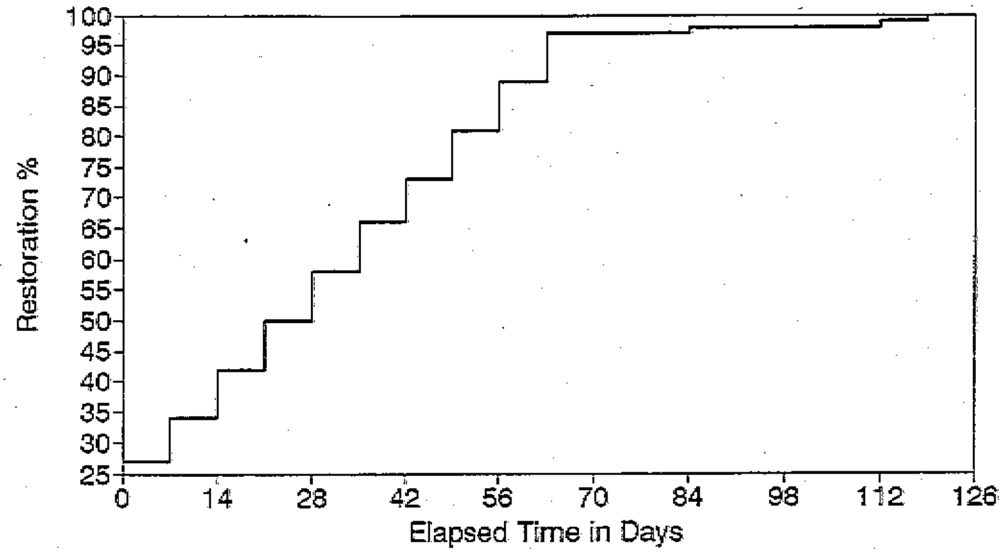


Figure C-47 Residual capacity of Rhode Island medical care centers following Cape Ann event (M=7.0).

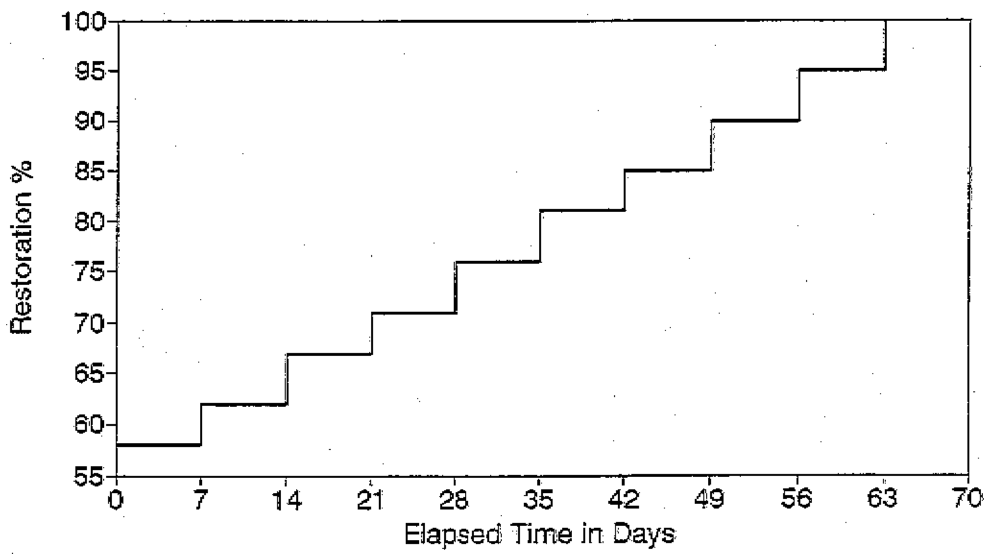


Figure C-48 Residual capacity of New Hampshire medical care centers following Cape Ann event (M=7.0).

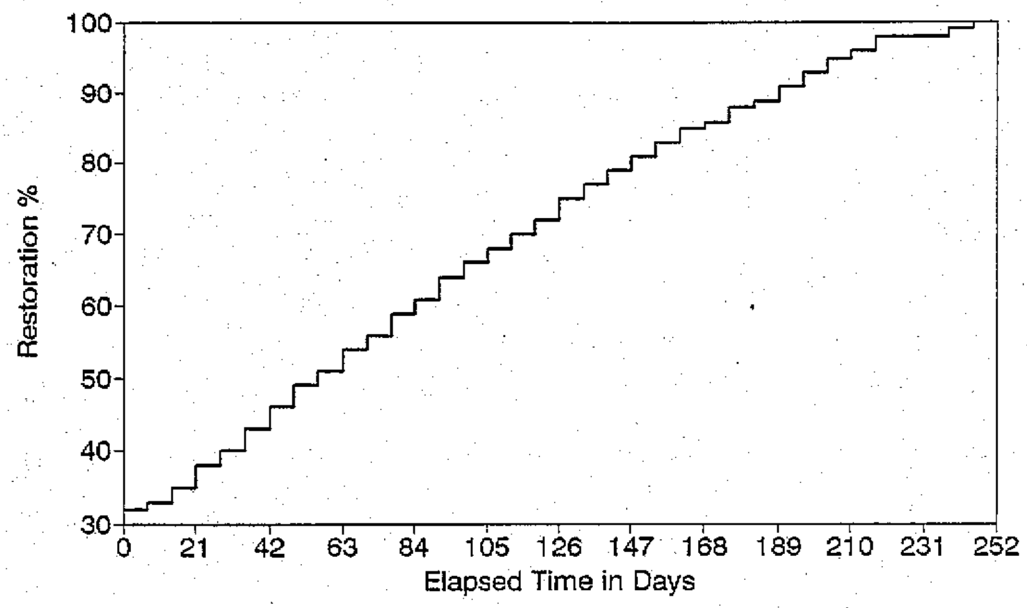


Figure C-49 Residual capacity of Utah medical care centers following Wasatch Front (M=7.5).

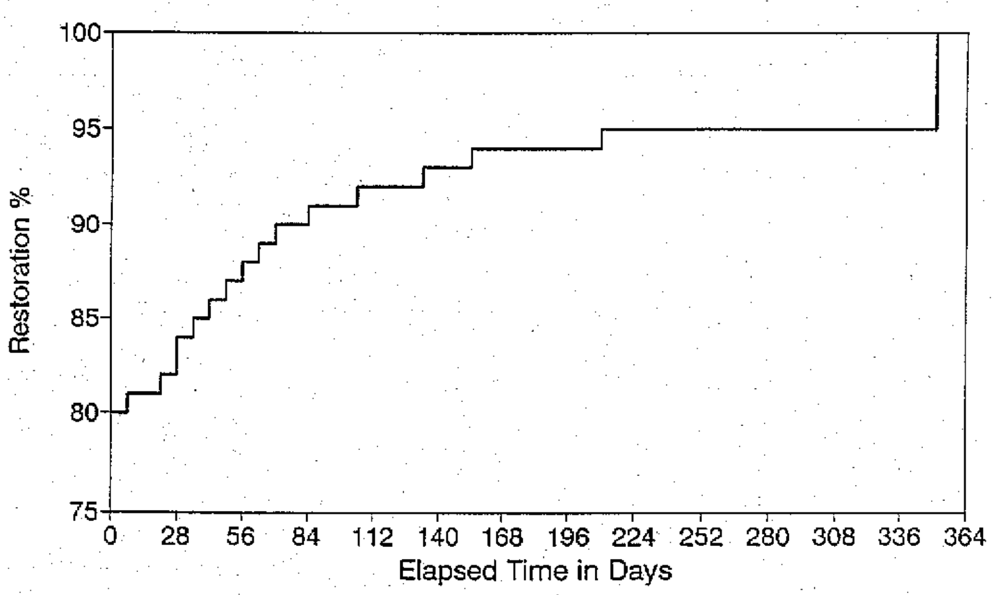


Figure C-50 Residual capacity of California medical care centers following Hayward event (M=7.5).

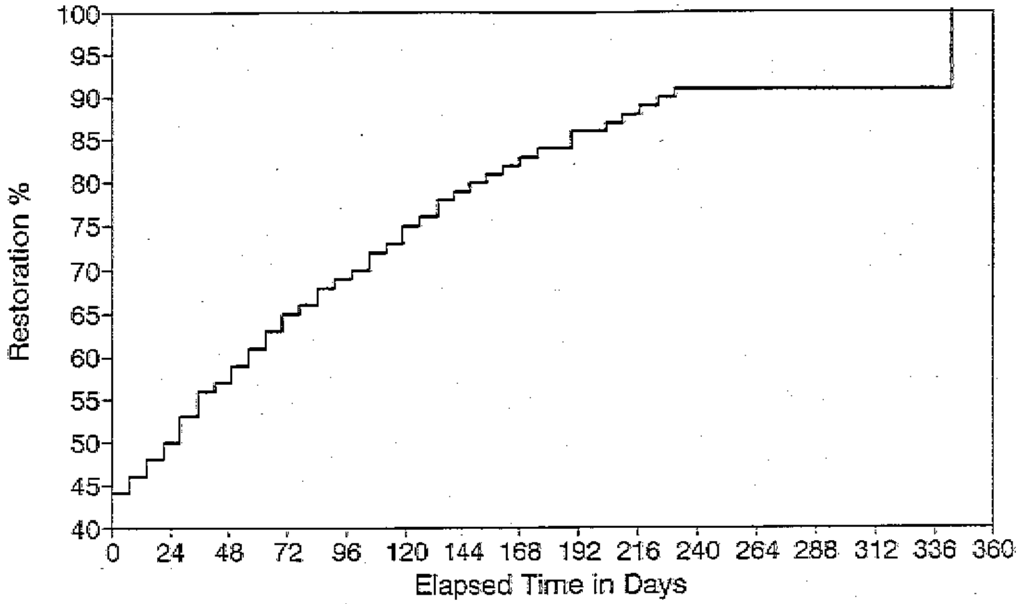


Figure C-51 Residual capacity of California medical care centers following Fort Tejon event (M=8.0).

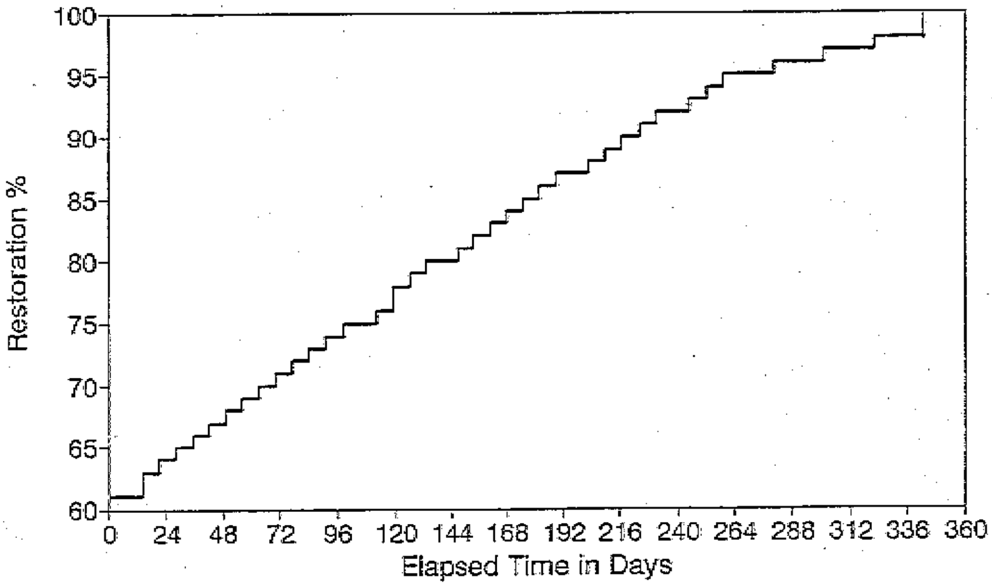


Figure C-52 Residual capacity of Washington medical care centers following Puget Sound event (M=7.5).

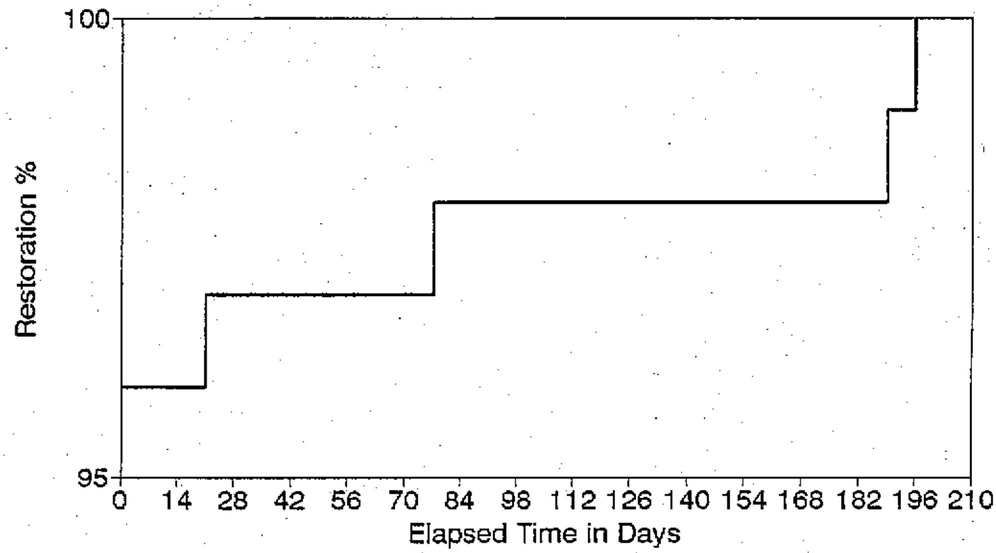


Figure C-53 Residual capacity of Missouri medical care centers following New Madrid event (M=7.0).

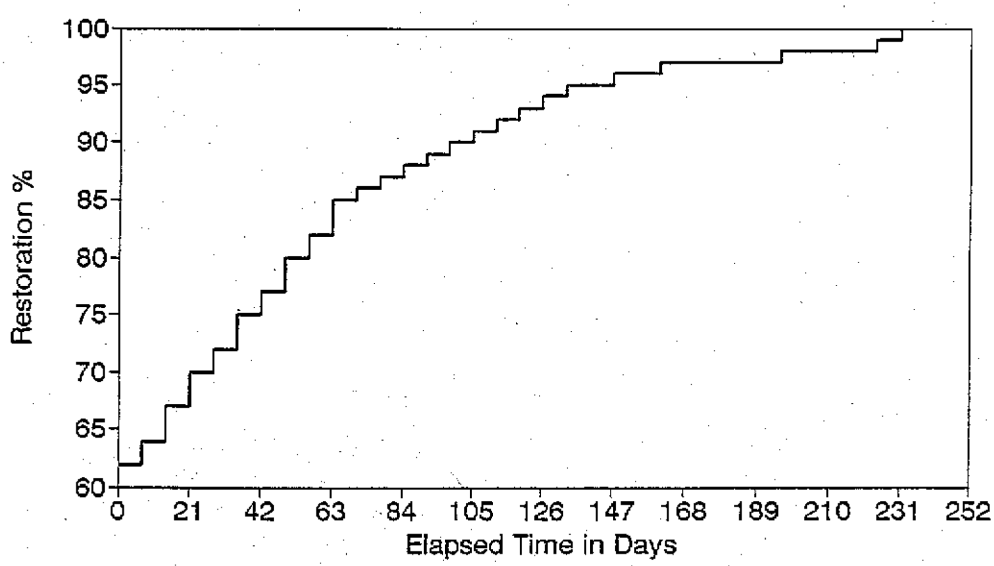


Figure C-54 Residual capacity of Arkansas medical care centers following New Madrid event (M=7.0).

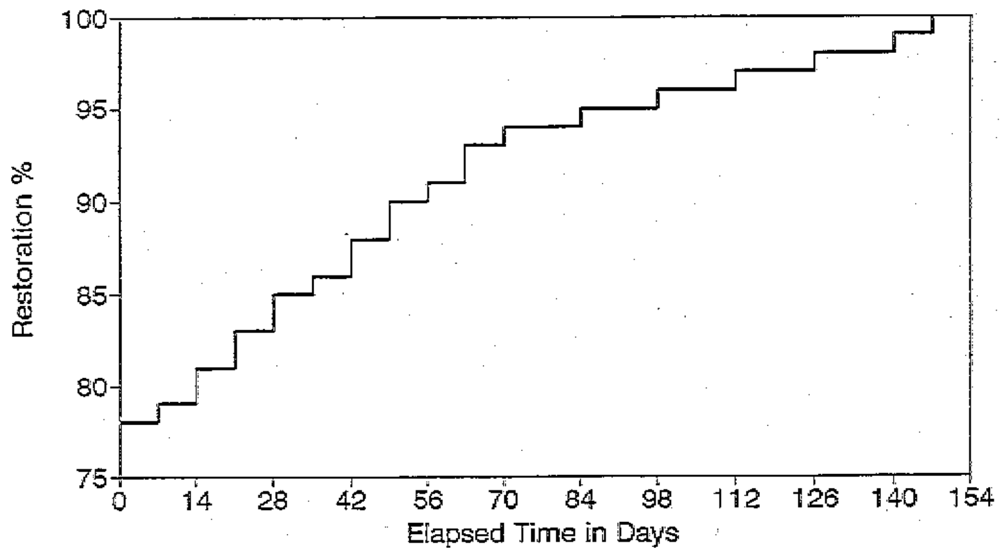


Figure C-55 Residual capacity of Tennessee medical care centers following New Madrid event (M=7.0).

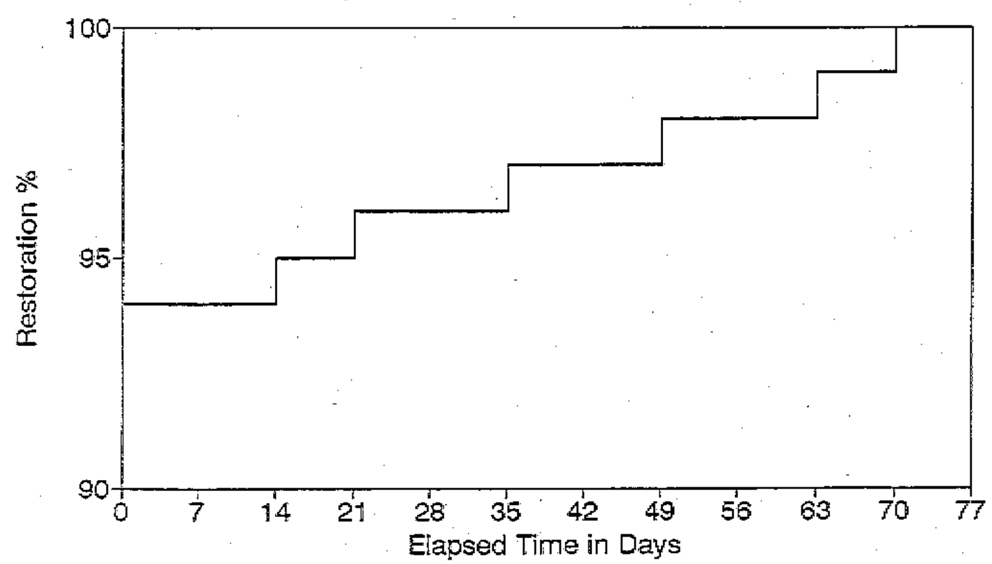


Figure C-56 Residual capacity of Kentucky medical care centers following New Madrid event (M=7.0).

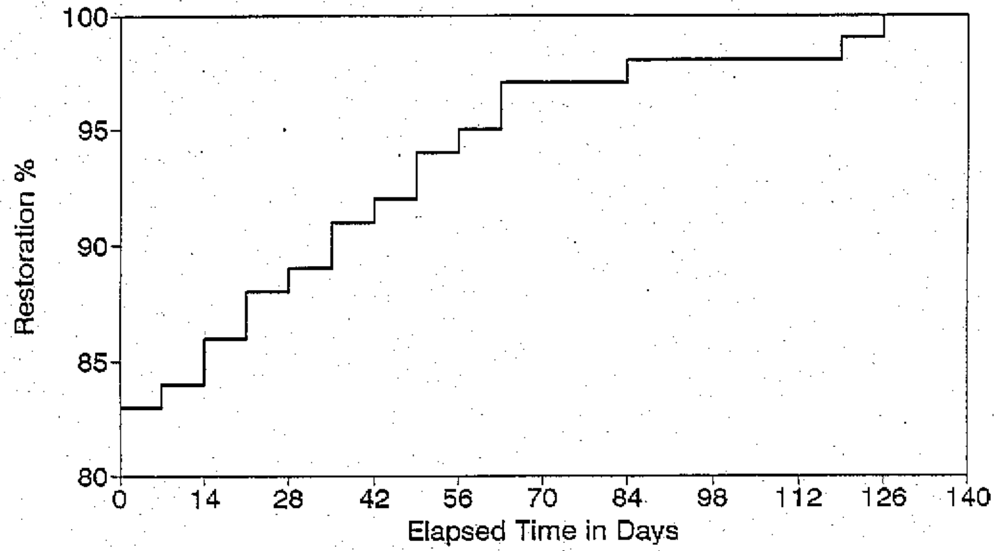


Figure C-57 Residual capacity of Mississippi medical care centers following New Madrid event (M=7.0).

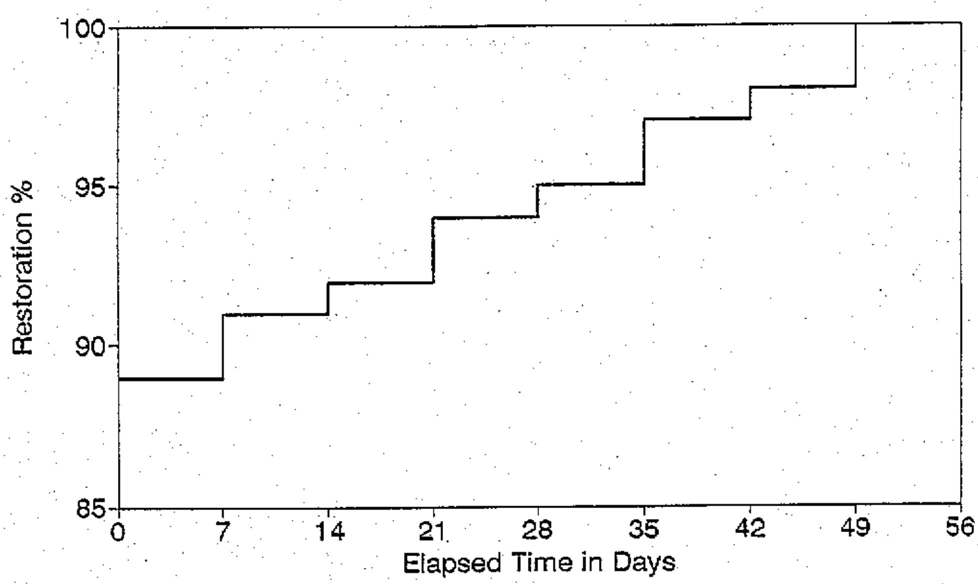


Figure C-58 Residual capacity of Illinois fire stations following New Madrid event (M=7.0).

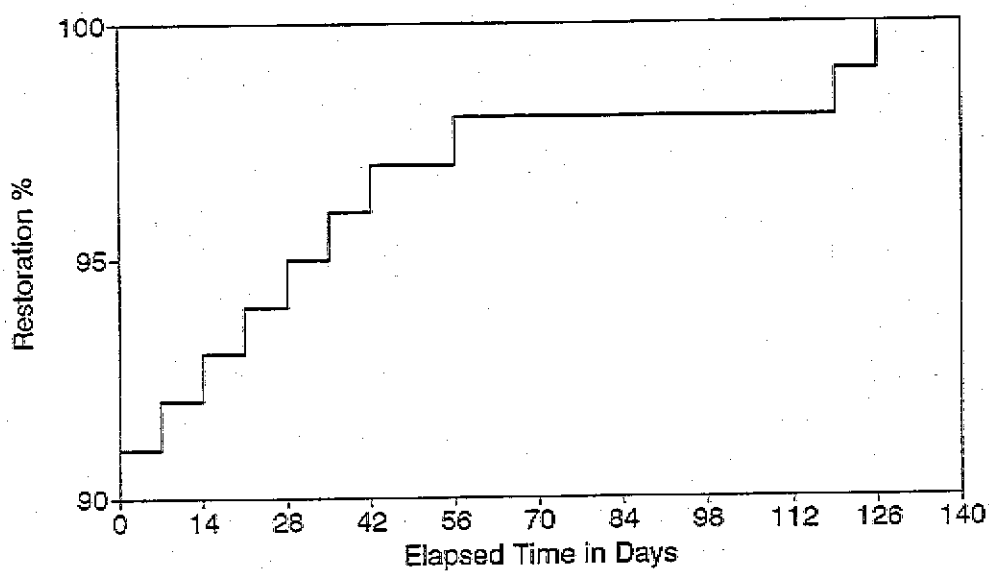


Figure C-59 Residual capacity of Missouri fire stations following New Madrid event (M=8.0).

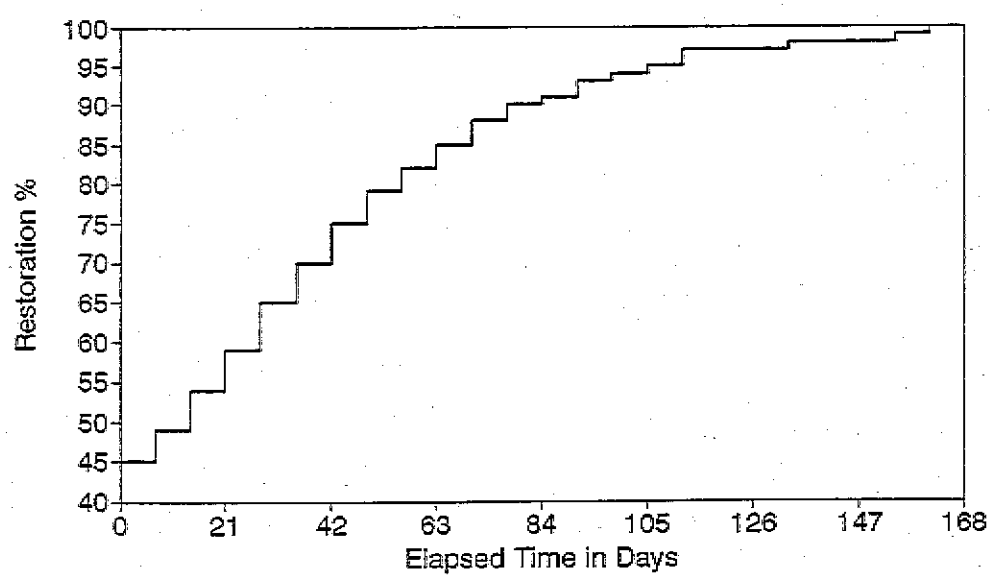


Figure C-60 Residual capacity of Arkansas fire stations following New Madrid event (M=8.0).

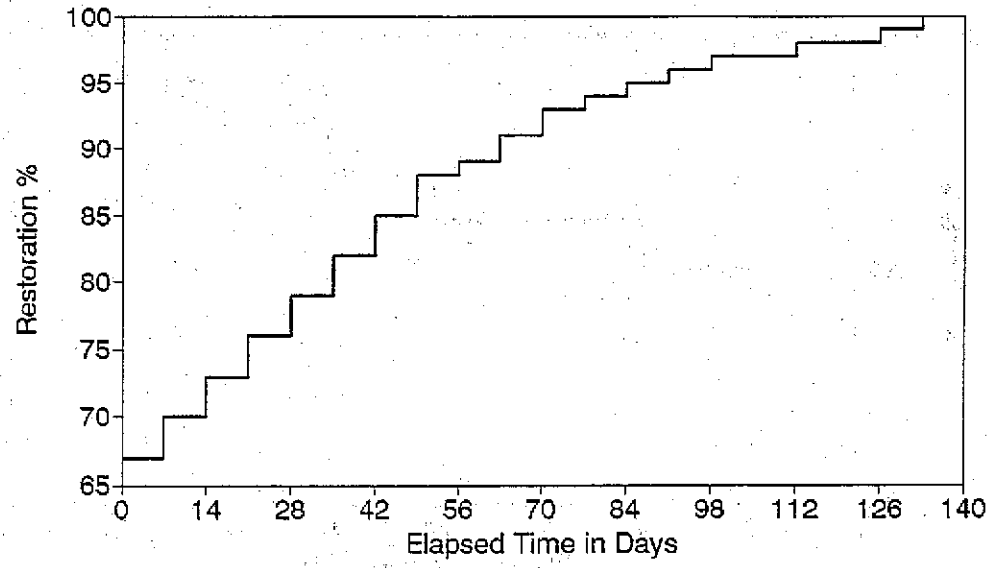


Figure C-61 Residual capacity of Tennessee fire stations following New Madrid event (M=8.0).

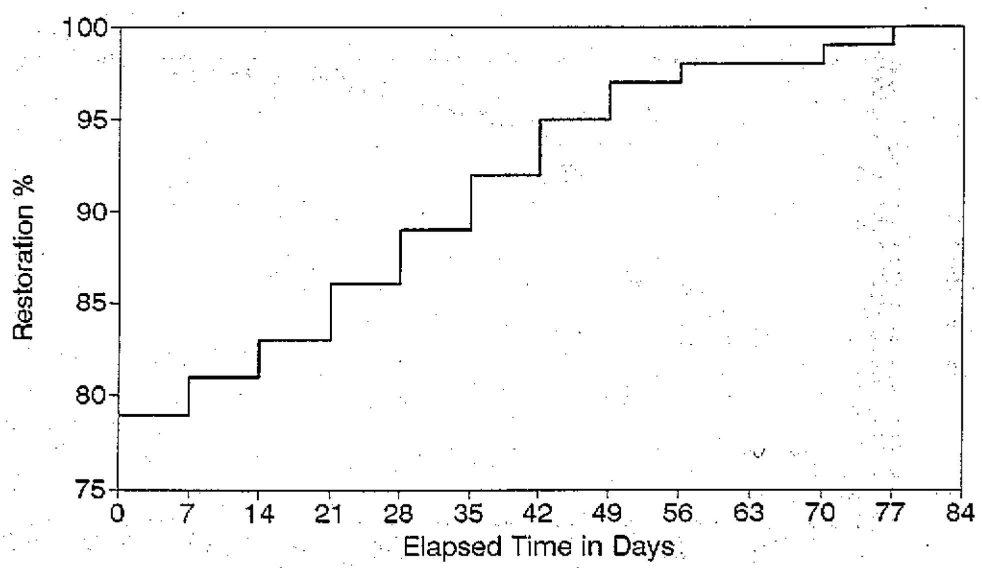


Figure C-62 Residual capacity of Indiana fire stations following New Madrid event (M=8.0).

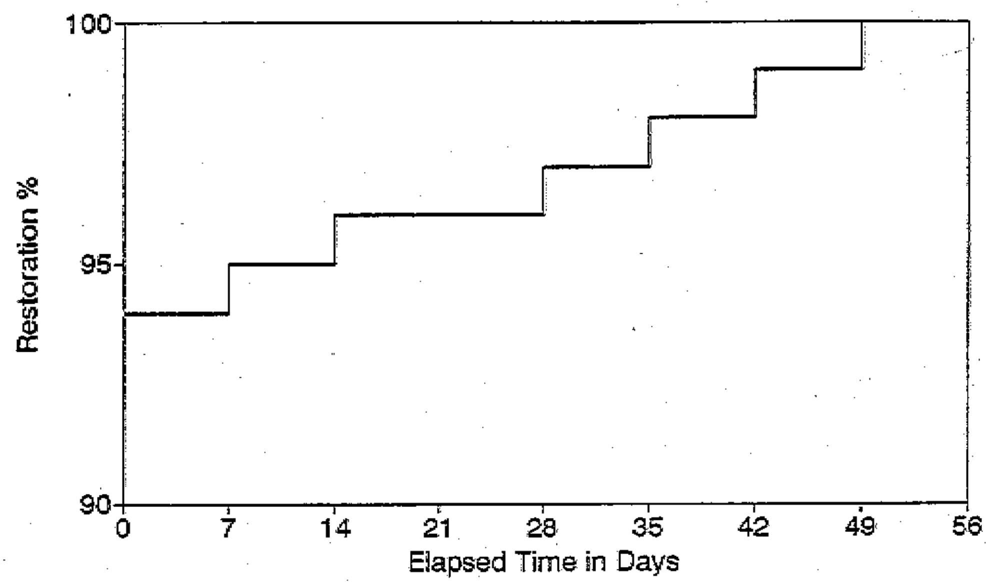


Figure C-63 Residual capacity of Kentucky fire stations following New Madrid event (M=8.0).

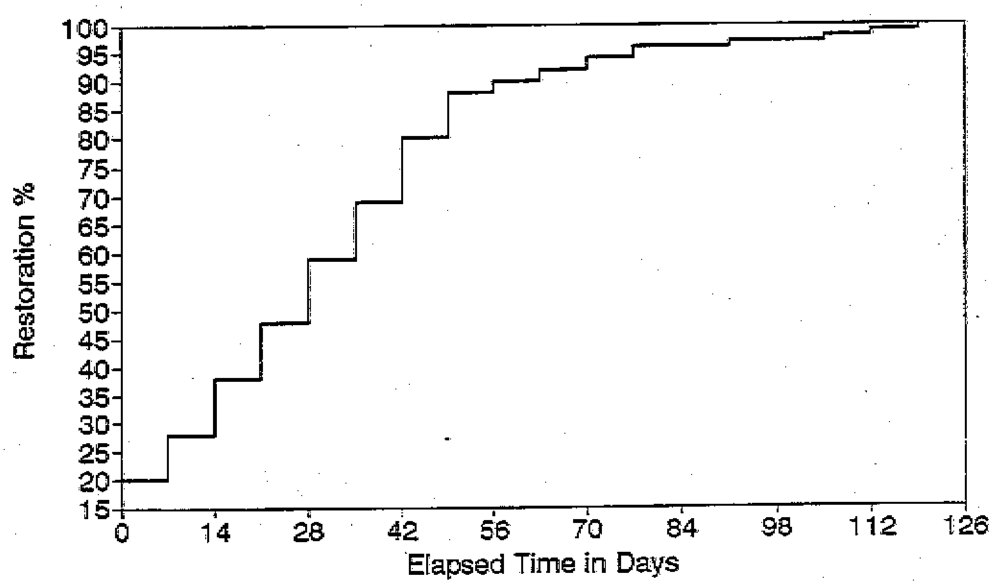


Figure C-64 Residual capacity of Mississippi fire stations following New Madrid event (M=8.0).

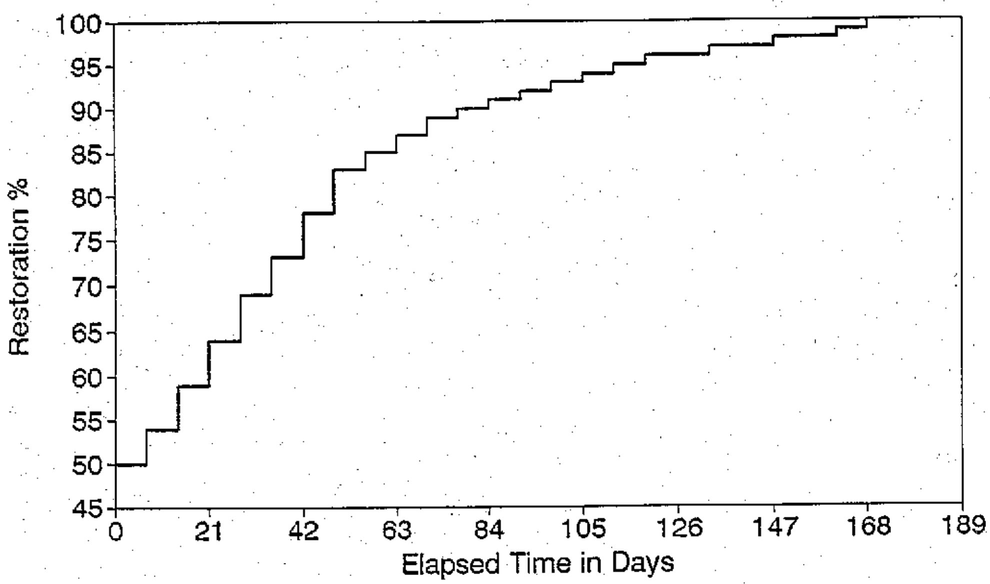


Figure C-65 Residual capacity of South Carolina fire stations following Charleston event (M=7.5).

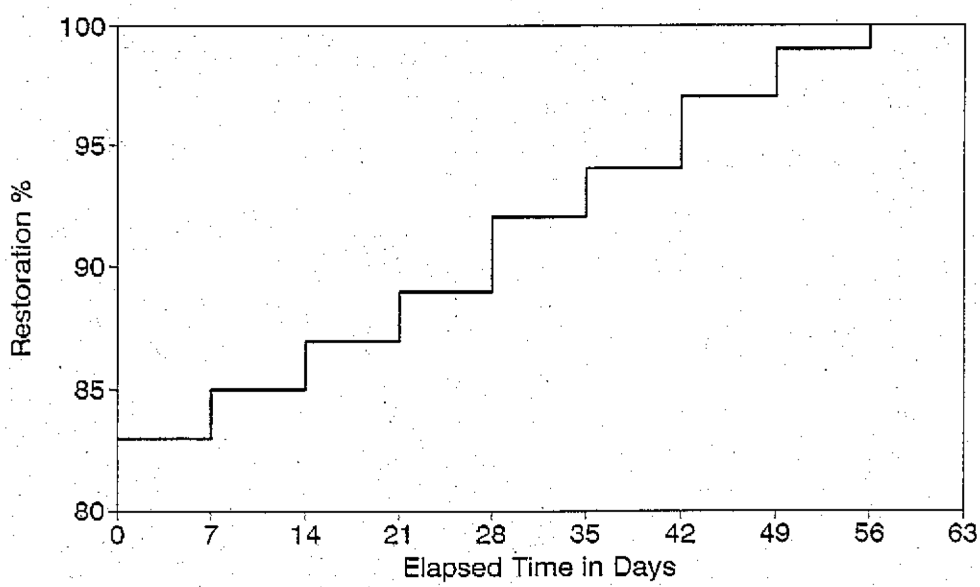


Figure C-66 Residual capacity of North Carolina fire stations following Charleston event (M=7.5).

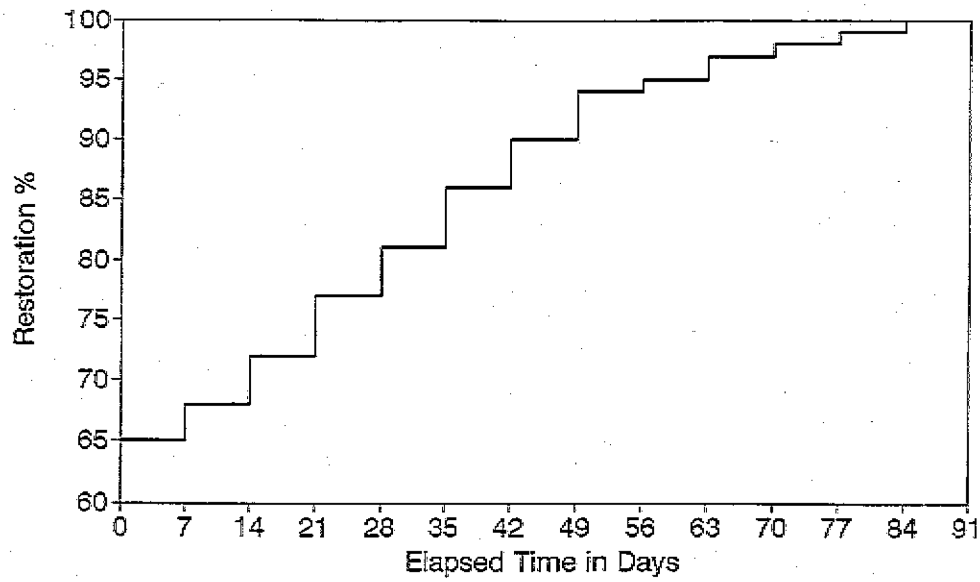


Figure C-67 Residual capacity of Georgia fire stations following Charleston event (M=7.5).

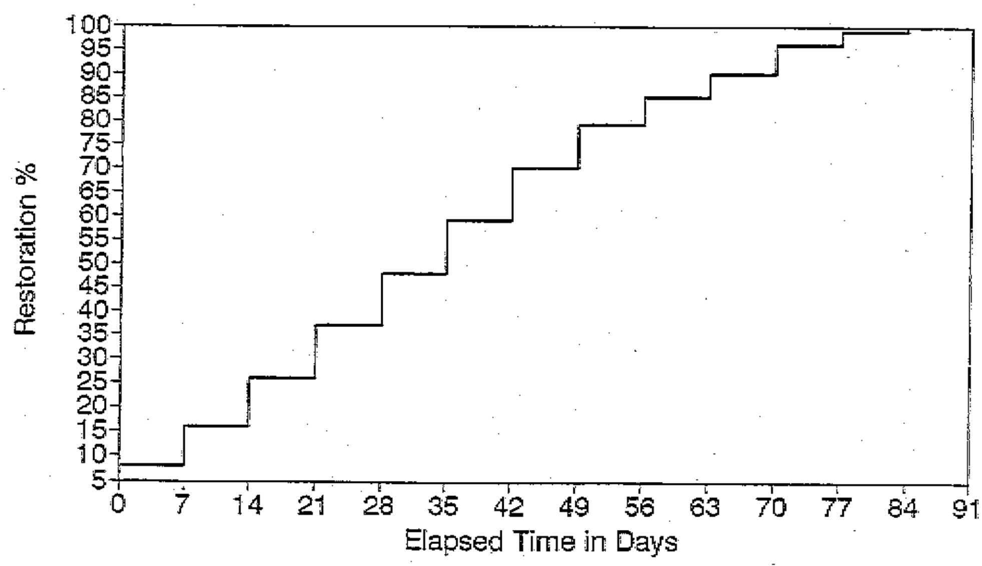


Figure C-68 Residual capacity of Massachusetts fire stations following Cape Ann event (M=7.0).

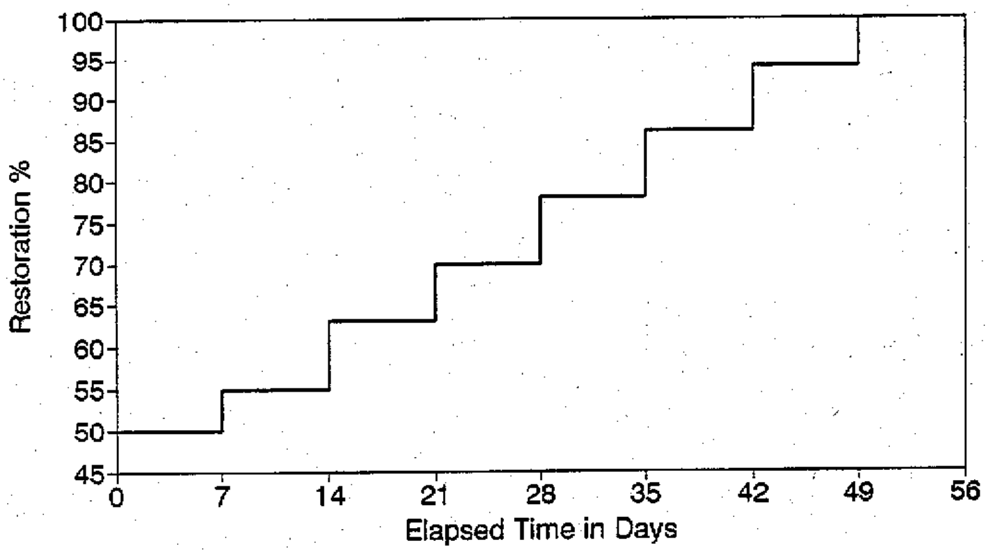


Figure C-69 Residual capacity of Connecticut fire stations following Cape Ann event (M=7.0).

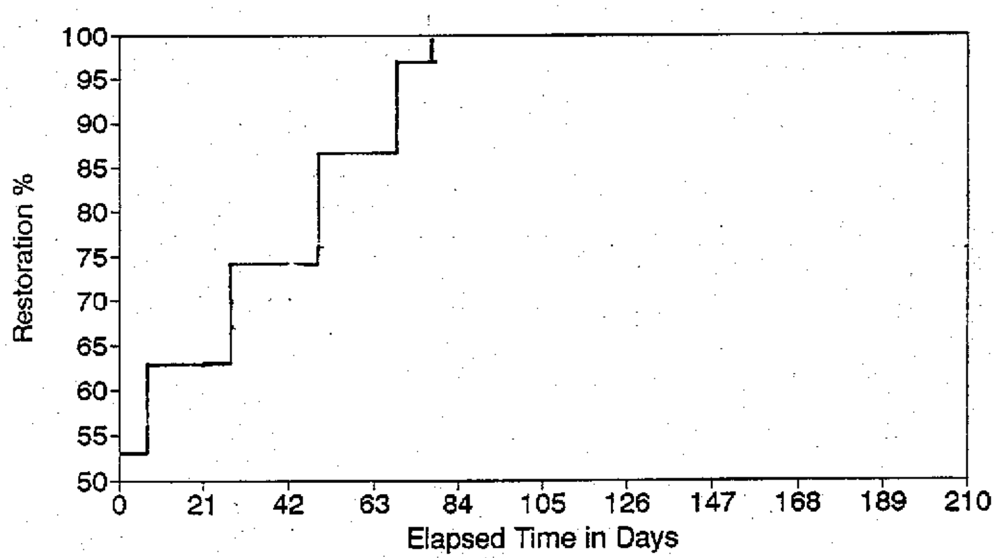


Figure C-70 Residual capacity of Delaware fire stations following Cape Ann event (M=7.0).

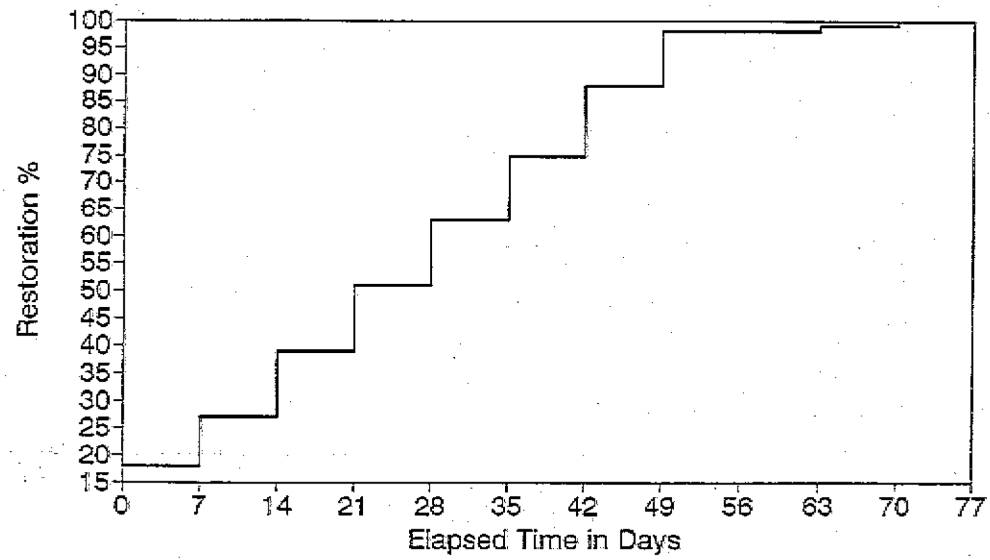


Figure C-71 Residual capacity of Rhode Island fire stations following Cape Ann event (M=7.0).

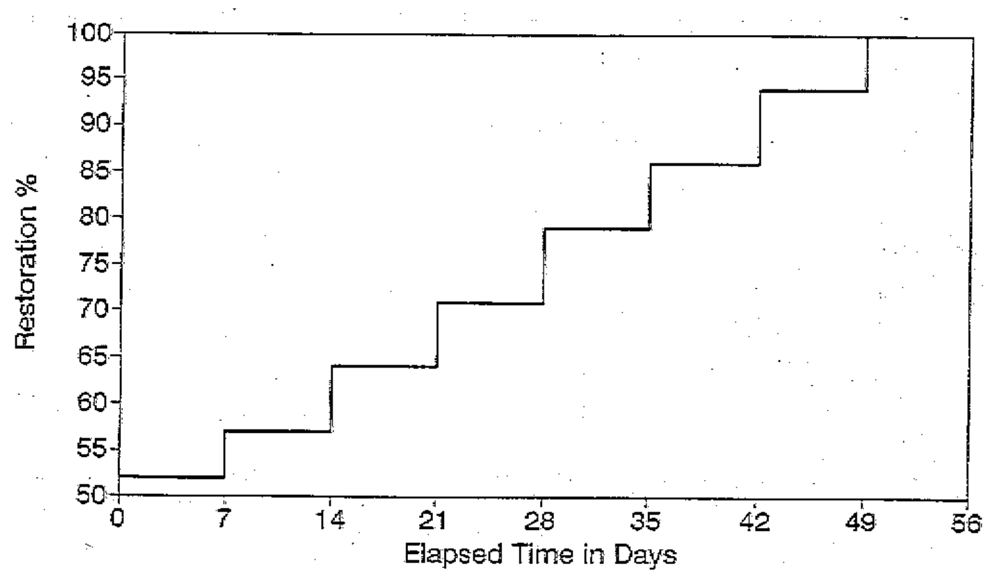


Figure C-72 Residual capacity of New Hampshire fire stations following Cape Ann event (M=7.0).

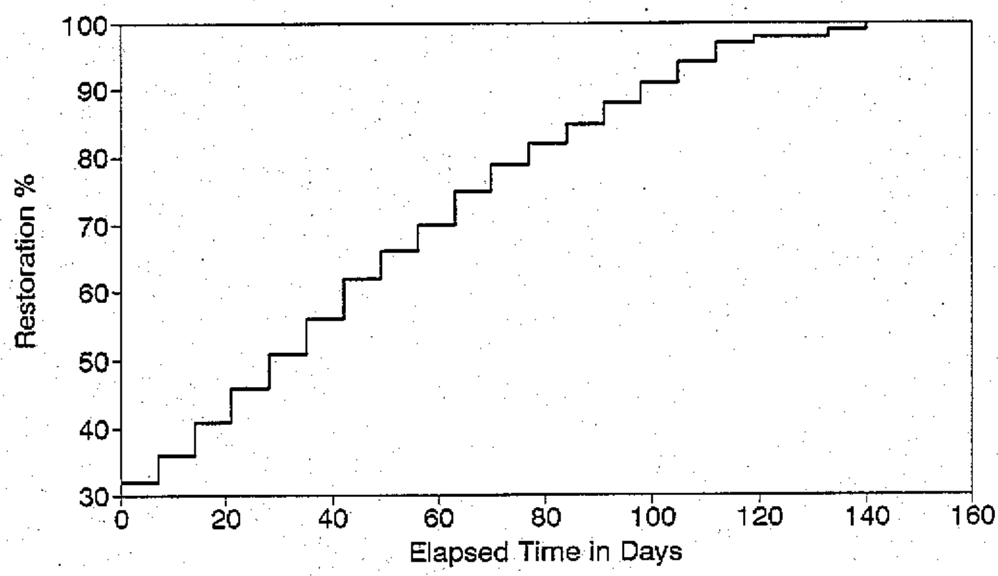


Figure C-73 Residual capacity of Utah fire stations following Wasatch Front event (M=7.5).

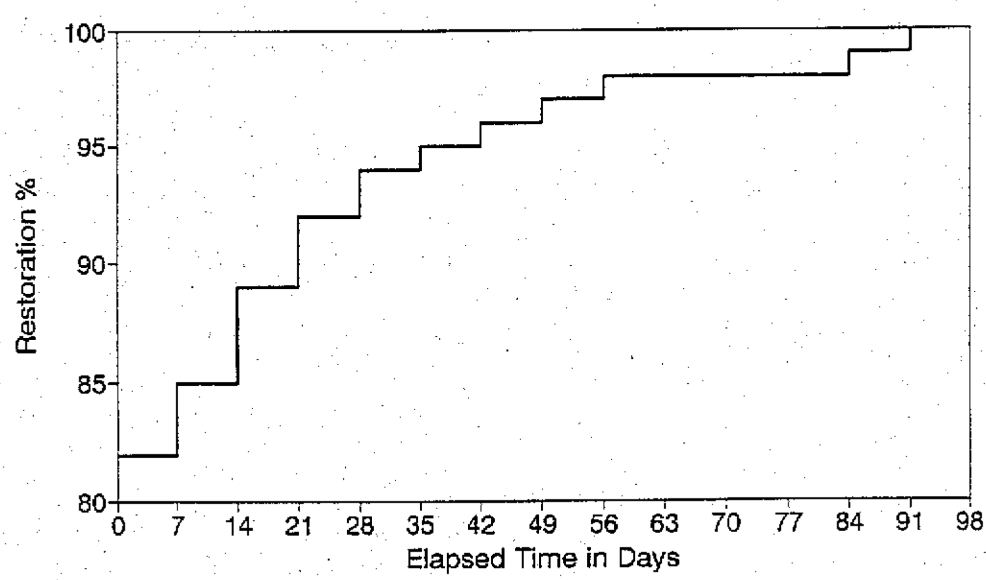


Figure C-74 Residual capacity of California fire stations following Hayward event (M=7.5).

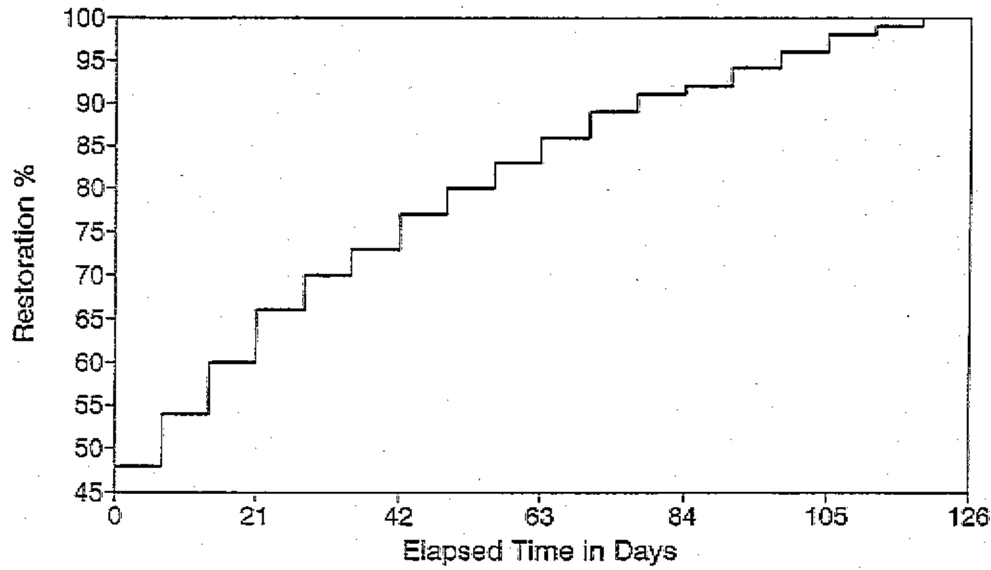


Figure C-75 Residual capacity of California fire stations following Fort Tejon event (M=8.0).

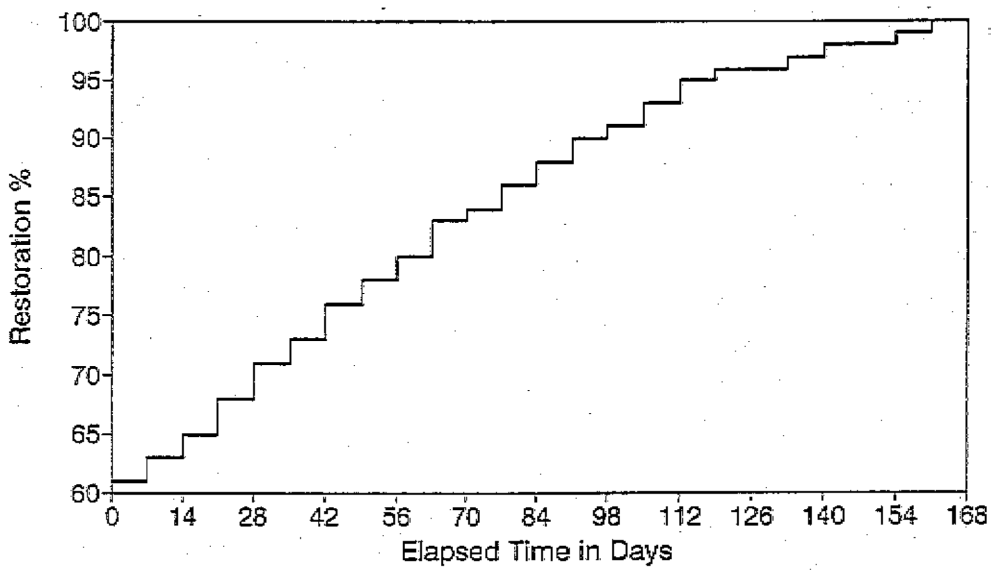


Figure C-76 Residual capacity of Washington fire stations following Puget Sound event (M=7.5).

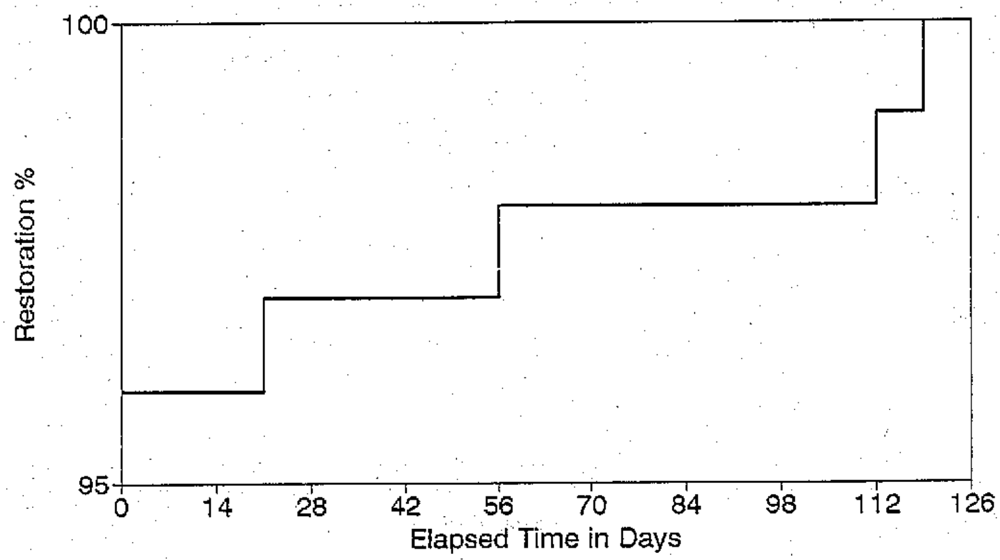


Figure C-77 Residual capacity of Missouri fire stations following New Madrid event (M=7.0).

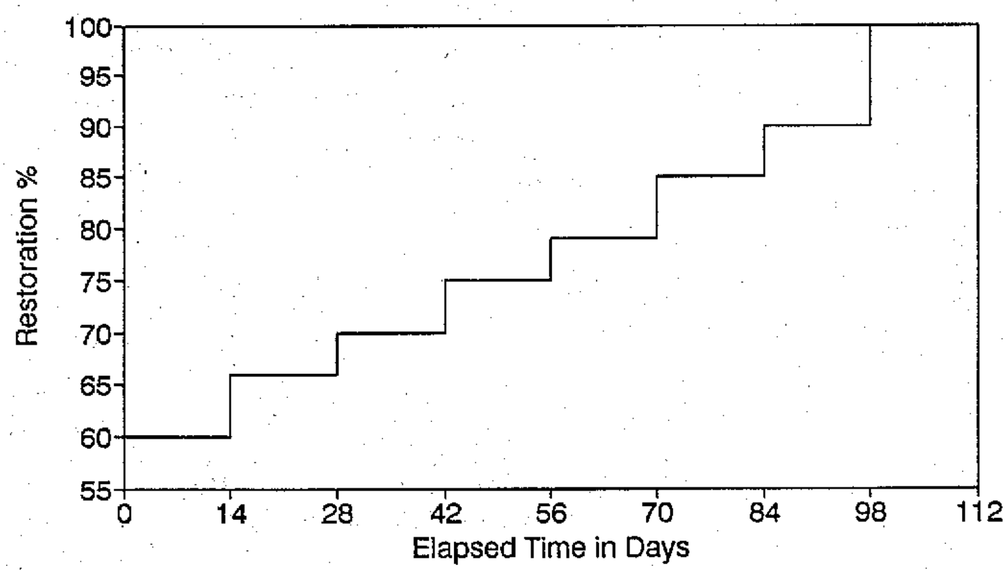


Figure C-78 Residual capacity of Arkansas fire stations following New Madrid event (M=7.0).

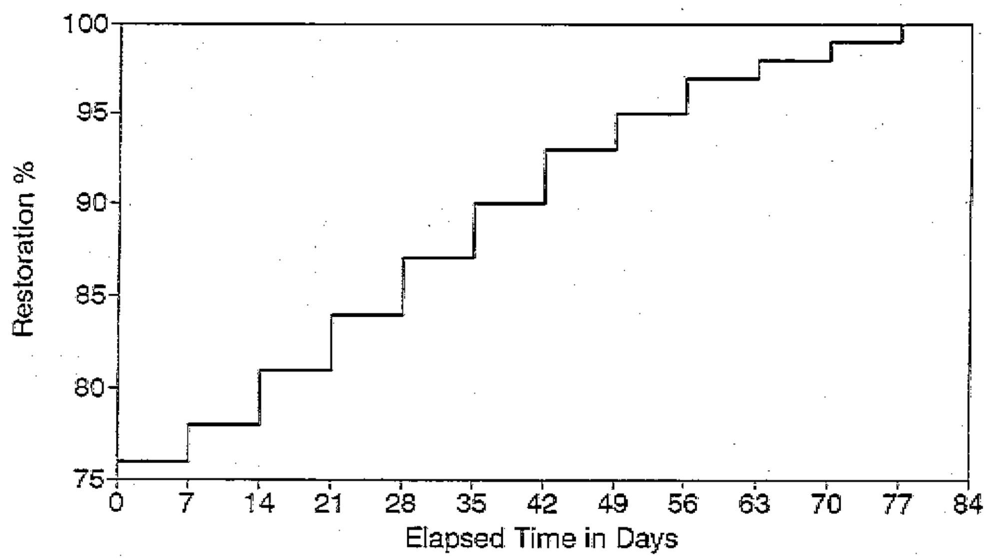


Figure C-79 Residual capacity of Tennessee fire stations following New Madrid event (M=7.0).

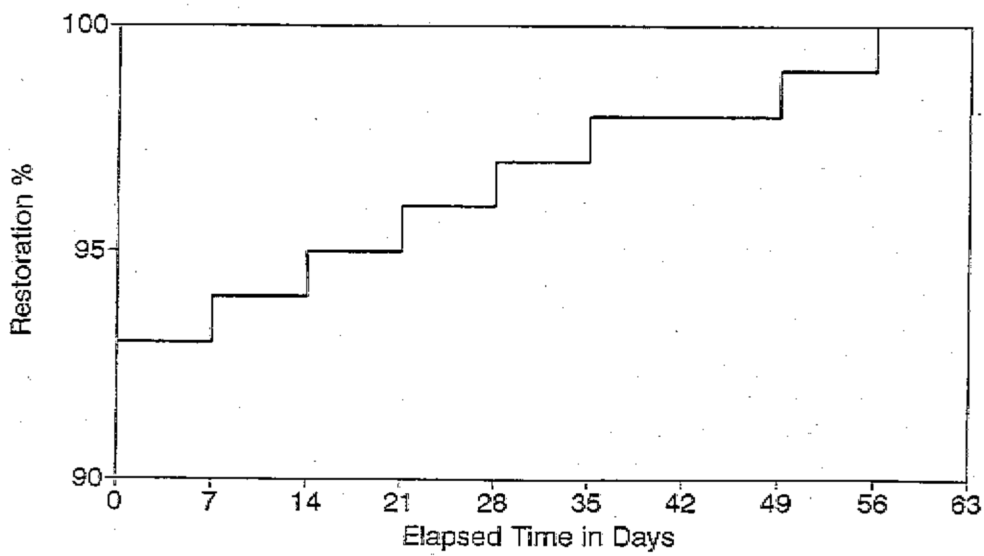


Figure C-80 Residual capacity of Kentucky fire stations following New Madrid event (M=7.0).

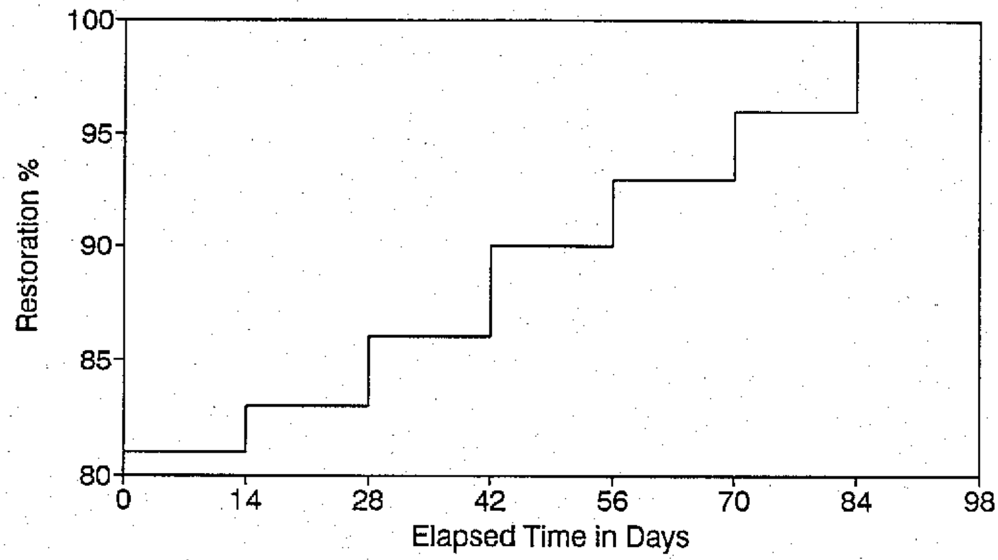


Figure C-81 Residual capacity of Mississippi fire stations following New Madrid event (M=7.0).

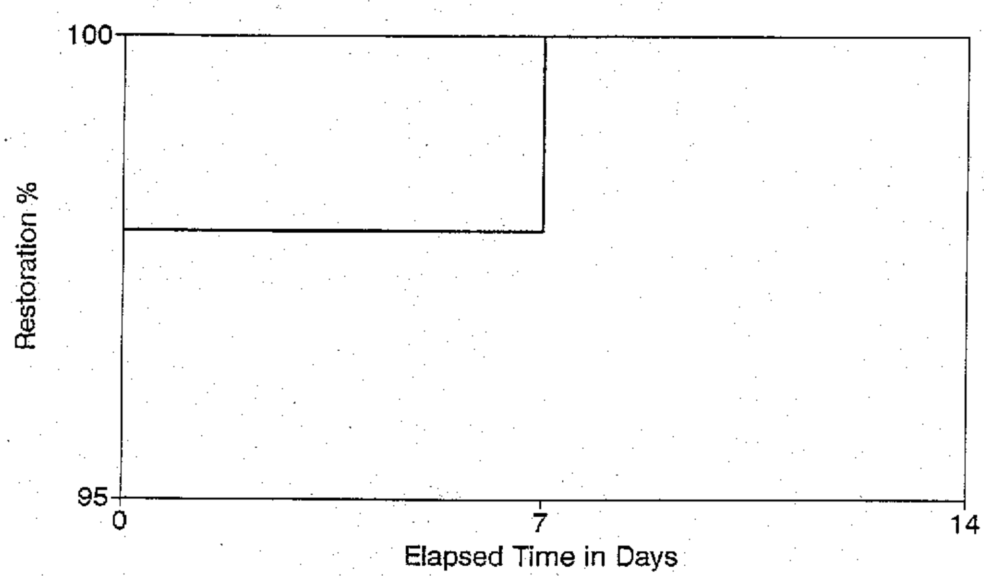


Figure C-82 Residual capacity of Illinois police stations following New Madrid event (M=8.0).

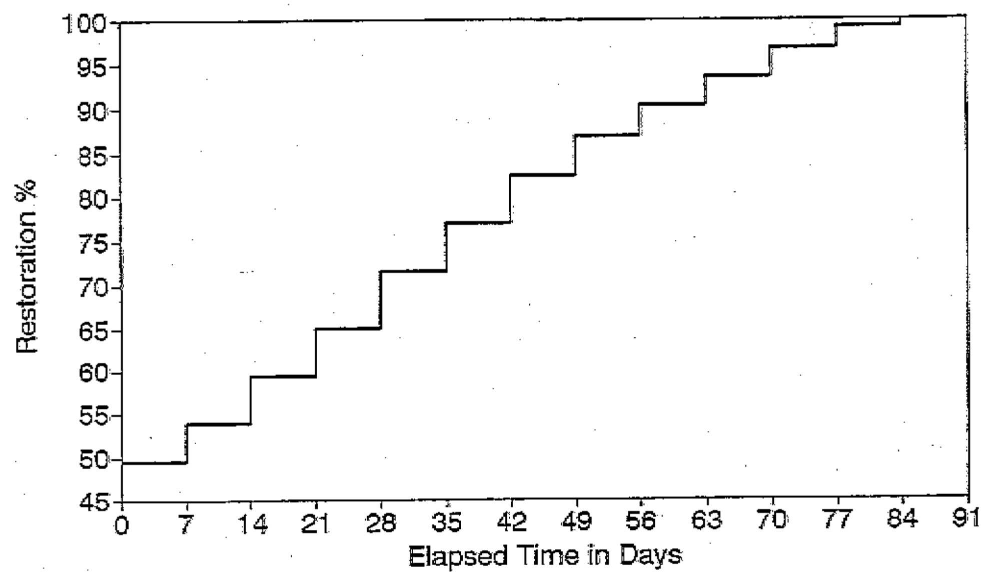


Figure C-83 Residual capacity of Arkansas police stations following New Madrid event (M=8.0).

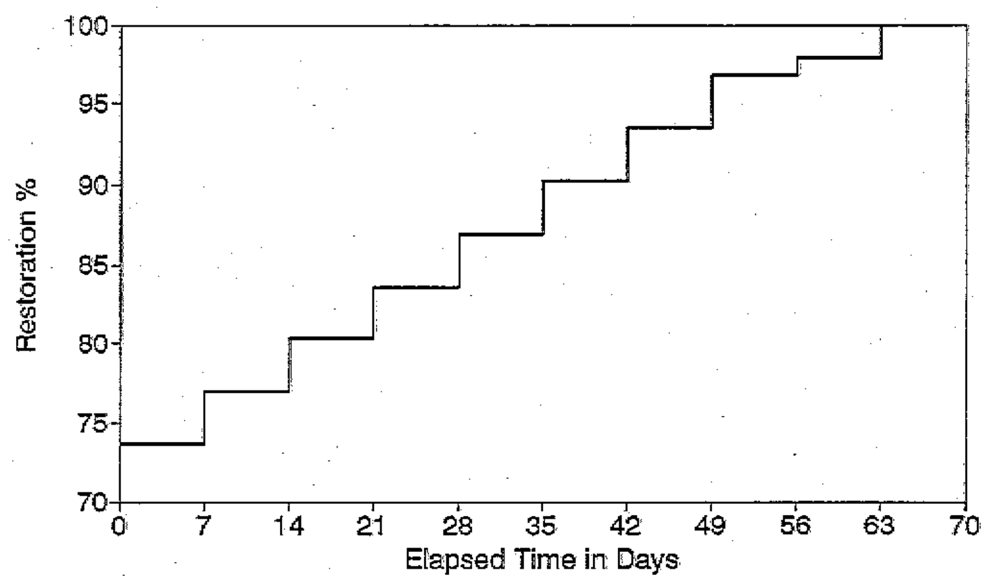


Figure C-84 Residual capacity of Tennessee police stations following New Madrid event (M=8.0).

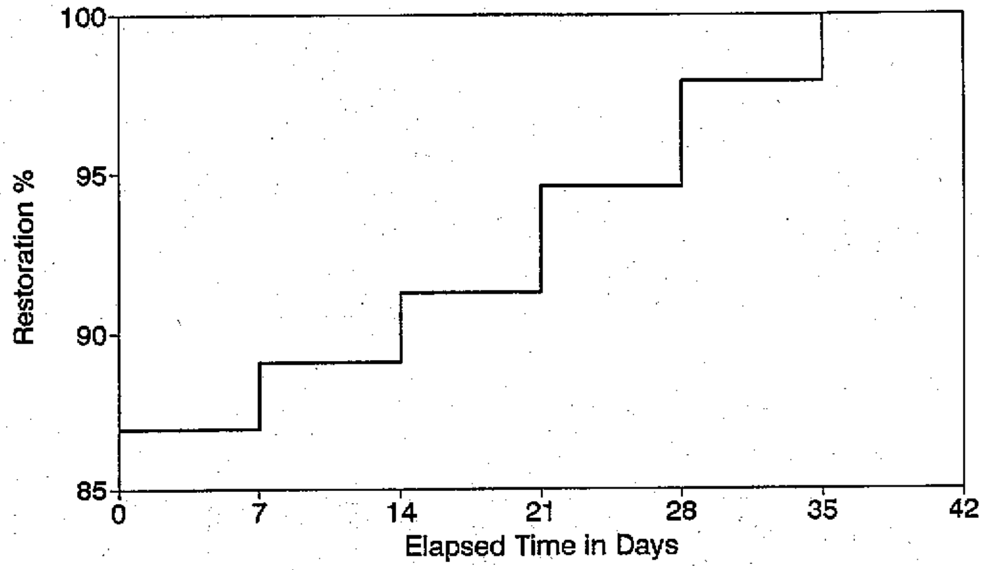


Figure C-85 Residual capacity of Kentucky police stations following New Madrid event (M=8.0).

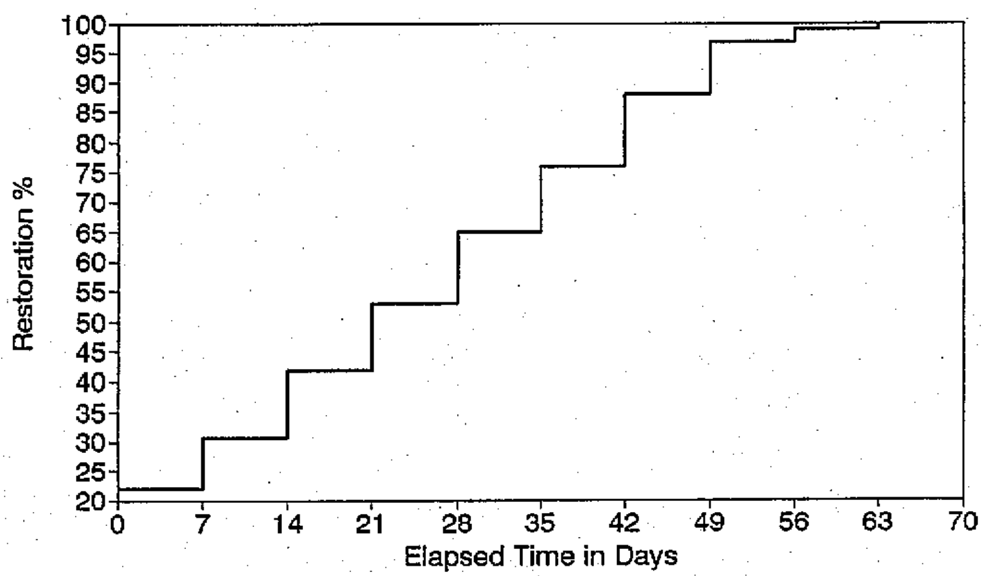


Figure C-86 Residual capacity of Mississippi police stations following New Madrid event (M=8.0).

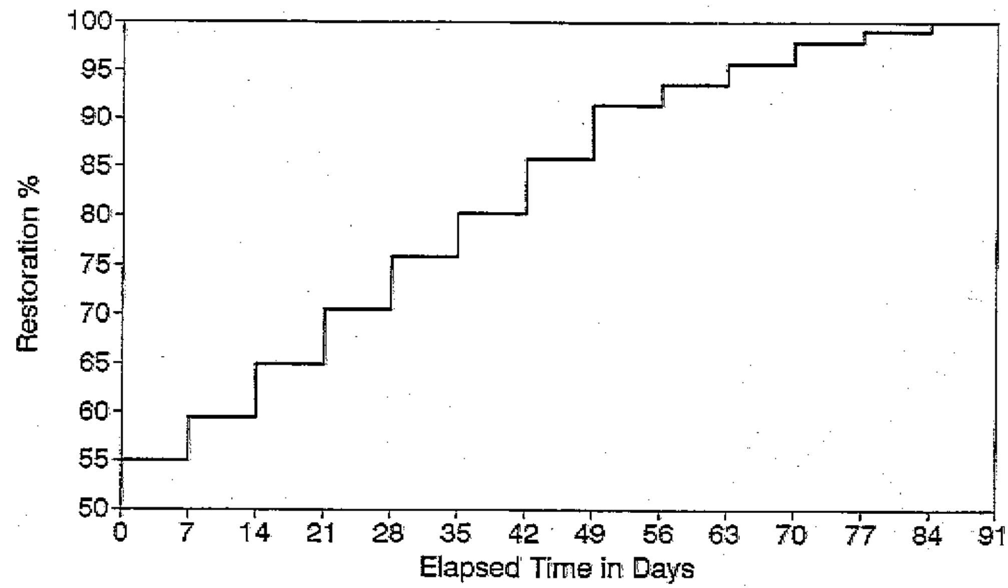


Figure C-87 Residual capacity of South Carolina police stations following Charleston event (M=7.5).

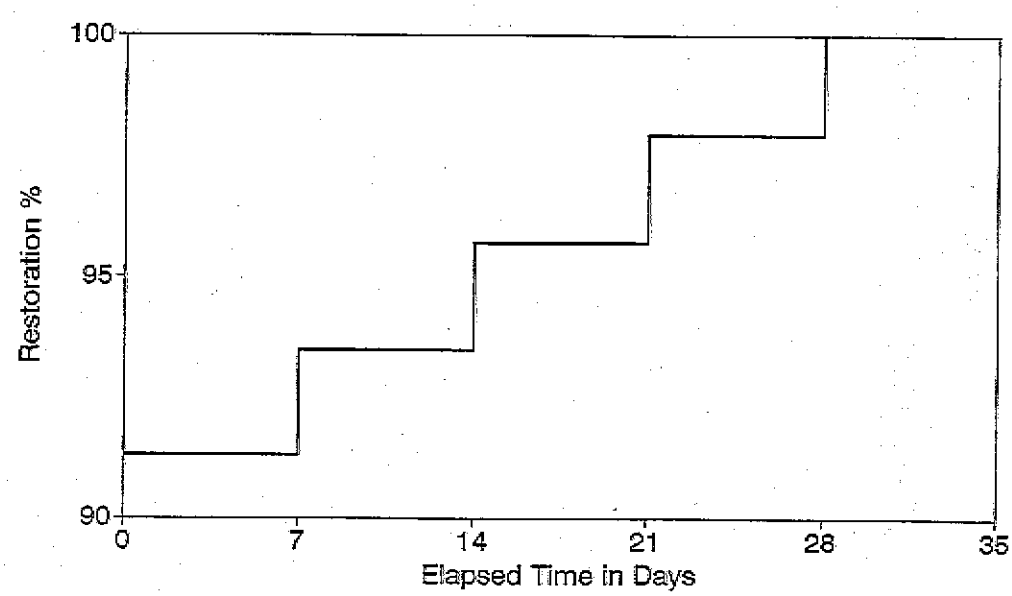


Figure C-88 Residual capacity of North Carolina police stations following Charleston event (M=7.5).

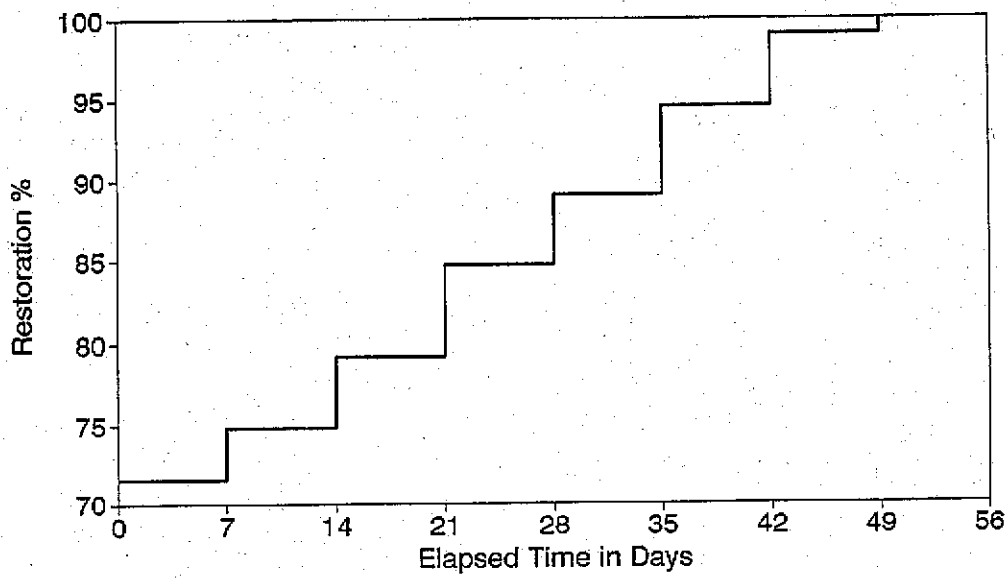


Figure C-89 Residual capacity of Georgia police stations following Charleston event (M=7.5)

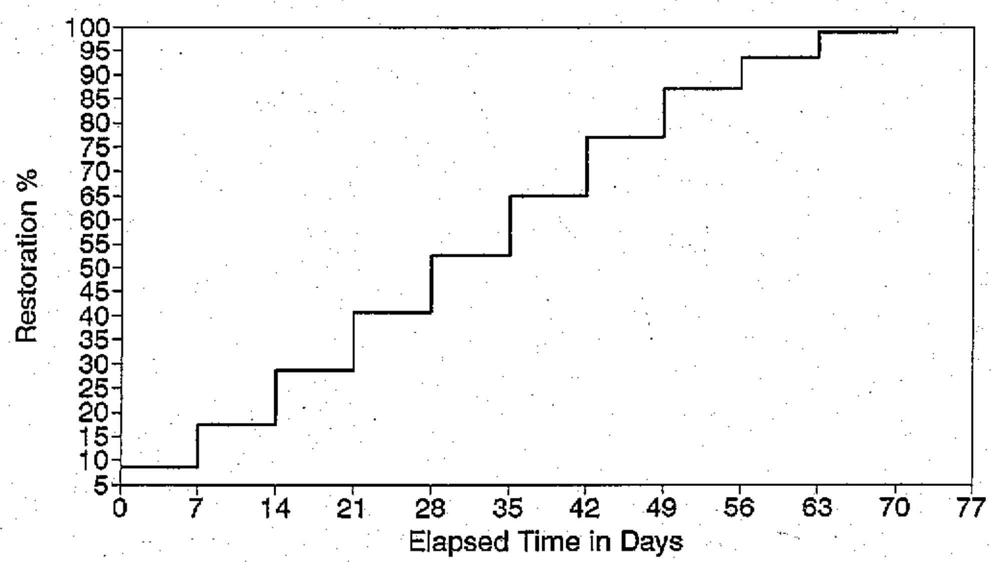


Figure C-90 Residual capacity of Massachusetts police stations following Cape Ann event (M=7.0)

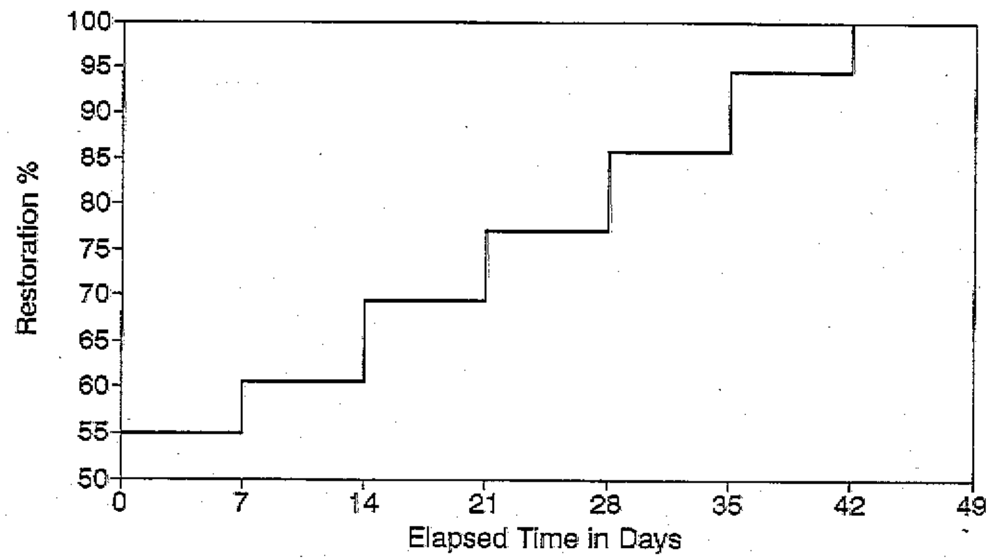


Figure C-91 Residual capacity of Connecticut police stations following Cape Ann event (M=7.0).

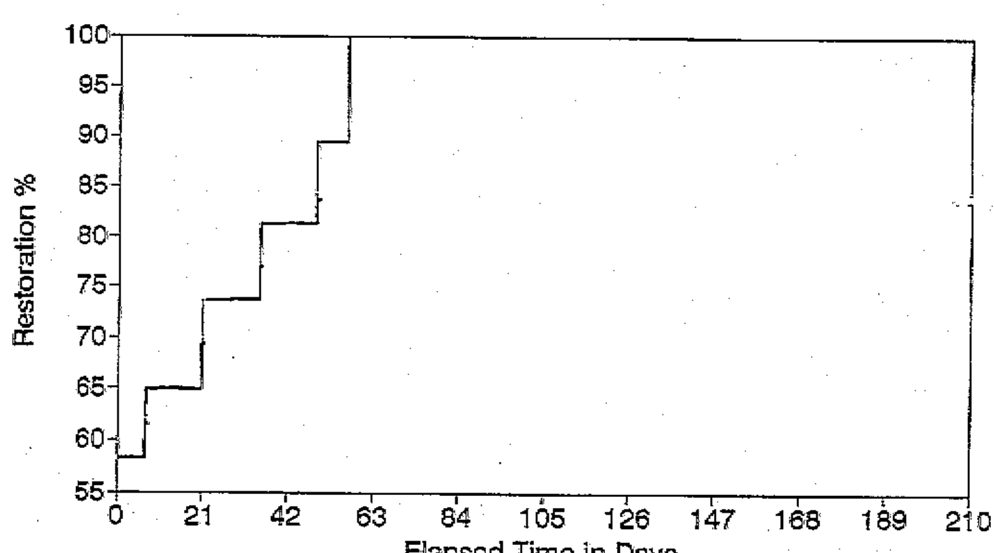


Figure C-92 Residual capacity of Delaware police stations following Cape Ann event (M=7.0).

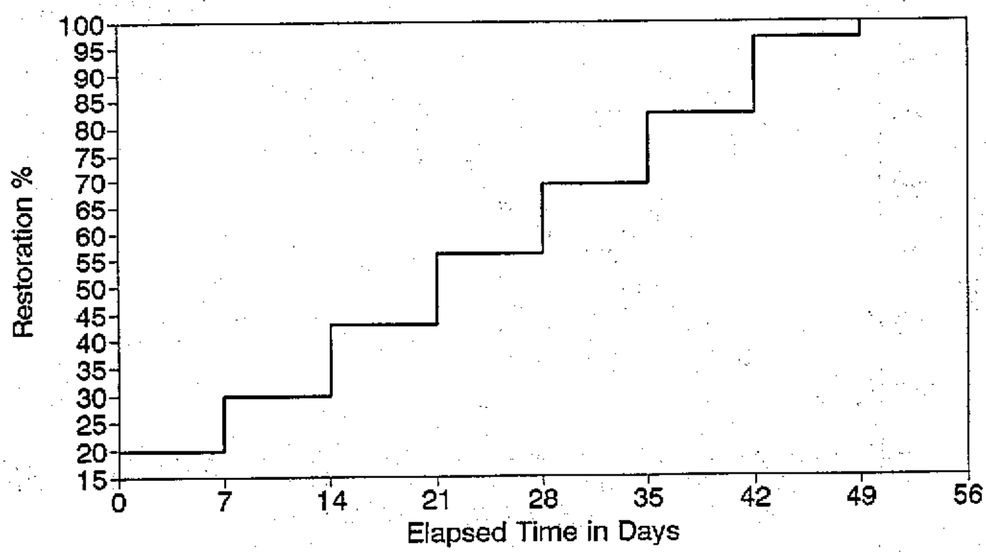


Figure C-93 Residual capacity of Rhode Island police stations following Cape Ann event (M=7.0).

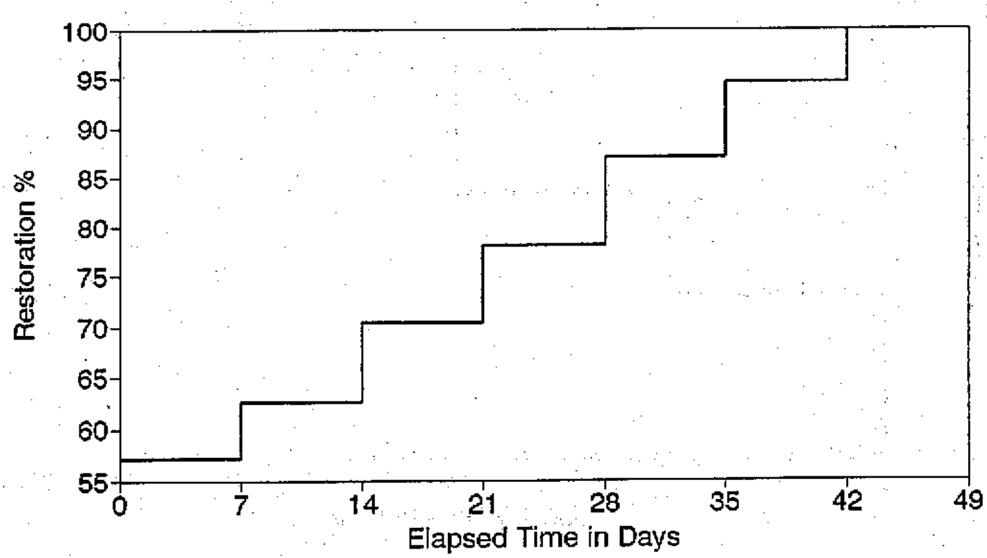


Figure C-94 Residual capacity of New Hampshire police stations following Cape Ann event (M=7.0).

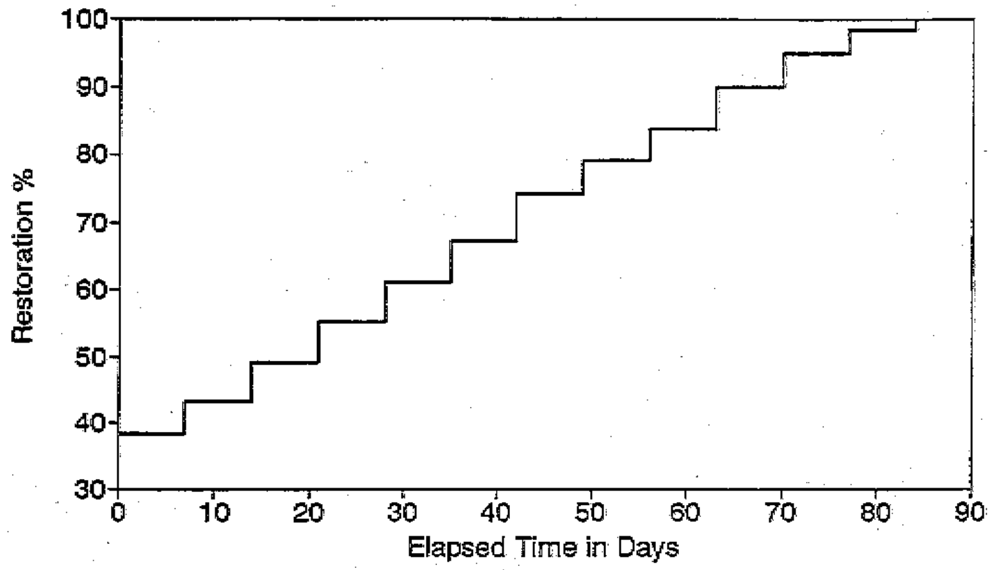


Figure C-95 Residual capacity of Utah police stations following Wasatch Front event (M=7.5).

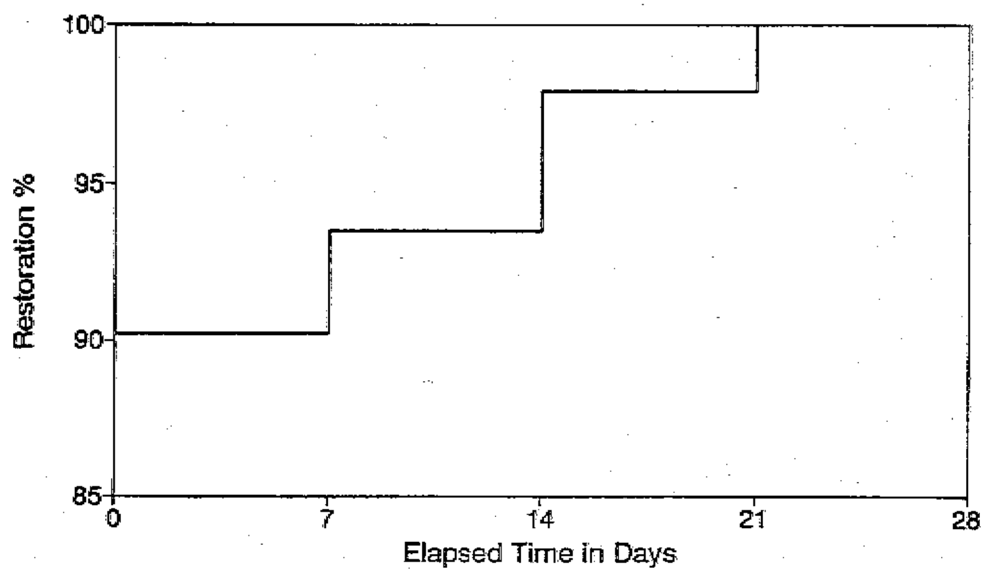


Figure C-96 Residual capacity of California police stations following Hayward event (M=7.5).

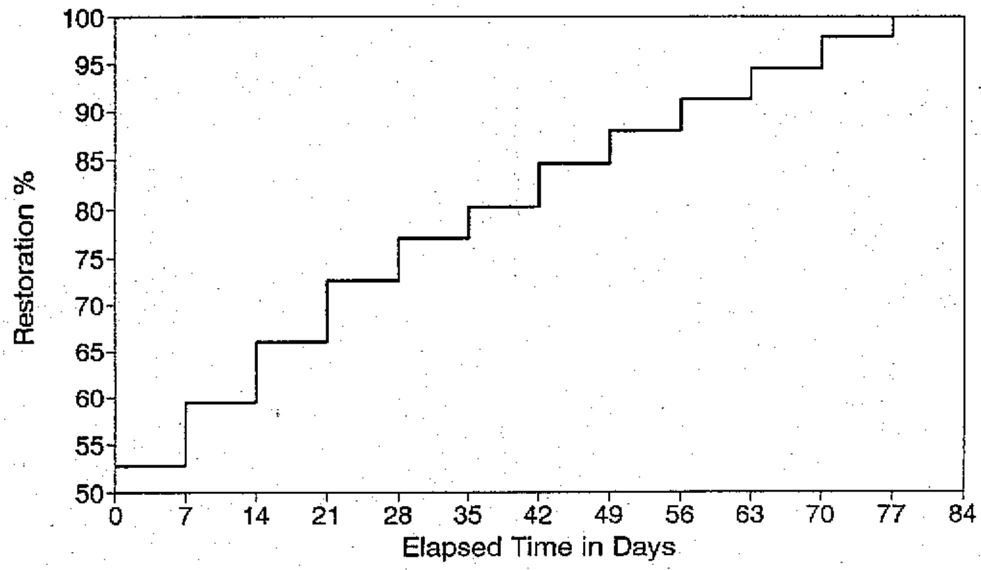


Figure C-97 Residual capacity of California police stations following Fort Tejon event (M=8.0).

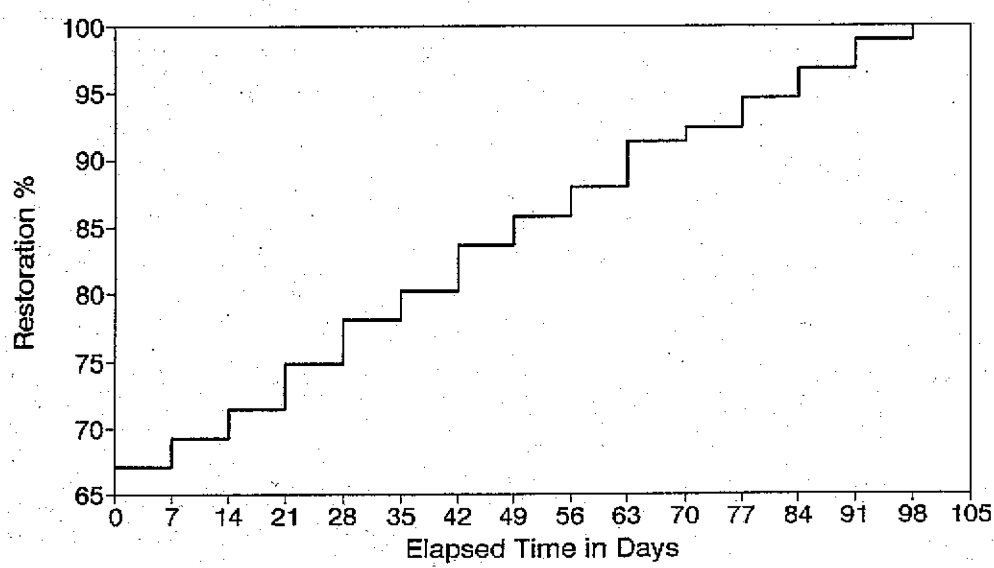


Figure C-98 Residual capacity of Washington police stations following Puget Sound event (M=7.5).

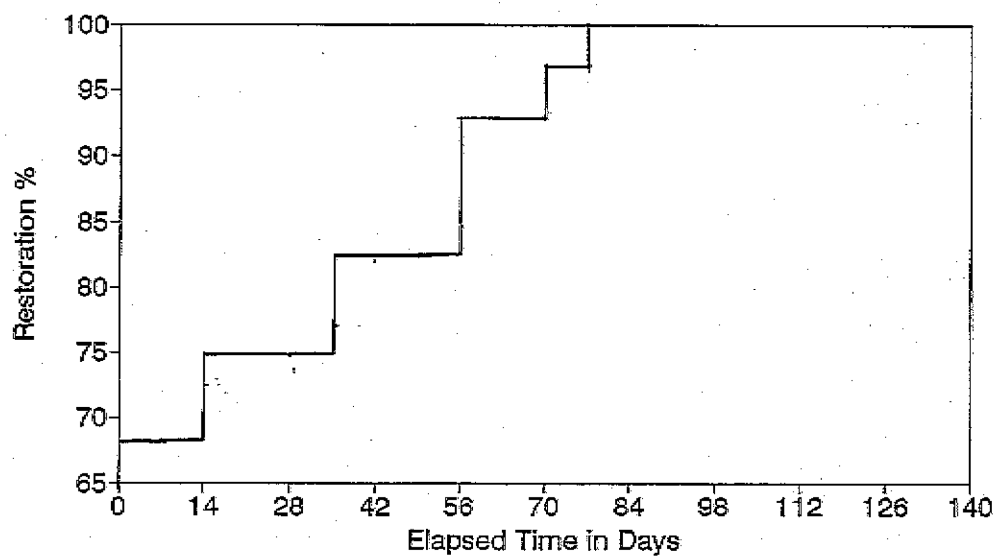


Figure C-99 Residual capacity of Arkansas police stations following New Madrid event (M=7.0).

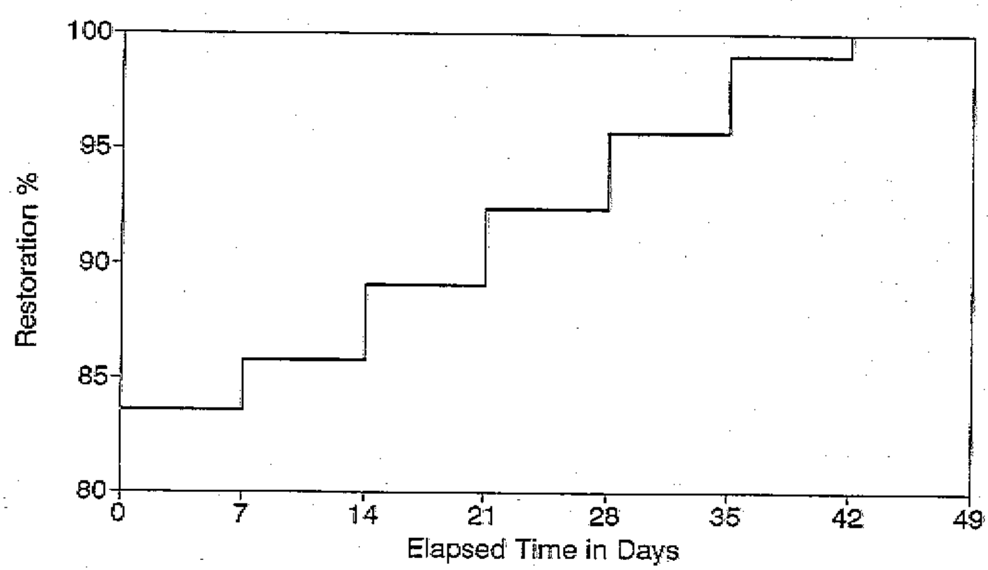


Figure C-100 Residual capacity of Tennessee police stations following New Madrid event (M=7.0).

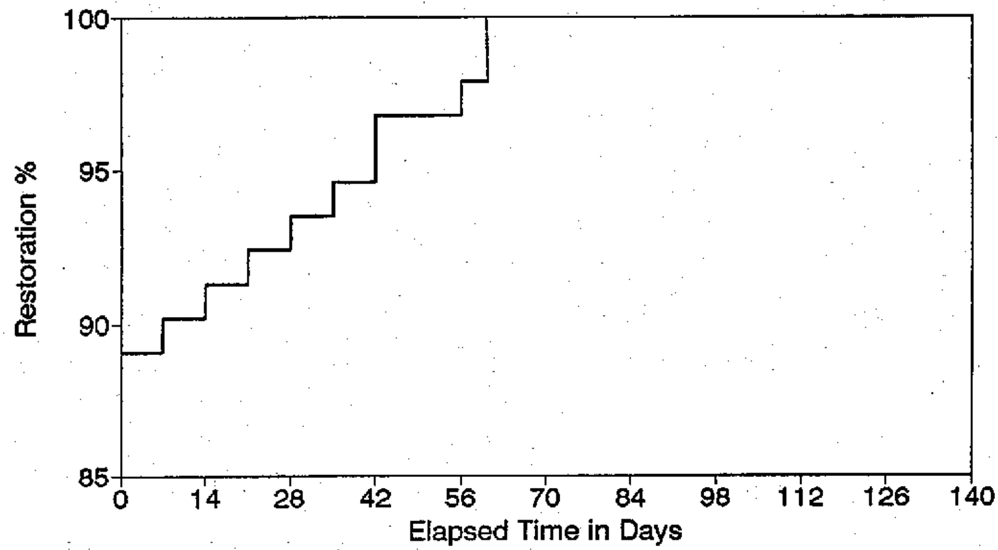


Figure C-101 Residual capacity of Mississippi police stations following New Madrid event (M=7.0).

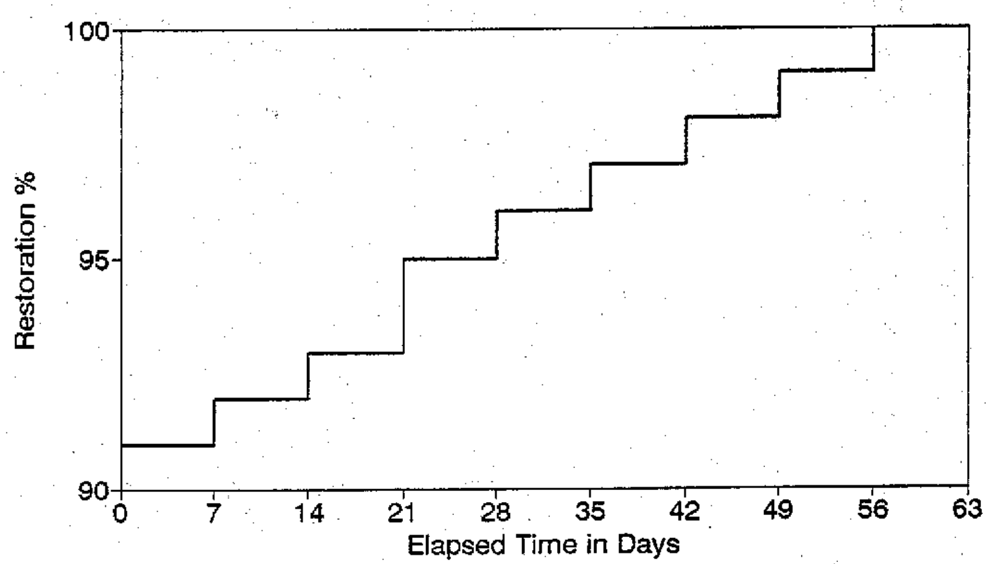


Figure C-102 Residual capacity of Illinois broadcast stations following New Madrid event (M=8.0).

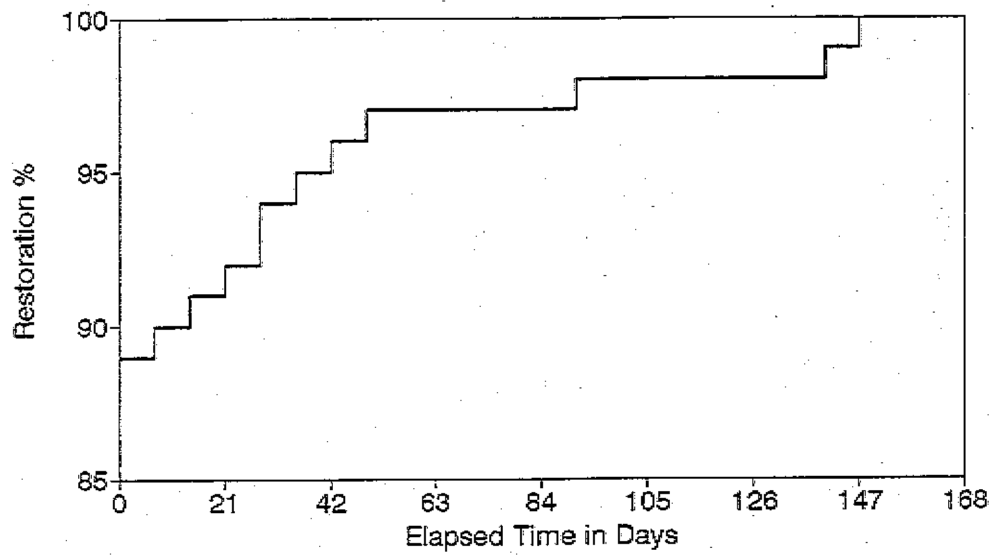


Figure C-103 Residual capacity of Missouri broadcast stations following New Madrid event (M=8.0).

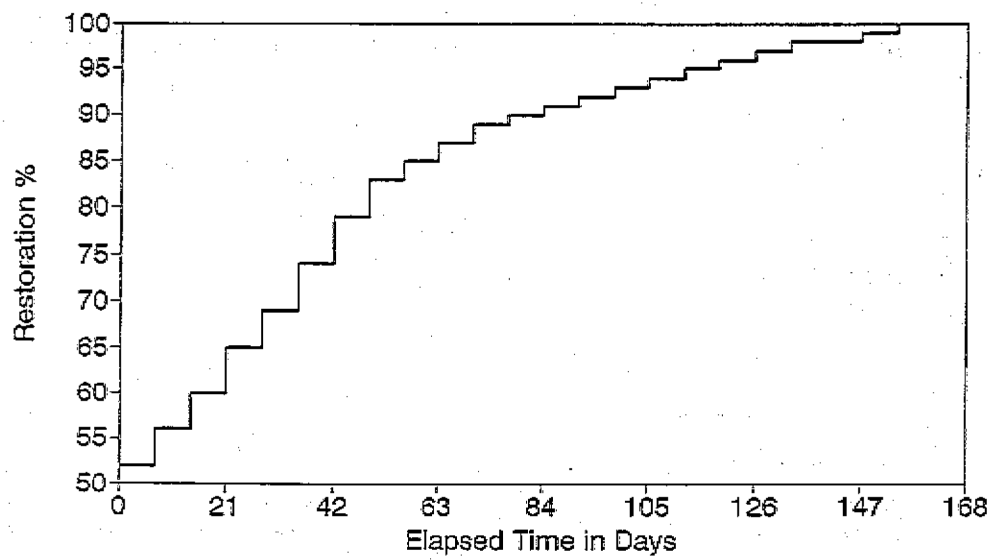


Figure C-104 Residual capacity of Arkansas broadcast stations following New Madrid event (M=8.0).

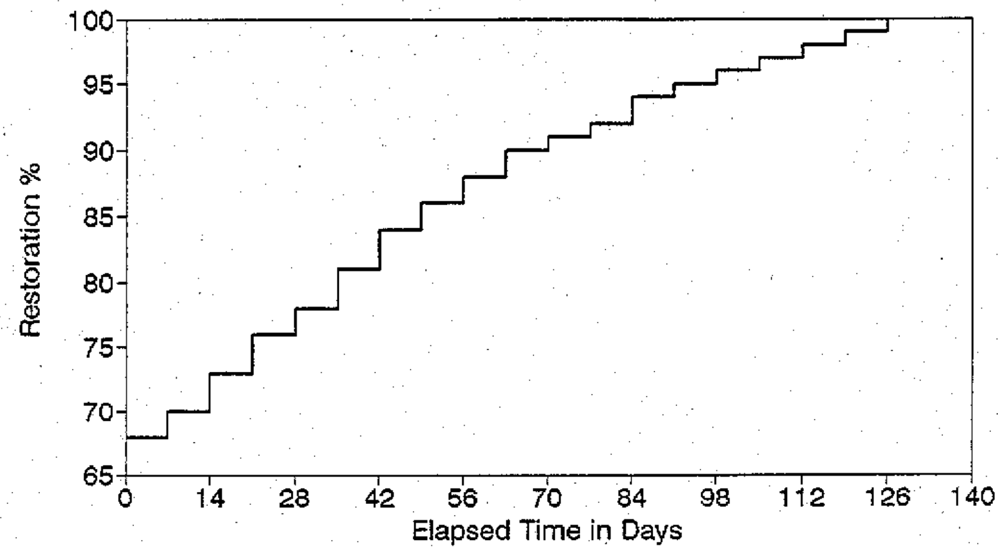


Figure C-105 Residual capacity of Tennessee broadcast stations following New Madrid event (M=8.0).

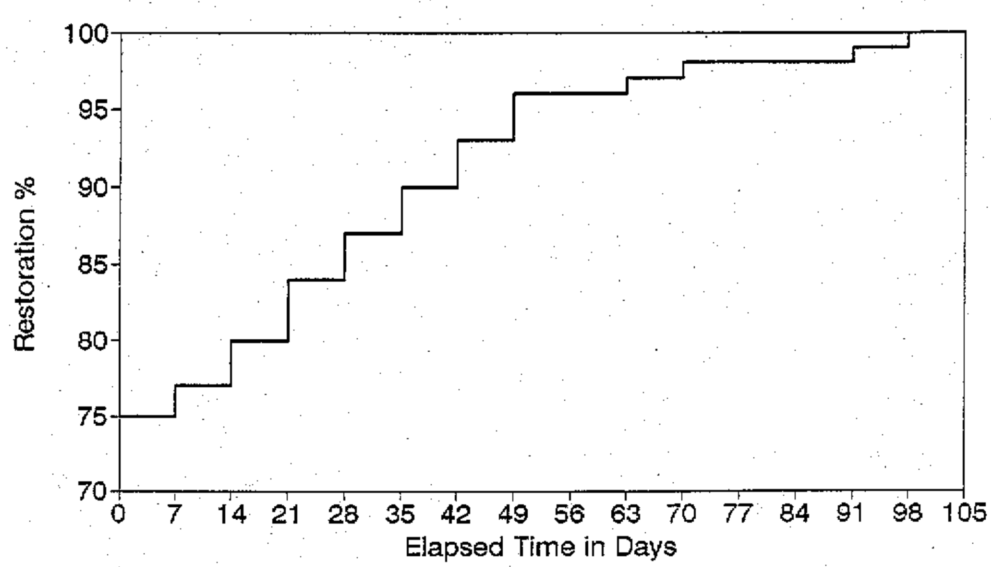


Figure C-106 Residual capacity of Kentucky broadcast stations following New Madrid event (M=8.0).

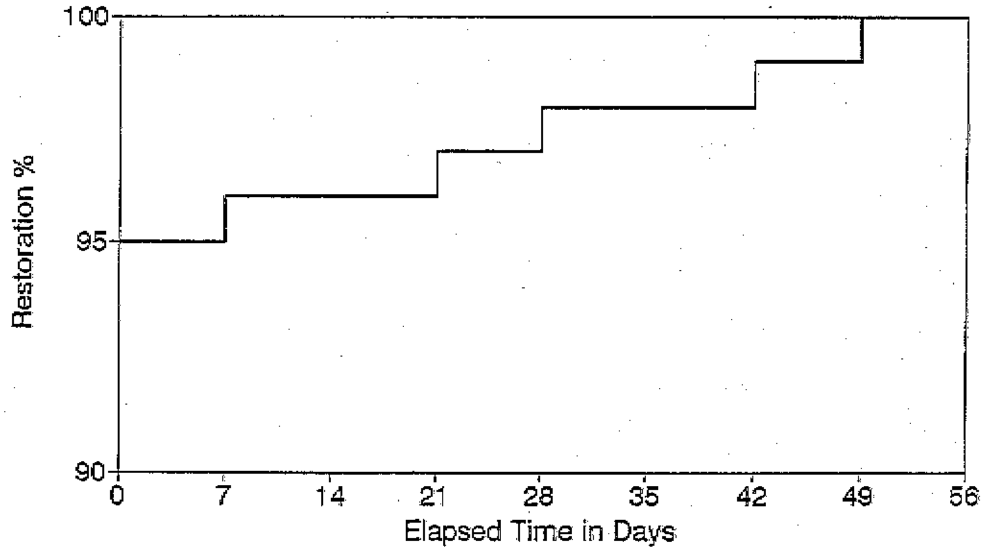


Figure C-107 Residual capacity of Indiana broadcast stations following New Madrid event (M=8.0).

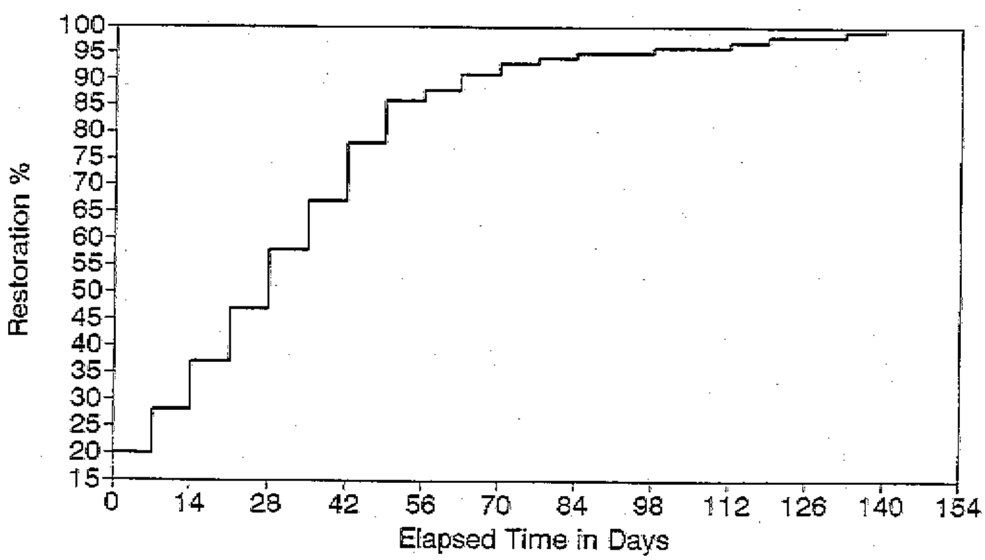


Figure C-108 Residual capacity of Mississippi broadcast stations following New Madrid event (M=8.0).

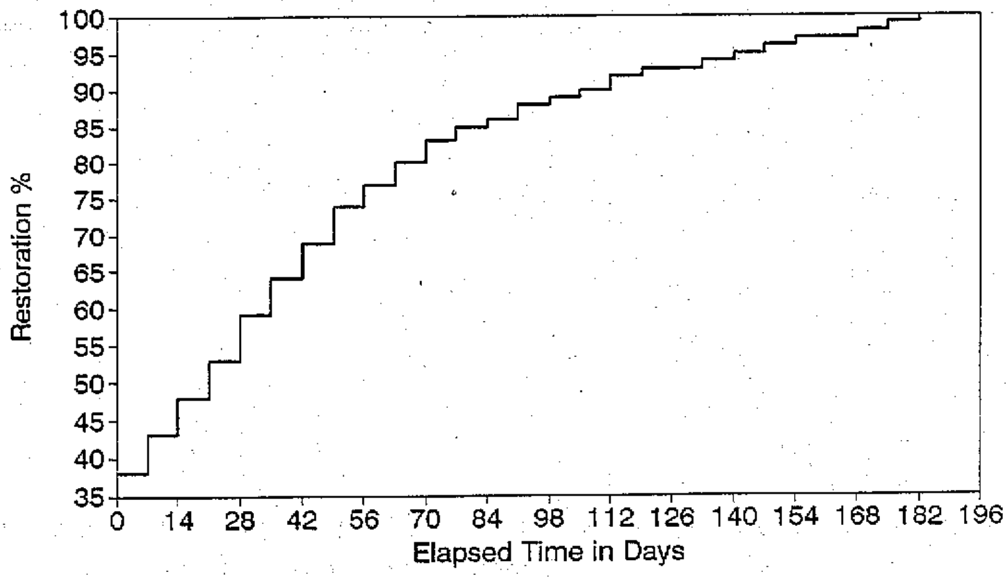


Figure C-109 Residual capacity of South Carolina broadcast stations following Charleston event (M=7.5).

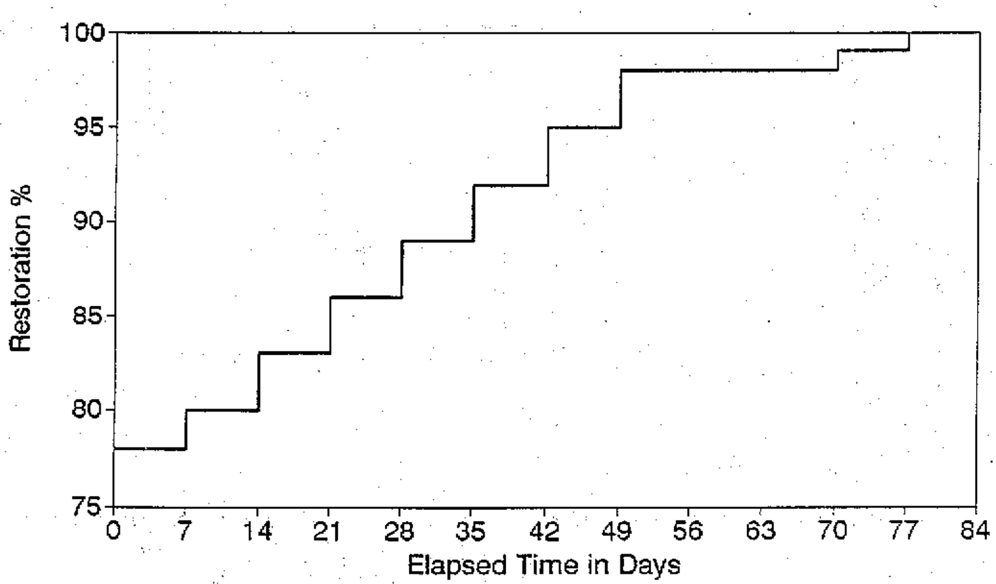


Figure C-110 Residual capacity of North Carolina broadcast stations following Charleston event (M=7.5).

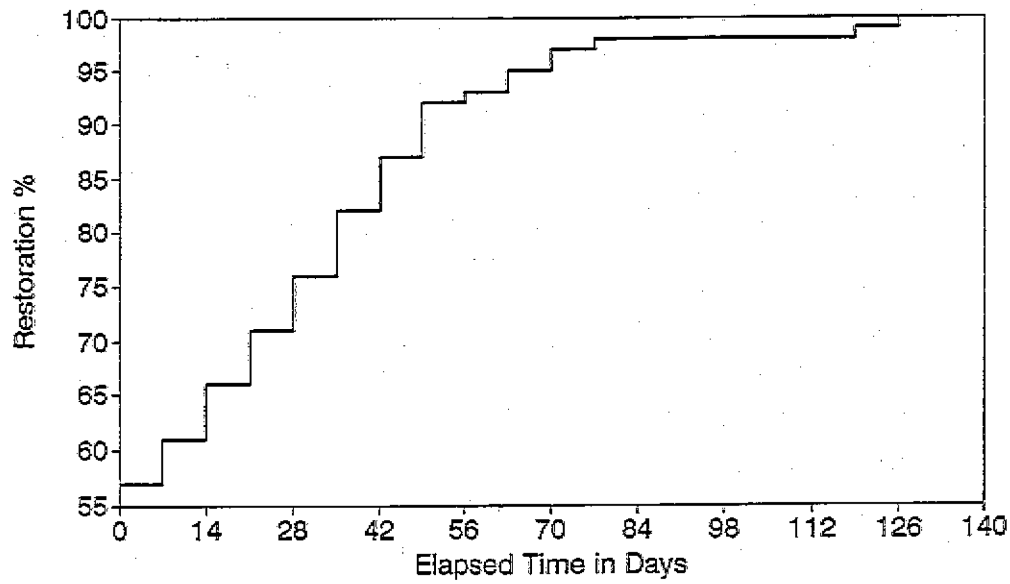


Figure C-111 Residual capacity of Georgia broadcast stations following Charleston event (M=7.5).

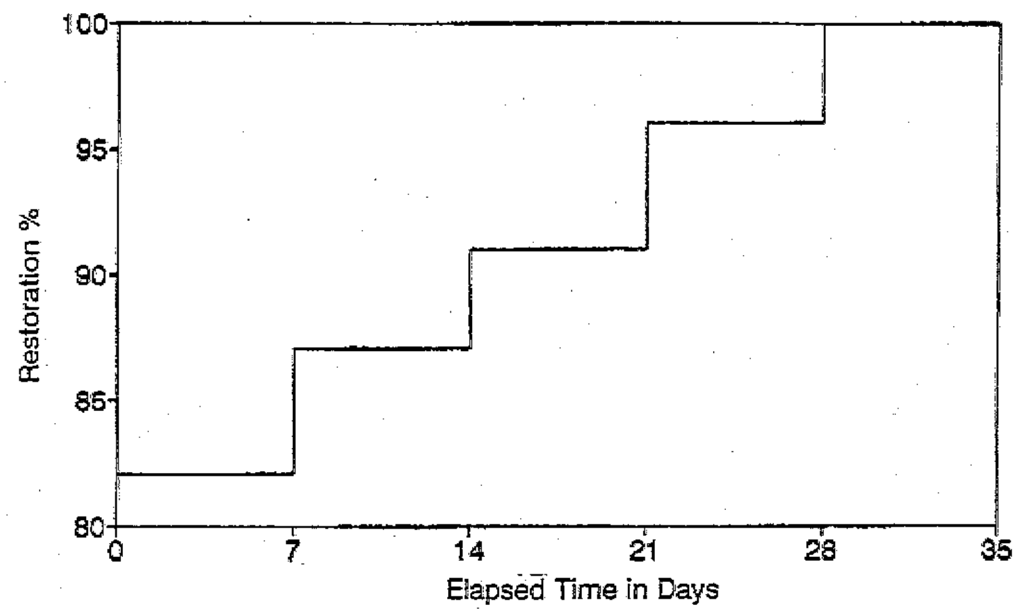


Figure C-112 Residual capacity of Florida broadcast stations following Charleston event (M=7.5).

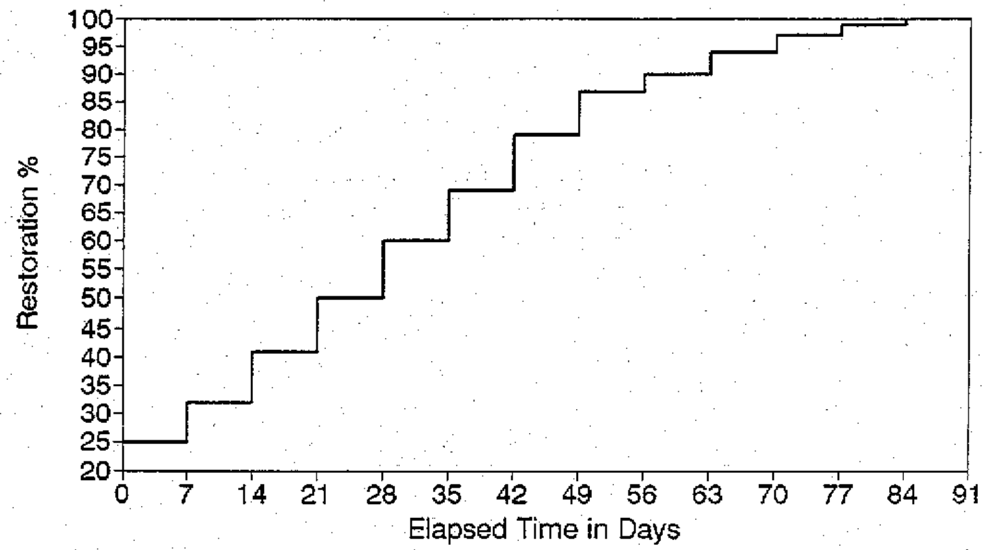


Figure C-113 Residual capacity of Massachusetts broadcast stations following Cape Ann event (M=7.0).

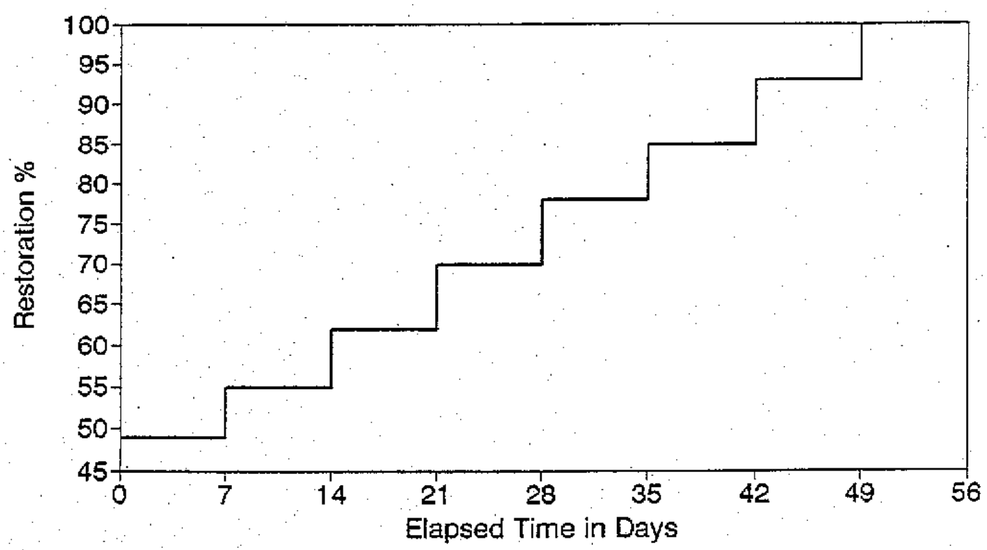


Figure C-114 Residual capacity of Connecticut broadcast stations following Cape Ann event (M=7.0).

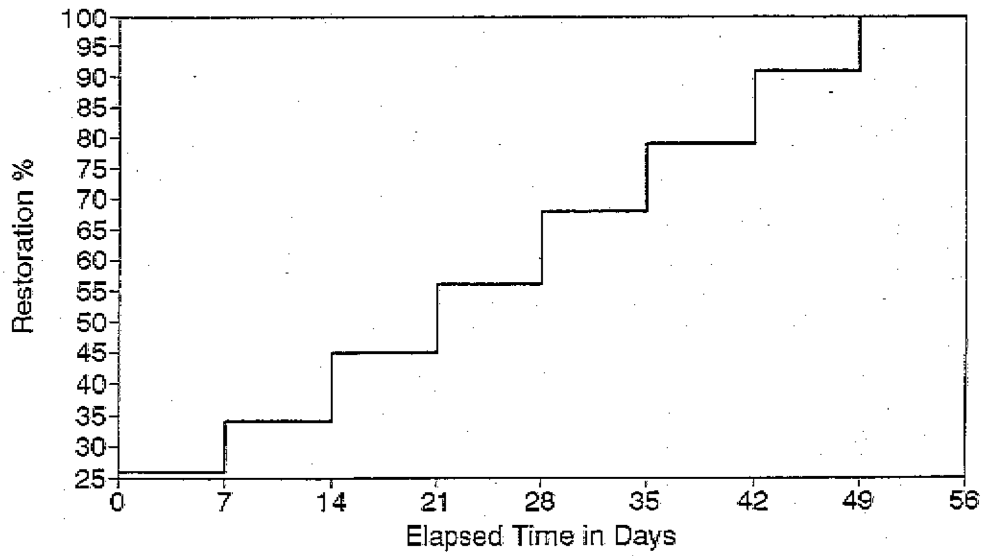


Figure C-115 Residual capacity of Delaware broadcast stations following Cape Ann event (M=7.0).

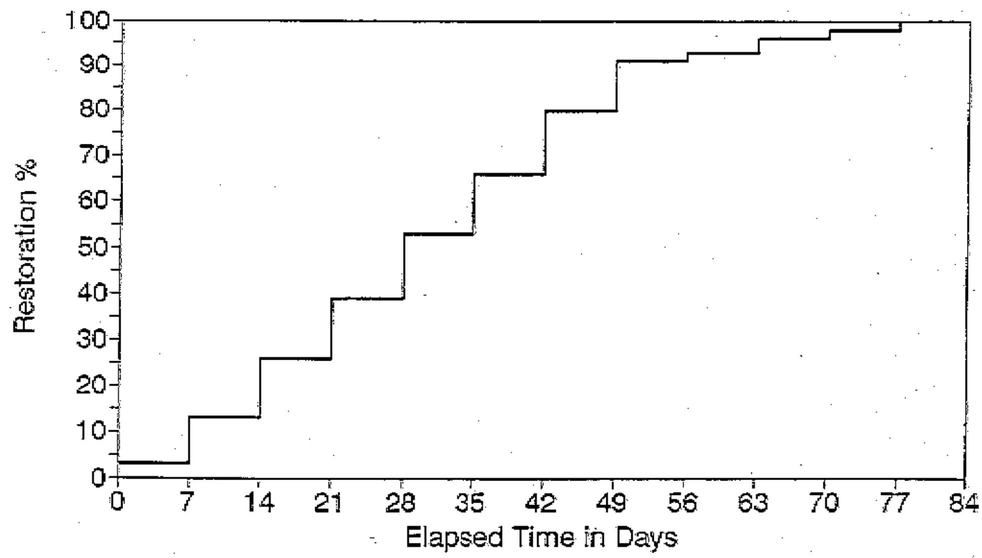


Figure C-116 Residual capacity of Rhode Island broadcast stations following Cape Ann event (M=7.0).

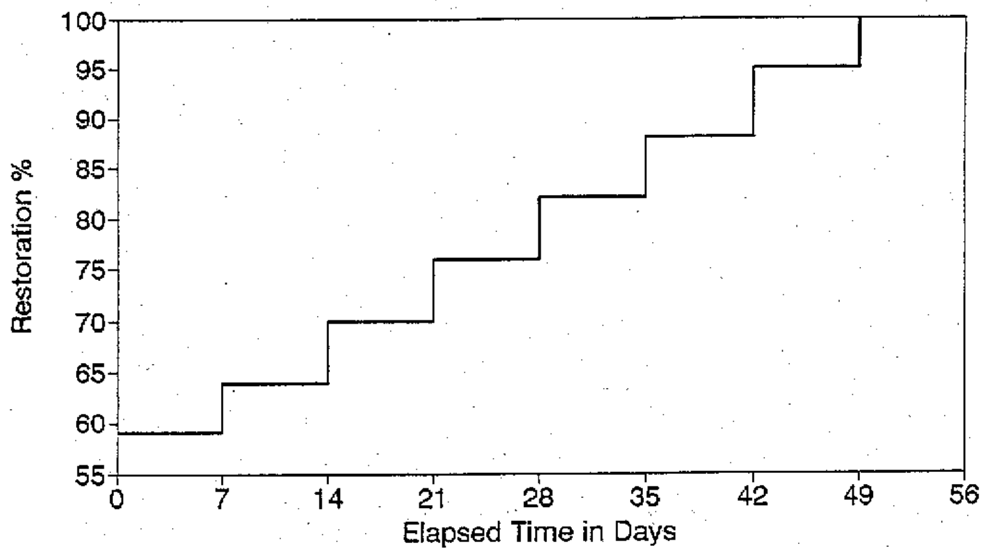


Figure C-117 Residual capacity of New Hampshire broadcast stations following Cape Ann event (M=7.0).

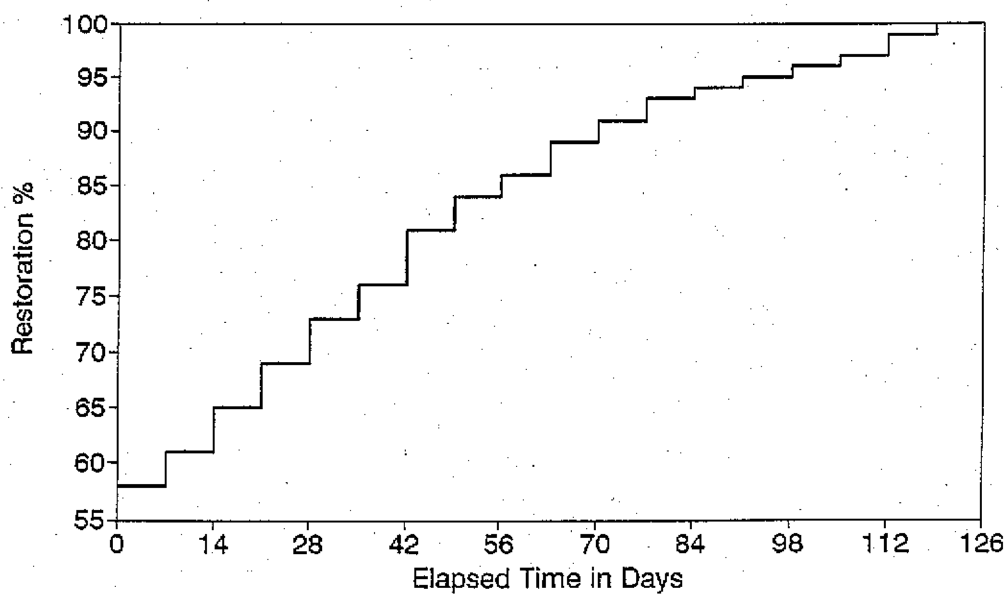


Figure C-118 Residual capacity of Utah broadcast stations following Wasatch Front event (M=7.5).

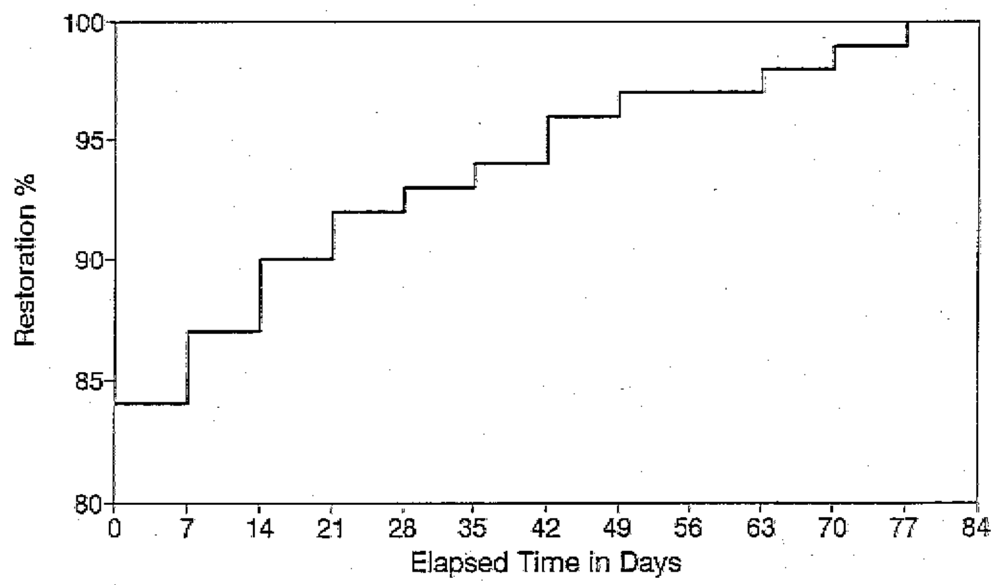


Figure C-119 Residual capacity of California broadcast stations following Hayward event (M=7.5).

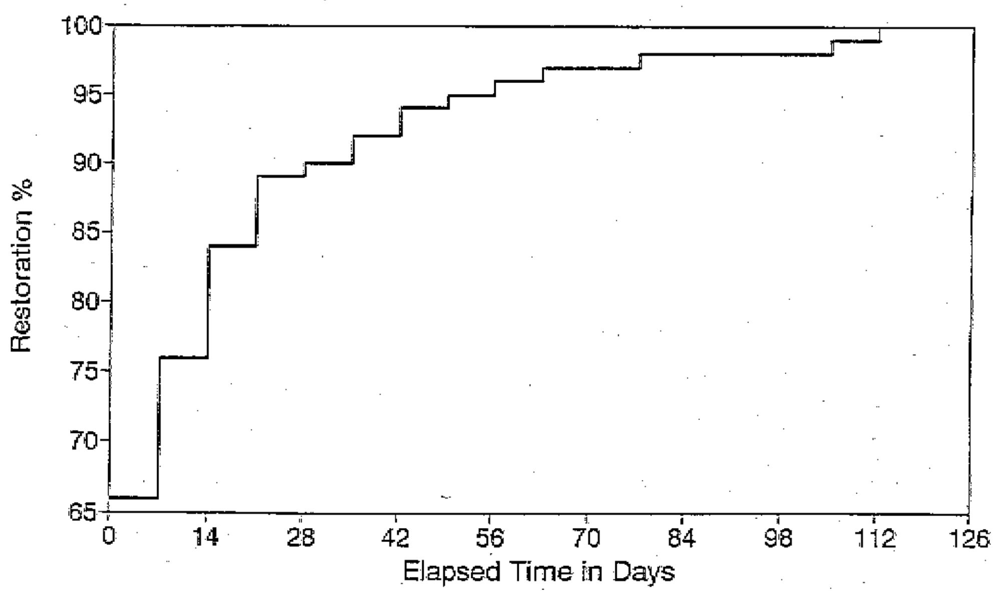


Figure C-120 Residual capacity of California broadcast stations following Fort Tejon event (M=8.0).

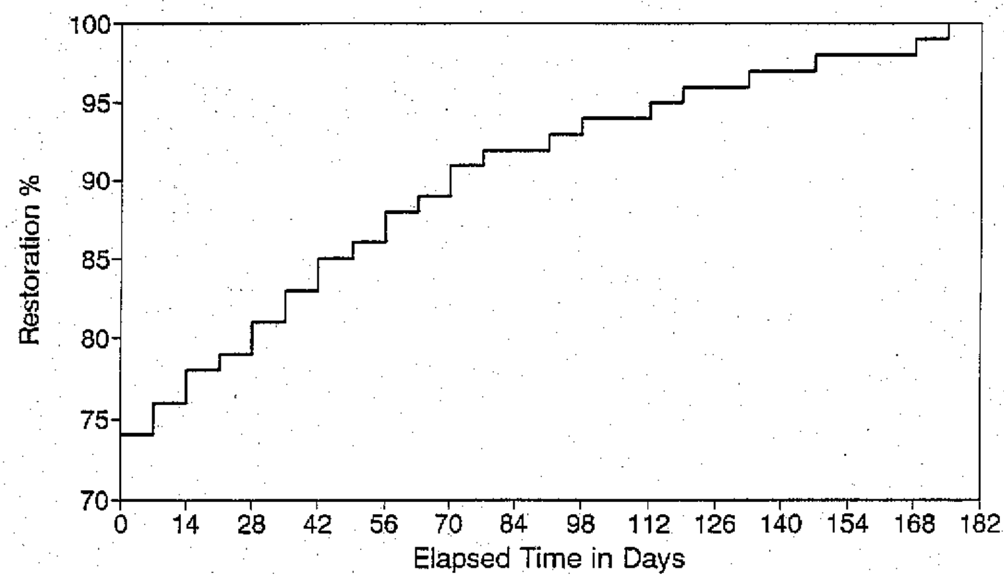


Figure C-121 Residual capacity of Washington broadcast stations following Puget Sound event (M=7.5).

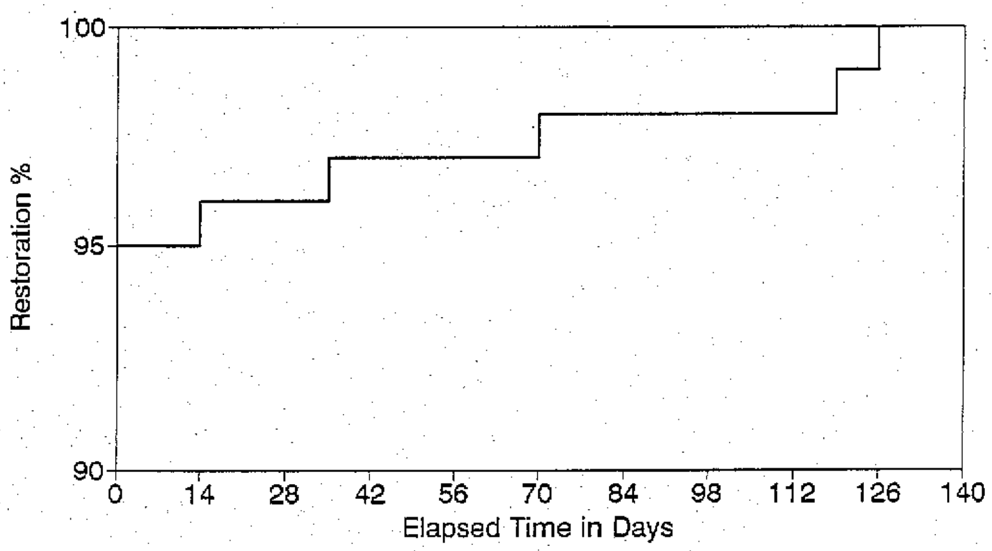


Figure C-122 Residual capacity of Missouri broadcast stations following New Madrid event (M=7.0).

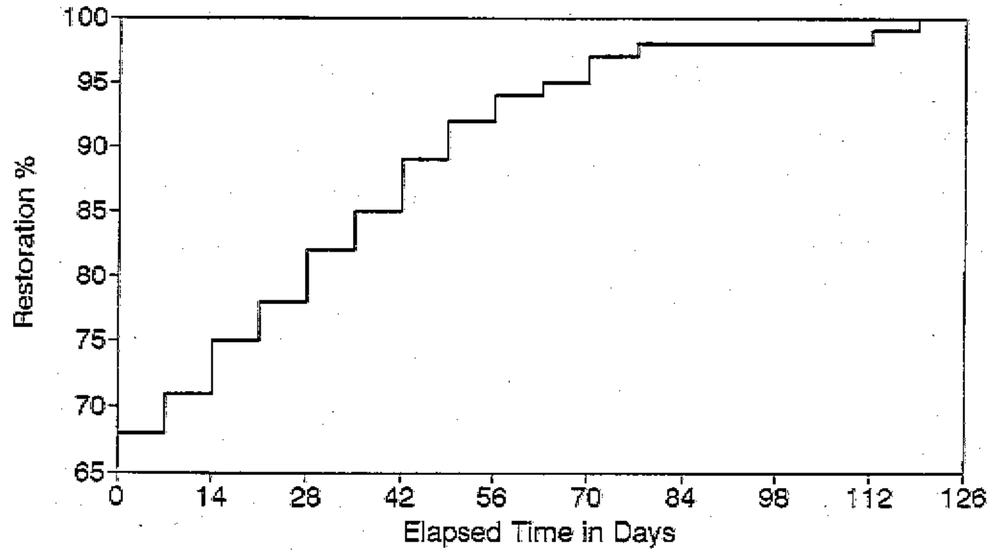


Figure C-123 Residual capacity of Arkansas broadcast stations following New Madrid event (M=7.0).

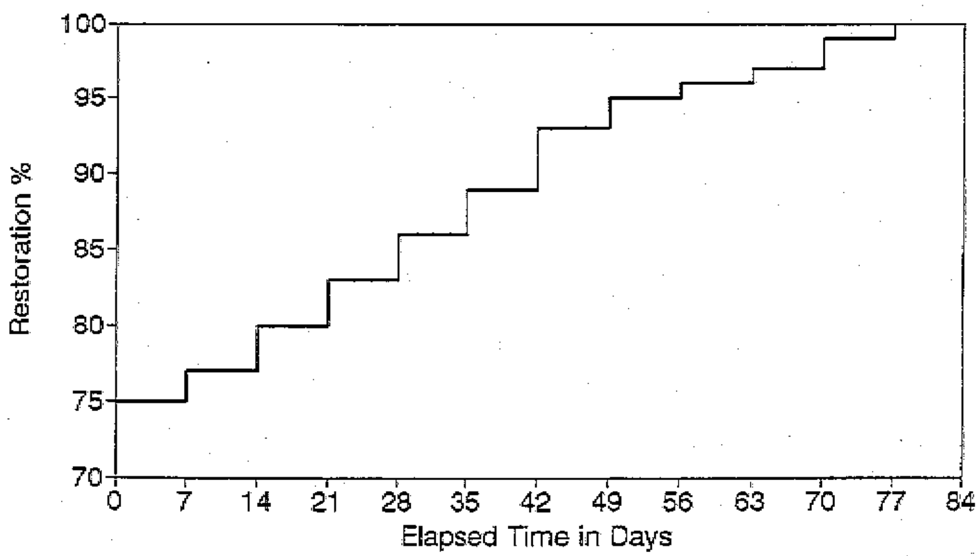


Figure C-124 Residual capacity of Tennessee broadcast stations following New Madrid event (M=7.0).

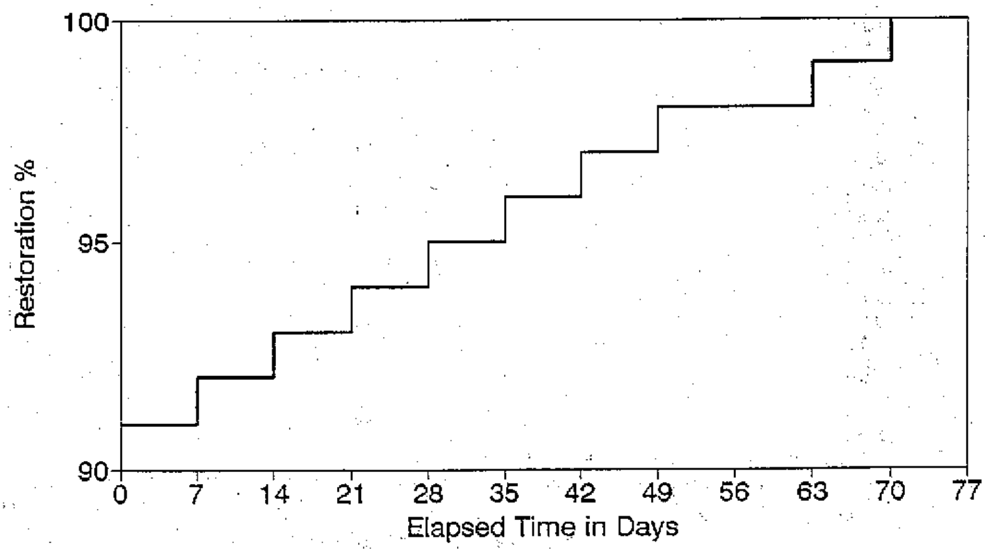


Figure C-125 Residual capacity of Kentucky broadcast stations following New Madrid event (M=7.0).

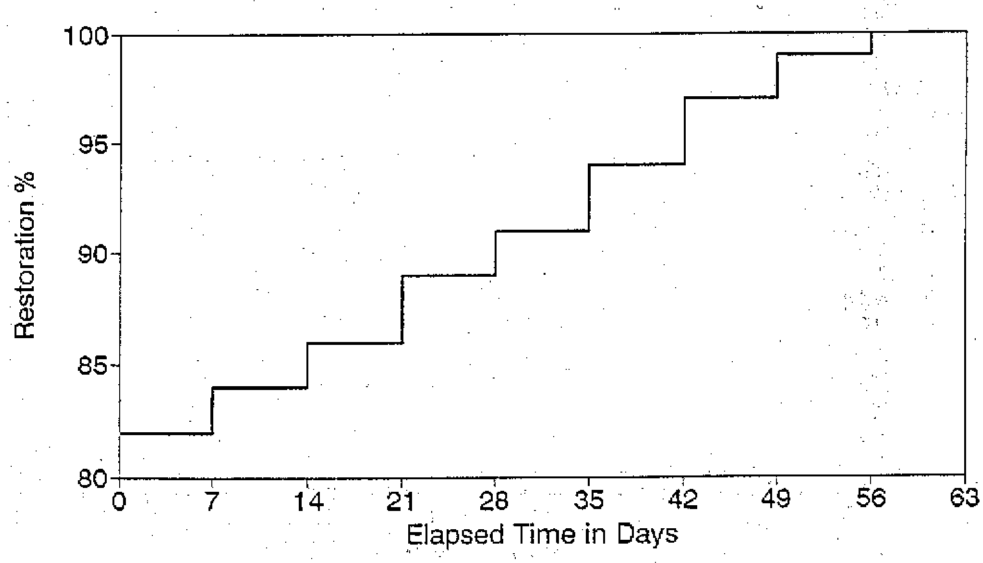


Figure C-126 Residual capacity of Mississippi broadcast stations following New Madrid event (M=7.0).

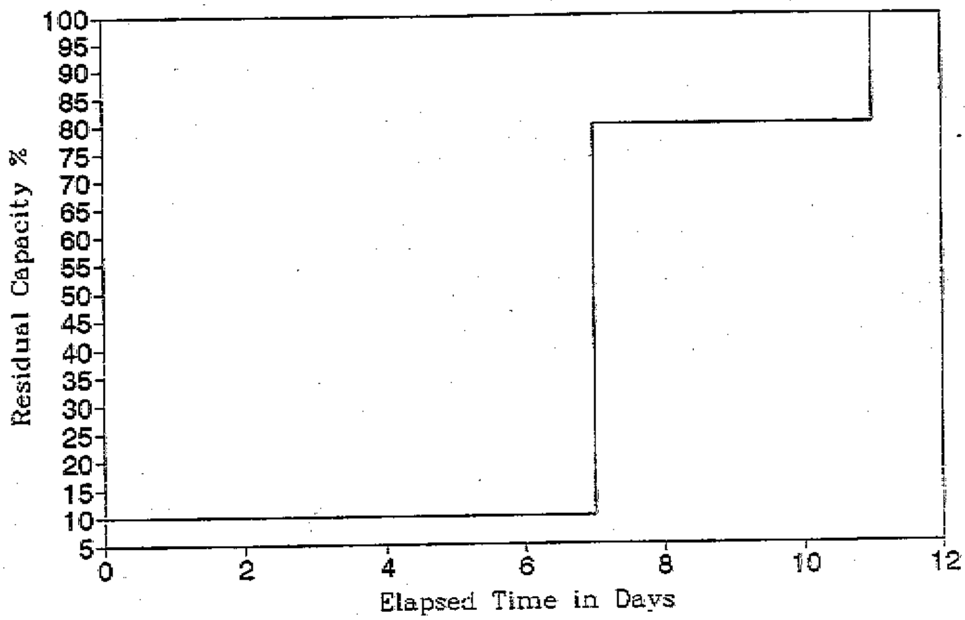


Figure C-127 Residual capacity of railroad system serving epicentral region following New Madrid event (M=8.0).

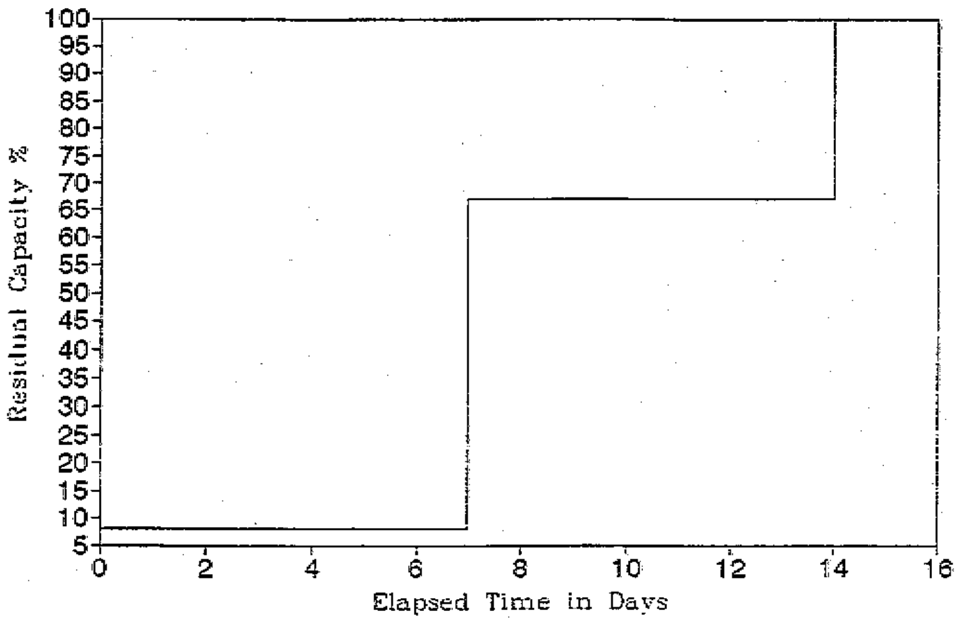


Figure C-128 Residual capacity of railroad system serving Charleston, South Carolina following Charleston event (M=7.5).

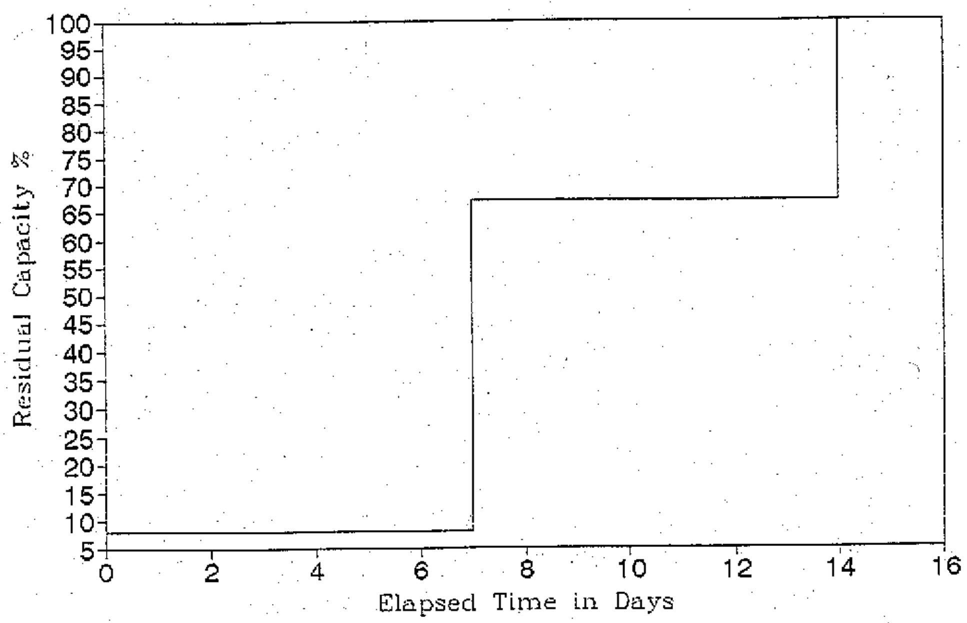


Figure C-129 Residual capacity of railroad system serving Cape Ann region following Cape Ann event (M=7.0).

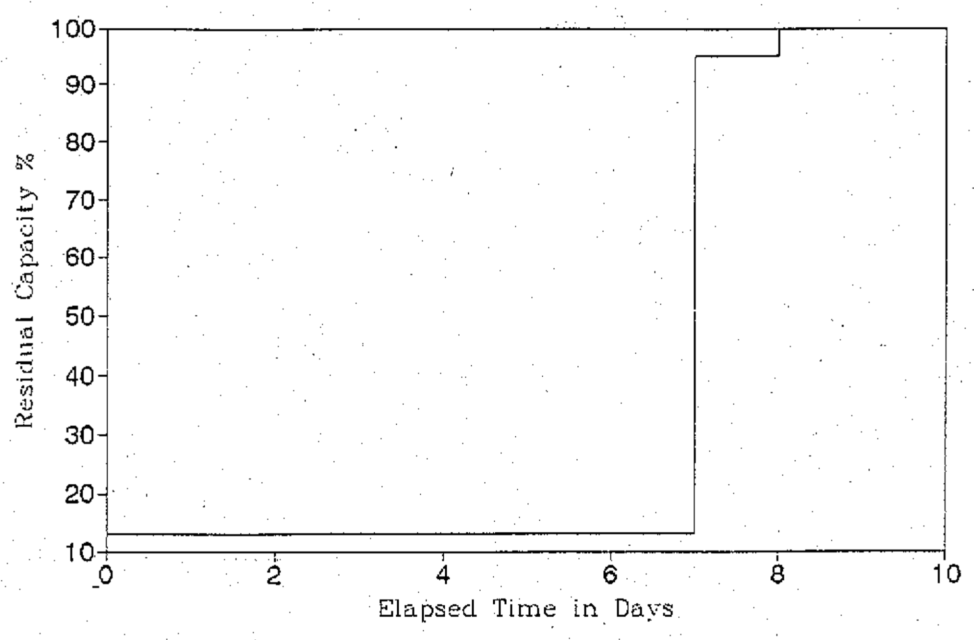


Figure C-130 Residual capacity of railroad system serving Salt Lake City following Wasatch Front event (M=7.5).

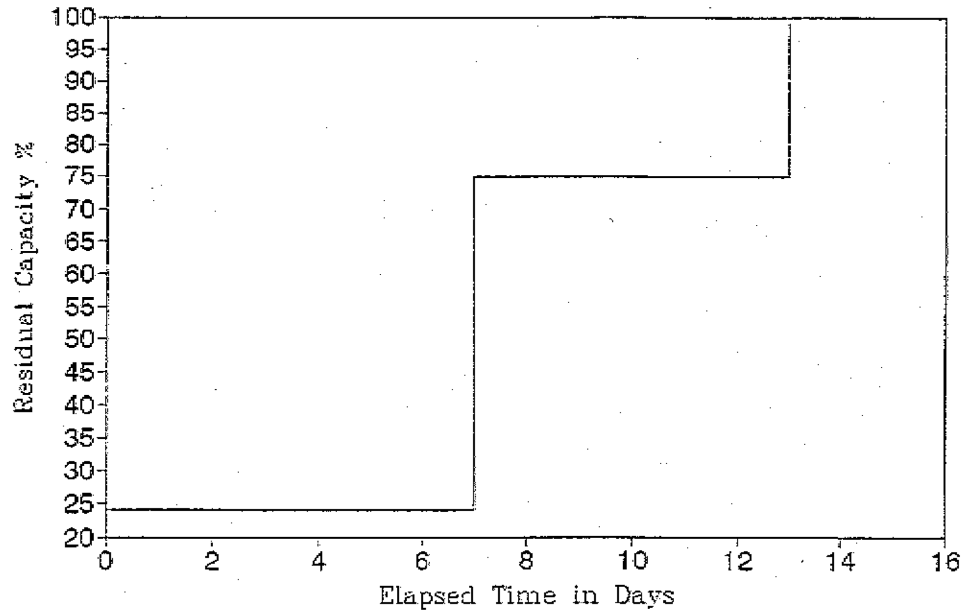


Figure C-131 Residual capacity of railroad system serving San Francisco County, Alameda County, and Contra Costa County following Hayward event (M=7.5).

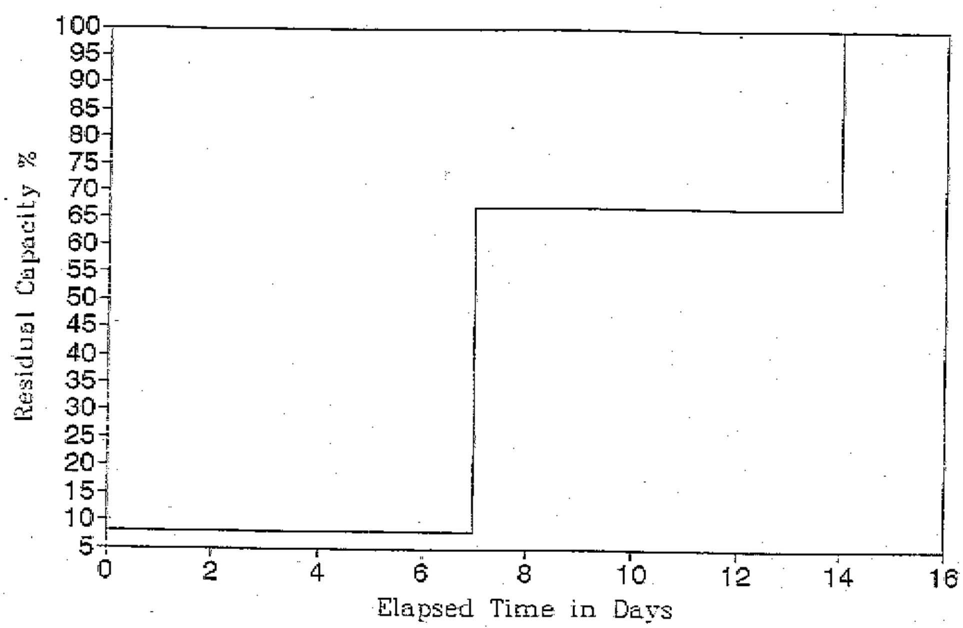


Figure C-132 Residual capacity of railroad system serving California following Fort Tejon event (M=8.0).

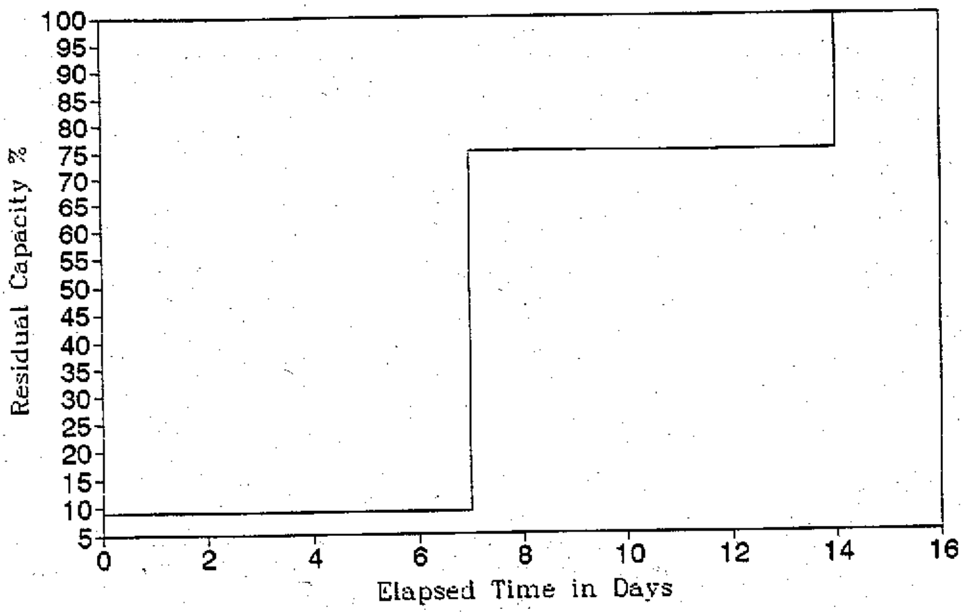


Figure C-133 Residual capacity of railroad system serving Seattle following Puget Sound event (M=7.5).

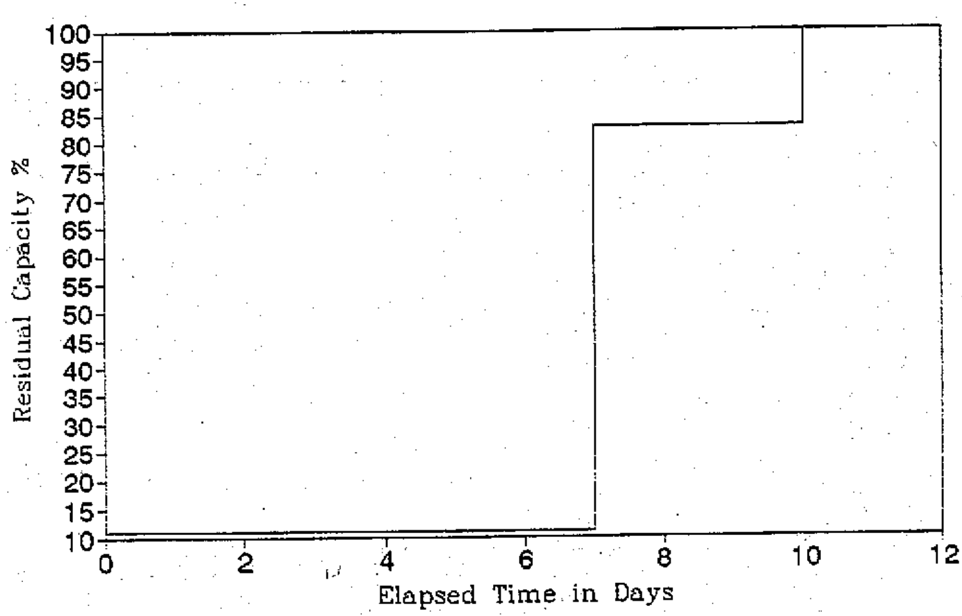


Figure C-134 Residual capacity of railroad system serving epicentral region following New Madrid event (M=7.0).

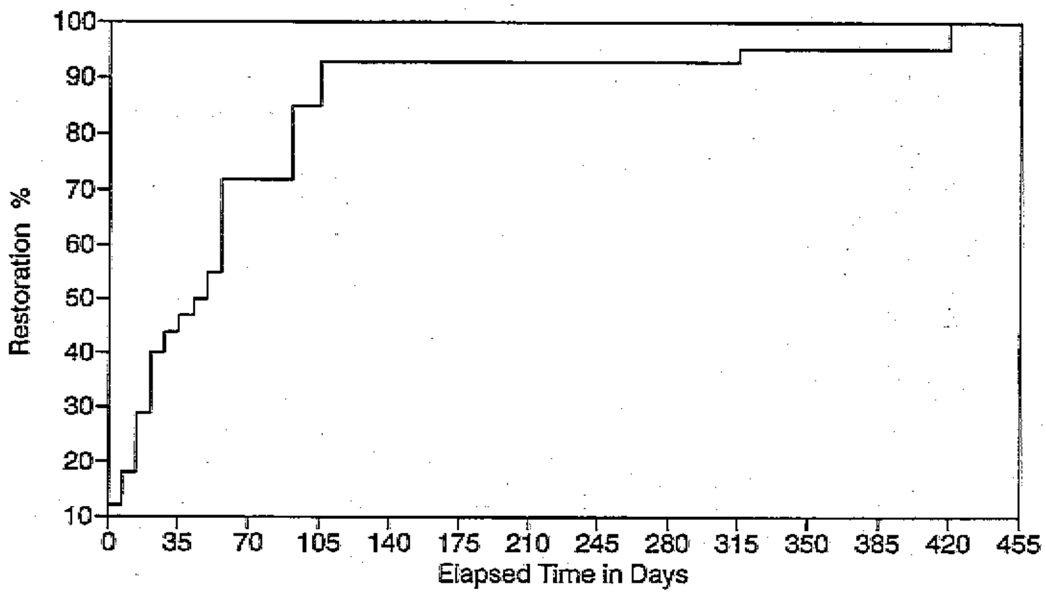


Figure C-135 Residual capacity of epicentral region highways following New Madrid event (M=8.0).

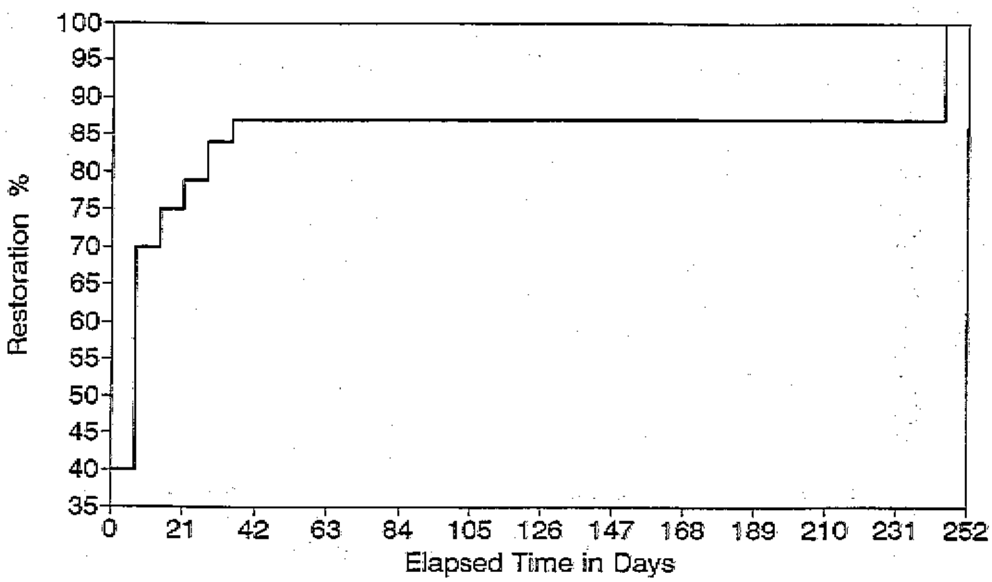


Figure C-136 Residual capacity of epicentral region highways following Charleston event (M=7.5).

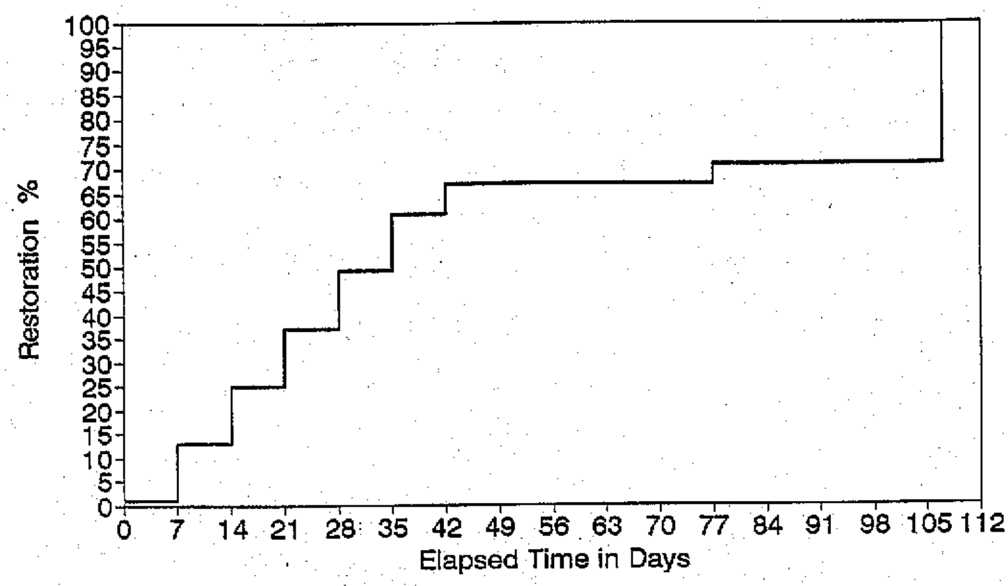


Figure C-137 Residual capacity of epicentral region highways following Cape Ann event (M=7.0).

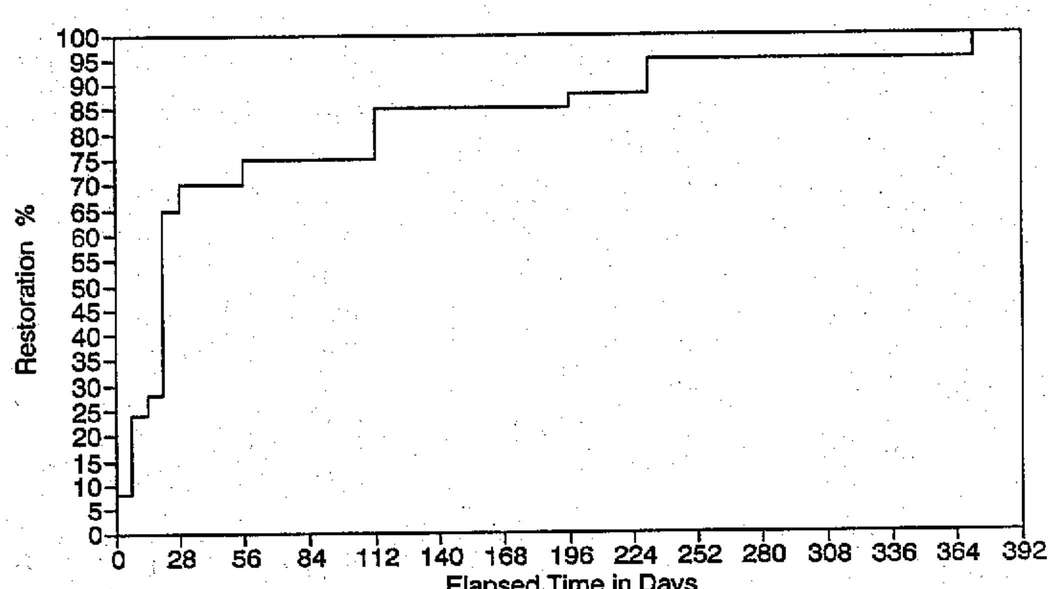


Figure C-138 Residual capacity of epicentral region highways following Wasatch Front event (M=7.5).

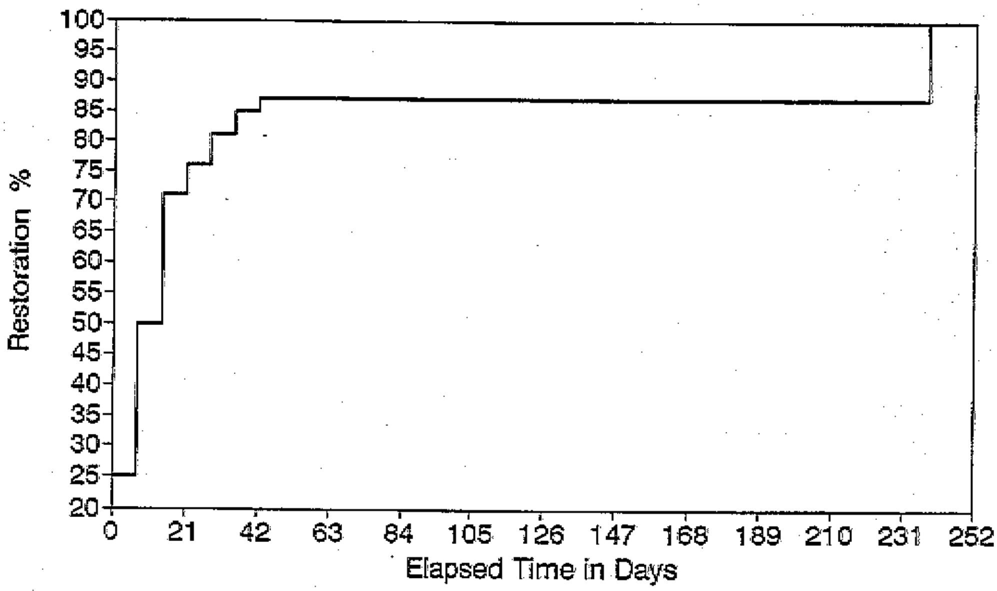


Figure C-139 Residual capacity of epicentral region highways following Hayward event (M=7.5).

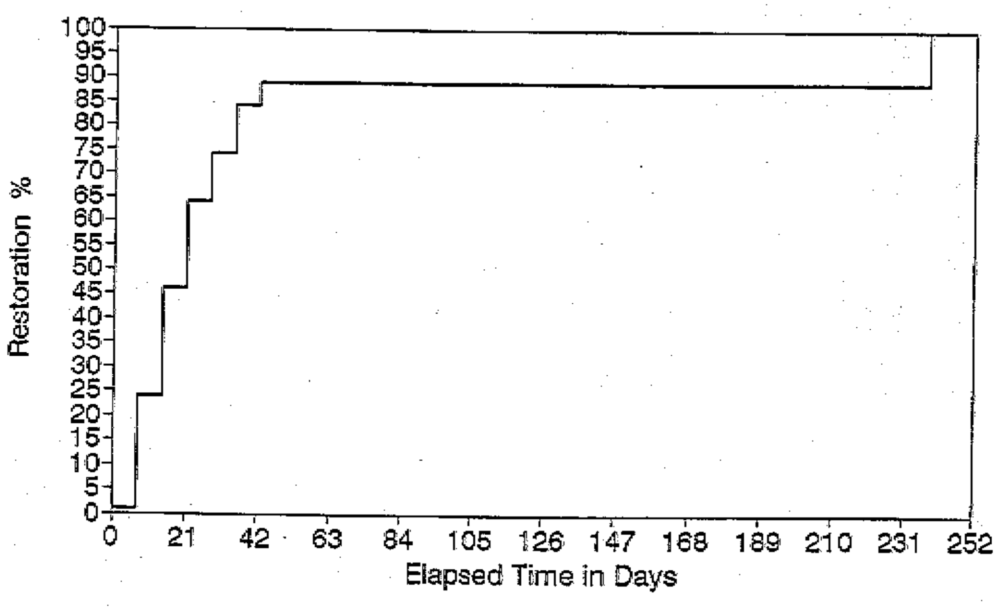


Figure C-140 Residual capacity of epicentral region highways following Fort Tejon event (M=8.0)

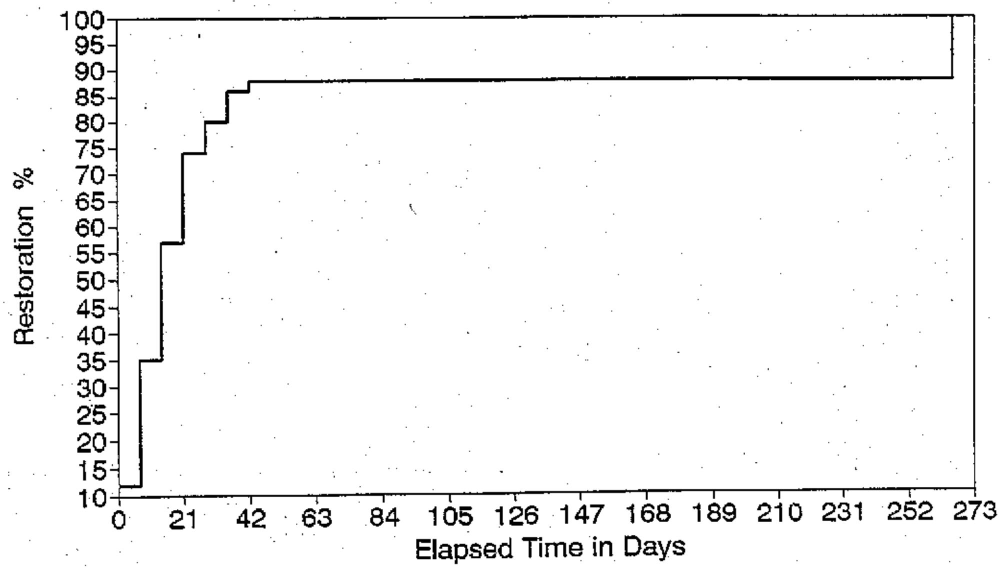


Figure C-141 Residual capacity of epicentral region highways following Puget Sound event (M=7.5).

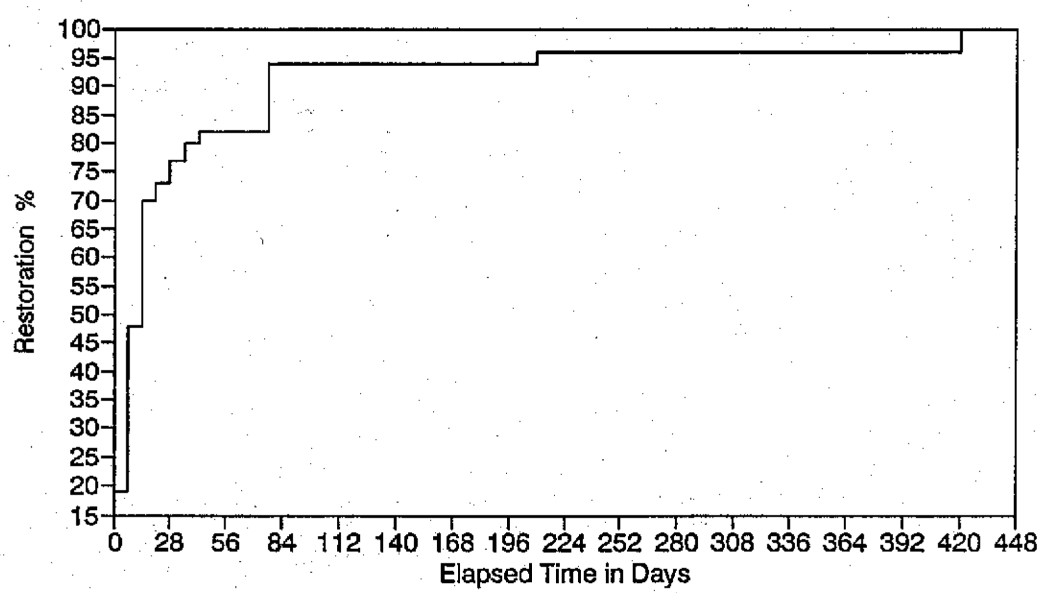


Figure C-142 Residual capacity of epicentral region highways following New Madrid event (M=7.0)

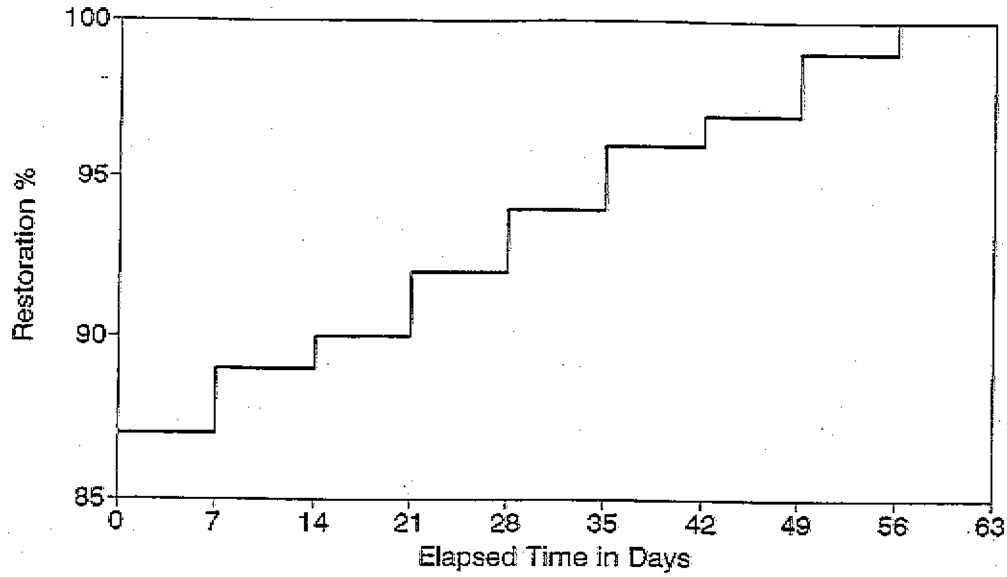


Figure C-143 Residual capacity of Illinois electric power following New Madrid event (M=8.0).

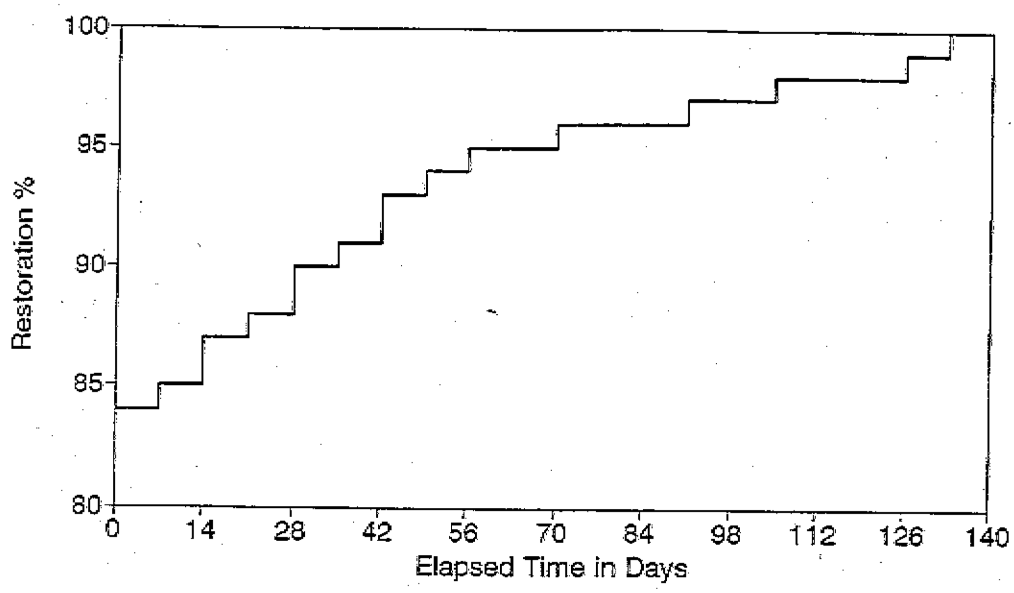


Figure C-144 Residual capacity of Missouri electric power following New Madrid event (M=8.0)

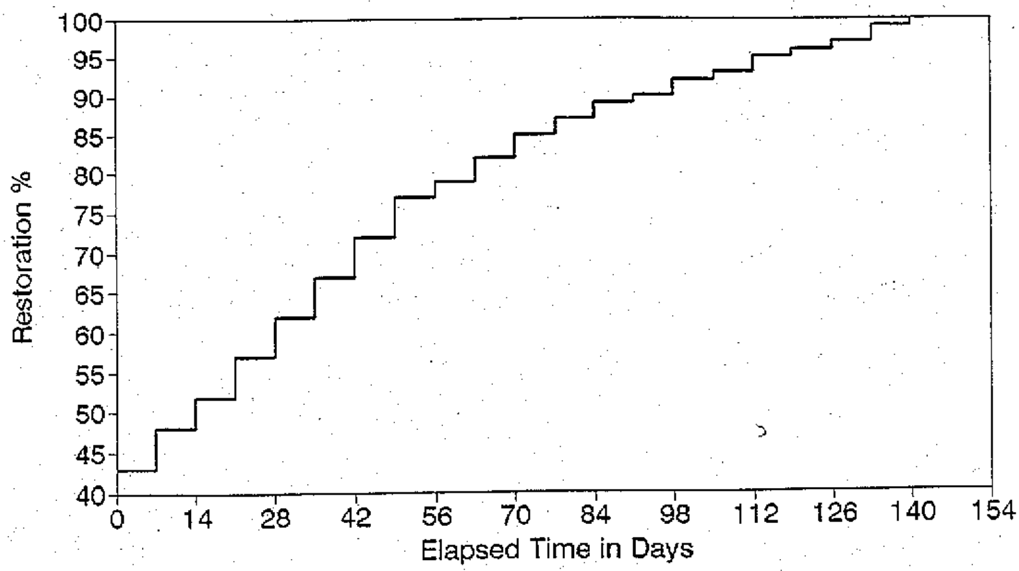


Figure C-145 Residual capacity of Arkansas electric power following New Madrid event (M=8.0).

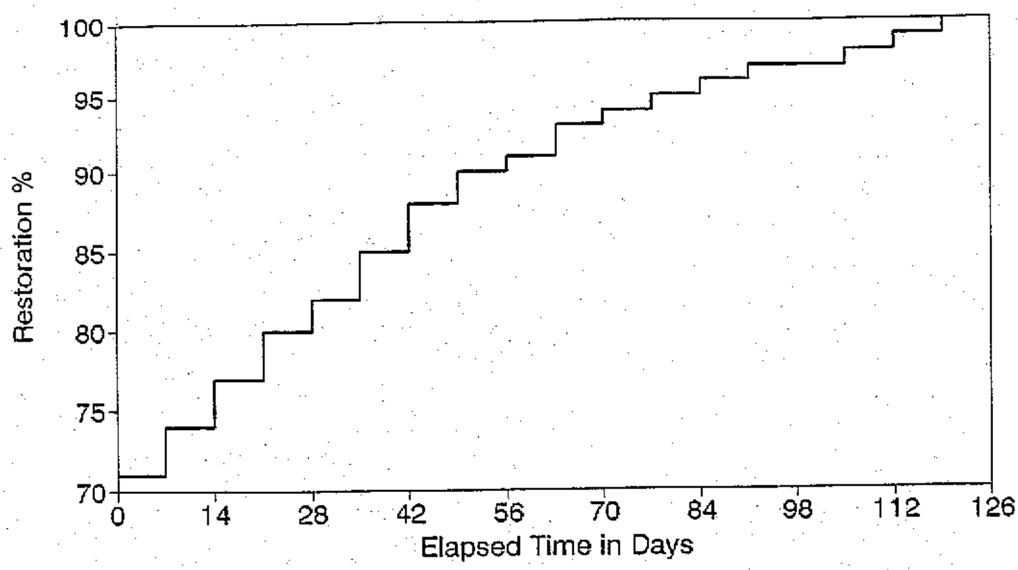


Figure C-146 Residual capacity of Tennessee electric power following New Madrid event (M=8.0)

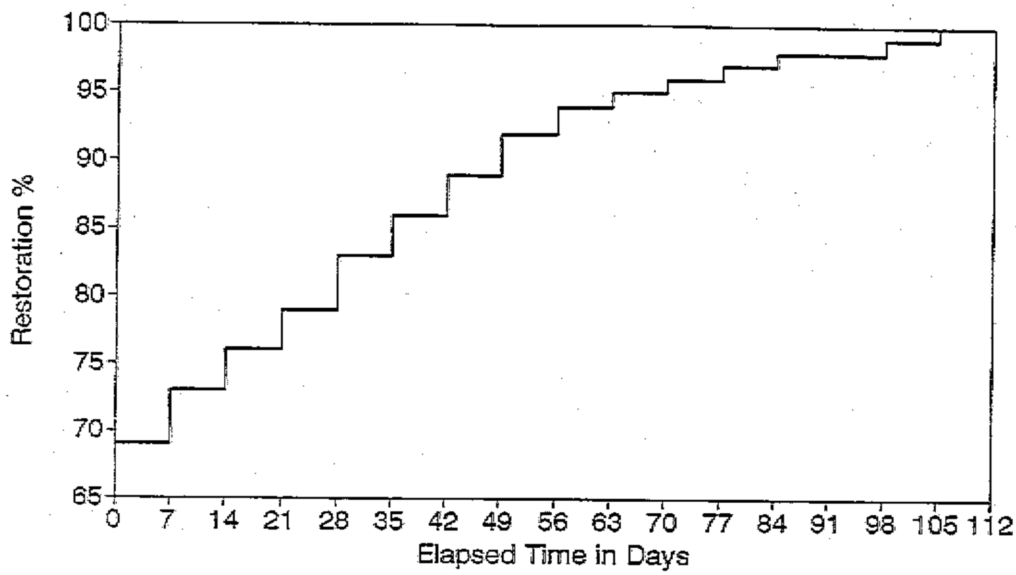


Figure C-147 Residual capacity of Kentucky electric power following New Madrid event (M=8.0).

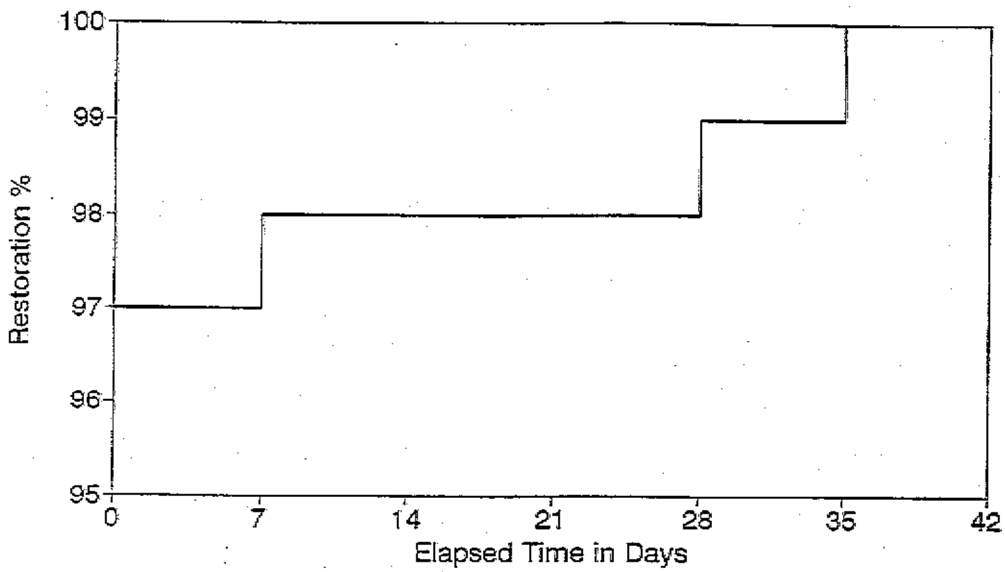
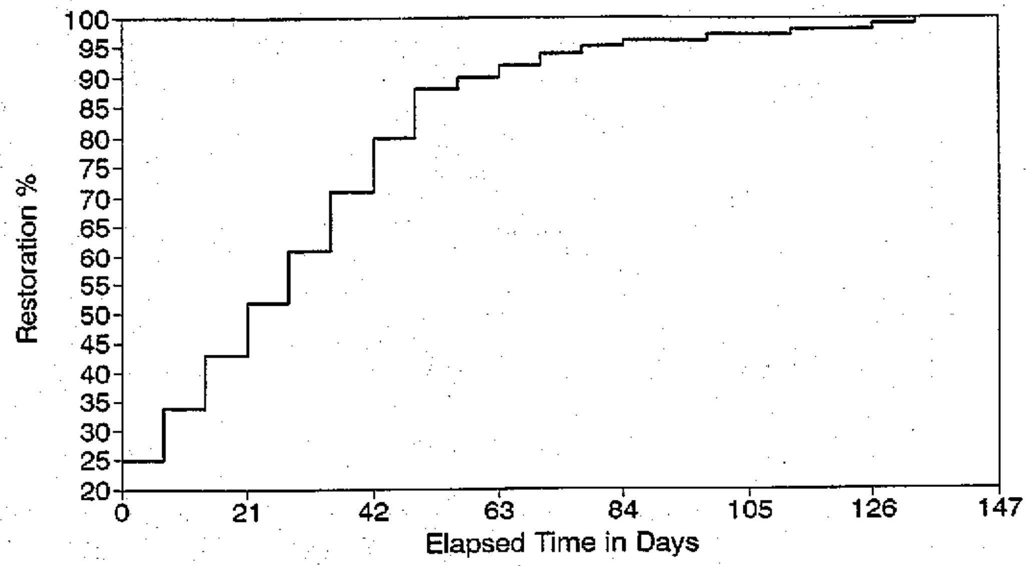


Figure C-148 Residual capacity of Indiana electric power following New Madrid event (M=8.0)



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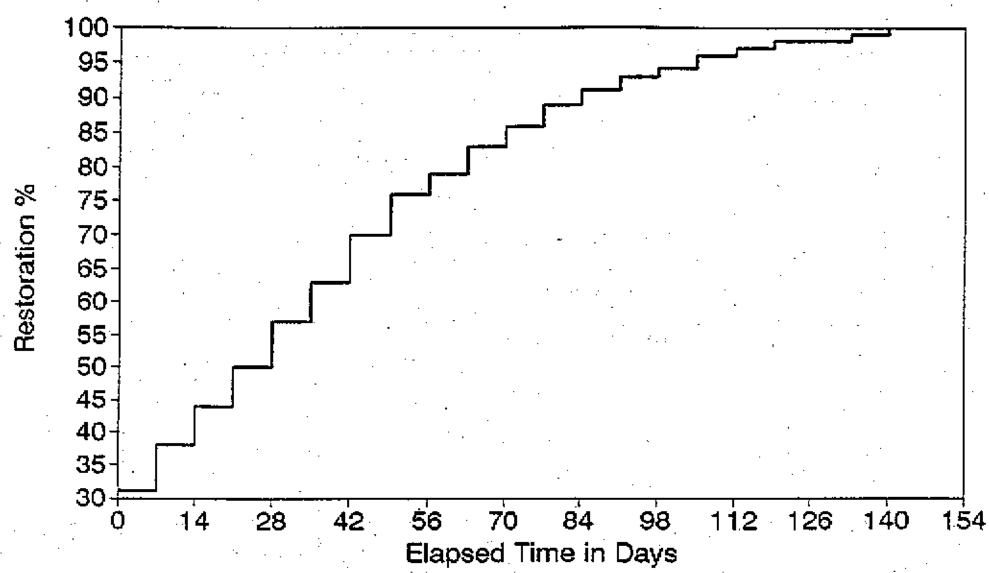
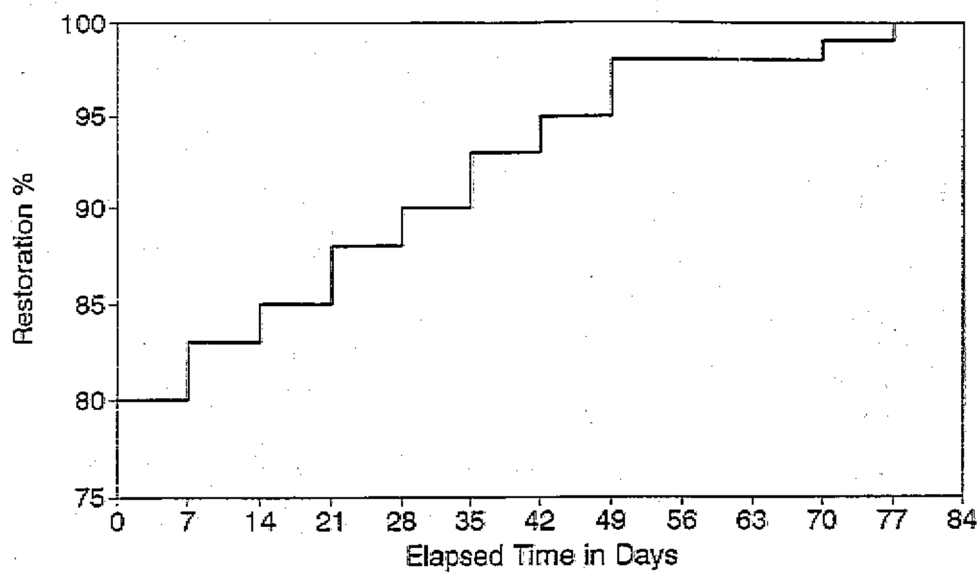


Figure C-150 Residual capacity of South Carolina electric power following Charleston event (M=7.5).



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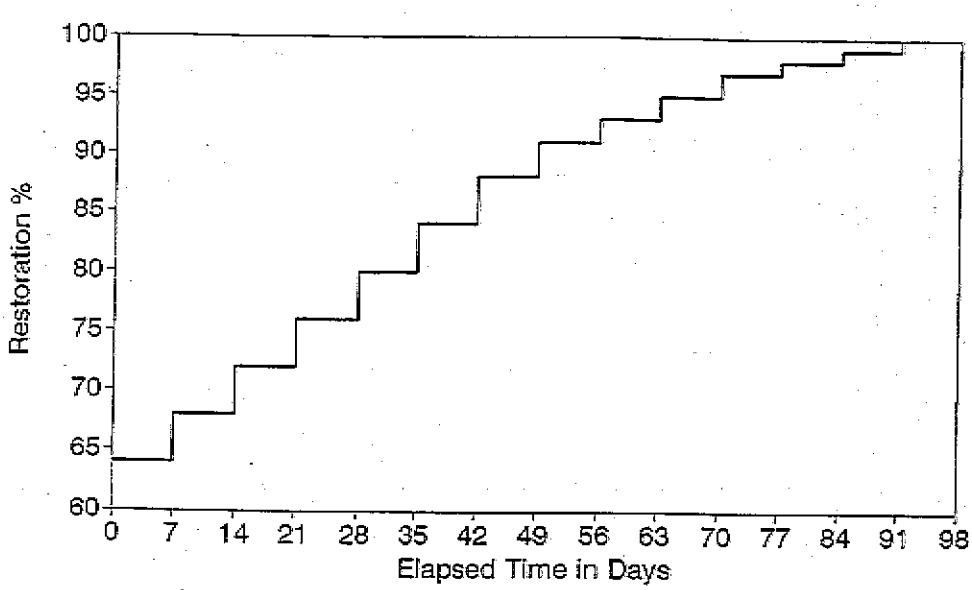


Figure C-152 Residual capacity of Georgia electric power following Charleston event (M=7.5).

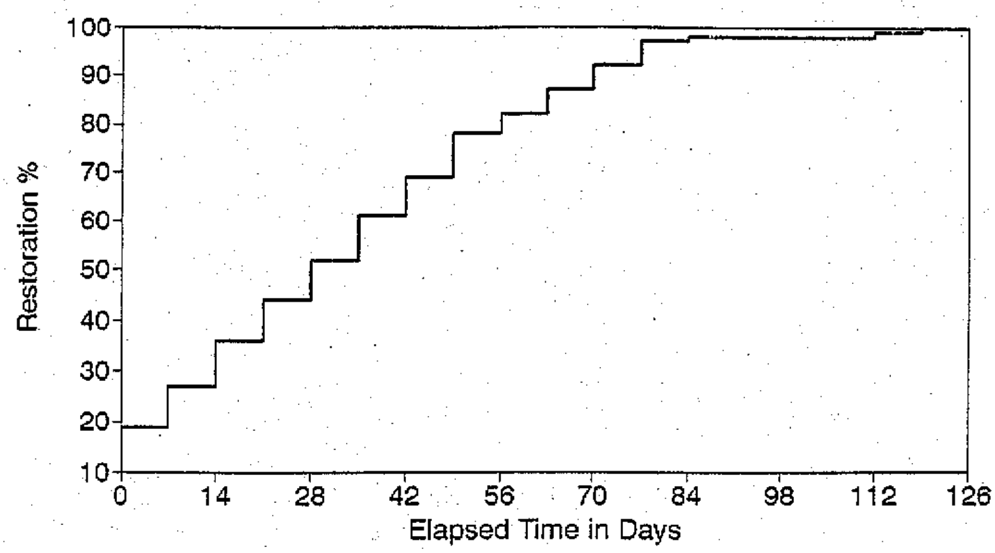


Figure C-153 Residual capacity of Massachusetts electric power following Cape Ann event (M=7.0).

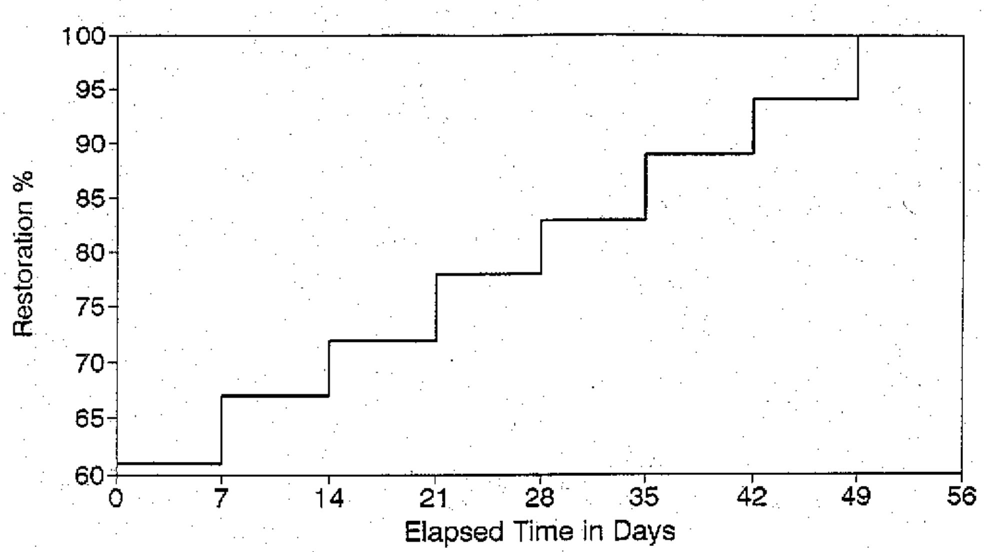
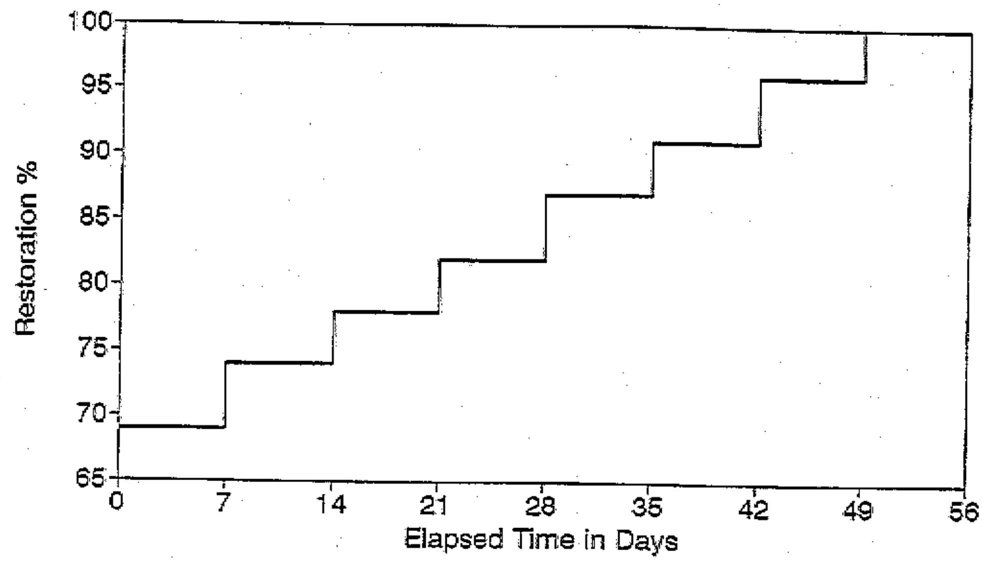


Figure C-154 Residual capacity of Connecticut electric power following Cape Ann event (M=7.0).



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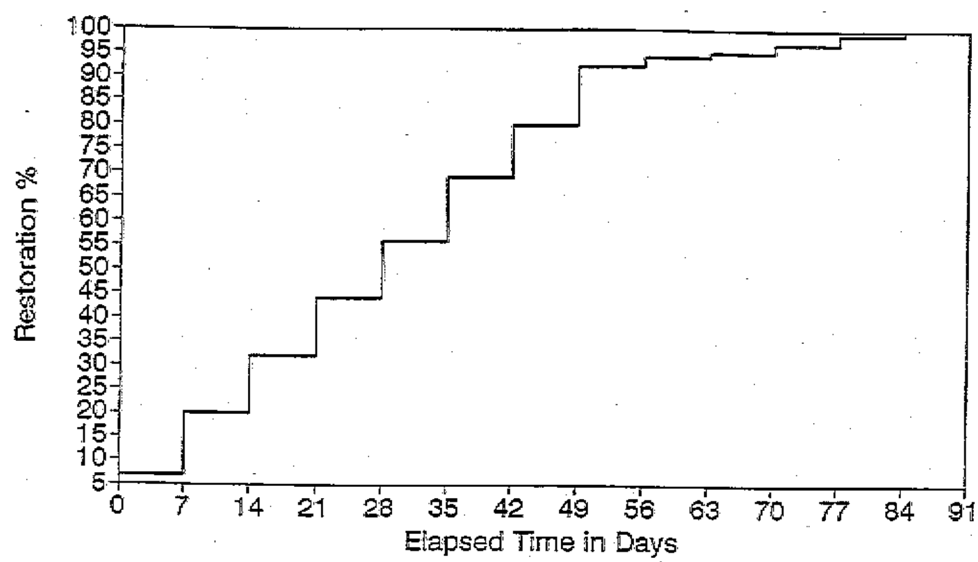

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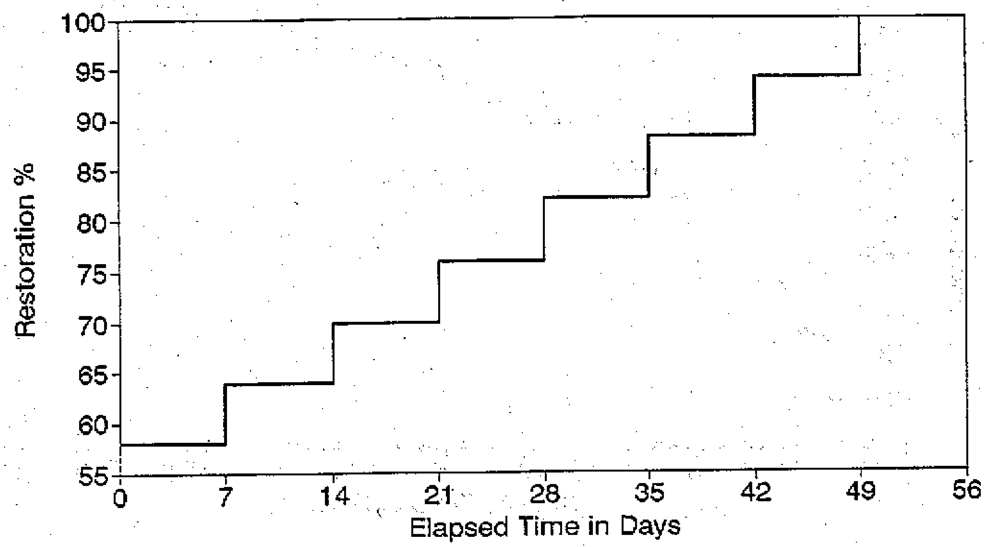

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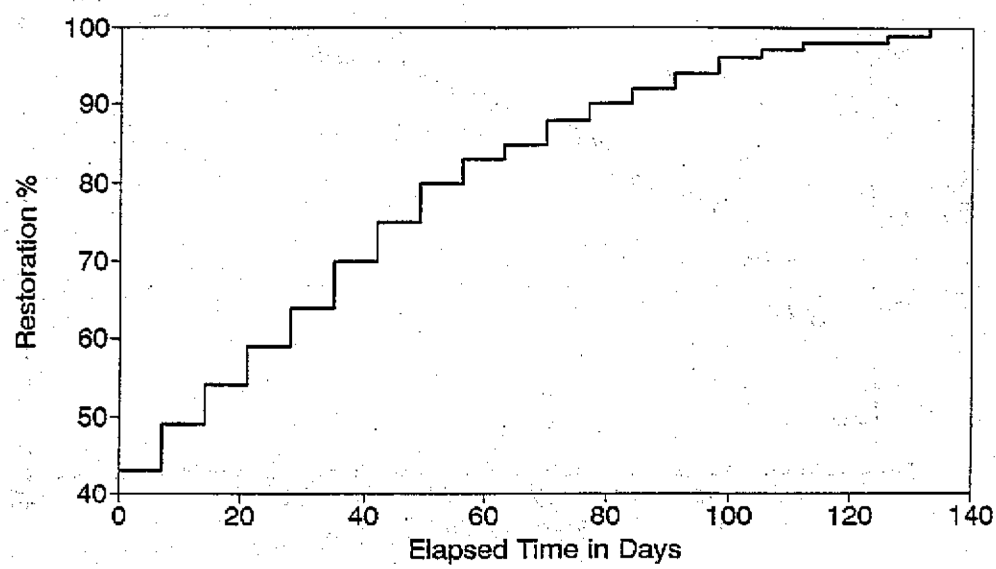

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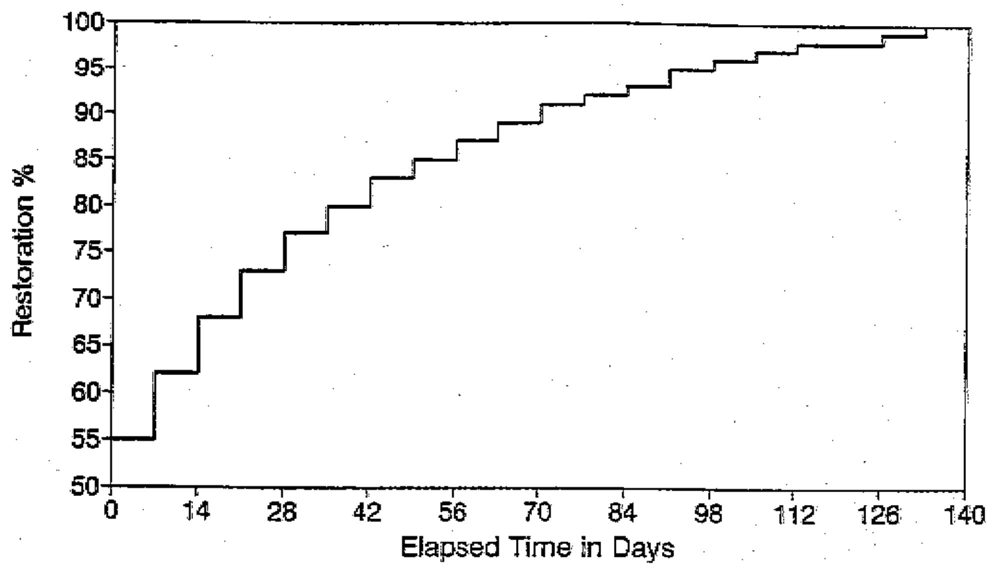
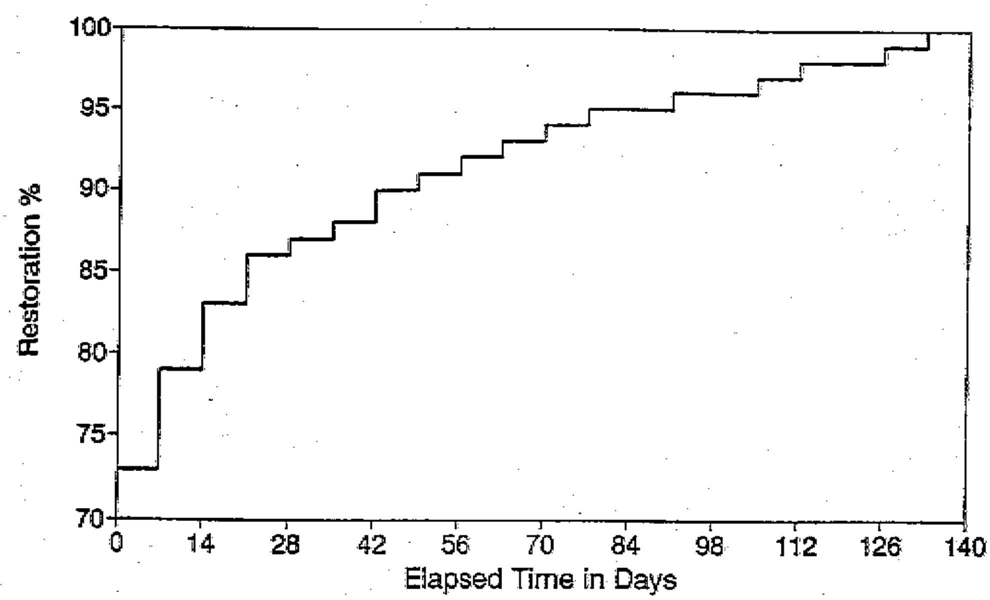


Figure C-159 Residual capacity of California electric power following Hayward event (M=7.5).



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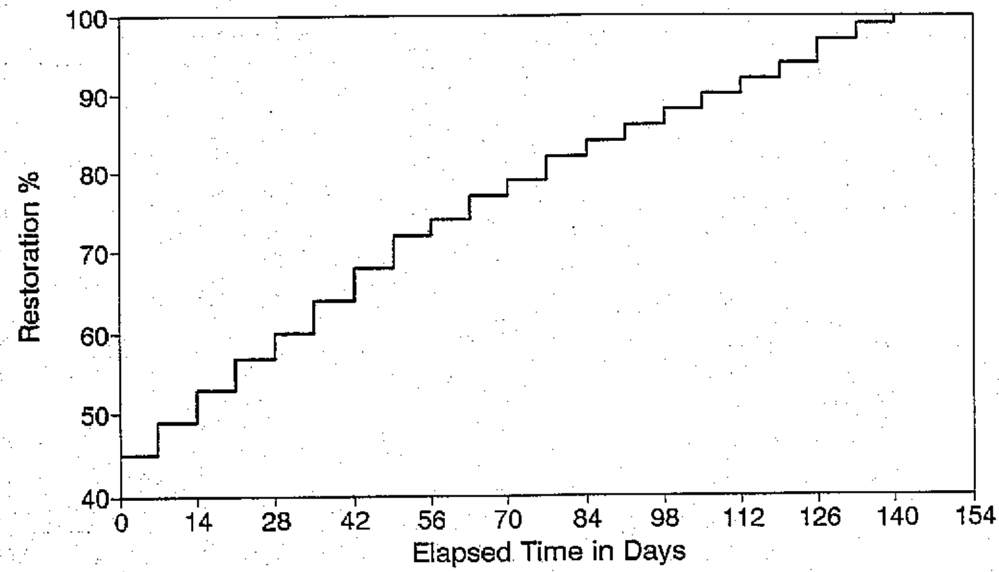

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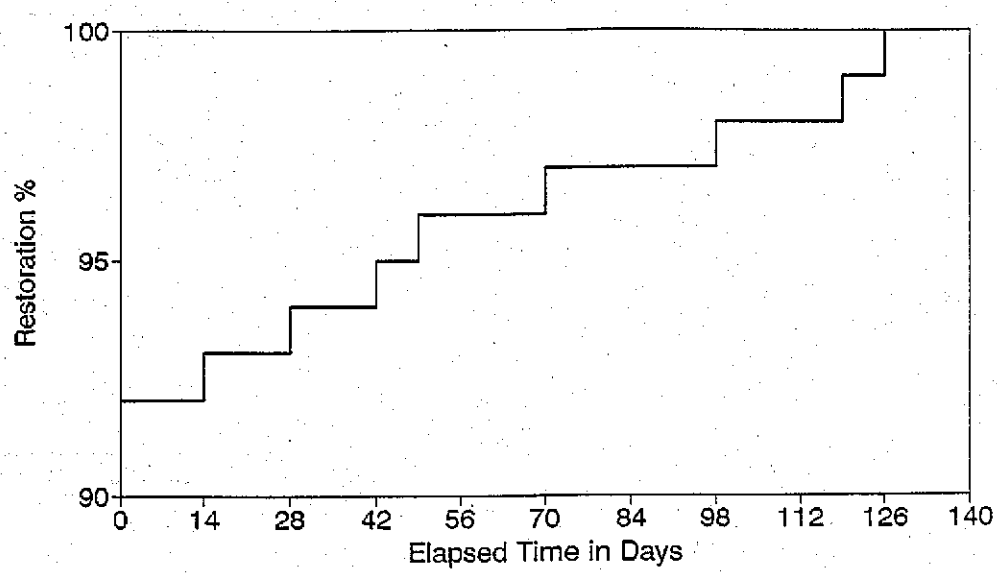

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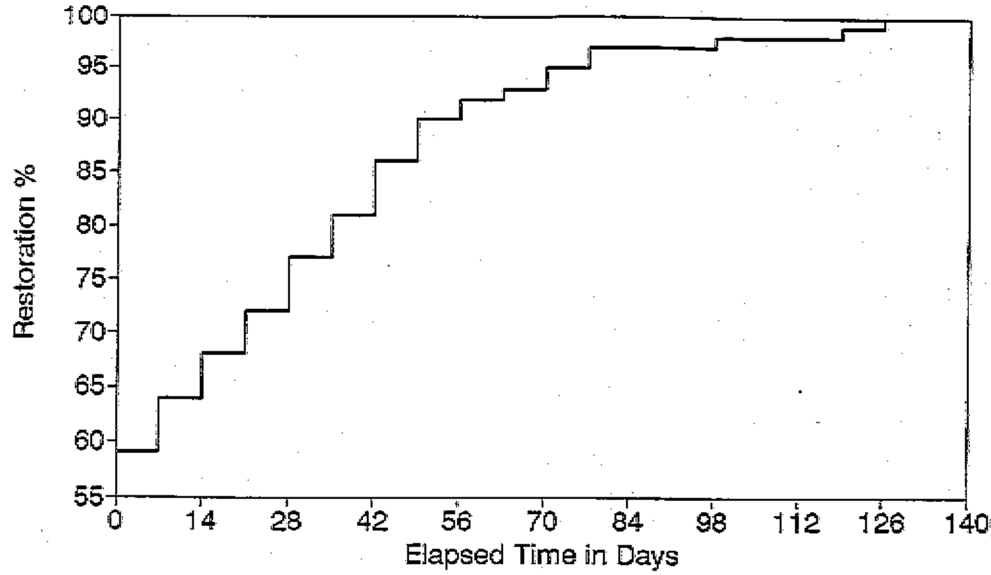

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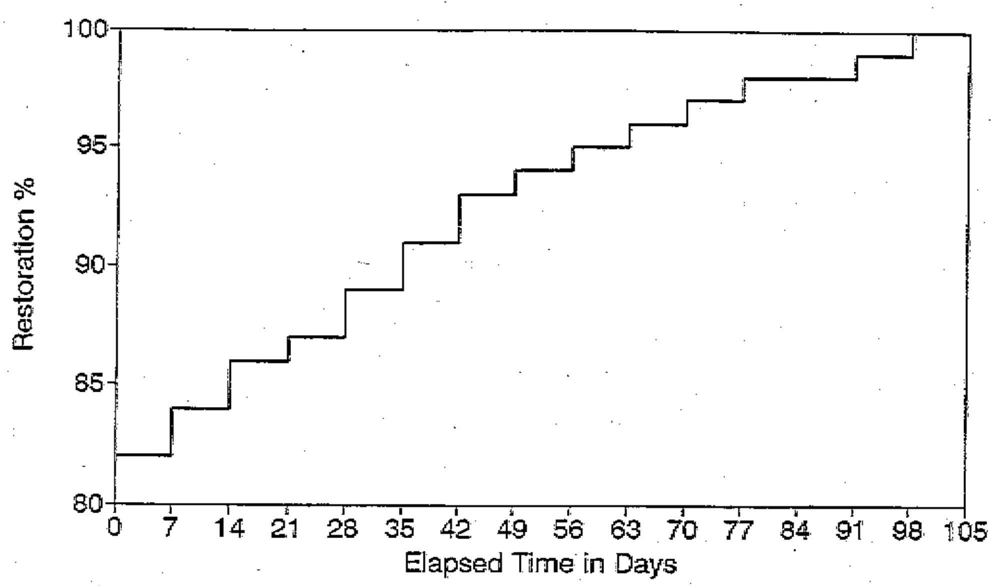

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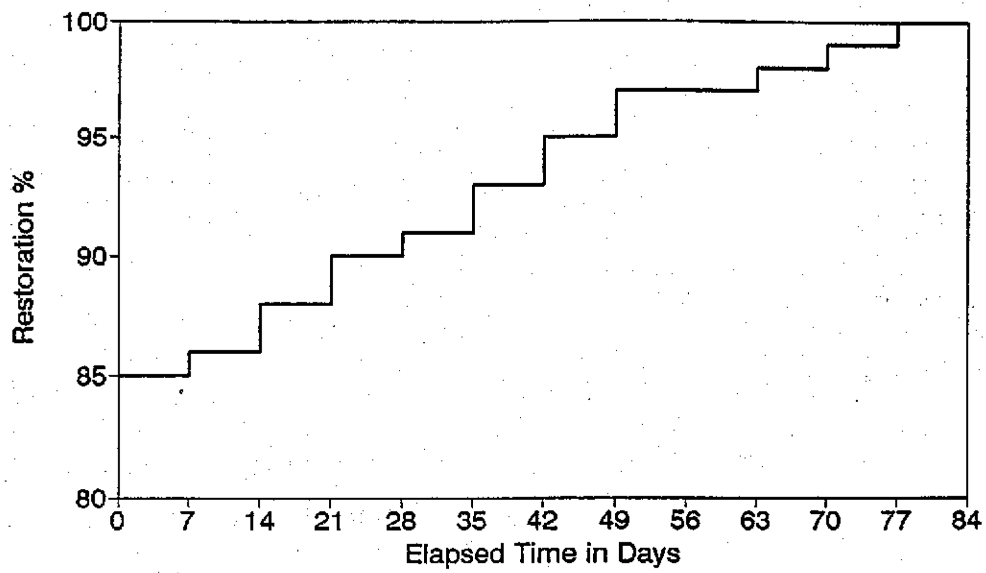

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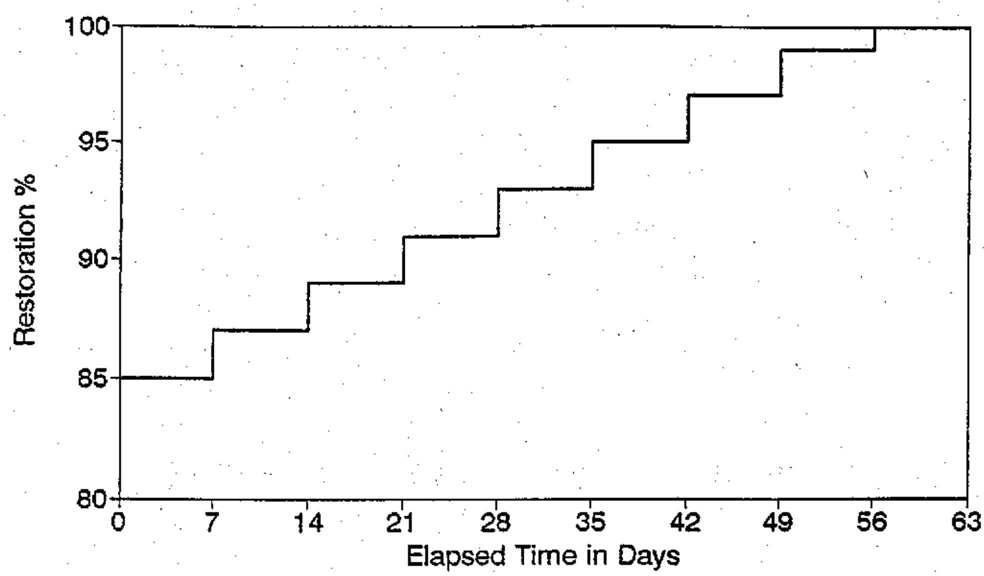

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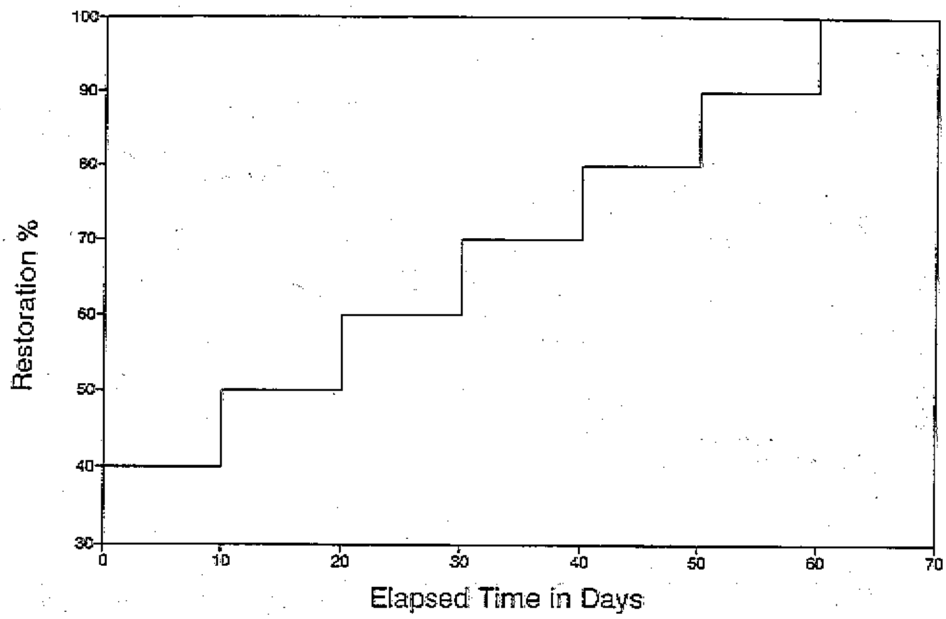

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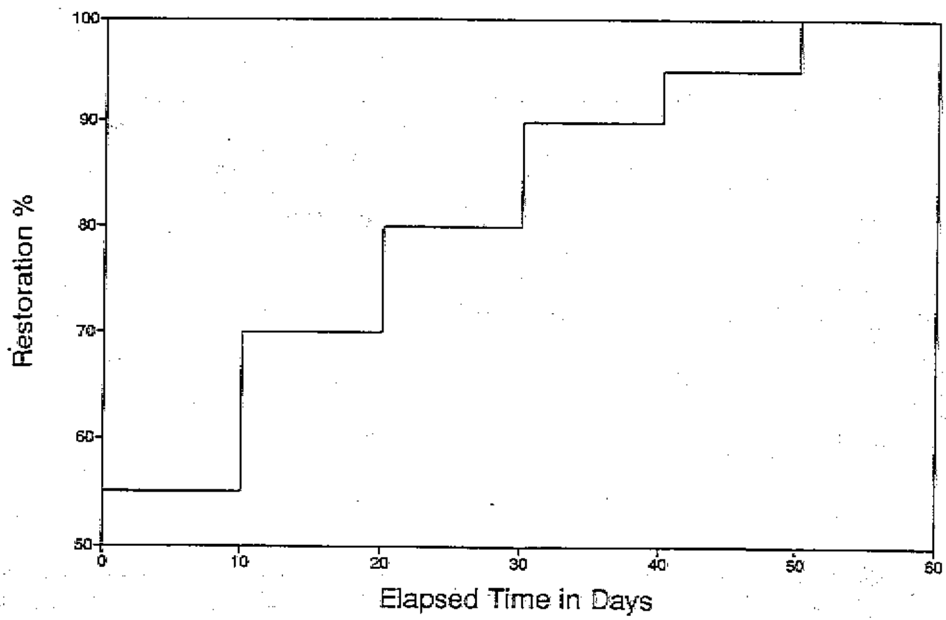

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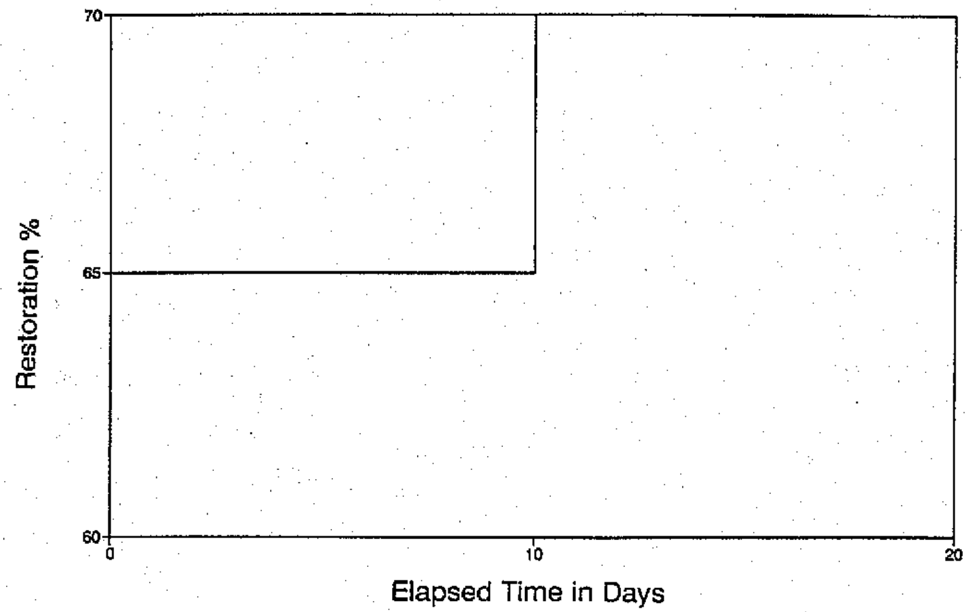

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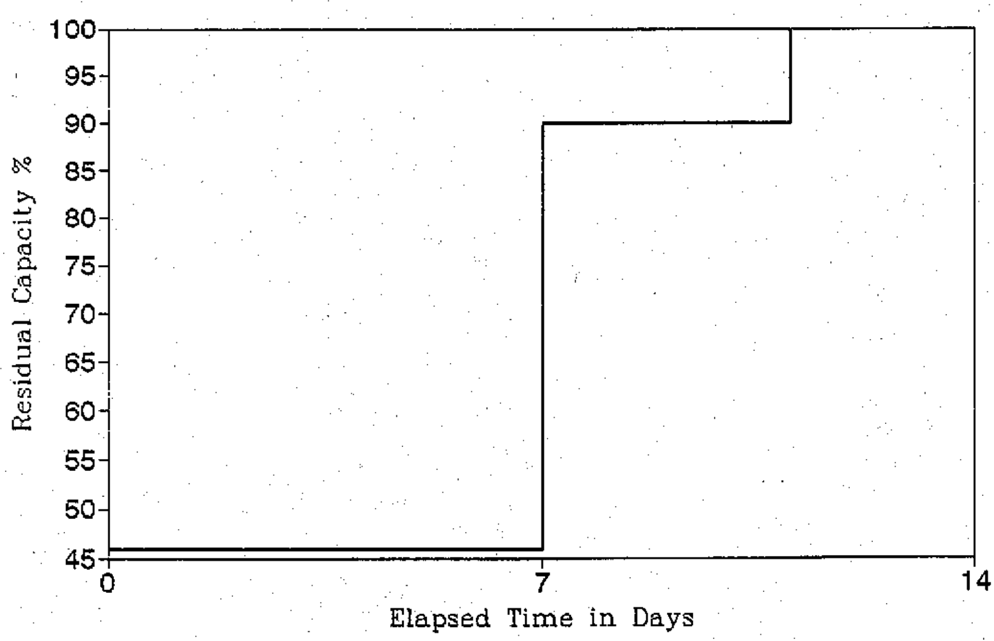


Figure C-170 Residual capacity of crude oil delivery from Texas and Louisiana to Chicago following New Madrid event (M=8.0).

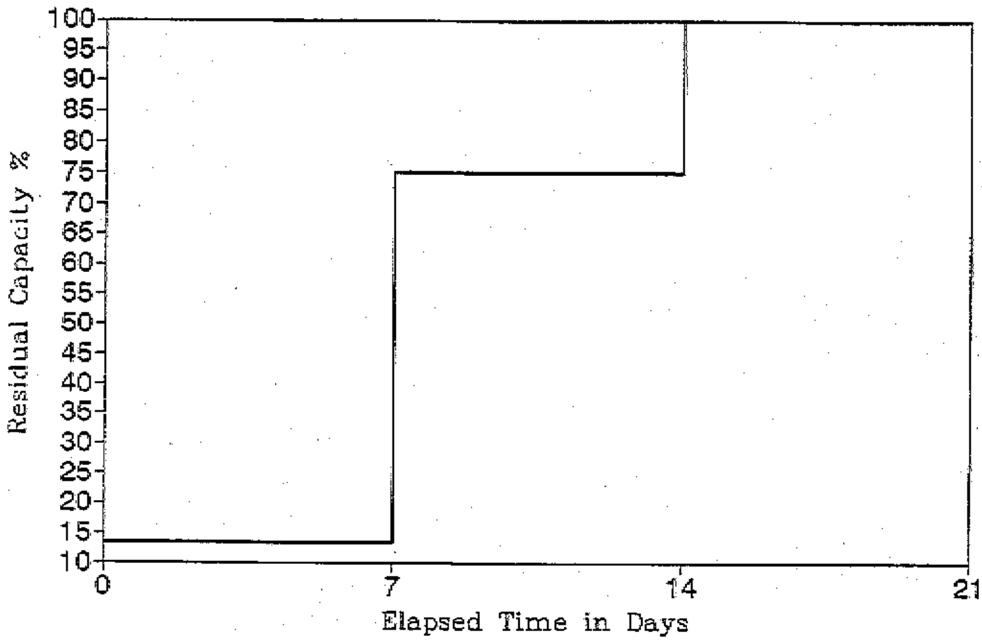
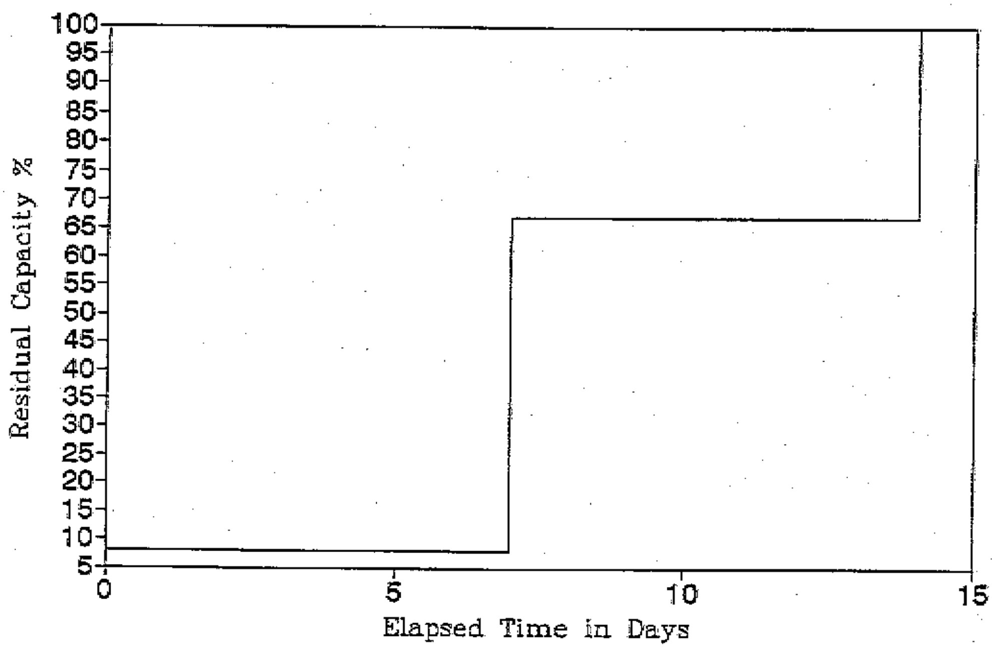


Figure C-171 Residual capacity of crude oil delivery from Texas to Southern California following Fort Tejon event (M=8.0).



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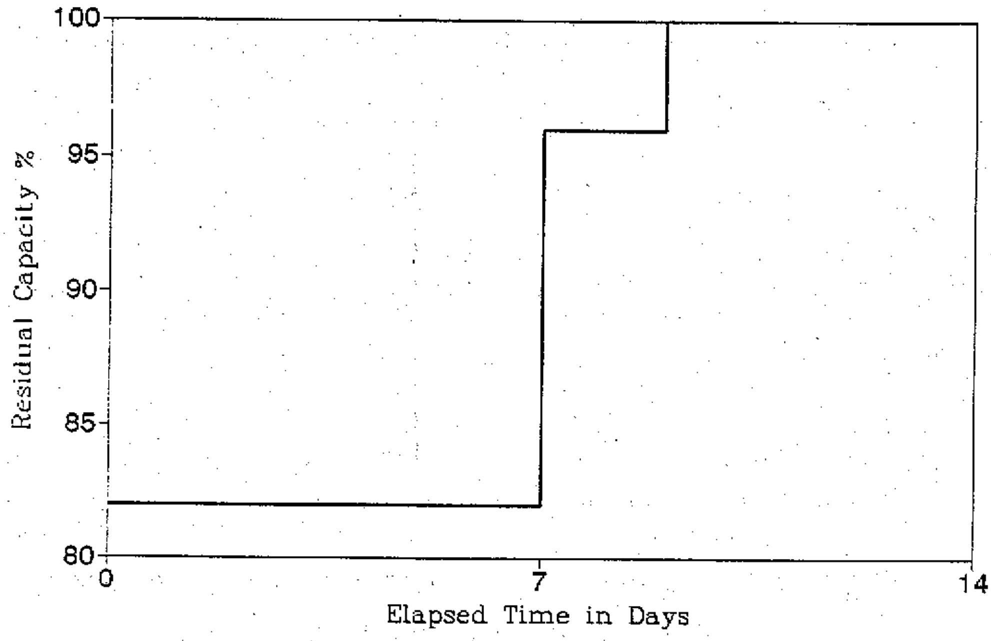

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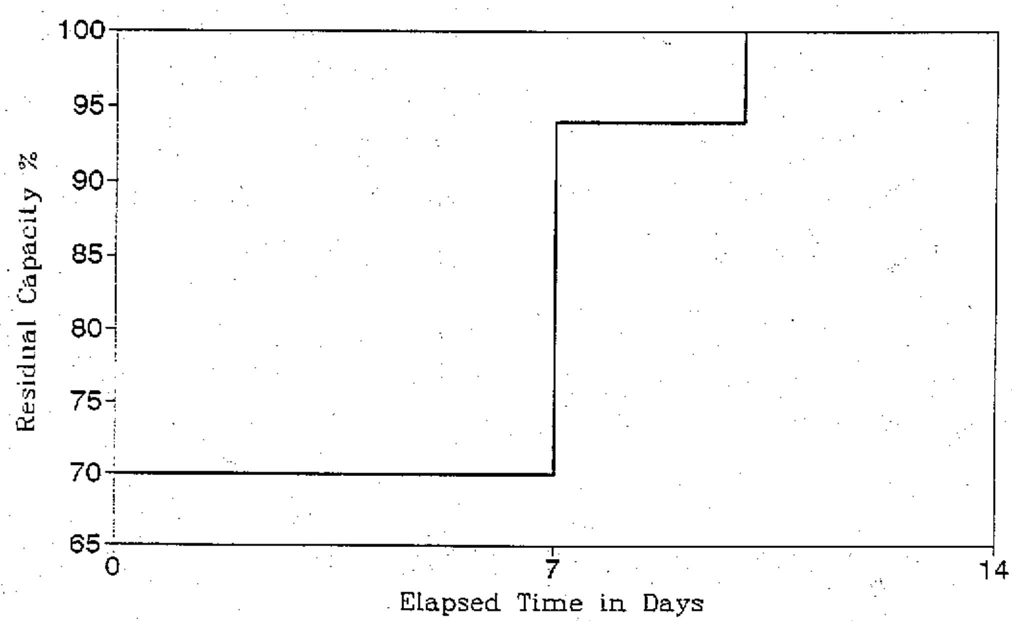

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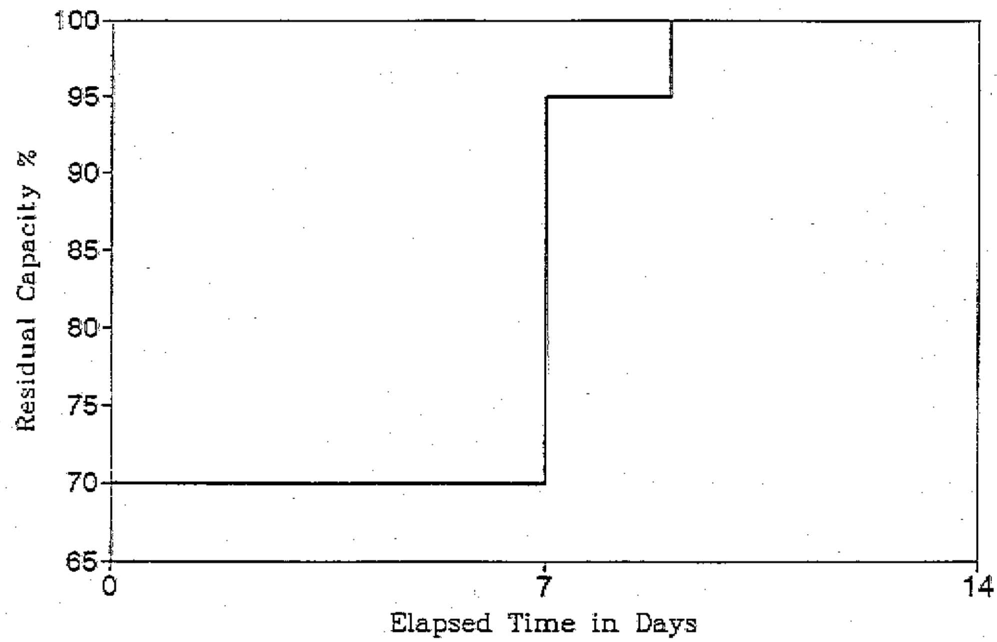

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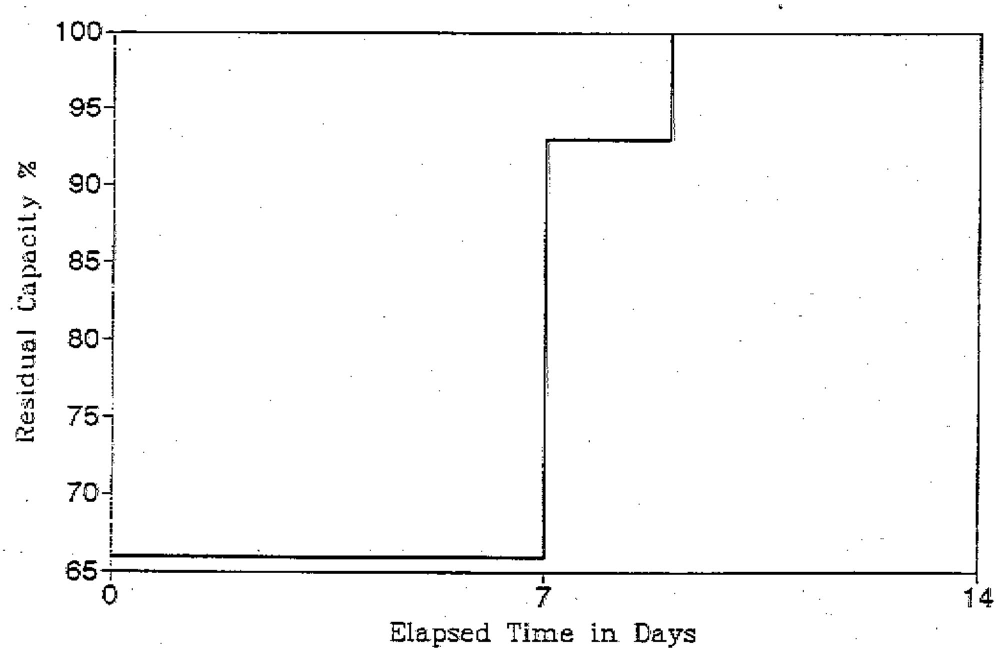
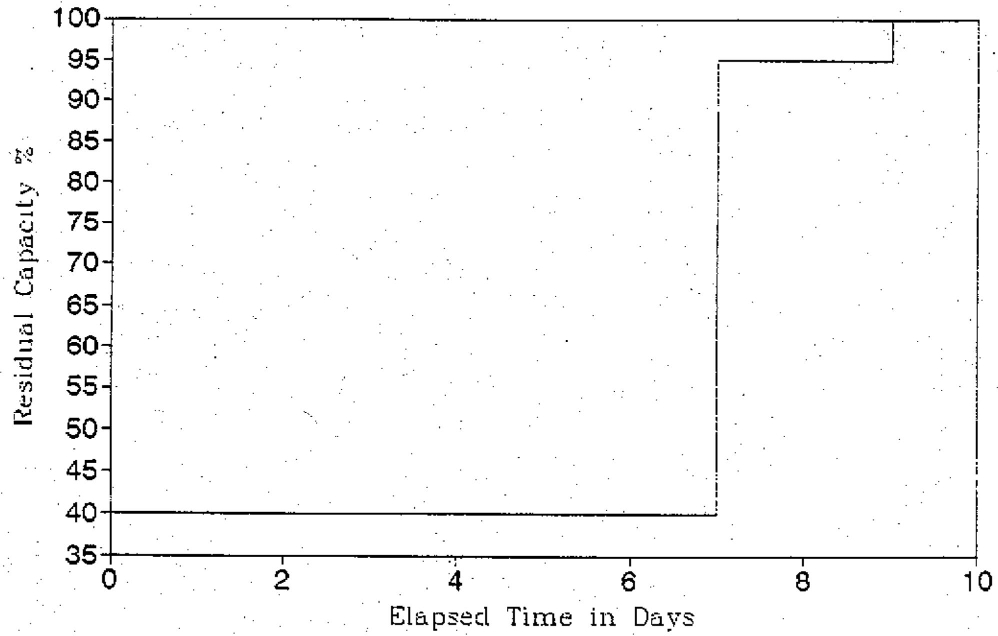


Figure C-176 Residual capacity of natural gas delivery from Texas and Louisiana to Chicago following New Madrid event (M=8.0).



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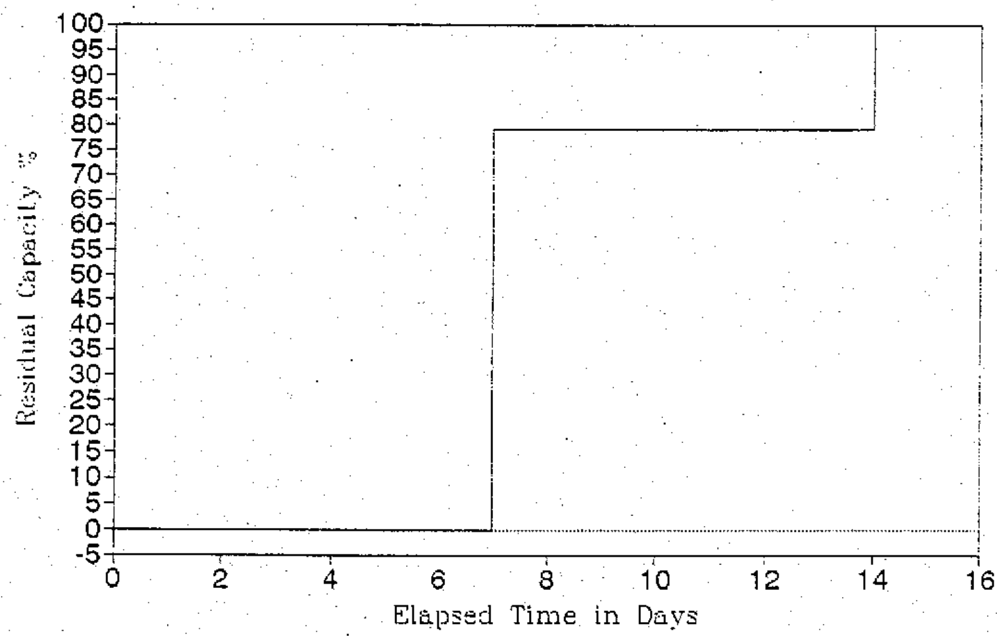

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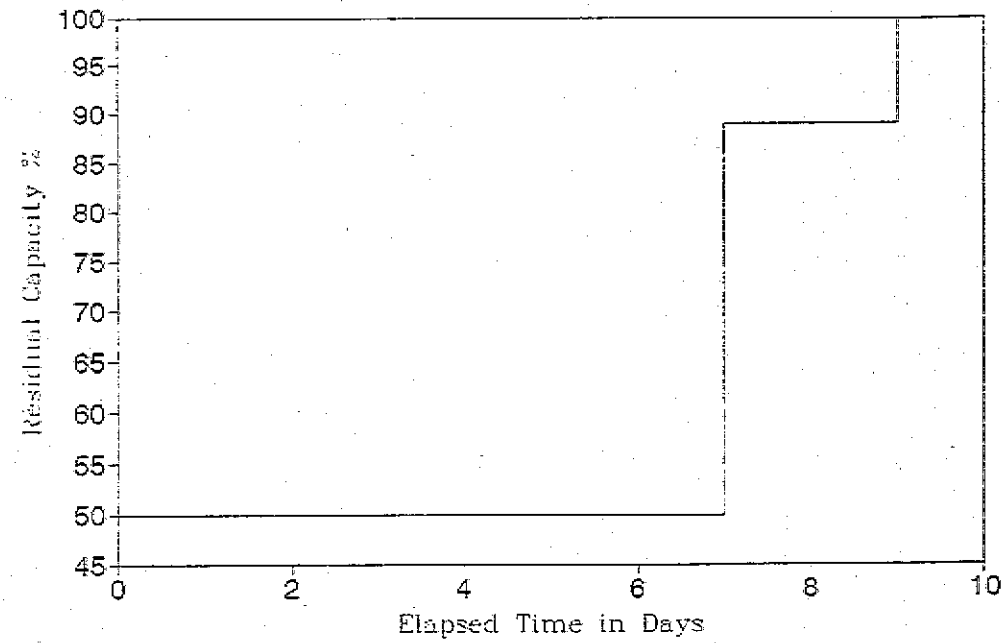

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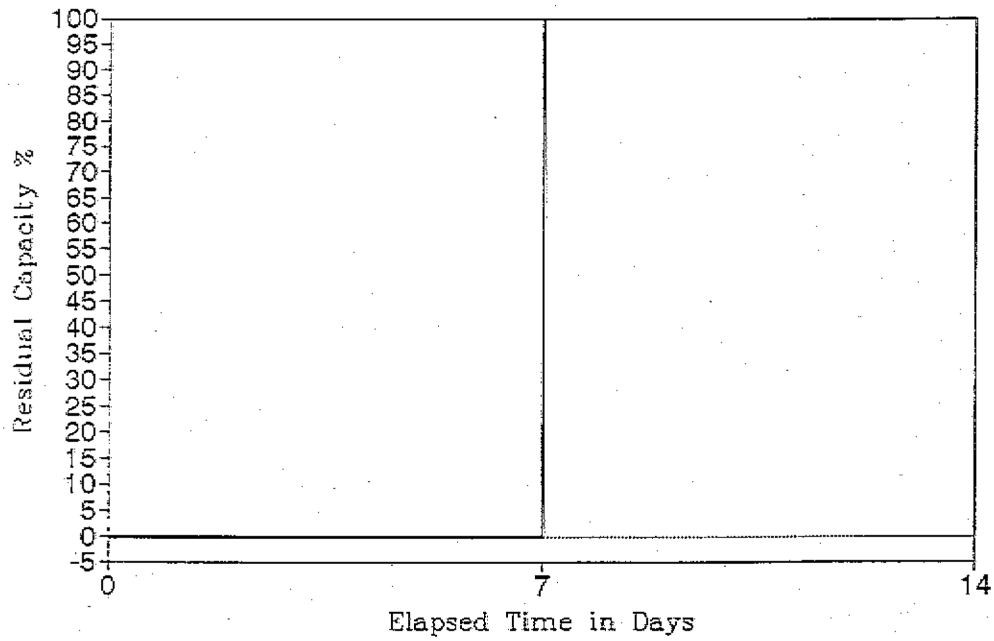

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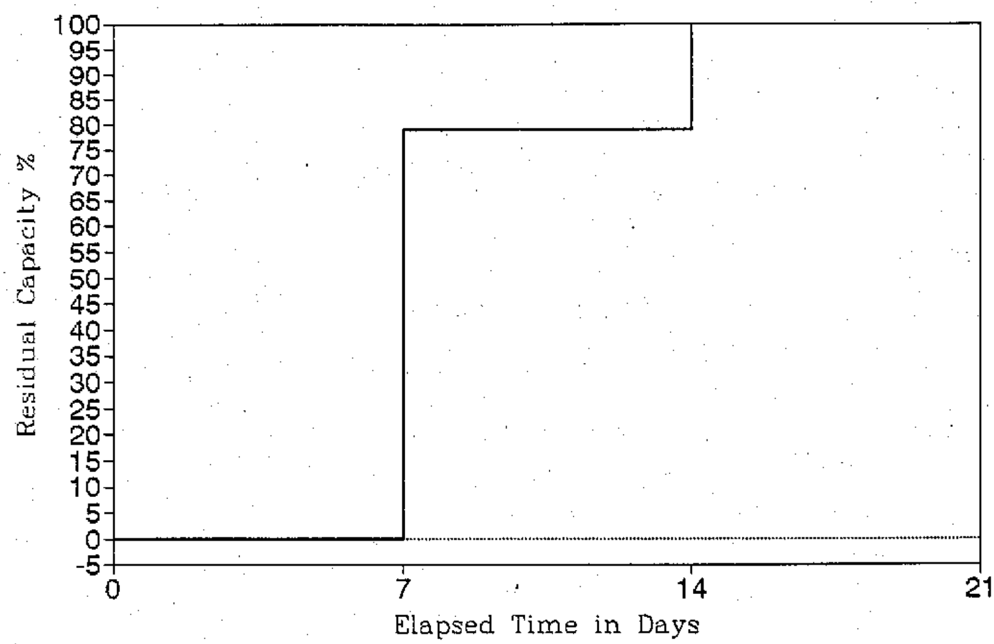

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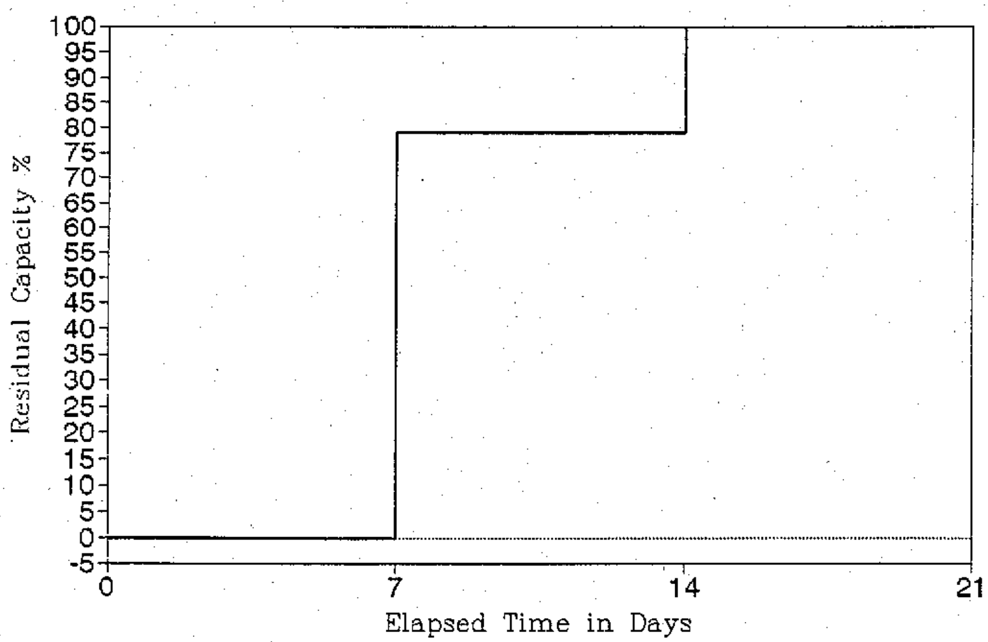

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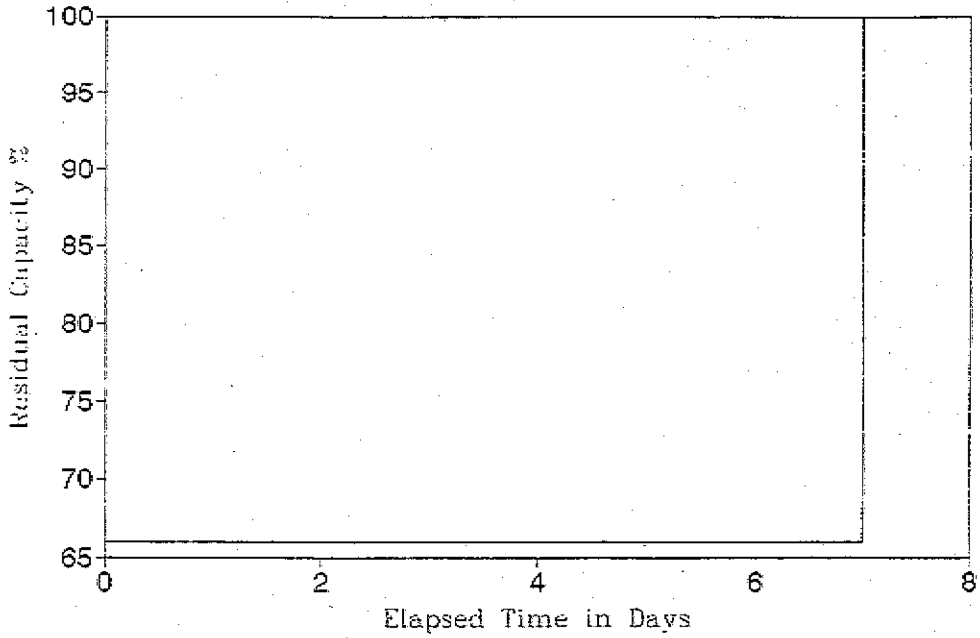

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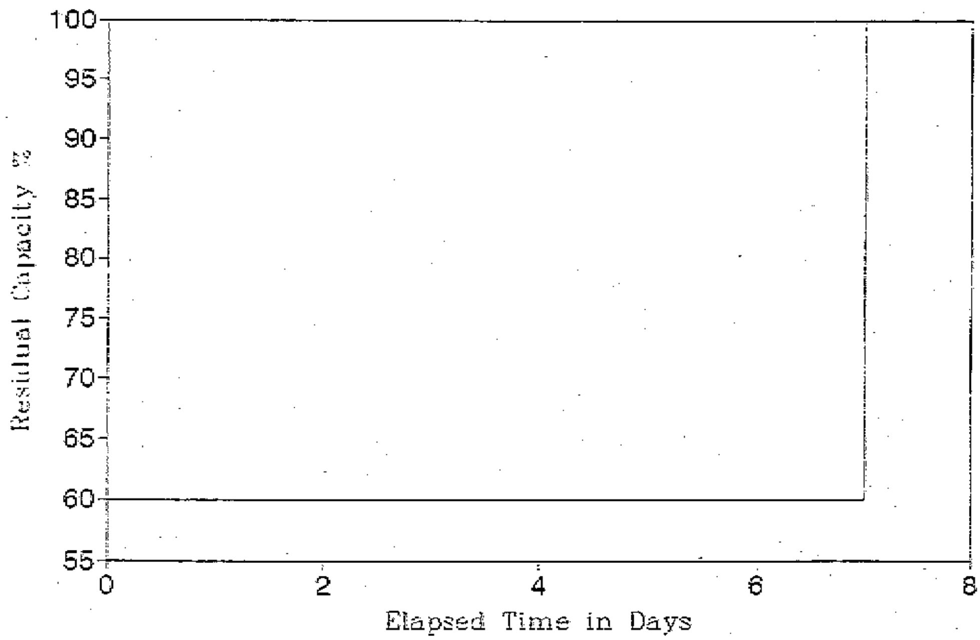

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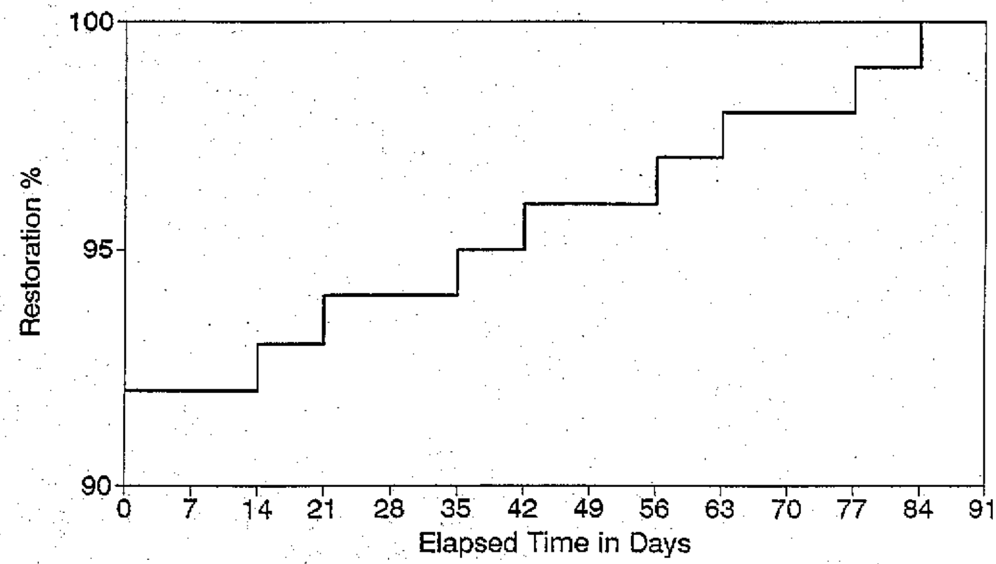

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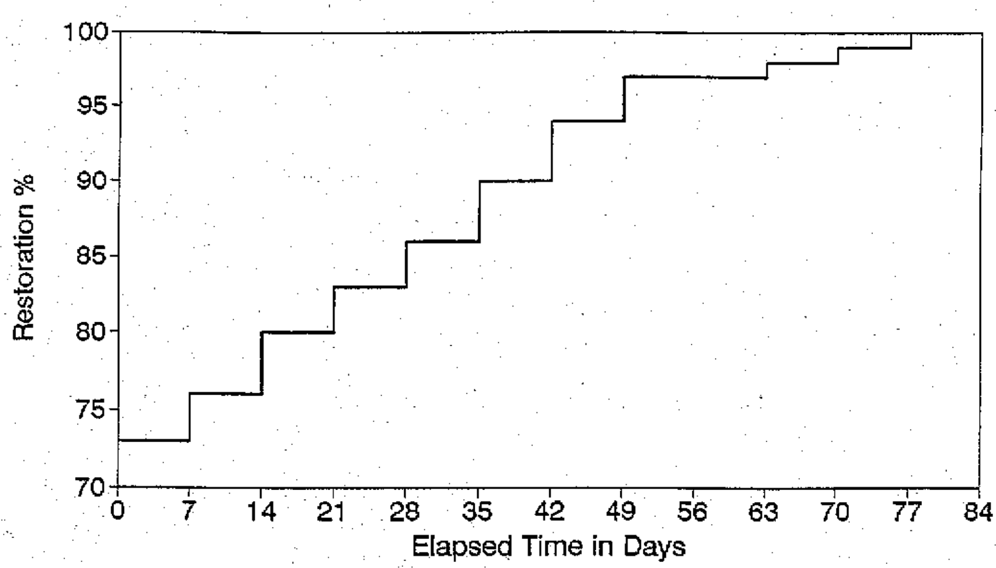

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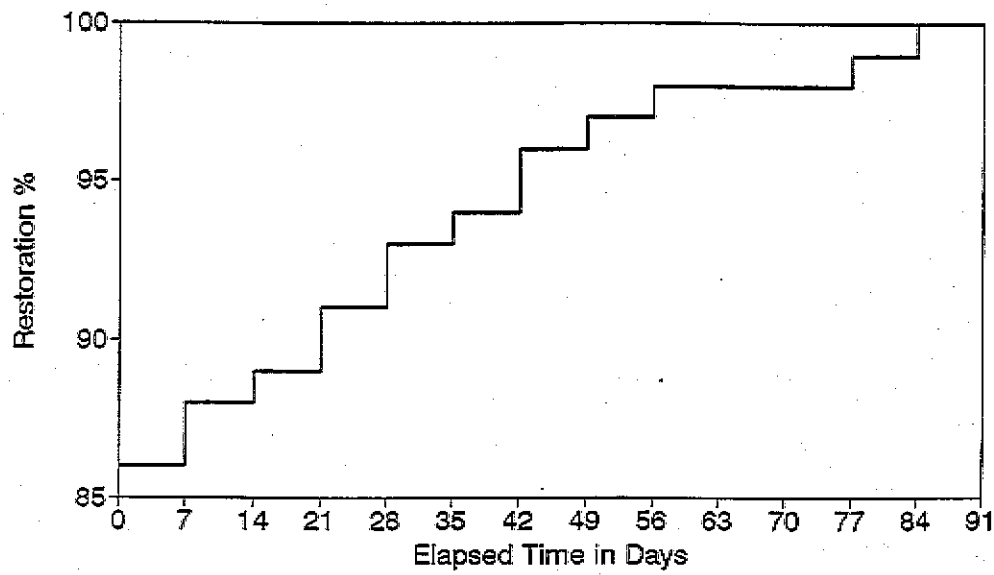

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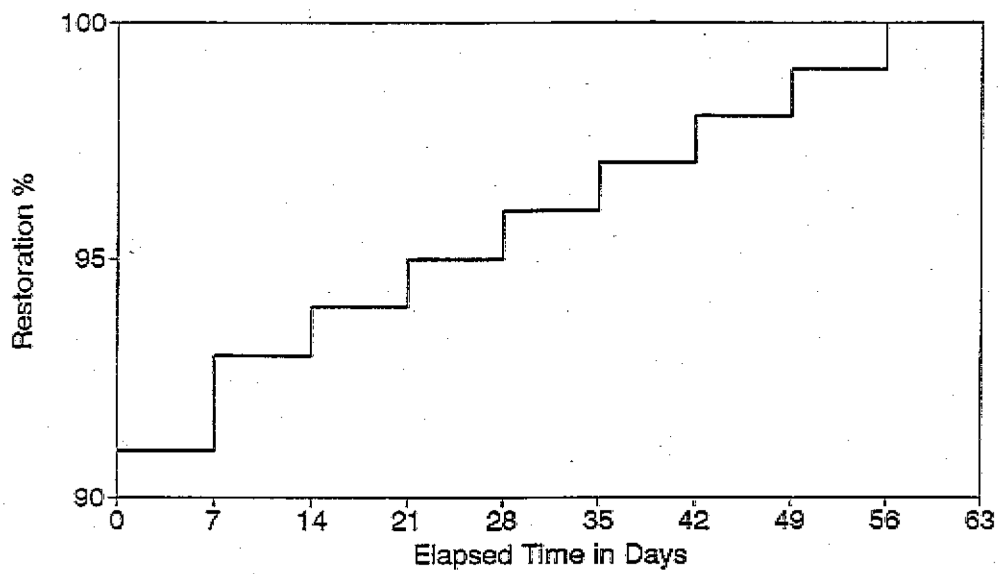

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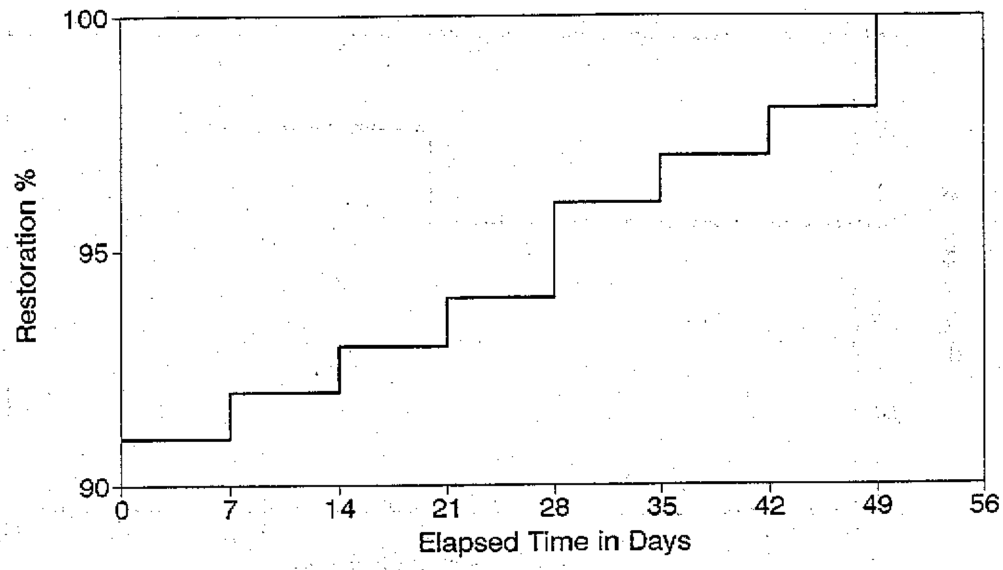

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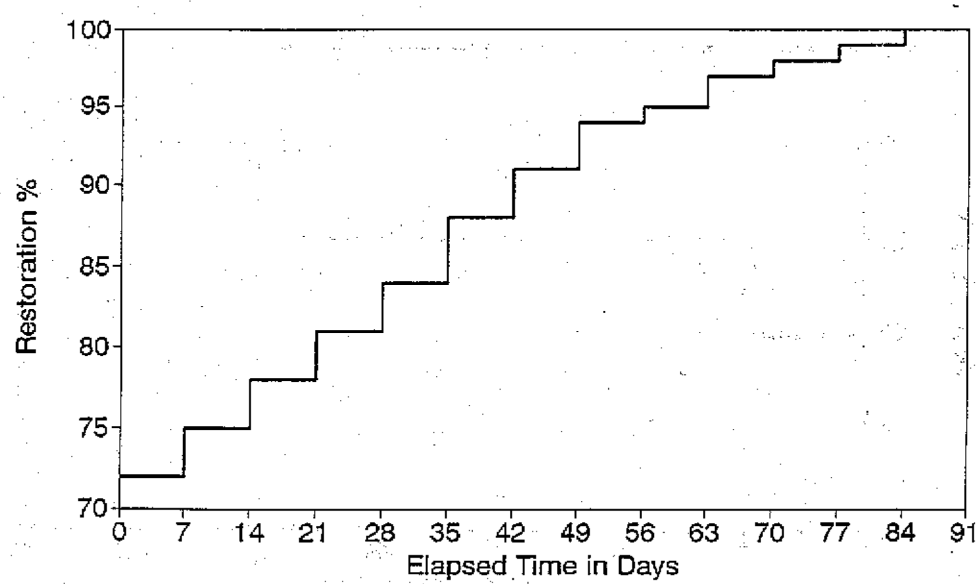

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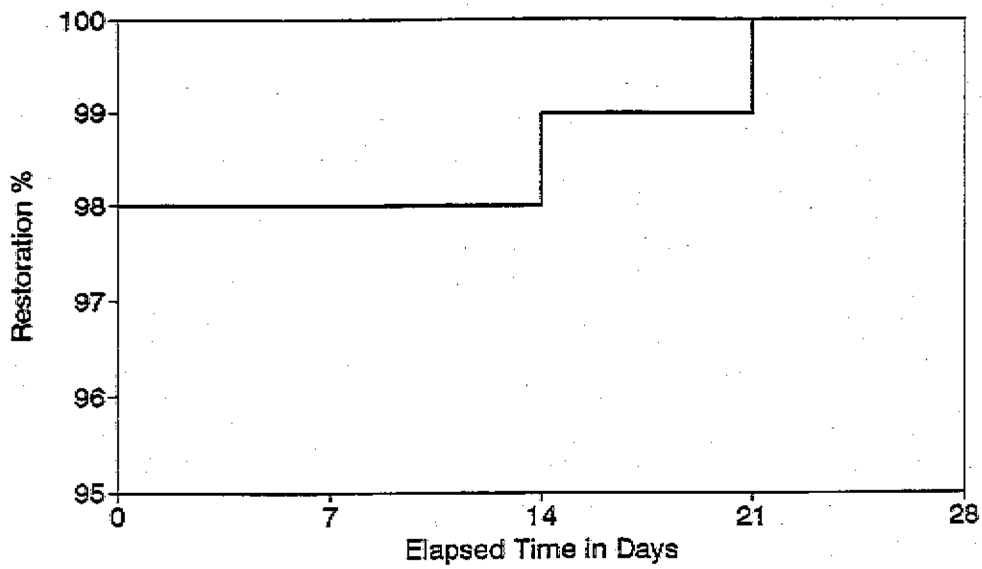

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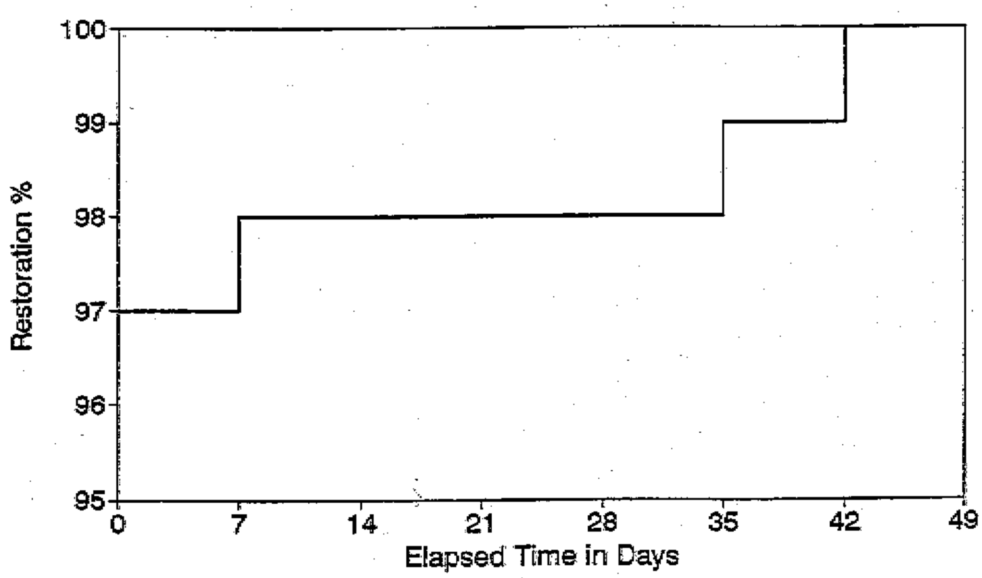

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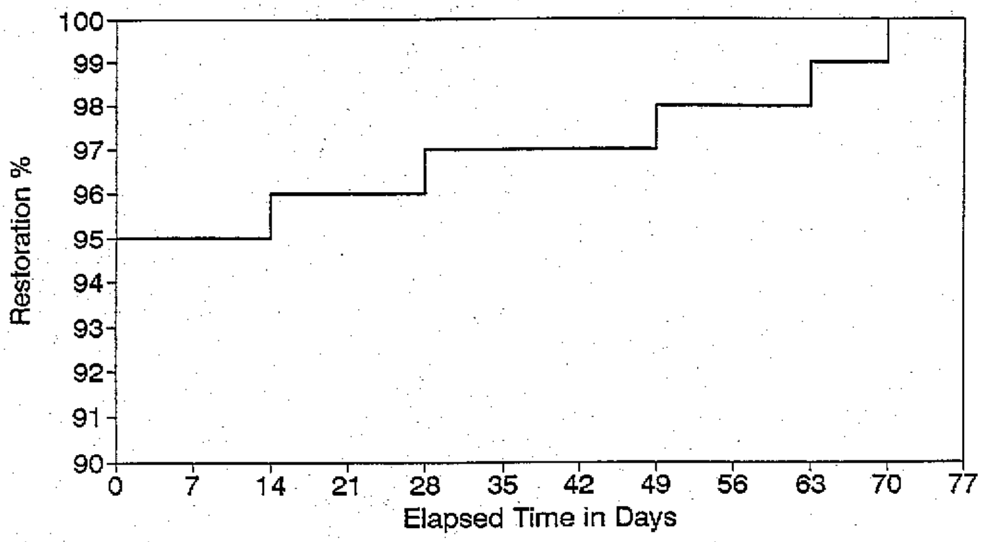

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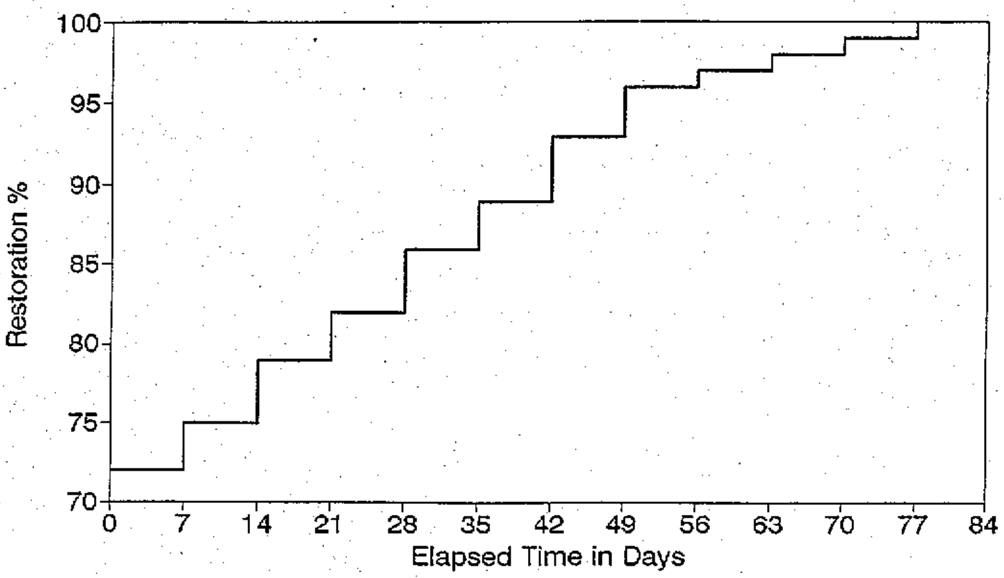

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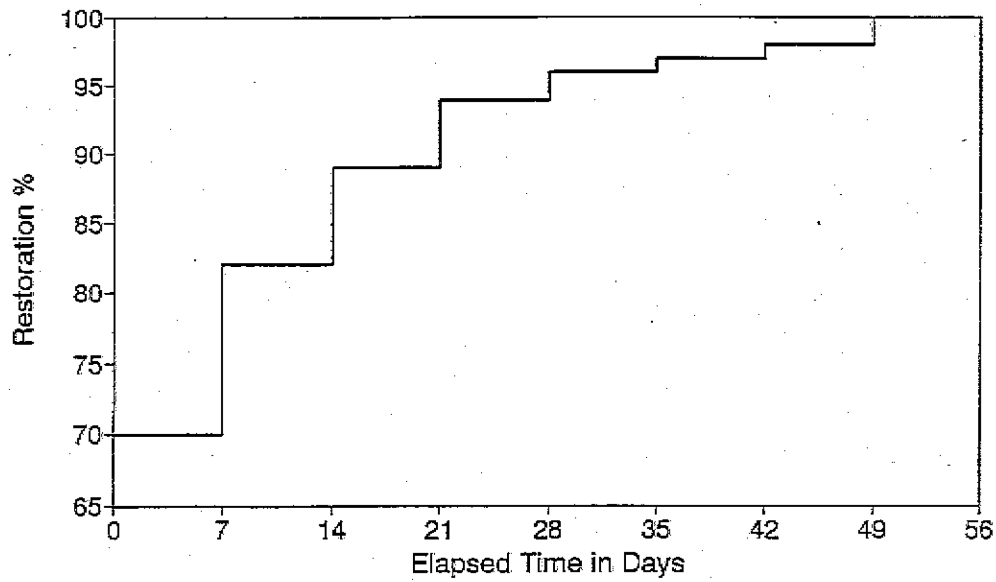

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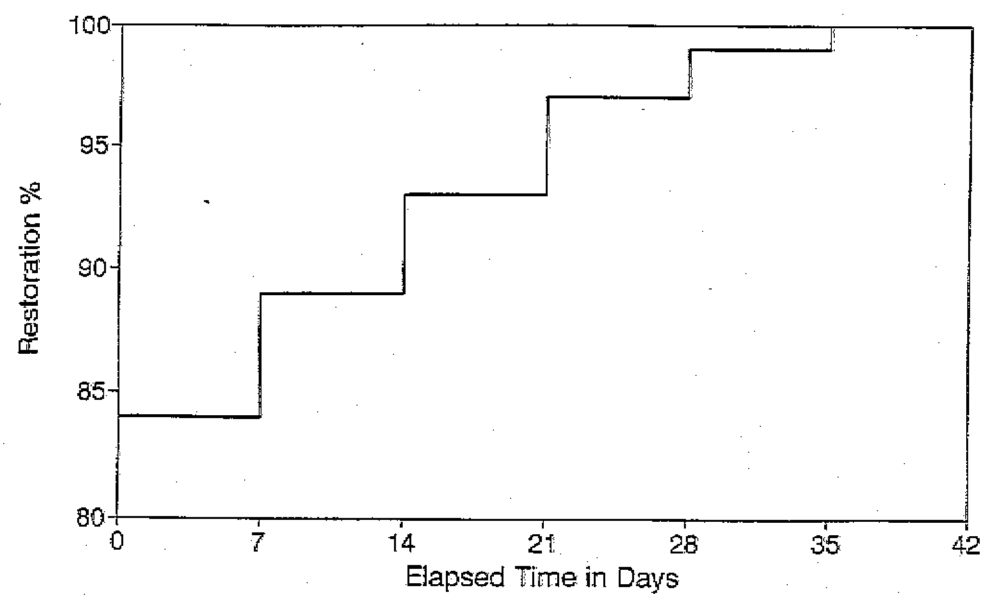

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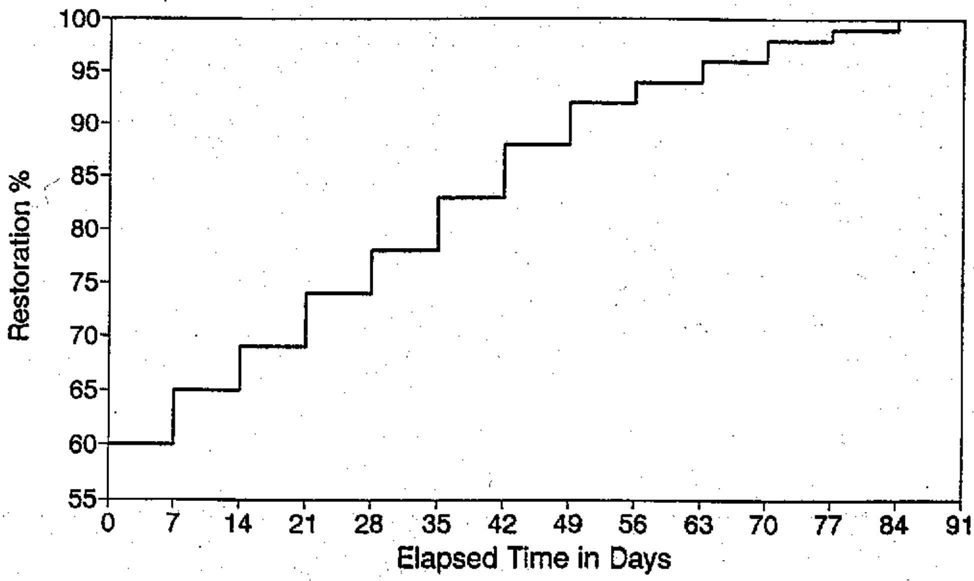

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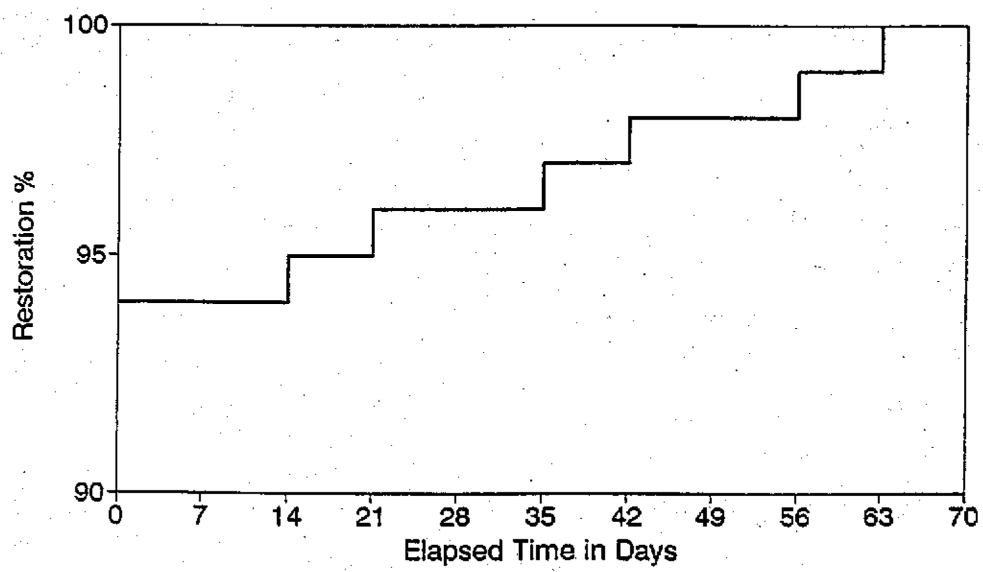

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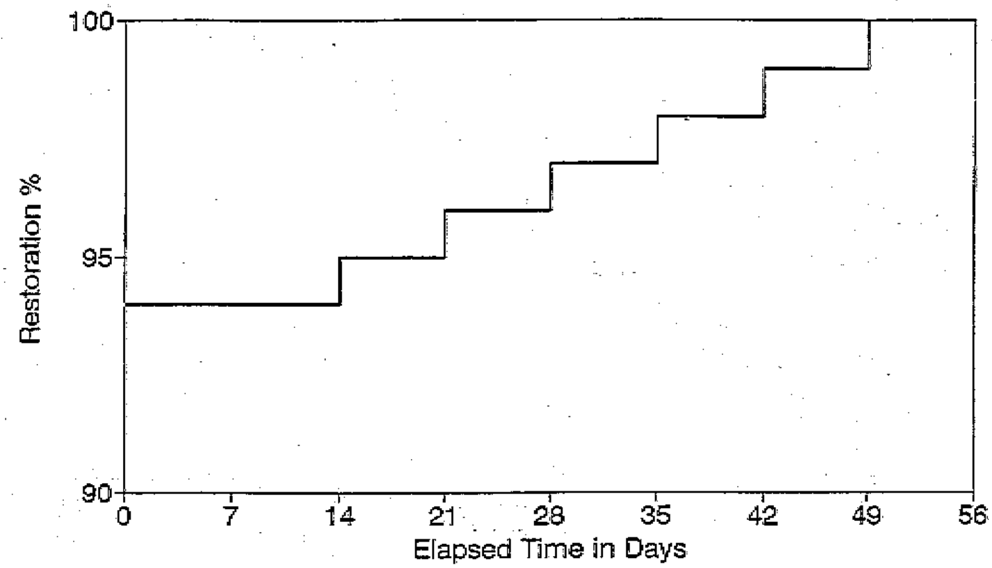

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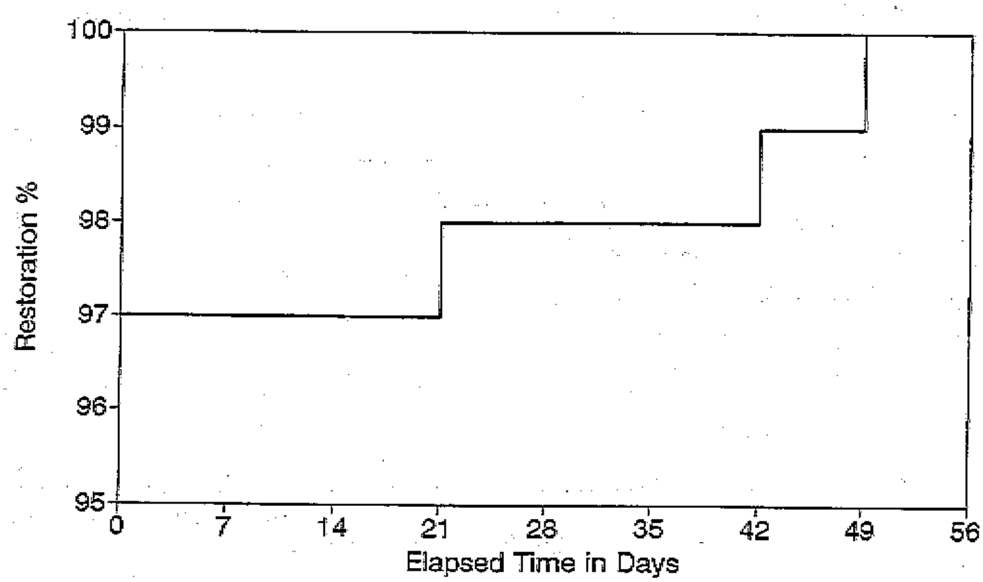

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Table D-1 Percent Value-Added Lost Due to Specified Percent Loss of Water Supply Lifeline

L/L Capacity Loss-->	*U.S. Econ. Value Added (Percent)*	*10%*	*20%*	*30%*	*40%*	*50%*	*60%*	*70%*	*80%*	*90%*	*100%*
1 Livestock	0.45%	2.37%	7.11%	11.84%	16.58%	21.32%	26.05%	30.79%	35.53%	40.26%	45.00%
2 Agr. Prod.	1.06%	3.68%	11.05%	18.42%	25.79%	33.16%	40.53%	47.89%	55.26%	62.63%	70.00%
3 AgServ For. Fish	0.11%	2.37%	7.11%	11.84%	16.58%	21.32%	26.05%	30.79%	35.53%	40.26%	45.00%
4 Mining	3.89%	0.79%	2.37%	3.95%	5.53%	7.11%	8.68%	10.26%	11.84%	13.42%	15.00%
5 Construction	5.52%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
6 Food Tobacco	2.41%	3.68%	11.05%	18.42%	25.79%	33.16%	40.53%	47.89%	55.26%	62.63%	70.00%
7 Textile Goods	0.37%	3.68%	11.05%	18.42%	25.79%	33.16%	40.53%	47.89%	55.26%	62.63%	70.00%
8 Misc Text. Prod.	0.73%	3.68%	11.05%	18.42%	25.79%	33.16%	40.53%	47.89%	55.26%	62.63%	70.00%
9 Lumber & Wood	0.52%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
10 Furniture	0.34%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
11 Pulp & Paper	0.87%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
12 Print & Publish	1.31%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
13 Chemical & Drugs	1.40%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
14 Petrol. Refining	0.96%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
15 Rubber & Plastic	1.03%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
16 Leather Prods.	0.12%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
17 Glass Stone Clay	0.62%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
18 Prim. Metal Prod.	1.04%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
19 Fab. Metal Prod.	1.64%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
20 Mach. Exc. Elec.	1.56%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
21 Elec. & Electron	2.52%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
22 Transport Eq.	2.62%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
23 Instruments	0.68%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
24 Misc. Manufact.	0.69%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
25 Transp & Whse.	3.46%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
26 Utilities	5.89%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
27 Wholesale Trade	5.63%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
28 Retail Trade	5.63%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
29 F.I.R.E.	16.64%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
30 Pers./Prof. Serv.	8.03%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
31 Eating Drinking	2.12%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
32 Auto Serv.	1.09%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
33 Amuse & Rec.	0.70%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
34 Health Ed. Soc.	6.30%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
35 Govt & Govt Ind.	11.79%	1.32%	3.95%	6.58%	9.21%	11.84%	14.47%	17.11%	19.74%	22.37%	25.00%
36 Households	0.25%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
TOTAL	100.00%	2.70% Avg.	8.11% Avg.	13.52% Avg.	18.93% Avg.	24.34% Avg.	29.75% Avg.	35.16% Avg.	40.57% Avg.	45.98% Avg.	51.39% Total V.A Pct. V.A.

Table D-2 Percent Value-Added Lost Due to Specified Percent Loss of Electric Lifeline

L/L Capacity Loss-->	U.S. Econ. Value Added (Percent)	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
1 Livestock	0.45%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
2 Agr. Prod.	1.06%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
3 AgServ For. Fish	0.11%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
4 Mining	3.89%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
5 Construction	5.52%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
6 Food Tobacco	2.41%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
7 Textile Goods	0.37%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
8 Misc Text. Prod.	0.73%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
9 Lumber & Wood	0.52%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
10 Furniture	0.34%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
11 Pulp & Paper	0.87%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
12 Print & Publish	1.31%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
13 Chemical & Drugs	1.40%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
14 Petrol. Refining	0.96%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
15 Rubber & Plastic	1.03%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
16 Leather Prods.	0.12%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
17 Glass Stone Clay	0.62%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
18 Prim. Metal Prod.	1.04%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
19 Fab. Metal Prod.	1.64%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
20 Mach. Exc. Elec.	1.56%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
21 Elec. & Electron	2.52%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
22 Transport Eq.	2.62%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
23 Instruments	0.68%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
24 Misc. Manufact.	0.69%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
25 Transp & Whse.	3.46%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
26 Utilities	5.89%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
27 Wholesale Trade	5.63%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
28 Retail Trade	5.63%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
29 F.I.R.E.	16.64%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
30 Pers./Prof. Serv.	8.03%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
31 Eating Drinking	2.12%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
32 Auto Serv.	1.09%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
33 Amuse & Rec.	0.70%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
34 Health Ed. Soc.	6.30%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
35 Govt & Govt Ind.	11.79%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
36 Households	0.25%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
TOTAL	100.00%	4.52% Avg.	13.55% Avg.	22.59% Avg.	31.62% Avg.	40.66% Avg.	49.69% Avg.	58.73% Avg.	67.76% Avg.	76.80% Avg.	85.83% Total V.A Pct. V.A.

Table D-3 Percent Value-Added Lost Due to Specified Percent Loss of Oil Supply Lifeline

L/L Capacity Loss-->	U.S. Econ. Value Added (Percent)	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
1 Livestock	0.45%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
2 Agr. Prod.	1.06%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
3 AgServ For. Fish	0.11%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
4 Mining	3.89%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
5 Construction	5.52%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
6 Food Tobacco	2.41%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
7 Textile Goods	0.37%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
8 Misc Text. Prod.	0.73%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
9 Lumber & Wood	0.52%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
10 Furniture	0.34%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
11 Pulp & Paper	0.87%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
12 Print & Publish	1.31%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
13 Chemical Drugs	1.40%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
14 Petrol. Refining	0.96%	5.26%	15.79%	26.32%	36.84%	47.37%	57.89%	68.42%	78.95%	89.47%	100.00%
15 Rubber & Plastic	1.03%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
16 Leather Prods.	0.12%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
17 Glass Stone Clay	0.62%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
18 Prim. Metal Prod.	1.04%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
19 Fab. Metal Prod.	1.64%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
20 Mach. Exc. Elec.	1.56%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
21 Elec. & Electron	2.52%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
22 Transport Eq.	2.62%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
23 Instruments	0.68%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
24 Misc. Manufact.	0.69%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
25 Transp & Whse.	3.46%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
26 Utilities	5.89%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
27 Wholesale Trade	5.63%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
28 Retail Trade	5.63%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
29 F.I.R.E.	16.64%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
30 Pers./Prof. Serv.	8.03%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
31 Eating Drinking	2.12%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
32 Auto Serv.	1.09%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
33 Amuse & Rec.	0.70%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
34 Health Ed. Soc.	6.30%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
35 Govt & Govt Ind.	11.79%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
36 Households	0.25%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
TOTAL	100.00%	3.25% Avg.	9.74% Avg.	16.23% Avg.	22.72% Avg.	29.21% Avg.	35.70% Avg.	42.19% Avg.	48.68% Avg.	55.18% Avg.	61.67% Total V.A Pct. V.A.

Table D-4 Percent Value-Added Lost Due to Specified Percent Loss of Natural Gas Supply Lifeline

L/L Capacity Loss-->	*U.S. Econ. Value Added (Percent)*	*10%*	*20%*	*30%*	*40%*	*50%*	*60%*	*70%*	*80%*	*90%*	*100%*
1 Livestock	0.45%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
2 Agr. Prod.	1.06%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
3 AgServ For. Fish	0.11%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
4 Mining	3.89%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
5 Construction	5.52%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
6 Food Tobacco	2.41%	1.32%	3.95%	6.58%	9.21%	11.84%	14.47%	17.11%	19.74%	22.37%	25.00%
7 Textile Goods	0.37%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
8 Misc Text. Prod.	0.73%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
9 Lumber & Wood	0.52%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
10 Furniture	0.34%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
11 Pulp & Paper	0.87%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
12 Print & Publish	1.31%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
13 Chemical & Drugs	1.40%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
14 Petrol. Refining	0.96%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
15 Rubber & Plastic	1.03%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
16 Leather Prods.	0.12%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
17 Glass Stone Clay	0.62%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
18 Prim. Metal Prod.	1.04%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
19 Fab. Metal Prod.	1.64%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
20 Mach. Exc. Elec.	1.56%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
21 Elec. & Electron	2.52%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
22 Transport Eq.	2.62%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
23 Instruments	0.68%	3.95%	11.84%	19.74%	27.63%	35.53%	43.42%	51.32%	59.21%	67.11%	75.00%
24 Misc. Manufact.	0.69%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
25 Transp & Whse.	3.46%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
26 Utilities	5.89%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
27 Wholesale Trade	5.63%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
28 Retail Trade	5.63%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
29 F.I.R.E.	16.64%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
30 Pers./Prof Serv.	8.03%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
31 Eating Drinking	2.12%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
32 Auto Serv.	1.09%	0.26%	0.79%	1.32%	1.84%	2.37%	2.89%	3.42%	3.95%	4.47%	5.00%
33 Amuse & Rec.	0.70%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
34 Health Ed. Soc.	6.30%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
35 Govt & Govt Ind.	11.79%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
36 Households	0.25%	1.84%	5.53%	9.21%	12.89%	16.58%	20.26%	23.95%	27.63%	31.32%	35.00%
TOTAL	100.00%	1.68% Avg.	5.04% Avg.	8.41% Avg.	11.77% Avg.	15.13% Avg.	18.49% Avg.	21.86% Avg.	25.22% Avg.	28.58% Avg.	31.94% Total V.A Pct. V.A.

Table D-5 Percent Value-Added Lost Due to Specified Percent Loss of Highways Lifeline

L/L Capacity Loss-->	*U.S. Econ. Value Added (Percent)*	*10%*	*20%*	*30%*	*40%*	*50%*	*60%*	*70%*	*80%*	*90%*	*100%*
1 Livestock	0.45%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
2 Agr. Prod/	1.06%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
3 AgServ For. Fish	0.11%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
4 Mining	3.89%	1.84%	5.53%	9.21%	12.89%	16.58%	20.26%	23.95%	27.63%	31.32%	35.00%
5 Construction	5.52%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
6 Food Tobacco	2.41%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
7 Textile Goods	0.37%	3.95%	11.84%	19.74%	27.63%	35.53%	43.42%	51.32%	59.21%	67.11%	75.00%
8 Misc Text. Prod.	0.73%	3.95%	11.84%	19.74%	27.63%	35.53%	43.42%	51.32%	59.21%	67.11%	75.00%
9 Lumber & Wood	0.52%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
10 Furniture	0.34%	3.95%	11.84%	19.74%	27.63%	35.53%	43.42%	51.32%	59.21%	67.11%	75.00%
11 Pulp & Paper	0.87%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
12 Print & Publish	1.31%	3.95%	11.84%	19.74%	27.63%	35.53%	43.42%	51.32%	59.21%	67.11%	75.00%
13 Chemical & Drugs	1.40%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
14 Petrol. Refining	0.96%	4.74%	14.21%	23.68%	33.16%	42.63%	52.11%	61.58%	71.05%	80.53%	90.00%
15 Rubber & Plastic	1.03%	3.95%	11.84%	19.74%	27.63%	35.53%	43.42%	51.32%	59.21%	67.11%	75.00%
16 Leather Prods.	0.12%	3.95%	11.84%	19.74%	27.63%	35.53%	43.42%	51.32%	59.21%	67.11%	75.00%
17 Glass Stone Clay	0.62%	3.95%	11.84%	19.74%	27.63%	35.53%	43.42%	51.32%	59.21%	67.11%	75.00%
18 Prim. Metal Prod.	1.04%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
19 Fab. Metal Prod.	1.64%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
20 Mach. Exc. Elec.	1.56%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
21 Elec. & Electron	2.52%	3.95%	11.84%	19.74%	27.63%	35.53%	43.42%	51.32%	59.21%	67.11%	75.00%
22 Transport Eq.	2.62%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
23 Instruments	0.68%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
24 Misc. Manufact.	0.69%	3.95%	11.84%	19.74%	27.63%	35.53%	43.42%	51.32%	59.21%	67.11%	75.00%
25 Transp & Whse.	3.46%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
26 Utilities	5.89%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
27 Wholesale Trade	5.63%	3.68%	11.05%	18.42%	25.79%	33.16%	40.53%	47.89%	55.26%	62.63%	70.00%
28 Retail Trade	5.63%	2.89%	8.68%	14.47%	20.26%	26.05%	31.84%	37.63%	43.42%	49.21%	55.00%
29 F.I.R.E.	16.64%	2.37%	7.11%	11.84%	16.58%	21.32%	26.05%	30.79%	35.53%	40.26%	45.00%
30 Pers./Prof. Serv.	8.03%	2.37%	7.11%	11.84%	16.58%	21.32%	26.05%	30.79%	35.53%	40.26%	45.00%
31 Eating Drinking	2.12%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
32 Auto Serv.	1.09%	2.89%	8.68%	14.47%	20.26%	26.05%	31.84%	37.63%	43.42%	49.21%	55.00%
33 Amuse & Rec.	0.70%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
34 Health Ed. Soc.	6.30%	2.89%	8.68%	14.47%	20.26%	26.05%	31.84%	37.63%	43.42%	49.21%	55.00%
35 Govt & Govt Ind.	11.79%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
36 Households	0.25%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
TOTAL	100.00%	3.50% Avg.	10.50% Avg.	17.51% Avg.	24.51% Avg.	31.51% Avg.	38.52% Avg.	45.52% Avg.	52.52% Avg.	59.52% Avg.	66.53% Total V.A Pct. V.A.

Table D-6 Percent Value-Added Lost Due to Specified Percent Loss of Railroads Lifeline

L/L Capacity Loss-->	*U.S. Econ. Value Added (Percent)*	*10%*	*20%*	*30%*	*40%*	*50%*	*60%*	*70%*	*80%*	*90%*	*100%*
1 Livestock	0.45%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
2 Agr. Prod.	1.06%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
3 AgServ For. Fish	0.11%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
4 Mining	3.89%	1.84%	5.53%	9.21%	12.89%	16.58%	20.26%	23.95%	27.63%	31.32%	35.00%
5 Construction	5.52%	0.26%	0.79%	1.32%	1.84%	2.37%	2.89%	3.42%	3.95%	4.47%	5.00%
6 Food Tobacco	2.41%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
7 Textile Goods	0.37%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
8 Misc Text. Prod.	0.73%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
9 Lumber & Wood	0.52%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
10 Furniture	0.34%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
11 Pulp & Paper	0.87%	2.37%	7.11%	11.84%	16.58%	21.32%	26.05%	30.79%	35.53%	40.26%	45.00%
12 Print & Publish	1.31%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
13 Chemical	1.40%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
14 Petrol. Refining	0.96%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
15 Rubber & Plastic	1.03%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
16 Leather Prods.	0.12%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
17 Glass Stone Clay	0.62%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
18 Prim. Metal Prod.	1.04%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
19 Fab. Metal Prod.	1.64%	2.37%	7.11%	11.84%	16.58%	21.32%	26.05%	30.79%	35.53%	40.26%	45.00%
20 Mach. Exc. Elec.	1.56%	2.37%	7.11%	11.84%	16.58%	21.32%	26.05%	30.79%	35.53%	40.26%	45.00%
21 Elec. & Electron	2.52%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
22 Transport Eq.	2.62%	2.37%	7.11%	11.84%	16.58%	21.32%	26.05%	30.79%	35.53%	40.26%	45.00%
23 Instruments	0.68%	0.26%	0.79%	1.32%	1.84%	2.37%	2.89%	3.42%	3.95%	4.47%	5.00%
24 Misc. Manufact.	0.69%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
25 Transp & Whse.	3.46%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
26 Utilities	5.89%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
27 Wholesale Trade	5.63%	0.79%	2.37%	3.95%	5.53%	7.11%	8.68%	10.26%	11.84%	13.42%	15.00%
28 Retail Trade	5.63%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
29 F.I.R.E.	16.64%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
30 Pers./Prof. Serv.	8.03%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
31 Eating Drinking	2.12%	0.26%	0.79%	1.32%	1.84%	2.37%	2.89%	3.42%	3.95%	4.47%	5.00%
32 Auto Serv.	1.09%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
33 Amuse & Rec.	0.70%	0.26%	0.79%	1.32%	1.84%	2.37%	2.89%	3.42%	3.95%	4.47%	5.00%
34 Health Ed. Soc.	6.30%	0.26%	0.79%	1.32%	1.84%	2.37%	2.89%	3.42%	3.95%	4.47%	5.00%
35 Govt & Govt Ind.	11.79%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
36 Households	0.25%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
TOTAL	100.00%	1.18% Avg.	3.53% Avg.	5.88% Avg.	8.24% Avg.	10.59% Avg.	12.95% Avg.	15.30% Avg.	17.65% Avg.	20.01% Avg.	22.36% Total V.A Pct. V.A.

Table D-7 Percent Value-Added Lost Due to Specified Percent Loss of Sanitary Sewer Lifeline

L/L Capacity Loss-->	*U.S. Econ. Value Added (Percent)*	*10%*	*20%*	*30%*	*40%*	*50%*	*60%*	*70%*	*80%*	*90%*	*100%*
1 Livestock	0.45%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%
2 Agr. Prod.	1.06%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%
3 AgServ For. Fish	0.11%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%
4 Mining	3.89%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%
5 Construction	5.52%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%
6 Food Tobacco	2.41%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%
7 Textile Goods	0.37%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%
8 Misc Text. Prod.	0.73%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%	-3.68%
9 Lumber & Wood	0.52%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%
10 Furniture	0.34%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%
11 Pulp & Paper	0.87%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%
12 Print & Publish	1.31%	-1.58%	-1.58%	-1.58%	-1.58%	-1.58%	-1.58%	-1.58%	-1.58%	-1.58%	-1.58%
13 Chemical & Drugs	1.40%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%
14 Petrol. Refining	0.96%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%
15 Rubber & Plastic	1.03%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%
16 Leather Prods.	0.12%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%
17 Glass Stone Clay	0.62%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%	-2.63%
18 Prim. Metal Prod.	1.04%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%
19 Fab. Metal Prod.	1.64%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%
20 Mach. Exc. Elec.	1.56%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%
21 Elec. & Electron	2.52%	-4.74%	-4.74%	-4.74%	-4.74%	-4.74%	-4.74%	-4.74%	-4.74%	-4.74%	-4.74%
22 Transport Eq.	2.62%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%
23 Instruments	0.68%	-3.16%	-3.16%	-3.16%	-3.16%	-3.16%	-3.16%	-3.16%	-3.16%	-3.16%	-3.16%
24 Misc. Manufact.	0.69%	-3.16%	-3.16%	-3.16%	-3.16%	-3.16%	-3.16%	-3.16%	-3.16%	-3.16%	-3.16%
25 Transp & Whse.	3.46%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%
26 Utilities	5.89%	-1.26%	-1.26%	-1.26%	-1.26%	-1.26%	-1.26%	-1.26%	-1.26%	-1.26%	-1.26%
27 Wholesale Trade	5.63%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%	-0.53%
28 Retail Trade	5.63%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%
29 F.I.R.E.	16.64%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%
30 Pers./Prof Serv.	8.03%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%
31 Eating Drinking	2.12%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%
32 Auto Serv.	1.09%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%
33 Amuse & Rec.	0.70%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%
34 Health Ed. Soc.	6.30%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%	-4.21%
35 Govt & Govt Ind.	11.79%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%	-1.05%
36 Households	0.25%	-3.95%	-3.95%	-3.95%	-3.95%	-3.95%	-3.95%	-3.95%	-3.95%	-3.95%	-3.95%
TOTAL	100.00%	-2.69% Avg.	-2.69% Avg.	-2.69% Avg.	-2.69% Avg.	-2.69% Avg.	-2.69% Avg.	-2.69% Avg.	-2.69% Avg.	-2.69% Avg.	-2.69% Total V.A Pct. V.A.

Table D-8 Percent Value-Added Lost Due to Specified Percent Loss of Air Transportation Lifeline

L/L Capacity Loss-->	*U.S. Econ. Value Added (Percent)*	*10%*	*20%*	*30%*	*40%*	*50%*	*60%*	*70%*	*80%*	*90%*	*100%*
1 Livestock	0.45%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
2 Agr. Prod.	1.06%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
3 AgServ For. Fish	0.11%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
4 Mining	3.89%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
5 Construction	5.52%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
6 Food Tobacco	2.41%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
7 Textile Goods	0.37%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
8 Misc Text. Prod.	0.73%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
9 Lumber & Wood	0.52%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
10 Furniture	0.34%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
11 Pulp & Paper	0.87%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
12 Print & Publish	1.31%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
13 Chemical & Drugs	1.40%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
14 Petrol. Refining	0.96%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
15 Rubber & Plastic	1.03%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
16 Leather Prods.	0.12%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
17 Glass Stone Clay	0.62%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
18 Prim. Metal Prod.	1.04%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
19 Fab. Metal Prod.	1.64%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
20 Mach. Exc. Elec.	1.56%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
21 Elec. & Electron	2.52%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
22 Transport Eq.	2.62%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
23 Instruments	0.68%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
24 Misc. Manufact.	0.69%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
25 Transp & Whse.	3.46%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
26 Utilities	5.89%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
27 Wholesale Trade	5.63%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
28 Retail Trade	5.63%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
29 F.I.R.E.	16.64%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
30 Pers./Prof Serv.	8.03%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
31 Eating Drinking	2.12%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
32 Auto Serv.	1.09%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
33 Amuse & Rec.	0.70%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
34 Health Ed. Soc.	6.30%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
35 Govt & Govt. Ind.	11.79%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
36 Households	0.25%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
TOTAL	100.00%	0.92% Avg.	2.76% Avg.	4.61% Avg.	6.45% Avg.	8.29% Avg.	10.13% Avg.	11.97% Avg.	13.82% Avg.	15.66% Avg.	17.50% Total V.A Pct. V.A.

Table D-9 Percent Value-Added Lost Due to Specified Percent Loss of Water Transportation Lifeline (Ports)

L/L Capacity Loss-->	*U.S. Econ. Value Added (Percent)*	*10%*	*20%*	*30%*	*40%*	*50%*	*60%*	*70%*	*80%*	*90%*	*100%*
1 Livestock	0.45%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
2 Agr. Prod.	1.06%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
3 AgServ For. Fish	0.11%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
4 Mining	3.89%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
5 Construction	5.52%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
6 Food Tobacco	2.41%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
7 Textile Goods	0.37%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
8 Misc Text. Prod.	0.73%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
9 Lumber & Wood	0.52%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
10 Furniture	0.34%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
11 Pulp & Paper	0.87%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
12 Print & Publish	1.31%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
13 Chemical & Drugs	1.40%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
14 Petrol. Refining	0.96%	4.21%	12.63%	21.05%	29.47%	37.89%	46.32%	54.74%	63.16%	71.58%	80.00%
15 Rubber & Plastic	1.03%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
16 Leather Prods.	0.12%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
17 Glass Stone Clay	0.62%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
18 Prim. Metal Prod.	1.04%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
19 Fab. Metal Prod.	1.64%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
20 Mach. Exc. Elec.	1.56%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
21 Elec. & Electron	2.52%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
22 Transport Eq.	2.62%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
23 Instruments	0.68%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
24 Misc. Manufact.	0.69%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
25 Transp & Whse.	3.46%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
26 Utilities	5.89%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
27 Wholesale Trade	5.63%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
28 Retail Trade	5.63%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
29 F.I.R.E.	16.64%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
30 Pers./Prof. Serv.	8.03%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
31 Eating Drinking	2.12%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
32 Auto Serv.	1.09%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
33 Amuse & Rec.	0.70%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
34 Health Ed. Soc.	6.30%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
35 Govt & Govt Ind.	11.79%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
36 Households	0.25%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
TOTAL	100.00%	0.99% Avg.	2.98% Avg.	4.97% Avg.	6.96% Avg.	8.95% Avg.	10.94% Avg.	12.92% Avg.	14.91% Avg.	16.90% Avg.	18.89% Total V.A Pct. V.A.

Table D-10 Percent Value-Added Lost Due to Specified Percent Loss of Telephone Lifeline

L/L Capacity Loss-->	*U.S. Econ. Value Added (Percent)*	*10%*	*20%*	*30%*	*40%*	*50%*	*60%*	*70%*	*80%*	*90%*	*100%*
1 Livestock	0.45%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
2 Agr. Prod.	1.06%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
3 AgServ For. Fish	0.11%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
4 Mining	3.89%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
5 Construction	5.52%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
6 Food Tobacco	2.41%	0.79%	2.37%	3.95%	5.53%	7.11%	8.68%	10.26%	11.84%	13.42%	15.00%
7 Textile Goods	0.37%	0.79%	2.37%	3.95%	5.53%	7.11%	8.68%	10.26%	11.84%	13.42%	15.00%
8 Misc Text. Prod.	0.73%	0.79%	2.37%	3.95%	5.53%	7.11%	8.68%	10.26%	11.84%	13.42%	15.00%
9 Lumber & Wood	0.52%	0.79%	2.37%	3.95%	5.53%	7.11%	8.68%	10.26%	11.84%	13.42%	15.00%
10 Furniture	0.34%	0.79%	2.37%	3.95%	5.53%	7.11%	8.68%	10.26%	11.84%	13.42%	15.00%
11 Pulp & Paper	0.87%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
12 Print & Publish	1.31%	0.79%	2.37%	3.95%	5.53%	7.11%	8.68%	10.26%	11.84%	13.42%	15.00%
13 Chemical & Drugs	1.40%	0.79%	2.37%	3.95%	5.53%	7.11%	8.68%	10.26%	11.84%	13.42%	15.00%
14 Petrol. Refining	0.96%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
15 Rubber & Plastic	1.03%	0.79%	2.37%	3.95%	5.53%	7.11%	8.68%	10.26%	11.84%	13.42%	15.00%
16 Leather Prods.	0.12%	0.79%	2.37%	3.95%	5.53%	7.11%	8.68%	10.26%	11.84%	13.42%	15.00%
17 Glass Stone Clay	0.62%	0.79%	2.37%	3.95%	5.53%	7.11%	8.68%	10.26%	11.84%	13.42%	15.00%
18 Prim. Metal Prod.	1.04%	0.79%	2.37%	3.95%	5.53%	7.11%	8.68%	10.26%	11.84%	13.42%	15.00%
19 Fab. Metal Prod.	1.64%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
20 Mach. Exc. Elec.	1.56%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
21 Elec. & Electron	2.52%	0.79%	2.37%	3.95%	5.53%	7.11%	8.68%	10.26%	11.84%	13.42%	15.00%
22 Transport Eq.	2.62%	0.53%	1.58%	2.63%	3.68%	4.74%	5.79%	6.84%	7.89%	8.95%	10.00%
23 Instruments	0.68%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
24 Misc. Manufact.	0.69%	0.79%	2.37%	3.95%	5.53%	7.11%	8.68%	10.26%	11.84%	13.42%	15.00%
25 Transp & Whse.	3.46%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
26 Utilities	5.89%	1.58%	4.74%	7.89%	11.05%	14.21%	17.37%	20.53%	23.68%	26.84%	30.00%
27 Wholesale Trade	5.63%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
28 Retail Trade	5.63%	2.63%	7.89%	13.16%	18.42%	23.68%	28.95%	34.21%	39.47%	44.74%	50.00%
29 F.I.R.E.	16.64%	3.16%	9.47%	15.79%	22.11%	28.42%	34.74%	41.05%	47.37%	53.68%	60.00%
30 Pers./Prof. Serv.	8.03%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
31 Eating Drinking	2.12%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
32 Auto Serv.	1.09%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
33 Amuse & Rec.	0.70%	2.11%	6.32%	10.53%	14.74%	18.95%	23.16%	27.37%	31.58%	35.79%	40.00%
34 Health Ed. Soc.	6.30%	0.79%	2.37%	3.95%	5.53%	7.11%	8.68%	10.26%	11.84%	13.42%	15.00%
35 Govt & Govt Ind.	11.79%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
36 Households	0.25%	1.05%	3.16%	5.26%	7.37%	9.47%	11.58%	13.68%	15.79%	17.89%	20.00%
TOTAL	100.00%	1.15% Avg.	3.46% Avg.	5.77% Avg.	8.08% Avg.	10.39% Avg.	12.70% Avg.	15.01% Avg.	17.32% Avg.	19.63% Avg.	21.94% Total V.A Pct. V.A.

Table D-11 Residual Value-Added After Loss of Capacity--Water Supply Lifeline

0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0.45%	0.44%	0.42%	0.40%	0.38%	0.36%	0.34%	0.31%	0.29%	0.27%	0.25%
1.06%	1.02%	0.94%	0.86%	0.79%	0.71%	0.63%	0.55%	0.47%	0.40%	0.32%
0.11%	0.11%	0.10%	0.10%	0.09%	0.09%	0.08%	0.08%	0.07%	0.07%	0.06%
3.89%	3.86%	3.80%	3.74%	3.67%	3.61%	3.55%	3.49%	3.43%	3.37%	3.31%
5.52%	5.37%	5.08%	4.79%	4.50%	4.21%	3.92%	3.63%	3.34%	3.05%	2.76%
2.41%	2.32%	2.14%	1.96%	1.79%	1.61%	1.43%	1.25%	1.08%	0.90%	0.72%
0.37%	0.36%	0.33%	0.30%	0.28%	0.25%	0.22%	0.19%	0.17%	0.14%	0.11%
0.73%	0.70%	0.65%	0.59%	0.54%	0.49%	0.43%	0.38%	0.33%	0.27%	0.22%
0.52%	0.50%	0.48%	0.45%	0.42%	0.39%	0.37%	0.34%	0.31%	0.29%	0.26%
0.34%	0.33%	0.31%	0.29%	0.28%	0.26%	0.24%	0.22%	0.21%	0.19%	0.17%
0.87%	0.84%	0.79%	0.73%	0.68%	0.62%	0.57%	0.51%	0.46%	0.40%	0.35%
1.31%	1.29%	1.25%	1.21%	1.17%	1.13%	1.08%	1.04%	1.00%	0.96%	0.92%
1.40%	1.34%	1.23%	1.11%	0.99%	0.87%	0.75%	0.64%	0.52%	0.40%	0.28%
0.96%	0.94%	0.89%	0.84%	0.79%	0.73%	0.68%	0.63%	0.58%	0.53%	0.48%
1.03%	1.00%	0.95%	0.89%	0.84%	0.79%	0.73%	0.68%	0.62%	0.57%	0.51%
0.12%	0.12%	0.11%	0.11%	0.10%	0.09%	0.09%	0.08%	0.07%	0.07%	0.06%
0.62%	0.60%	0.57%	0.54%	0.50%	0.47%	0.44%	0.41%	0.37%	0.34%	0.31%
1.04%	0.99%	0.89%	0.79%	0.70%	0.60%	0.50%	0.40%	0.30%	0.20%	0.10%
1.64%	1.57%	1.43%	1.30%	1.16%	1.02%	0.88%	0.74%	0.60%	0.47%	0.33%
1.56%	1.51%	1.41%	1.31%	1.22%	1.12%	1.02%	0.92%	0.82%	0.72%	0.62%
2.52%	2.40%	2.16%	1.92%	1.69%	1.45%	1.21%	0.97%	0.73%	0.49%	0.25%
2.62%	2.54%	2.37%	2.21%	2.04%	1.87%	1.71%	1.54%	1.38%	1.21%	1.05%
0.68%	0.65%	0.58%	0.52%	0.45%	0.39%	0.33%	0.26%	0.20%	0.13%	0.07%
0.69%	0.67%	0.62%	0.58%	0.54%	0.49%	0.45%	0.41%	0.36%	0.32%	0.27%
3.46%	3.42%	3.35%	3.28%	3.21%	3.13%	3.06%	2.99%	2.91%	2.84%	2.77%
5.89%	5.76%	5.51%	5.27%	5.02%	4.77%	4.52%	4.28%	4.03%	3.78%	3.53%
5.63%	5.57%	5.46%	5.34%	5.22%	5.10%	4.98%	4.86%	4.74%	4.63%	4.51%
5.63%	5.57%	5.46%	5.34%	5.22%	5.10%	4.98%	4.86%	4.74%	4.63%	4.51%
16.64%	16.47%	16.12%	15.77%	15.42%	15.07%	14.72%	14.36%	14.01%	13.66%	13.31%
8.03%	7.95%	7.78%	7.61%	7.44%	7.27%	7.10%	6.93%	6.76%	6.59%	6.42%
2.12%	2.03%	1.85%	1.67%	1.50%	1.32%	1.14%	0.96%	0.78%	0.60%	0.42%
1.09%	1.09%	1.08%	1.07%	1.05%	1.04%	1.03%	1.02%	1.01%	1.00%	0.99%
0.70%	0.67%	0.61%	0.55%	0.49%	0.43%	0.37%	0.32%	0.26%	0.20%	0.14%
6.30%	6.17%	5.90%	5.64%	5.37%	5.11%	4.84%	4.57%	4.31%	4.04%	3.78%
11.79%	11.64%	11.33%	11.02%	10.70%	10.39%	10.08%	9.77%	9.46%	9.15%	8.84%
0.25%	0.25%	0.24%	0.22%	0.21%	0.20%	0.19%	0.18%	0.17%	0.16%	0.15%
100.00%	98.06%	94.18%	90.30%	86.43%	82.55%	78.67%	74.79%	70.91%	67.04%	63.16%
100%	98%	94%	90%	86%	83%	79%	75%	71%	67%	63%

Table D-12 Residual Value-Added After Loss of Capacity--Electric Lifeline

0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0.45%	0.44%	0.42%	0.39%	0.37%	0.35%	0.32%	0.30%	0.27%	0.25%	0.23%
1.06%	1.03%	0.98%	0.92%	0.86%	0.81%	0.75%	0.70%	0.64%	0.59%	0.53%
0.11%	0.11%	0.10%	0.10%	0.09%	0.08%	0.08%	0.07%	0.07%	0.06%	0.06%
3.89%	3.70%	3.34%	2.97%	2.60%	2.23%	1.86%	1.49%	1.13%	0.76%	0.39%
5.52%	5.40%	5.17%	4.94%	4.71%	4.47%	4.24%	4.01%	3.78%	3.54%	3.31%
2.41%	2.29%	2.06%	1.84%	1.61%	1.38%	1.15%	0.92%	0.70%	0.47%	0.24%
0.37%	0.35%	0.31%	0.27%	0.24%	0.20%	0.16%	0.12%	0.08%	0.04%	0.00%
0.73%	0.69%	0.61%	0.54%	0.46%	0.38%	0.31%	0.23%	0.15%	0.08%	0.00%
0.52%	0.49%	0.43%	0.38%	0.33%	0.27%	0.22%	0.16%	0.11%	0.05%	0.00%
0.34%	0.32%	0.29%	0.25%	0.21%	0.18%	0.14%	0.11%	0.07%	0.04%	0.00%
0.87%	0.83%	0.73%	0.64%	0.55%	0.46%	0.37%	0.28%	0.18%	0.09%	0.00%
1.31%	1.24%	1.10%	0.97%	0.83%	0.69%	0.55%	0.41%	0.28%	0.14%	0.00%
1.40%	1.34%	1.20%	1.07%	0.94%	0.81%	0.67%	0.54%	0.41%	0.27%	0.14%
0.96%	0.91%	0.81%	0.71%	0.61%	0.51%	0.41%	0.30%	0.20%	0.10%	0.00%
1.03%	0.98%	0.87%	0.76%	0.65%	0.54%	0.43%	0.33%	0.22%	0.11%	0.00%
0.12%	0.12%	0.10%	0.09%	0.08%	0.06%	0.05%	0.04%	0.03%	0.01%	0.00%
0.62%	0.59%	0.52%	0.46%	0.39%	0.33%	0.26%	0.20%	0.13%	0.07%	0.00%
1.04%	0.99%	0.89%	0.79%	0.70%	0.60%	0.50%	0.40%	0.30%	0.20%	0.10%
1.64%	1.55%	1.38%	1.21%	1.04%	0.86%	0.69%	0.52%	0.35%	0.17%	0.00%
1.56%	1.48%	1.31%	1.15%	0.99%	0.82%	0.66%	0.49%	0.33%	0.16%	0.00%
2.52%	2.39%	2.12%	1.86%	1.59%	1.33%	1.06%	0.80%	0.53%	0.27%	0.00%
2.62%	2.48%	2.21%	1.93%	1.65%	1.38%	1.10%	0.83%	0.55%	0.28%	0.00%
0.68%	0.64%	0.57%	0.50%	0.43%	0.36%	0.29%	0.21%	0.14%	0.07%	0.00%
0.69%	0.65%	0.58%	0.51%	0.43%	0.36%	0.29%	0.22%	0.14%	0.07%	0.00%
3.46%	3.41%	3.30%	3.19%	3.08%	2.97%	2.86%	2.75%	2.64%	2.53%	2.42%
5.89%	5.64%	5.14%	4.65%	4.15%	3.66%	3.16%	2.66%	2.17%	1.67%	1.18%
5.63%	5.37%	4.83%	4.30%	3.77%	3.23%	2.70%	2.16%	1.63%	1.10%	0.56%
5.63%	5.37%	4.83%	4.30%	3.77%	3.23%	2.70%	2.16%	1.63%	1.10%	0.56%
16.64%	15.85%	14.28%	12.70%	11.12%	9.55%	7.97%	6.39%	4.82%	3.24%	1.66%
8.03%	7.65%	6.89%	6.13%	5.37%	4.61%	3.85%	3.09%	2.32%	1.56%	0.80%
2.12%	2.03%	1.85%	1.67%	1.50%	1.32%	1.14%	0.96%	0.78%	0.60%	0.42%
1.09%	1.04%	0.94%	0.84%	0.73%	0.63%	0.52%	0.42%	0.32%	0.21%	0.11%
0.70%	0.67%	0.61%	0.55%	0.49%	0.43%	0.37%	0.32%	0.26%	0.20%	0.14%
6.30%	6.03%	5.50%	4.97%	4.44%	3.91%	3.38%	2.85%	2.32%	1.79%	1.26%
11.79%	11.42%	10.67%	9.93%	9.18%	8.44%	7.70%	6.95%	6.21%	5.46%	4.72%
0.25%	0.24%	0.22%	0.20%	0.18%	0.16%	0.13%	0.11%	0.09%	0.07%	0.05%
100.00%	95.73%	87.19%	78.66%	70.12%	61.58%	53.04%	44.50%	35.97%	27.43%	18.89%
100%	96%	87%	79%	70%	62%	53%	45%	36%	27%	19%

Table D-13 Residual Value-Added After Loss of Capacity--Oil Supply Lifeline

0%	*10%*	*20%*	*30%*	*40%*	*50%*	*60%*	*70%*	*80%*	*90%*	*100%*
0.45%	0.44%	0.42%	0.39%	0.37%	0.35%	0.32%	0.30%	0.27%	0.25%	0.23%
1.06%	1.01%	0.93%	0.84%	0.75%	0.66%	0.57%	0.48%	0.39%	0.30%	0.21%
0.11%	0.11%	0.10%	0.09%	0.08%	0.07%	0.06%	0.05%	0.04%	0.03%	0.02%
3.89%	3.70%	3.34%	2.97%	2.60%	2.23%	1.86%	1.49%	1.13%	0.76%	0.39%
5.52%	5.26%	4.73%	4.21%	3.69%	3.17%	2.64%	2.12%	1.60%	1.07%	0.55%
2.41%	2.34%	2.22%	2.09%	1.96%	1.84%	1.71%	1.58%	1.46%	1.33%	1.20%
0.37%	0.36%	0.34%	0.32%	0.30%	0.28%	0.26%	0.25%	0.23%	0.21%	0.19%
0.73%	0.71%	0.67%	0.63%	0.59%	0.55%	0.52%	0.48%	0.44%	0.40%	0.36%
0.52%	0.50%	0.48%	0.45%	0.42%	0.39%	0.37%	0.34%	0.31%	0.29%	0.26%
0.34%	0.33%	0.31%	0.29%	0.28%	0.26%	0.24%	0.22%	0.21%	0.19%	0.17%
0.87%	0.85%	0.80%	0.76%	0.71%	0.66%	0.62%	0.57%	0.53%	0.48%	0.44%
1.31%	1.28%	1.21%	1.14%	1.07%	1.00%	0.93%	0.86%	0.79%	0.72%	0.66%
1.40%	1.37%	1.29%	1.22%	1.15%	1.07%	1.00%	0.92%	0.85%	0.78%	0.70%
0.96%	0.91%	0.81%	0.71%	0.61%	0.51%	0.41%	0.30%	0.20%	0.10%	0.00%
1.03%	1.00%	0.95%	0.89%	0.84%	0.79%	0.73%	0.68%	0.62%	0.57%	0.51%
0.12%	0.12%	0.11%	0.11%	0.10%	0.09%	0.09%	0.08%	0.07%	0.07%	0.06%
0.62%	0.60%	0.57%	0.54%	0.50%	0.47%	0.44%	0.41%	0.37%	0.34%	0.31%
1.04%	0.99%	0.89%	0.79%	0.70%	0.60%	0.50%	0.40%	0.30%	0.20%	0.10%
1.64%	1.60%	1.51%	1.42%	1.34%	1.25%	1.17%	1.08%	0.99%	0.91%	0.82%
1.56%	1.52%	1.44%	1.35%	1.27%	1.19%	1.11%	1.03%	0.94%	0.86%	0.78%
2.52%	2.46%	2.32%	2.19%	2.06%	1.92%	1.79%	1.66%	1.53%	1.39%	1.26%
2.62%	2.49%	2.25%	2.00%	1.75%	1.50%	1.25%	1.01%	0.76%	0.51%	0.26%
0.68%	0.66%	0.63%	0.59%	0.55%	0.52%	0.48%	0.45%	0.41%	0.38%	0.34%
0.69%	0.67%	0.63%	0.60%	0.56%	0.52%	0.49%	0.45%	0.42%	0.38%	0.34%
3.46%	3.30%	2.97%	2.64%	2.31%	1.99%	1.66%	1.33%	1.00%	0.67%	0.35%
5.89%	5.73%	5.42%	5.11%	4.80%	4.49%	4.18%	3.87%	3.56%	3.25%	2.94%
5.63%	5.49%	5.19%	4.89%	4.60%	4.30%	4.00%	3.71%	3.41%	3.11%	2.82%
5.63%	5.37%	4.83%	4.30%	3.77%	3.23%	2.70%	2.16%	1.63%	1.10%	0.56%
16.64%	16.12%	15.07%	14.01%	12.96%	11.91%	10.86%	9.81%	8.76%	7.71%	6.66%
8.03%	7.78%	7.27%	6.76%	6.26%	5.75%	5.24%	4.73%	4.23%	3.72%	3.21%
2.12%	2.03%	1.85%	1.67%	1.50%	1.32%	1.14%	0.96%	0.78%	0.60%	0.42%
1.09%	1.04%	0.94%	0.84%	0.73%	0.63%	0.52%	0.42%	0.32%	0.21%	0.11%
0.70%	0.66%	0.60%	0.53%	0.47%	0.40%	0.33%	0.27%	0.20%	0.14%	0.07%
6.30%	6.23%	6.10%	5.97%	5.83%	5.70%	5.57%	5.44%	5.30%	5.17%	5.04%
11.79%	11.67%	11.42%	11.17%	10.92%	10.67%	10.43%	10.18%	9.93%	9.68%	9.43%
0.25%	0.24%	0.23%	0.22%	0.21%	0.19%	0.18%	0.17%	0.15%	0.14%	0.13%
100.00%	96.94%	90.83%	84.71%	78.60%	72.48%	66.37%	60.25%	54.14%	48.02%	41.91%
100%	97%	91%	85%	79%	72%	66%	60%	54%	48%	42%

Table D-14 Residual Value-Added After Loss of Capacity--Natural Gas Lifeline

0%	*10%*	*20%*	*30%*	*40%*	*50%*	*60%*	*70%*	*80%*	*90%*	*100%*
0.45%	0.45%	0.45%	0.44%	0.44%	0.43%	0.43%	0.42%	0.42%	0.41%	0.41%
1.06%	1.04%	1.01%	0.98%	0.94%	0.91%	0.88%	0.84%	0.81%	0.77%	0.74%
0.11%	0.11%	0.11%	0.10%	0.10%	0.09%	0.09%	0.09%	0.08%	0.08%	0.08%
3.89%	3.87%	3.83%	3.79%	3.75%	3.70%	3.66%	3.62%	3.58%	3.54%	3.50%
5.52%	5.52%	5.52%	5.52%	5.52%	5.52%	5.52%	5.52%	5.52%	5.52%	5.52%
2.41%	2.37%	2.31%	2.25%	2.18%	2.12%	2.06%	1.99%	1.93%	1.87%	1.80%
0.37%	0.37%	0.36%	0.35%	0.35%	0.34%	0.33%	0.32%	0.31%	0.31%	0.30%
0.73%	0.72%	0.70%	0.69%	0.67%	0.66%	0.64%	0.63%	0.61%	0.60%	0.58%
0.52%	0.51%	0.50%	0.49%	0.48%	0.47%	0.46%	0.45%	0.43%	0.42%	0.41%
0.34%	0.34%	0.33%	0.32%	0.31%	0.31%	0.30%	0.29%	0.29%	0.28%	0.27%
0.87%	0.85%	0.82%	0.78%	0.74%	0.71%	0.67%	0.63%	0.60%	0.56%	0.52%
1.31%	1.30%	1.27%	1.24%	1.22%	1.19%	1.16%	1.13%	1.10%	1.08%	1.05%
1.40%	1.34%	1.20%	1.07%	0.94%	0.81%	0.67%	0.54%	0.41%	0.27%	0.14%
0.96%	0.94%	0.89%	0.84%	0.79%	0.73%	0.68%	0.63%	0.58%	0.53%	0.48%
1.03%	1.00%	0.95%	0.89%	0.84%	0.79%	0.73%	0.68%	0.62%	0.57%	0.51%
0.12%	0.12%	0.12%	0.12%	0.11%	0.11%	0.11%	0.11%	0.10%	0.10%	0.10%
0.62%	0.60%	0.57%	0.54%	0.50%	0.47%	0.44%	0.41%	0.37%	0.34%	0.31%
1.04%	1.01%	0.96%	0.90%	0.85%	0.79%	0.74%	0.68%	0.63%	0.58%	0.52%
1.64%	1.60%	1.51%	1.42%	1.34%	1.25%	1.17%	1.08%	0.99%	0.91%	0.82%
1.56%	1.52%	1.44%	1.35%	1.27%	1.19%	1.11%	1.03%	0.94%	0.86%	0.78%
2.52%	2.46%	2.32%	2.19%	2.06%	1.92%	1.79%	1.66%	1.53%	1.39%	1.26%
2.62%	2.55%	2.41%	2.27%	2.14%	2.00%	1.86%	1.72%	1.59%	1.45%	1.31%
0.68%	0.65%	0.60%	0.55%	0.49%	0.44%	0.38%	0.33%	0.28%	0.22%	0.17%
0.69%	0.67%	0.63%	0.60%	0.56%	0.52%	0.49%	0.45%	0.42%	0.38%	0.34%
3.46%	3.46%	3.46%	3.46%	3.46%	3.46%	3.46%	3.46%	3.46%	3.46%	3.46%
5.89%	5.76%	5.51%	5.27%	5.02%	4.77%	4.52%	4.28%	4.03%	3.78%	3.53%
5.63%	5.60%	5.54%	5.49%	5.43%	5.37%	5.31%	5.25%	5.19%	5.13%	5.07%
5.63%	5.57%	5.46%	5.34%	5.22%	5.10%	4.98%	4.86%	4.74%	4.63%	4.51%
16.64%	16.47%	16.12%	15.77%	15.42%	15.07%	14.72%	14.36%	14.01%	13.66%	13.31%
8.03%	7.95%	7.78%	7.61%	7.44%	7.27%	7.10%	6.93%	6.76%	6.59%	6.42%
2.12%	2.08%	1.99%	1.90%	1.81%	1.72%	1.63%	1.54%	1.45%	1.36%	1.27%
1.09%	1.09%	1.09%	1.08%	1.07%	1.07%	1.06%	1.06%	1.05%	1.05%	1.04%
0.70%	0.68%	0.65%	0.62%	0.59%	0.56%	0.54%	0.51%	0.48%	0.45%	0.42%
6.30%	6.23%	6.10%	5.97%	5.83%	5.70%	5.57%	5.44%	5.30%	5.17%	5.04%
11.79%	11.67%	11.42%	11.17%	10.92%	10.67%	10.43%	10.18%	9.93%	9.68%	9.43%
0.25%	0.25%	0.24%	0.23%	0.22%	0.21%	0.20%	0.19%	0.18%	0.17%	0.16%
100.00%	98.72%	96.15%	93.58%	91.01%	88.45%	85.88%	83.31%	80.74%	78.17%	75.61%
100%	99%	96%	94%	91%	88%	86%	83%	81%	78%	76%

Table D-15 Residual Value-Added After Loss of Capacity--Highways Lifeline

0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0.45%	0.44%	0.42%	0.39%	0.37%	0.35%	0.32%	0.30%	0.27%	0.25%	0.23%
1.06%	1.01%	0.93%	0.84%	0.75%	0.66%	0.57%	0.48%	0.39%	0.30%	0.21%
0.11%	0.11%	0.10%	0.09%	0.08%	0.07%	0.06%	0.05%	0.04%	0.03%	0.02%
3.89%	3.82%	3.67%	3.53%	3.39%	3.24%	3.10%	2.96%	2.81%	2.67%	2.53%
5.52%	5.40%	5.17%	4.94%	4.71%	4.47%	4.24%	4.01%	3.78%	3.54%	3.31%
2.41%	2.31%	2.10%	1.90%	1.70%	1.49%	1.29%	1.09%	0.89%	0.68%	0.48%
0.37%	0.36%	0.33%	0.30%	0.27%	0.24%	0.21%	0.18%	0.15%	0.12%	0.09%
0.73%	0.70%	0.64%	0.58%	0.53%	0.47%	0.41%	0.35%	0.30%	0.24%	0.18%
0.52%	0.49%	0.44%	0.39%	0.34%	0.30%	0.25%	0.20%	0.15%	0.10%	0.05%
0.34%	0.33%	0.30%	0.27%	0.25%	0.22%	0.19%	0.16%	0.14%	0.11%	0.08%
0.87%	0.83%	0.76%	0.69%	0.61%	0.54%	0.47%	0.39%	0.32%	0.25%	0.17%
1.31%	1.26%	1.16%	1.05%	0.95%	0.85%	0.74%	0.64%	0.54%	0.43%	0.33%
1.40%	1.34%	1.23%	1.11%	0.99%	0.87%	0.75%	0.64%	0.52%	0.40%	0.28%
0.96%	0.92%	0.83%	0.73%	0.64%	0.55%	0.46%	0.37%	0.28%	0.19%	0.10%
1.03%	0.99%	0.91%	0.83%	0.75%	0.66%	0.58%	0.50%	0.42%	0.34%	0.26%
0.12%	0.12%	0.11%	0.10%	0.09%	0.08%	0.07%	0.06%	0.05%	0.04%	0.03%
0.62%	0.59%	0.54%	0.50%	0.45%	0.40%	0.35%	0.30%	0.25%	0.20%	0.15%
1.04%	1.00%	0.91%	0.82%	0.73%	0.65%	0.56%	0.47%	0.38%	0.30%	0.21%
1.64%	1.57%	1.43%	1.30%	1.16%	1.02%	0.88%	0.74%	0.60%	0.47%	0.33%
1.56%	1.49%	1.36%	1.23%	1.10%	0.97%	0.84%	0.71%	0.57%	0.44%	0.31%
2.52%	2.42%	2.22%	2.02%	1.83%	1.63%	1.43%	1.23%	1.03%	0.83%	0.63%
2.62%	2.51%	2.29%	2.07%	1.85%	1.63%	1.41%	1.19%	0.96%	0.74%	0.52%
0.68%	0.65%	0.59%	0.54%	0.48%	0.42%	0.36%	0.31%	0.25%	0.19%	0.14%
0.69%	0.66%	0.61%	0.55%	0.50%	0.44%	0.39%	0.33%	0.28%	0.23%	0.17%
3.46%	3.31%	3.02%	2.73%	2.44%	2.15%	1.86%	1.57%	1.27%	0.98%	0.69%
5.89%	5.76%	5.51%	5.27%	5.02%	4.77%	4.52%	4.28%	4.03%	3.78%	3.53%
5.63%	5.43%	5.01%	4.60%	4.18%	3.77%	3.35%	2.94%	2.52%	2.11%	1.69%
5.63%	5.47%	5.14%	4.82%	4.49%	4.17%	3.84%	3.51%	3.19%	2.86%	2.54%
16.64%	16.25%	15.46%	14.67%	13.88%	13.09%	12.31%	11.52%	10.73%	9.94%	9.15%
8.03%	7.84%	7.46%	7.08%	6.70%	6.32%	5.94%	5.56%	5.18%	4.80%	4.42%
2.12%	2.06%	1.95%	1.84%	1.73%	1.62%	1.51%	1.40%	1.28%	1.17%	1.06%
1.09%	1.06%	1.00%	0.94%	0.87%	0.81%	0.75%	0.68%	0.62%	0.56%	0.49%
0.70%	0.68%	0.64%	0.60%	0.57%	0.53%	0.49%	0.46%	0.42%	0.38%	0.35%
6.30%	6.12%	5.75%	5.39%	5.02%	4.66%	4.29%	3.93%	3.56%	3.20%	2.83%
11.79%	11.60%	11.23%	10.86%	10.49%	10.12%	9.74%	9.37%	9.00%	8.63%	8.25%
0.25%	0.25%	0.24%	0.22%	0.21%	0.20%	0.19%	0.18%	0.17%	0.16%	0.15%
100.00%	97.16%	91.47%	85.79%	80.10%	74.41%	68.73%	63.04%	57.36%	51.67%	45.98%
100%	97%	91%	86%	80%	74%	69%	63%	57%	52%	46%

Table D-16 Residual Value-Added After Loss of Capacity--Railroads Lifeline

0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0.45%	0.44%	0.42%	0.41%	0.39%	0.37%	0.35%	0.33%	0.31%	0.29%	0.27%
1.06%	1.04%	0.99%	0.95%	0.90%	0.86%	0.81%	0.77%	0.72%	0.68%	0.64%
0.11%	0.11%	0.10%	0.10%	0.09%	0.09%	0.08%	0.08%	0.08%	0.07%	0.07%
3.89%	3.82%	3.67%	3.53%	3.39%	3.24%	3.10%	2.96%	2.81%	2.67%	2.53%
5.52%	5.50%	5.48%	5.45%	5.42%	5.39%	5.36%	5.33%	5.30%	5.27%	5.24%
2.41%	2.38%	2.33%	2.28%	2.23%	2.18%	2.13%	2.08%	2.03%	1.98%	1.93%
0.37%	0.37%	0.36%	0.35%	0.35%	0.34%	0.33%	0.32%	0.31%	0.31%	0.30%
0.73%	0.72%	0.70%	0.69%	0.67%	0.66%	0.64%	0.63%	0.61%	0.60%	0.58%
0.52%	0.50%	0.48%	0.46%	0.44%	0.42%	0.40%	0.37%	0.35%	0.33%	0.31%
0.34%	0.34%	0.33%	0.32%	0.31%	0.31%	0.30%	0.29%	0.29%	0.28%	0.27%
0.87%	0.85%	0.81%	0.77%	0.73%	0.69%	0.64%	0.60%	0.56%	0.52%	0.48%
1.31%	1.30%	1.27%	1.24%	1.22%	1.19%	1.16%	1.13%	1.10%	1.08%	1.05%
1.40%	1.39%	1.36%	1.33%	1.30%	1.27%	1.24%	1.21%	1.18%	1.15%	1.12%
0.96%	0.94%	0.90%	0.86%	0.82%	0.78%	0.74%	0.70%	0.66%	0.62%	0.58%
1.03%	1.02%	1.00%	0.98%	0.95%	0.93%	0.91%	0.89%	0.87%	0.85%	0.82%
0.12%	0.12%	0.12%	0.12%	0.11%	0.11%	0.11%	0.11%	0.10%	0.10%	0.10%
0.62%	0.61%	0.60%	0.59%	0.57%	0.56%	0.55%	0.53%	0.52%	0.51%	0.49%
1.04%	1.01%	0.96%	0.90%	0.85%	0.79%	0.74%	0.68%	0.63%	0.58%	0.52%
1.64%	1.60%	1.52%	1.45%	1.37%	1.29%	1.21%	1.14%	1.06%	0.98%	0.90%
1.56%	1.52%	1.45%	1.38%	1.30%	1.23%	1.15%	1.08%	1.01%	0.93%	0.86%
2.52%	2.50%	2.44%	2.39%	2.34%	2.28%	2.23%	2.18%	2.12%	2.07%	2.02%
2.62%	2.56%	2.43%	2.31%	2.18%	2.06%	1.94%	1.81%	1.69%	1.56%	1.44%
0.68%	0.68%	0.67%	0.67%	0.67%	0.66%	0.66%	0.66%	0.65%	0.65%	0.65%
0.69%	0.68%	0.67%	0.65%	0.64%	0.62%	0.61%	0.59%	0.58%	0.56%	0.55%
3.46%	3.41%	3.30%	3.19%	3.08%	2.97%	2.86%	2.75%	2.64%	2.53%	2.42%
5.89%	5.89%	5.89%	5.89%	5.89%	5.89%	5.89%	5.89%	5.89%	5.89%	5.89%
5.63%	5.59%	5.50%	5.41%	5.32%	5.23%	5.14%	5.06%	4.97%	4.88%	4.79%
5.63%	5.57%	5.46%	5.34%	5.22%	5.10%	4.98%	4.86%	4.74%	4.63%	4.51%
16.64%	16.55%	16.38%	16.20%	16.03%	15.85%	15.68%	15.50%	15.33%	15.15%	14.98%
8.03%	7.99%	7.90%	7.82%	7.74%	7.65%	7.57%	7.48%	7.40%	7.31%	7.23%
2.12%	2.12%	2.10%	2.09%	2.08%	2.07%	2.06%	2.05%	2.04%	2.03%	2.01%
1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%
0.70%	0.69%	0.69%	0.69%	0.68%	0.68%	0.68%	0.67%	0.67%	0.67%	0.66%
6.30%	6.28%	6.25%	6.22%	6.18%	6.15%	6.12%	6.08%	6.05%	6.02%	5.98%
11.79%	11.73%	11.60%	11.48%	11.36%	11.23%	11.11%	10.98%	10.86%	10.74%	10.61%
0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%
100.00%	99.17%	97.50%	95.83%	94.16%	92.49%	90.82%	89.15%	87.48%	85.81%	84.14%
100%	99%	97%	96%	94%	92%	91%	89%	87%	86%	84%

Table D-17 Residual Value-Added After Loss of Capacity--Sanitary Sewer Lifeline

0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0.45%	0.46%	0.46%	0.46%	0.46%	0.46%	0.46%	0.46%	0.46%	0.46%	0.46%
1.06%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%
0.11%	0.11%	0.11%	0.11%	0.11%	0.11%	0.11%	0.11%	0.11%	0.11%	0.11%
3.89%	3.91%	3.91%	3.91%	3.91%	3.91%	3.91%	3.91%	3.91%	3.91%	3.91%
5.52%	5.58%	5.58%	5.58%	5.58%	5.58%	5.58%	5.58%	5.58%	5.58%	5.58%
2.41%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%	2.50%
0.37%	0.39%	0.39%	0.39%	0.39%	0.39%	0.39%	0.39%	0.39%	0.39%	0.39%
0.73%	0.75%	0.75%	0.75%	0.75%	0.75%	0.75%	0.75%	0.75%	0.75%	0.75%
0.52%	0.53%	0.53%	0.53%	0.53%	0.53%	0.53%	0.53%	0.53%	0.53%	0.53%
0.34%	0.35%	0.35%	0.35%	0.35%	0.35%	0.35%	0.35%	0.35%	0.35%	0.35%
0.87%	0.91%	0.91%	0.91%	0.91%	0.91%	0.91%	0.91%	0.91%	0.91%	0.91%
1.31%	1.33%	1.33%	1.33%	1.33%	1.33%	1.33%	1.33%	1.33%	1.33%	1.33%
1.40%	1.46%	1.46%	1.46%	1.46%	1.46%	1.46%	1.46%	1.46%	1.46%	1.46%
0.96%	0.99%	0.99%	0.99%	0.99%	0.99%	0.99%	0.99%	0.99%	0.99%	0.99%
1.03%	1.06%	1.06%	1.06%	1.06%	1.06%	1.06%	1.06%	1.06%	1.06%	1.06%
0.12%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%	0.13%
0.62%	0.63%	0.63%	0.63%	0.63%	0.63%	0.63%	0.63%	0.63%	0.63%	0.63%
1.04%	1.08%	1.08%	1.08%	1.08%	1.08%	1.08%	1.08%	1.08%	1.08%	1.08%
1.64%	1.71%	1.71%	1.71%	1.71%	1.71%	1.71%	1.71%	1.71%	1.71%	1.71%
1.56%	1.63%	1.63%	1.63%	1.63%	1.63%	1.63%	1.63%	1.63%	1.63%	1.63%
2.52%	2.64%	2.64%	2.64%	2.64%	2.64%	2.64%	2.64%	2.64%	2.64%	2.64%
2.62%	2.73%	2.73%	2.73%	2.73%	2.73%	2.73%	2.73%	2.73%	2.73%	2.73%
0.68%	0.70%	0.70%	0.70%	0.70%	0.70%	0.70%	0.70%	0.70%	0.70%	0.70%
0.69%	0.71%	0.71%	0.71%	0.71%	0.71%	0.71%	0.71%	0.71%	0.71%	0.71%
3.46%	3.48%	3.48%	3.48%	3.48%	3.48%	3.48%	3.48%	3.48%	3.48%	3.48%
5.89%	5.96%	5.96%	5.96%	5.96%	5.96%	5.96%	5.96%	5.96%	5.96%	5.96%
5.63%	5.66%	5.66%	5.66%	5.66%	5.66%	5.66%	5.66%	5.66%	5.66%	5.66%
5.63%	5.69%	5.69%	5.69%	5.69%	5.69%	5.69%	5.69%	5.69%	5.69%	5.69%
16.64%	16.82%	16.82%	16.82%	16.82%	16.82%	16.82%	16.82%	16.82%	16.82%	16.82%
8.03%	8.12%	8.12%	8.12%	8.12%	8.12%	8.12%	8.12%	8.12%	8.12%	8.12%
2.12%	2.21%	2.21%	2.21%	2.21%	2.21%	2.21%	2.21%	2.21%	2.21%	2.21%
1.09%	1.11%	1.11%	1.11%	1.11%	1.11%	1.11%	1.11%	1.11%	1.11%	1.11%
0.70%	0.73%	0.73%	0.73%	0.73%	0.73%	0.73%	0.73%	0.73%	0.73%	0.73%
6.30%	6.56%	6.56%	6.56%	6.56%	6.56%	6.56%	6.56%	6.56%	6.56%	6.56%
11.79%	11.91%	11.91%	11.91%	11.91%	11.91%	11.91%	11.91%	11.91%	11.91%	11.91%
0.25%	0.26%	0.26%	0.26%	0.26%	0.26%	0.26%	0.26%	0.26%	0.26%	0.26%
100.00%	101.88%	101.88%	101.88%	101.88%	101.88%	101.88%	101.88%	101.88%	101.88%	101.88%
100%	102%	102%	102%	102%	102%	102%	102%	102%	102%	102%

Table D-18 Residual Value-Added After Loss of Capacity--Air Transportation Lifeline

0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0.45%	0.45%	0.45%	0.44%	0.44%	0.43%	0.43%	0.42%	0.42%	0.41%	0.41%
1.06%	1.05%	1.04%	1.03%	1.02%	1.01%	1.00%	0.99%	0.98%	0.96%	0.95%
0.11%	0.11%	0.11%	0.11%	0.11%	0.11%	0.10%	0.10%	0.10%	0.10%	0.10%
3.89%	3.87%	3.83%	3.79%	3.75%	3.70%	3.66%	3.62%	3.58%	3.54%	3.50%
5.52%	5.52%	5.52%	5.52%	5.52%	5.52%	5.52%	5.52%	5.52%	5.52%	5.52%
2.41%	2.38%	2.33%	2.28%	2.23%	2.18%	2.13%	2.08%	2.03%	1.98%	1.93%
0.37%	0.37%	0.36%	0.35%	0.35%	0.34%	0.33%	0.32%	0.31%	0.31%	0.30%
0.73%	0.72%	0.70%	0.69%	0.67%	0.66%	0.64%	0.63%	0.61%	0.60%	0.58%
0.52%	0.51%	0.50%	0.49%	0.48%	0.47%	0.46%	0.45%	0.43%	0.42%	0.41%
0.34%	0.34%	0.33%	0.32%	0.31%	0.31%	0.30%	0.29%	0.29%	0.28%	0.27%
0.87%	0.87%	0.86%	0.85%	0.84%	0.83%	0.82%	0.81%	0.80%	0.79%	0.78%
1.31%	1.30%	1.27%	1.24%	1.22%	1.19%	1.16%	1.13%	1.10%	1.08%	1.05%
1.40%	1.39%	1.36%	1.33%	1.30%	1.27%	1.24%	1.21%	1.18%	1.15%	1.12%
0.96%	0.96%	0.96%	0.96%	0.96%	0.96%	0.96%	0.96%	0.96%	0.96%	0.96%
1.03%	1.02%	1.00%	0.98%	0.95%	0.93%	0.91%	0.89%	0.87%	0.85%	0.82%
0.12%	0.12%	0.12%	0.12%	0.11%	0.11%	0.11%	0.11%	0.10%	0.10%	0.10%
0.62%	0.61%	0.60%	0.59%	0.57%	0.56%	0.55%	0.53%	0.52%	0.51%	0.49%
1.04%	1.04%	1.02%	1.01%	1.00%	0.99%	0.98%	0.97%	0.96%	0.95%	0.94%
1.64%	1.63%	1.61%	1.60%	1.58%	1.56%	1.55%	1.53%	1.51%	1.49%	1.48%
1.56%	1.54%	1.51%	1.48%	1.45%	1.41%	1.38%	1.35%	1.31%	1.28%	1.25%
2.52%	2.48%	2.40%	2.32%	2.24%	2.16%	2.08%	2.00%	1.92%	1.85%	1.77%
2.62%	2.58%	2.49%	2.41%	2.33%	2.25%	2.16%	2.08%	2.00%	1.92%	1.83%
0.68%	0.66%	0.64%	0.61%	0.58%	0.55%	0.52%	0.49%	0.46%	0.44%	0.41%
0.69%	0.68%	0.67%	0.65%	0.64%	0.62%	0.61%	0.59%	0.58%	0.56%	0.55%
3.46%	3.41%	3.30%	3.19%	3.08%	2.97%	2.86%	2.75%	2.64%	2.53%	2.42%
5.89%	5.89%	5.89%	5.89%	5.89%	5.89%	5.89%	5.89%	5.89%	5.89%	5.89%
5.63%	5.57%	5.46%	5.34%	5.22%	5.10%	4.98%	4.86%	4.74%	4.63%	4.51%
5.63%	5.57%	5.46%	5.34%	5.22%	5.10%	4.98%	4.86%	4.74%	4.63%	4.51%
16.64%	16.47%	16.12%	15.77%	15.42%	15.07%	14.72%	14.36%	14.01%	13.66%	13.31%
8.03%	7.95%	7.78%	7.61%	7.44%	7.27%	7.10%	6.93%	6.76%	6.59%	6.42%
2.12%	2.08%	1.99%	1.90%	1.81%	1.72%	1.63%	1.54%	1.45%	1.36%	1.27%
1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%
0.70%	0.68%	0.65%	0.62%	0.59%	0.56%	0.54%	0.51%	0.48%	0.45%	0.42%
6.30%	6.27%	6.20%	6.13%	6.07%	6.00%	5.93%	5.87%	5.80%	5.73%	5.67%
11.79%	11.67%	11.42%	11.17%	10.92%	10.67%	10.43%	10.18%	9.93%	9.68%	9.43%
0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%
100.00%	99.09%	97.27%	95.45%	93.63%	91.81%	90.00%	88.18%	86.36%	84.54%	82.72%
100%	99%	97%	95%	94%	92%	90%	88%	86%	85%	83%

Table D-19 Residual Value-Added After Loss of Capacity--Water Transportation Lifeline (Ports)

0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0.45%	0.44%	0.42%	0.41%	0.39%	0.37%	0.35%	0.33%	0.31%	0.29%	0.27%
1.06%	1.04%	0.99%	0.95%	0.90%	0.86%	0.81%	0.77%	0.72%	0.68%	0.64%
0.11%	0.11%	0.10%	0.10%	0.09%	0.09%	0.08%	0.08%	0.08%	0.07%	0.07%
3.89%	3.85%	3.77%	3.68%	3.60%	3.52%	3.44%	3.36%	3.27%	3.19%	3.11%
5.52%	5.46%	5.34%	5.23%	5.11%	5.00%	4.88%	4.76%	4.65%	4.53%	4.42%
2.41%	2.38%	2.33%	2.28%	2.23%	2.18%	2.13%	2.08%	2.03%	1.98%	1.93%
0.37%	0.37%	0.36%	0.35%	0.35%	0.34%	0.33%	0.32%	0.31%	0.31%	0.30%
0.73%	0.72%	0.70%	0.69%	0.67%	0.66%	0.64%	0.63%	0.61%	0.60%	0.58%
0.52%	0.51%	0.50%	0.49%	0.48%	0.47%	0.46%	0.45%	0.43%	0.42%	0.41%
0.34%	0.34%	0.33%	0.32%	0.31%	0.31%	0.30%	0.29%	0.29%	0.28%	0.27%
0.87%	0.86%	0.83%	0.80%	0.77%	0.75%	0.72%	0.69%	0.66%	0.64%	0.61%
1.31%	1.30%	1.27%	1.24%	1.22%	1.19%	1.16%	1.13%	1.10%	1.08%	1.05%
1.40%	1.39%	1.36%	1.33%	1.30%	1.27%	1.24%	1.21%	1.18%	1.15%	1.12%
0.96%	0.92%	0.84%	0.76%	0.68%	0.60%	0.52%	0.44%	0.35%	0.27%	0.19%
1.03%	1.02%	1.00%	0.98%	0.95%	0.93%	0.91%	0.89%	0.87%	0.85%	0.82%
0.12%	0.12%	0.12%	0.12%	0.11%	0.11%	0.11%	0.11%	0.10%	0.10%	0.10%
0.62%	0.61%	0.60%	0.59%	0.57%	0.56%	0.55%	0.53%	0.52%	0.51%	0.49%
1.04%	1.03%	1.01%	0.99%	0.96%	0.94%	0.92%	0.90%	0.88%	0.85%	0.83%
1.64%	1.61%	1.56%	1.51%	1.46%	1.41%	1.36%	1.30%	1.25%	1.20%	1.15%
1.56%	1.54%	1.49%	1.44%	1.39%	1.34%	1.29%	1.24%	1.19%	1.14%	1.09%
2.52%	2.50%	2.44%	2.39%	2.34%	2.28%	2.23%	2.18%	2.12%	2.07%	2.02%
2.62%	2.58%	2.49%	2.41%	2.33%	2.25%	2.16%	2.08%	2.00%	1.92%	1.83%
0.68%	0.68%	0.67%	0.66%	0.65%	0.65%	0.64%	0.63%	0.63%	0.62%	0.61%
0.69%	0.68%	0.67%	0.65%	0.64%	0.62%	0.61%	0.59%	0.58%	0.56%	0.55%
3.46%	3.41%	3.30%	3.19%	3.08%	2.97%	2.86%	2.75%	2.64%	2.53%	2.42%
5.89%	5.89%	5.89%	5.89%	5.89%	5.89%	5.89%	5.89%	5.89%	5.89%	5.89%
5.63%	5.57%	5.46%	5.34%	5.22%	5.10%	4.98%	4.86%	4.74%	4.63%	4.51%
5.63%	5.63%	5.63%	5.63%	5.63%	5.63%	5.63%	5.63%	5.63%	5.63%	5.63%
16.64%	16.64%	16.64%	16.64%	16.64%	16.64%	16.64%	16.64%	16.64%	16.64%	16.64%
8.03%	8.03%	8.03%	8.03%	8.03%	8.03%	8.03%	8.03%	8.03%	8.03%	8.03%
2.12%	2.12%	2.12%	2.12%	2.12%	2.12%	2.12%	2.12%	2.12%	2.12%	2.12%
1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%	1.09%
0.70%	0.70%	0.70%	0.70%	0.70%	0.70%	0.70%	0.70%	0.70%	0.70%	0.70%
6.30%	6.30%	6.30%	6.30%	6.30%	6.30%	6.30%	6.30%	6.30%	6.30%	6.30%
11.79%	11.79%	11.79%	11.79%	11.79%	11.79%	11.79%	11.79%	11.79%	11.79%	11.79%
0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%	0.25%
100.00%	99.47%	98.40%	97.33%	96.26%	95.19%	94.12%	93.05%	91.98%	90.91%	89.84%
100%	99%	98%	97%	96%	95%	94%	93%	92%	91%	90%

Table D-20 Residual Value-Added After Loss of Capacity--Telephone Lifeline

0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
0.45%	0.45%	0.44%	0.43%	0.42%	0.41%	0.40%	0.39%	0.38%	0.37%	0.36%
1.06%	1.05%	1.03%	1.00%	0.98%	0.96%	0.94%	0.91%	0.89%	0.87%	0.85%
0.11%	0.11%	0.11%	0.10%	0.10%	0.10%	0.10%	0.10%	0.09%	0.09%	0.09%
3.89%	3.87%	3.83%	3.79%	3.75%	3.70%	3.66%	3.62%	3.58%	3.54%	3.50%
5.52%	5.49%	5.43%	5.37%	5.32%	5.26%	5.20%	5.14%	5.08%	5.03%	4.97%
2.41%	2.39%	2.35%	2.31%	2.27%	2.24%	2.20%	2.16%	2.12%	2.08%	2.05%
0.37%	0.37%	0.36%	0.36%	0.35%	0.35%	0.34%	0.33%	0.33%	0.32%	0.32%
0.73%	0.72%	0.71%	0.70%	0.69%	0.67%	0.66%	0.65%	0.64%	0.63%	0.62%
0.52%	0.51%	0.50%	0.50%	0.49%	0.48%	0.47%	0.46%	0.45%	0.45%	0.44%
0.34%	0.34%	0.33%	0.33%	0.32%	0.31%	0.31%	0.30%	0.30%	0.29%	0.29%
0.87%	0.87%	0.86%	0.85%	0.84%	0.83%	0.82%	0.81%	0.80%	0.79%	0.78%
1.31%	1.30%	1.28%	1.26%	1.24%	1.22%	1.20%	1.18%	1.16%	1.14%	1.12%
1.40%	1.39%	1.37%	1.35%	1.33%	1.30%	1.28%	1.26%	1.24%	1.22%	1.19%
0.96%	0.96%	0.95%	0.94%	0.93%	0.92%	0.91%	0.90%	0.89%	0.88%	0.87%
1.03%	1.02%	1.01%	0.99%	0.97%	0.96%	0.94%	0.92%	0.91%	0.89%	0.88%
0.12%	0.12%	0.12%	0.12%	0.12%	0.11%	0.11%	0.11%	0.11%	0.11%	0.10%
0.62%	0.61%	0.60%	0.59%	0.58%	0.57%	0.56%	0.55%	0.54%	0.54%	0.53%
1.04%	1.03%	1.02%	1.00%	0.98%	0.97%	0.95%	0.93%	0.92%	0.90%	0.88%
1.64%	1.63%	1.61%	1.60%	1.58%	1.56%	1.55%	1.53%	1.51%	1.49%	1.48%
1.56%	1.55%	1.54%	1.52%	1.50%	1.49%	1.47%	1.45%	1.44%	1.42%	1.40%
2.52%	2.50%	2.46%	2.42%	2.38%	2.34%	2.30%	2.26%	2.22%	2.18%	2.14%
2.62%	2.61%	2.58%	2.55%	2.52%	2.49%	2.47%	2.44%	2.41%	2.38%	2.36%
0.68%	0.67%	0.65%	0.63%	0.60%	0.58%	0.56%	0.54%	0.52%	0.50%	0.48%
0.69%	0.68%	0.67%	0.66%	0.65%	0.64%	0.63%	0.62%	0.61%	0.60%	0.58%
3.46%	3.41%	3.30%	3.19%	3.08%	2.97%	2.86%	2.75%	2.64%	2.53%	2.42%
5.89%	5.79%	5.61%	5.42%	5.24%	5.05%	4.86%	4.68%	4.49%	4.31%	4.12%
5.63%	5.49%	5.19%	4.89%	4.60%	4.30%	4.00%	3.71%	3.41%	3.11%	2.82%
5.63%	5.49%	5.19%	4.89%	4.60%	4.30%	4.00%	3.71%	3.41%	3.11%	2.82%
16.64%	16.12%	15.07%	14.01%	12.96%	11.91%	10.86%	9.81%	8.76%	7.71%	6.66%
8.03%	7.86%	7.52%	7.19%	6.85%	6.51%	6.17%	5.83%	5.49%	5.16%	4.82%
2.12%	2.08%	1.99%	1.90%	1.81%	1.72%	1.63%	1.54%	1.45%	1.36%	1.27%
1.09%	1.07%	1.03%	0.98%	0.93%	0.89%	0.84%	0.80%	0.75%	0.70%	0.66%
0.70%	0.68%	0.65%	0.62%	0.59%	0.56%	0.54%	0.51%	0.48%	0.45%	0.42%
6.30%	6.25%	6.15%	6.05%	5.95%	5.85%	5.75%	5.65%	5.55%	5.45%	5.35%
11.79%	11.67%	11.42%	11.17%	10.92%	10.67%	10.43%	10.18%	9.93%	9.68%	9.43%
0.25%	0.25%	0.24%	0.24%	0.23%	0.23%	0.22%	0.22%	0.21%	0.21%	0.20%
100.00%	98.38%	95.14%	91.91%	88.67%	85.43%	82.20%	78.96%	75.72%	72.48%	69.25%
100%	98%	95%	92%	89%	85%	82%	79%	76%	72%	69%

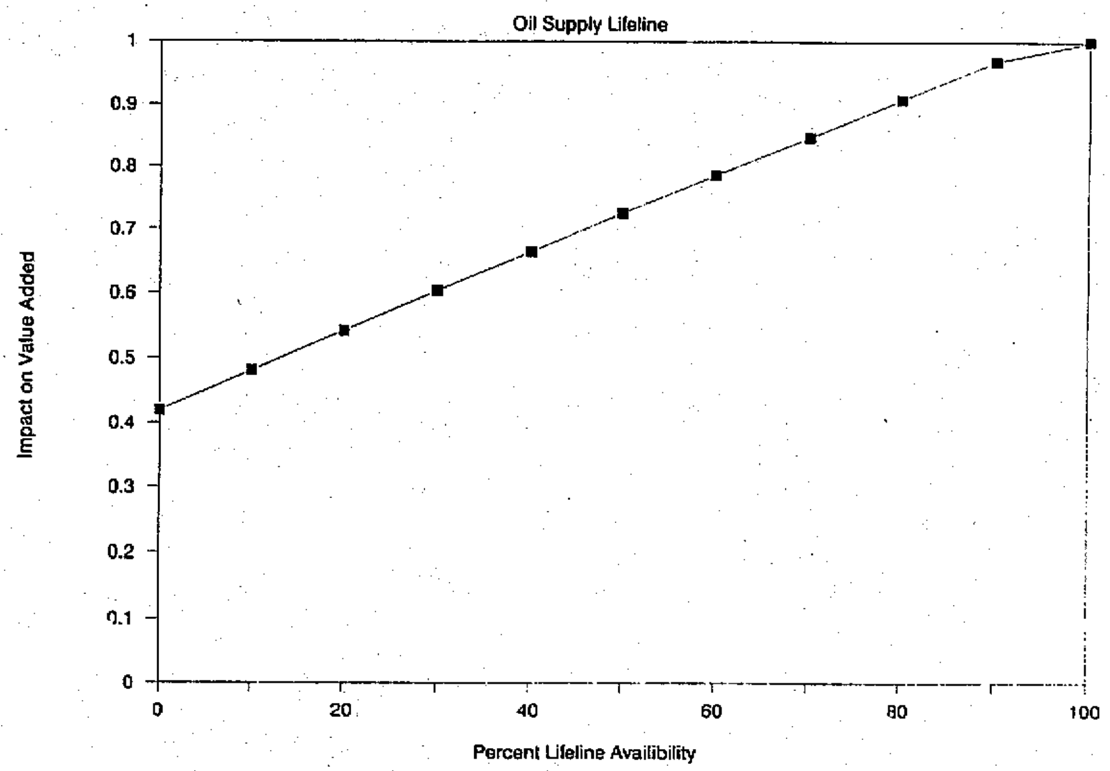

Figure D-1 Residual Value Added as a Function of Oil Supply Lifeline Residual Capacity.

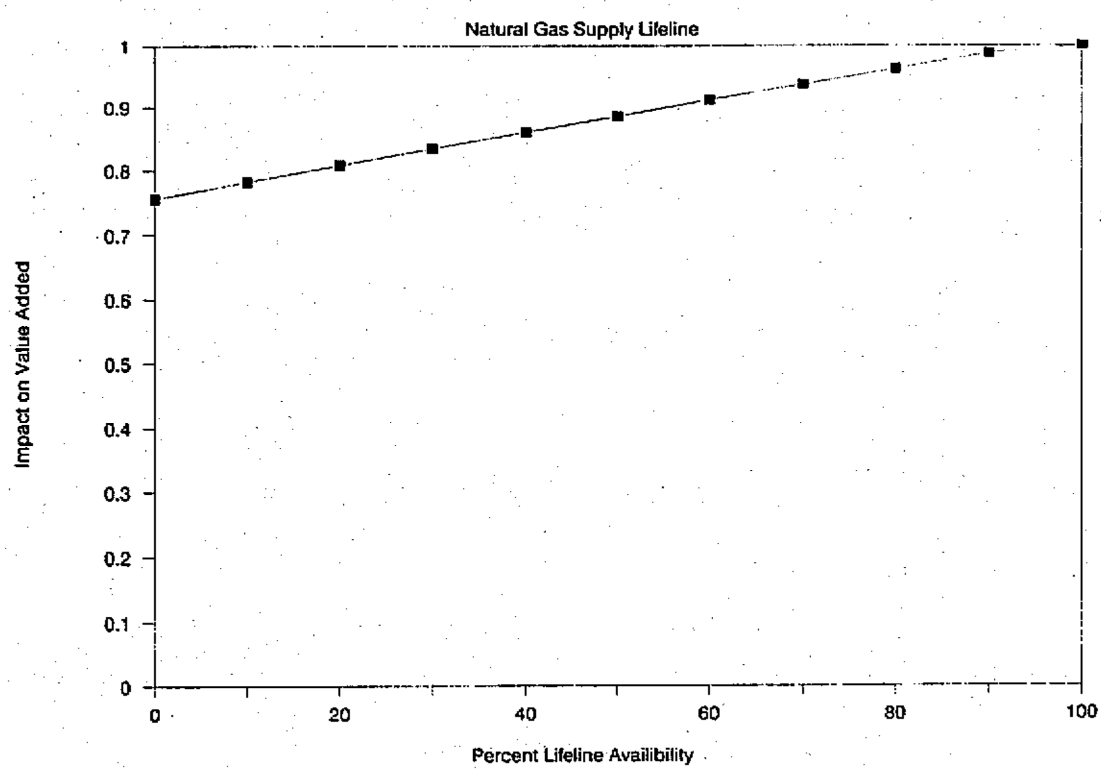

Figure D-2 Residual Value Added as a Function of Natural Gas Supply Lifeline Residual Capacity.

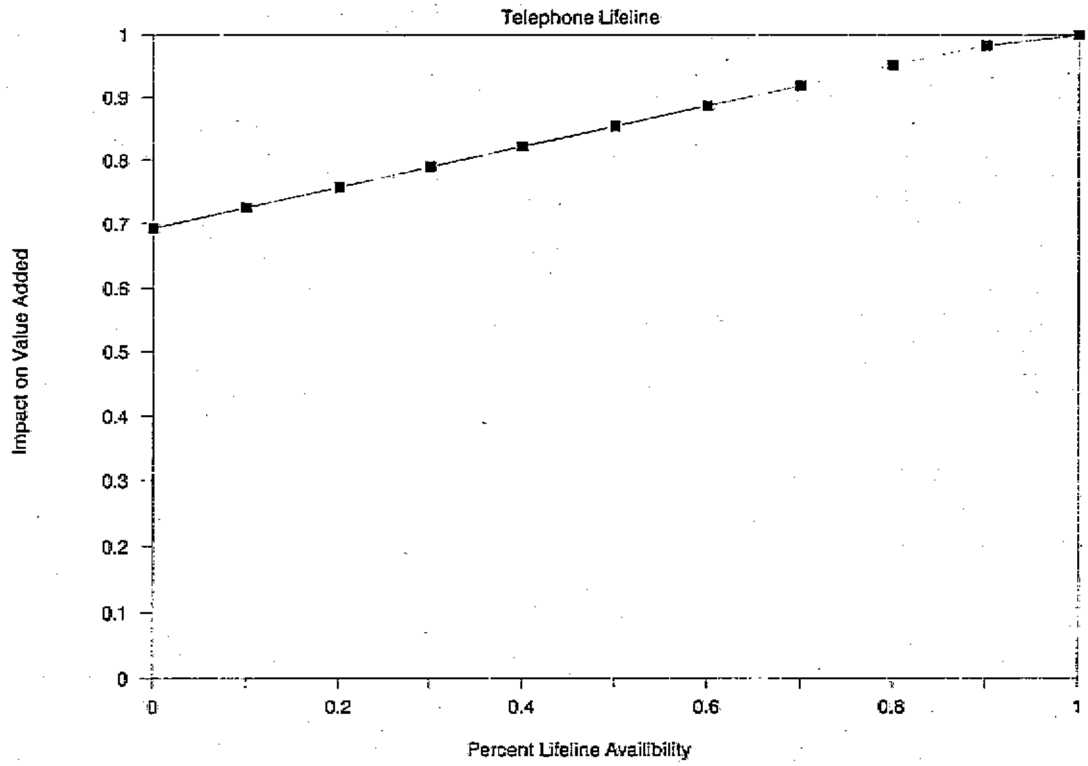

Figure D-3 Residual Value Added as a Function of Telephone Lifeline Residual Capacity.

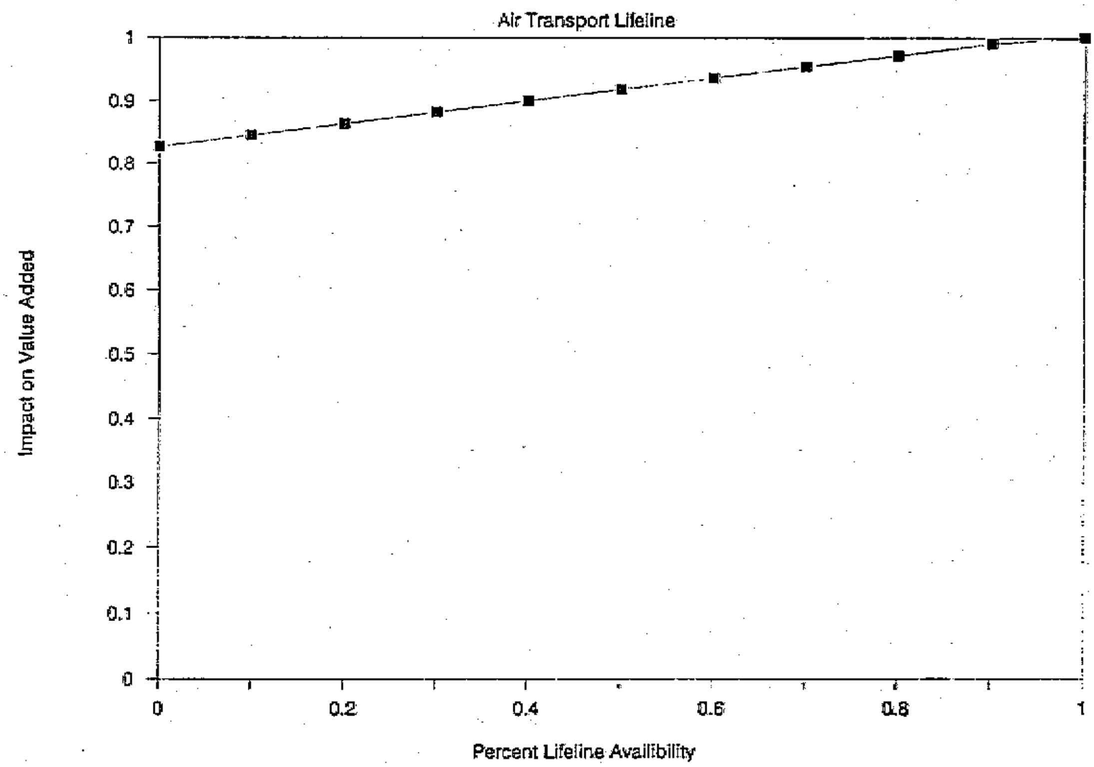

Figure D-4 Residual Value Added as a Function of Air Transportation Lifeline Residual Capacity.

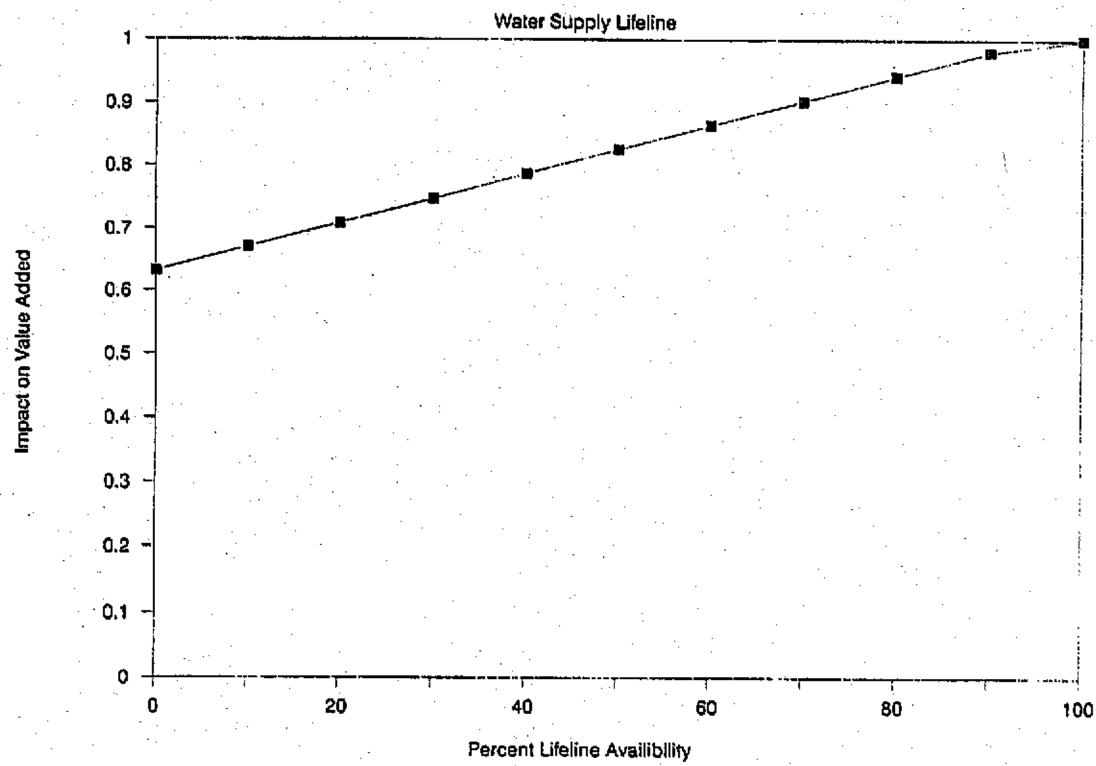

Figure D-5 Residual Value Added as a Function of Water Supply Lifeline Residual Capacity.

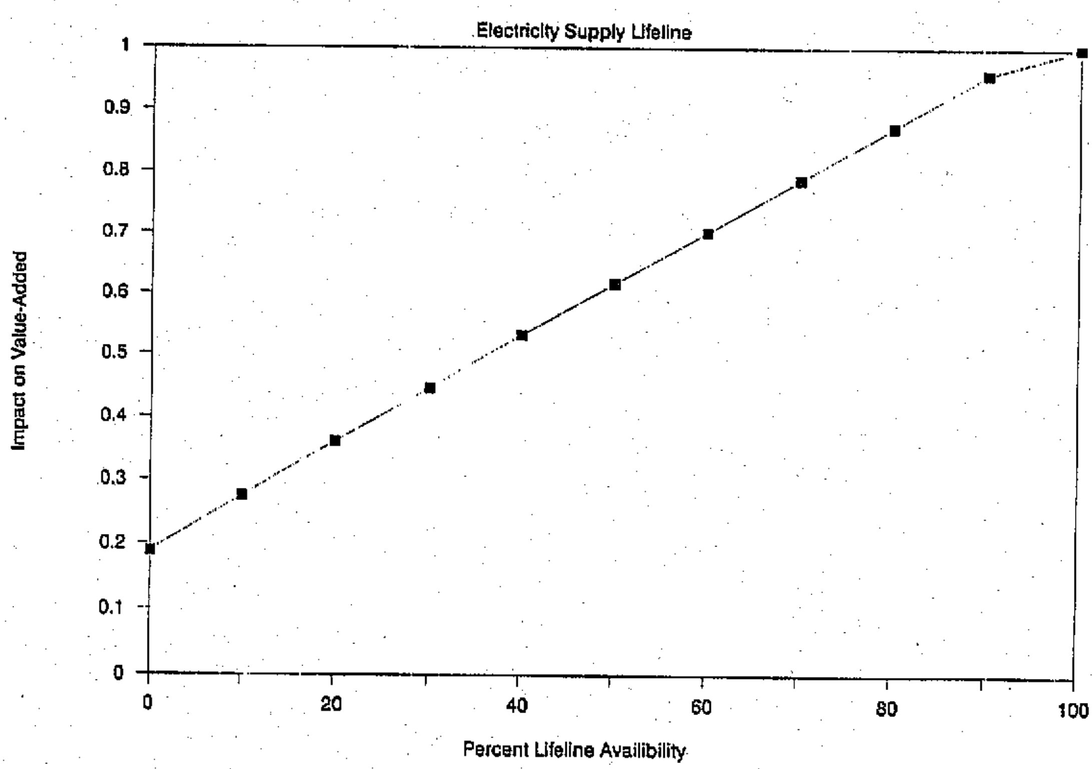

Figure D-6 Residual Value Added as a Function of Electric Lifeline Residual Capacity.

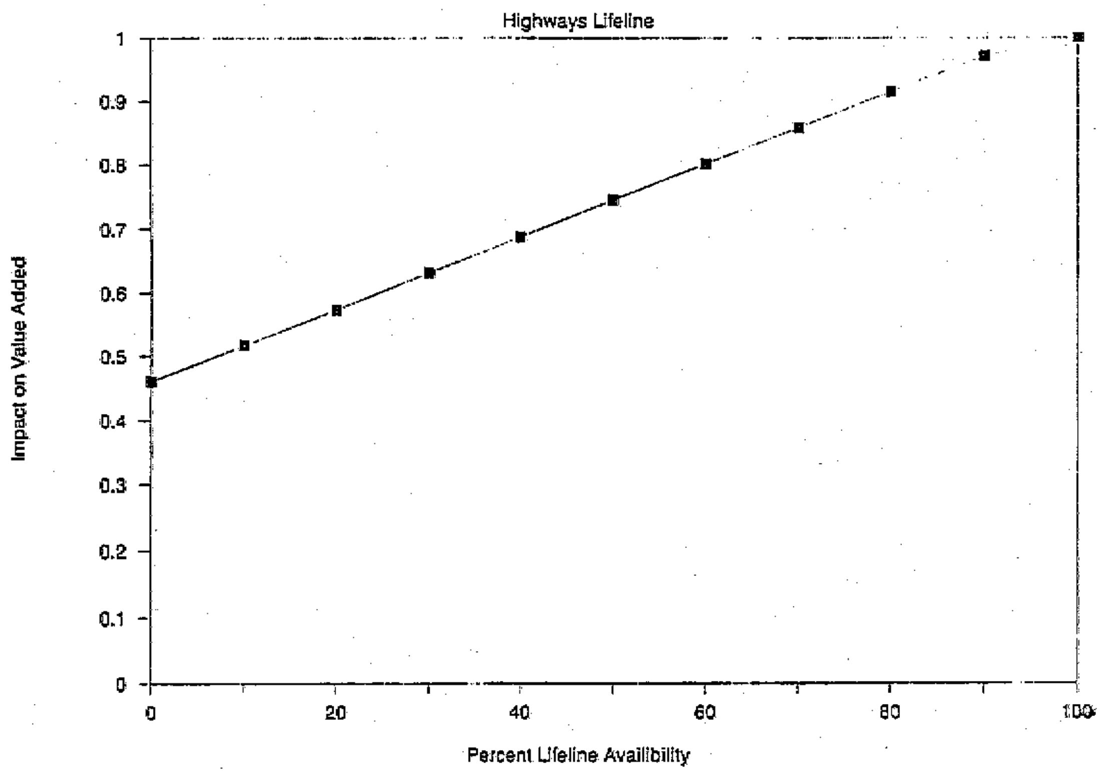

Figure D-7 Residual Value Added as a Function of Highway Lifeline Residual Capacity.

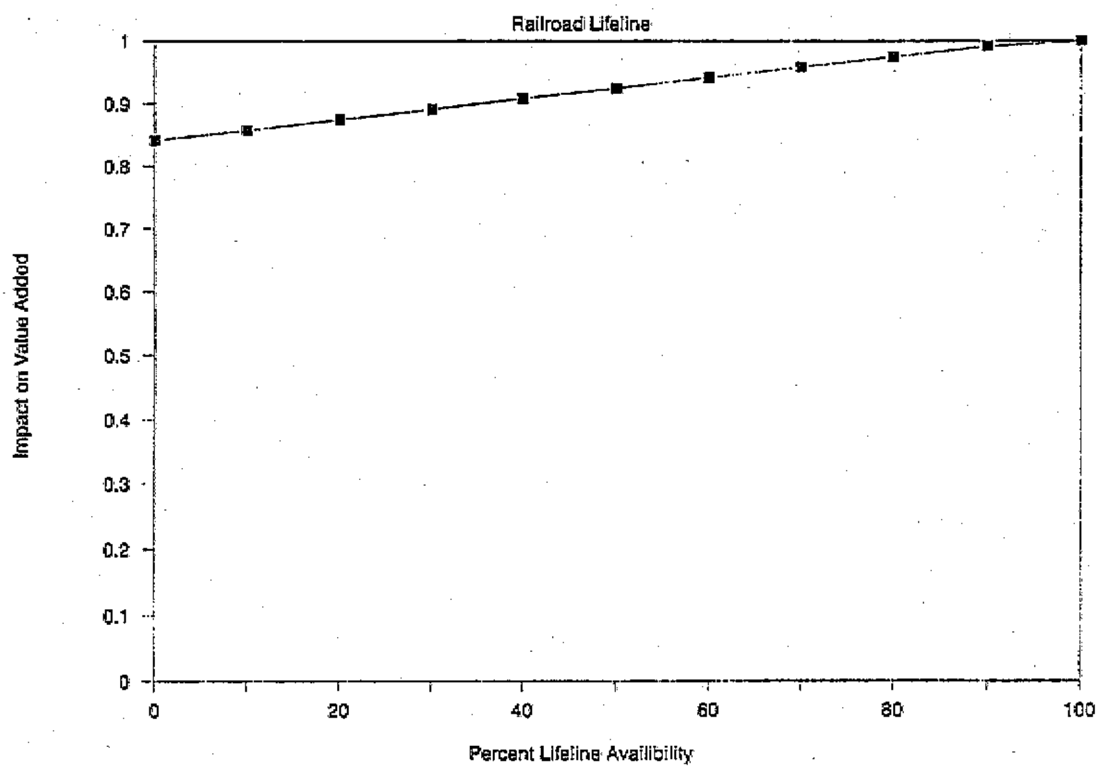

Figure D-8 Residual Value Added as a Function of Railroad Lifeline Residual Capacity.

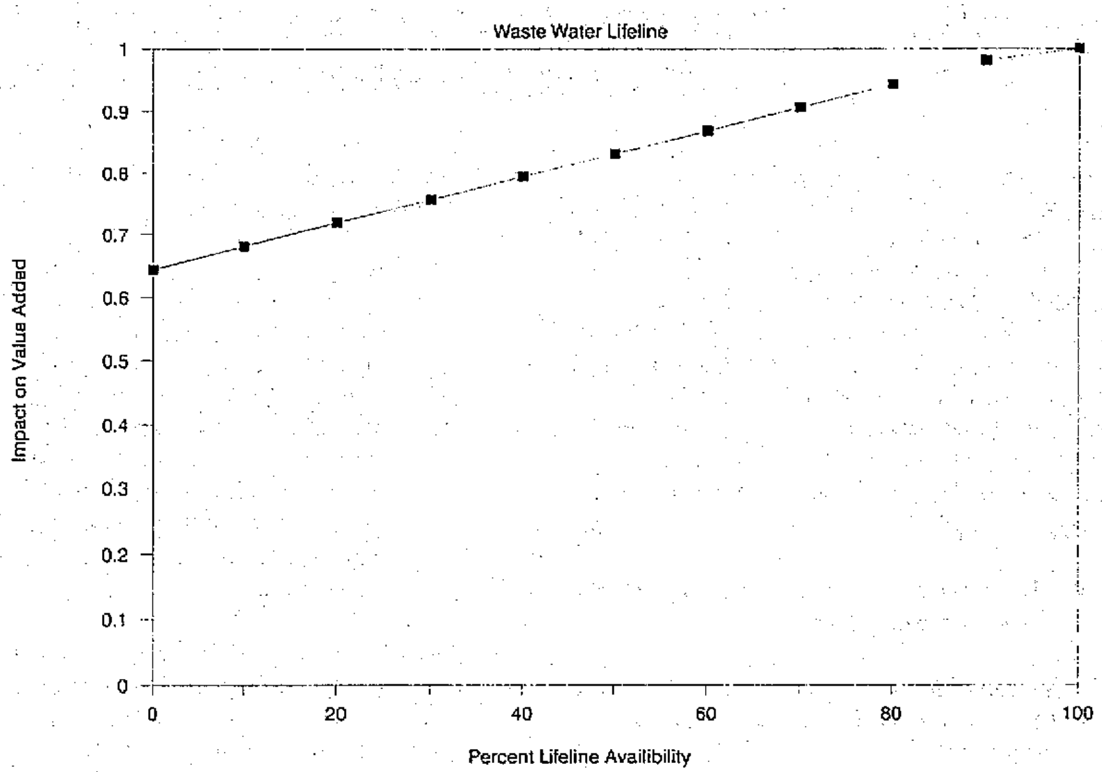

Figure D-9 Residual Value Added as a Function of Sanitary Sewer Lifeline Residual Capacity.

Appendix E: Applied Technology Council Projects and Report Information

One of the primary purposes of Applied Technology Council is to develop resource documents that translate and summarize useful information to practicing engineers. This includes the development of guidelines and manuals, as well as the development of research recommendations for specific areas determined by the profession. ATC is not a code development organization, although several of the ATC project reports serve as resource documents for the development of codes, standards and specifications.

Applied Technology Council conducts projects that meet the following criteria:

1. The primary audience or benefactor is the design practitioner in structural engineering.

2. A cross section or consensus of engineering opinion is required to be obtained and presented by a neutral source.

3. ATC is requested to conduct the project by the project sponsor.

A brief description of several major completed projects and reports, is given in the following section. Funding for projects is obtained from government agencies and tax-deductible contributions from the private sector.

ATC-1: This project resulted in five papers which were published as part of Building Practices for Disaster Mitigation, Building Science Series 46, proceedings of a workshop sponsored by the National Science Foundation (NSF) and the National Bureau of Standards (NBS). Available through the National Technical Information Service (NTIS), 5285 Port Royal Road, Springfield, VA 22151, as NTIS report No. COM-73-50188.

ATC-2: The report, *An Evaluation of a Response Spectrum Approach to Seismic Design of Buildings*, was funded by NSF and NBS and was conducted as part of the Cooperative Federal Program in Building Practices for Disaster Mitigation. Available through the ATC office. (270 Pages)

> Abstract: This study evaluated the applicability and cost of the response spectrum approach to seismic analysis and design that was proposed by various segments of the engineering profession. Specific building designs, design procedures and parameter values were evaluated for future application. Eleven existing buildings of varying dimensions were redesigned according to the procedures.

ATC-3: The report, *Tentative Provisions for the Development of Seismic Regulations for Buildings (ATC-3-06)*, was funded by NSF and NBS. The second printing of this report, which included proposed amendments, is available through the ATC office. (505 pages plus proposed amendments)

> Abstract: The tentative provisions in this document represent the result of a concerted effort by a multi-disciplinary team of 85 nationally recognized experts in earthquake engineering. The project involved representation from all sections of the United States and had wide review by affected building industry and regulatory groups. The provisions embodied several new concepts that were significant departures from existing seismic design provisions. The second printing of this document contains proposed amendments prepared by a joint committee of the Building Seismic Safety Council (BSSC) and the NBS; the proposed amendments were published separately by BSSC and NBS in 1982.

ATC-3-2: The project, Comparative Test Designs of Buildings Using ATC-3-06 Tentative Provisions, was funded by NSF. The project consisted of a study to develop and plan a program for making comparative test designs of the ATC-3-06 Tentative Provisions. The project report was written to be used by the Building

Seismic Safety Council in its refinement of the ATC-3-06 Tentative Provisions.

ATC-3-4: The report, *Redesign of Three Multistory Buildings: A Comparison Using ATC-3-06 and 1982 Uniform Building Code Design Provisions*, was published under a grant from NSF. Available through the ATC office. (112 pages)

Abstract: This report evaluates the cost and technical impact of using the 1978 ATC-3-06 report, *Tentative Provisions for the Development of Seismic Regulations for Buildings*, as amended by a joint committee of the Building Seismic Safety Council and the National Bureau of Standards in 1982. The evaluations are based on studies of three existing California buildings redesigned in accordance with the ATC-3-06 Tentative Provisions and the 1982 Uniform Building Code. Included in the report are recommendations to code implementing bodies.

ATC-3-5: This project, Assistance for First Phase of ATC-3-06 Trial Design Program Being Conducted by the Building Seismic Safety Council, was funded by the Buildings Seismic Safety Council and provided the services of the ATC Senior Consultant and other ATC personnel to assist the BSSC in the conduct of the first phase of its Trial Design Program. The first phase provided for trial designs conducted for buildings in Los Angeles, Seattle, Phoenix, and Memphis.

ATC-3-6: This project, Assistance for Second Phase of ATC-3-06 Trial Design Program Being Conducted by the Building Seismic Safety Council, was funded by the Building Seismic Safety Council and provided the services of the ATC Senior Consultant and other ATC personnel to assist the BSSC in the conduct of the second phase of its Trial Design Program. The second phase provided for trial designs conducted for buildings in New York, Chicago, St. Louis, Charleston, and Fort Worth.

ATC-4: The report, *A Methodology for Seismic Design and Construction of Single-Family Dwellings*, was published under a contract with the Department of Housing and Urban Development (HUD). Available through the ATC office. (576 pages)

Abstract: This report presents the results of an in-depth effort to develop design and construction details for single-family residences that minimize the potential economic loss and life-loss risk associated with earthquakes. The report: (1) discussed the ways structures behave when subjected to seismic forces, (2) sets forth suggested design criteria for conventional layouts of dwellings constructed with conventional materials, (3) presents construction details that do not require the designer to perform analytical calculations, (4) suggests procedures for efficient plan-checking, and (5) present recommendations including details and schedules for use in the field by construction personnel and building inspectors.

ATC-4-1: The report, *The Home Builders Guide for Earthquake Design*, was published under a contract with HUD. Available through the ATC office. (57 pages)

Abstract: This report is a 57-page abridged version of the ATC-4 report. The concise, easily understood text of the Guide is supplemented with illustrations and 46 construction details. The details are provided to ensure that houses contain structural features which are properly positioned, dimensioned and constructed to resist earthquake forces. A brief description is included on how earthquake forces impact on houses and some precautionary constraints are given with respect to site selection and architectural designs.

ATC-5: The report, *Guidelines for Seismic Design and Construction of Single-Story Masonry Dwellings in Seismic Zone 2*, was developed under a contract with HUD. Available through the ATC office. (38 pages)

Abstract: The report offers a concise methodology for the earthquake design and construction of single-story masonry dwellings in Seismic Zone 2 of the United States, as defined by the 1973 Uniform

Building Code. The guidelines are based in part on shaking table tests of masonry construction conducted at the University of California at Berkeley Earthquake Engineering Research Center. The report is written in simple language and includes basic house plans, wall evaluations, detail drawings, and material specifications.

ATC-6: The report, *Seismic Design Guidelines for Highway Bridges, was* published under a contract with the Federal Highway Administration (FHWA). Available through the ATC office. (210 pages)

> Abstract: The Guidelines are the recommendations of a team of sixteen nationally recognized experts that included consulting engineers, academics, state and federal agency representatives from throughout the United States. The Guidelines embody several new concepts that are significant departures from existing design provisions. An extensive commentary and an example demonstrating the use of the Guidelines are included. A draft of the Guidelines was used to seismically redesign 21 bridges and a summary of the redesigns is also included.

ATC-6-1: The report, *Proceedings of a Workshop on Earthquake Resistance of Highway Bridges*, was published under a grant from NSF. Available through the ATC office. (625 pages)

> Abstract: The report includes 23 state-of-the-art and state-of-practice papers on earthquake resistance of highway bridges. Seven of the twenty-three papers were authored by participants from Japan, New Zealand and Portugal. The Proceedings also contain recommendations for future research that were developed by the 45 workshop participants.

ATC-6-2: The report, *Seismic Retrofitting Guidelines for Highway Bridges*, was published under a contract with FHWA. Available through the ATC office. (220 pages)

> Abstract: The Guidelines are the recommendations of a team of thirteen nationally recognized experts that included consulting engineers, academics, state highway engineers, and federal agency representatives. The Guidelines, applicable for use in all parts of the U.S., include a preliminary screening procedure, methods for evaluating an existing bridge in detail, and potential retrofitting measures for the most common seismic deficiencies. Also included are special design requirements for various retrofitting measures.

ATC-7: The report, *Guidelines for the Design of Horizontal Wood Diaphragms*, was published under a grant from NSF. Available through the ATC office. (190 pages)

> Abstract: Guidelines are presented for designing roof and floor systems so these can function as horizontal diaphragms in a lateral force resisting system. Analytical procedures, connection details and design examples are included in the Guidelines.

ATC-7-1: The report, *Proceedings of a Workshop of Design of Horizontal Wood Diaphragms*, was published under a grant from NSF. Available through the ATC office. (302 pages)

> Abstract: The report includes seven papers on state-of-the-practice and two papers on recent research. Also included are recommendations for future research that were developed by the 35 participants.

ATC-8: This report, *Proceedings of a Workshop on the Design of Prefabricated Concrete Buildings for Earthquake Loads*, was funded by NSF. Available through the ATC office. (400 pages)

> Abstract: The report includes eighteen state-of-the-art papers and six summary papers. Also included are recommendations for future research that were developed by the 43 workshop participants.

ATC-9: The report, *An Evaluation of the Imperial County Services Building Earthquake Response and Associated Damage*, was published under a grant from NSF. Available through the ATC office. (231 pages)

Abstract: The report presents the results of an in-depth evaluation of the Imperial County Services Building, a 6-story reinforced concrete frame and shear wall building severely damaged by the October 15, 1979 Imperial Valley, California, earthquake. The report contains a review and evaluation of earthquake damage to the buildings; a review and evaluation of the seismic design; a comparison of the requirements of various building codes as they relate to the building; and conclusions and recommendations pertaining to future building code provisions and future research needs.

ATC-10: This report, *An Investigation of the Correlation Between Earthquake Ground Motion and Building Performance*, was funded by the U.S. Geological Survey (USGS). Available through the ATC office. (114 pages)

Abstract: The report contains an in-depth analytical evaluation of the ultimate or limit capacity of selected representative building framing types, a discussion of the factors affecting the seismic performance of buildings, and a summary and comparison of seismic design and seismic risk parameters currently in widespread use.

ATC-10-1: This report, *Critical Aspects of Earthquake Ground Motion and Building Damage Potential*, was co-funded by the USGS and the NSF. Available through the ATC office. (259 pages)

Abstract: This document contains 19 state-of-the-art papers on ground motion, structural response, and structural design issues presented by prominent engineers and earth scientists in an ATC seminar. The main theme of the papers is to identify the critical aspects of ground motion and building performance that currently are not being considered in building design. The report also contains conclusions and recommendations of working groups convened after the Seminar.

ATC-11: The report, *Seismic Resistance of Reinforced Concrete Shear Walls and Frame Joints: Implications of Recent Research for Design Engineers*, was published under a grant from NSF. Available through the ATC office. (184 pages)

Abstract: This document presents the results of an in-depth review and synthesis of research reports pertaining to cyclic loading of reinforced concrete shear walls and cyclic loading of joint reinforced concrete frames. More than 125 research reports published since 1971 are reviewed and evaluated in this report. The preparation of the report included a consensus process involving numerous experienced design professionals from throughout the United States. The report contains reviews of current and past design practices, summaries of research developments, and in-depth discussions of design implications of recent research results.

ATC-12: This report, *Comparison of United States and New Zealand Seismic Design Practices for Highway Bridges*, was published under a grant from NSF. Available through the ATC office. (270 pages)

Abstract: The report contains summaries of all aspects and innovative design procedures used in New Zealand as well as comparison of United States and New Zealand design practice. Also included are research recommendations developed at a 3-day workshop in New Zealand attended by 16 U.S. and 35 New Zealand bridge design engineers and researchers.

ATC-12-1: This report, *Proceedings of Second Joint U.S.-New Zealand Workshop on Seismic Resistance of Highway Bridges*, was published under a grant from NSF. Available through the ATC office. (272 pages)

Abstract: This report contains written versions of the papers presented at this 1985 Workshop as well as a list and prioritization of workshop recommendations. Included are summaries of research projects currently being conducted in both countries as well

as state-of-the-practice papers on various aspects of design practice. Topics discussed include bridge design philosophy and loadings; design of columns, footings, piles, abutments and retaining structures; geotechnical aspects of foundation design; seismic analysis techniques; seismic retrofitting; case studies using base isolation; strong-motion data acquisition and interpretation; and testing of bridge components and bridge systems.

ATC-13: The report, *Earthquake Damage Evaluation Data for California*, was developed under a contract with the Federal Emergency Management Agency (FEMA). Available through the ATC office. (492 pages)

> Abstract: This report presents expert-opinion earthquake damage and loss estimates for existing industrial, commercial, residential, utility and transportation facilities in California. Included are damage probability matrices for 78 classes of structures and estimates of time required to restore damaged facilities to pre-earthquake usability. The report also describes the inventory information essential for estimating economic losses and the methodology used to develop the required data.

ATC-14: The report, *Evaluating the Seismic Resistance of Existing Buildings*, was developed under a grant from the NSF. Available through the ATC office. (370 pages)

> Abstract: This report, written for practicing structural engineers, describes a methodology for performing preliminary and detailed building seismic evaluations. The report contains a state-of-practice review; seismic loading criteria; data collection procedures; a detailed description of the building classification system; preliminary and detailed analysis procedures; and example case studies, including non-structural considerations.

ATC-15: This report, *Comparison of Seismic Design Practices in the United States and Japan*, was published under a grant from NSF. Available through the ATC office. (317 pages)

> Abstract: The report contains detailed technical papers describing current design practices in the United States and Japan as well as recommendations emanating from a joint U.S.-Japan workshop held in Hawaii in March, 1984. Included are detailed descriptions of new seismic design methods for buildings in Japan and case studies of the design of specific buildings (in both countries). The report also contains an overview of the history and objectives of the Japan Structural Consultants Association.

ATC-15-1: The report, *Proceedings of Second U.S.-Japan Workshop on Improvement of Building Seismic Design and Construction Practices*, was published under a grant from NSF. Available through the ATC office. (412 pages)

> Abstract: This report contains 23 technical papers presented at this San Francisco workshop in August, 1986, by practitioners and researchers from the U.S. and Japan. Included are state-of-the-practice papers and case studies of actual building designs and information on regulatory, contractual, and licensing issues.

ATC-15-2: The report, *Proceedings of Third U.S.-Japan Workshop on Improvement of Building Structural Design and Construction Practices*, was published jointly by TAC and the Japan Structural Consultants Association. Available through the ATC office.

> Abstract: This report contains 21 technical papers presented at this Tokyo, Japan, workshop in July, 1988, by practitioners and researchers from the U.S., Japan, China, and New Zealand. Included are state-of-the-practice papers on various topics, including braced steel frame buildings, beam-column joints in reinforced concrete buildings, summaries of comparative U. S. and Japanese design, and base isolation and passive energy dissipation devices.

ATC-16: This project, Development of a 5-Year Plan for Reducing the Earthquake Hazards Posed by Existing Nonfederal Buildings, was funded by FEMA and was conducted by a joint venture of ATC, the Building Seismic Safety Council and the Earthquake Engineering Research Institute. The project involved a workshop in Phoenix, Arizona, where approximately 50 earthquake specialists met to identify the major tasks and goals for reducing the earthquake hazards posed by existing nonfederal buildings nationwide. The plan was developed on the basis of nine issue papers presented at the workshop and workshop working group discussions. The Workshop Proceedings and Five-Year Plan are available through the Federal Emergency Management Agency, 500 "C" Street, S.W., Washington, DC 20472.

ATC-17: This report, *Proceedings of a Seminar and Workshop on Base Isolation and Passive Energy Dissipation*, was published under a grant from NSF. Available through the ATC office. (478 pages)

> Abstract: The report contains 42 papers describing the state-of-the-art and state-of-the-practice in base-isolation and passive energy-dissipation technology. Included are papers describing case studies in the United States, applications and developments worldwide, recent innovations in technology development, and structural and ground motion issues. Also included is a proposed 5-year research agenda that addresses the following specific issues: (1) strong ground motion; (2) design criteria; (3) materials, quality control, and long-term reliability; (4) life cycle cost methodology; and (5) system response.

ATC-20: The report, *Procedures for Postearthquake Safety Evaluation of Buildings*, was developed under a contract from the California Office of Emergency Services (OES), California Office of Statewide Health Planning and Development (OSHPD) and FEMA. Available through the ATC office (152 pages)

> Abstract: This report provides procedures and guidelines for making on-the-spot evaluations and decisions regarding continued use and occupancy of earthquake damaged buildings. Written specifically for volunteer structural engineers and building inspectors, the report includes rapid and detailed evaluation procedures for inspecting buildings and posting them as "inspected" (apparently safe), "limited entry" or "unsafe". Also included are special procedures for evaluation of essential buildings (e.g., hospitals), and evaluation procedures for nonstructural elements, and geotechnical hazards.

ATC-20-1: The report, *Field Manual: Postearthquake Safety Evaluation of Buildings*, was developed under a contract from OES and OSHPD. Available through the ATC office (114 pages)

> Abstract: This report, a companion Field Manual for the ATC-20 report, summarizes the postearthquake safety evaluation procedures in brief concise format designed for ease of use in the field.

ATC-21: The report, *Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook*, was developed under a contract from FEMA. Available through the ATC office. (185 pages)

> Abstract: This report describes a rapid visual screening procedure for identifying those buildings that might pose serious risk of loss of life and injury, or of severe curtailment of community services, in case of a damaging earthquake. The screening procedure utilizes a methodology based on a "sidewalk survey" approach that involves identification of the primary structural load resisting system and building materials, and assignment of a basic structural hazards score and performance modification factors based on observed defects. Application of the methodology identifies those buildings that are potentially hazardous and should be analyzed in more detail by a professional engineer experienced in seismic design.

ATC-21-1: The report, *Rapid Visual Screening of Buildings for Potential Seismic Hazards: Supporting Documentation*, was developed under a contract from FEMA. Available through the ATC office. (137 pages)

Abstract: Included in this report are (1) a review and evaluation of existing procedures; (2) a listing of attributes considered ideal for a rapid visual screening procedures; and (3) a technical discussion of the recommended rapid visual screening procedure that is documented in the ATC-21 report.

ATC-21-2: The report, *Earthquake Damaged Buildings: An Overview of Heavy Debris and Victim Extrication*, was developed under a contract from FEMA. Available through the ATC office. (95 pages)

Abstract: Included in this report, a companion volume to the ATC-21 and ATC-21-1 reports, is state-of-the-art information on (1) the identification of those buildings that might collapse and trap victims in debris or generate debris of such a size that its handling would require special or heavy lifting equipment; (2) guidance in identifying these types of buildings, on the basis of their major exterior features, and (3) the types and life capacities of equipment required to remove the heavy portion of the debris that might result from the collapse of such buildings.

ATC-22: The report, *A Handbook for Seismic Evaluation of Existing Buildings (Preliminary)*, was developed under a contract from FEMA. Available through the ATC office. (169 pages)

Abstract: This handbook provides methodology for seismic evaluation of existing buildings of different types and occupancies in areas of different seismicity throughout the United States. The methodology, which has been field tested in several programs nationwide, utilizes the information and procedures developed for and documented in the ATC-14 report. The handbook includes checklists, diagrams, and sketches designed to assist the user.

ATC-22-1: The report, *Seismic Evaluation of Existing Buildings: Supporting Documentation*, was developed under a contract from FEMA. Available through the ATC office. (160 pages)

Abstract: Included in this report, a companion volume to the ATC-22 report, are (1) a review and evaluation of existing buildings seismic evaluation methodologies; (2) results from field tests of the ATC-14 methodology; and (3) summaries of evaluations of ATC-14 conducted by the National Center for Earthquake Engineering Research (State University of New York at Buffalo) and the City of San Francisco.

*U.S. GOVERNMENT PRINTING OFFICE:1998-618-146/90604