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).
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> 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

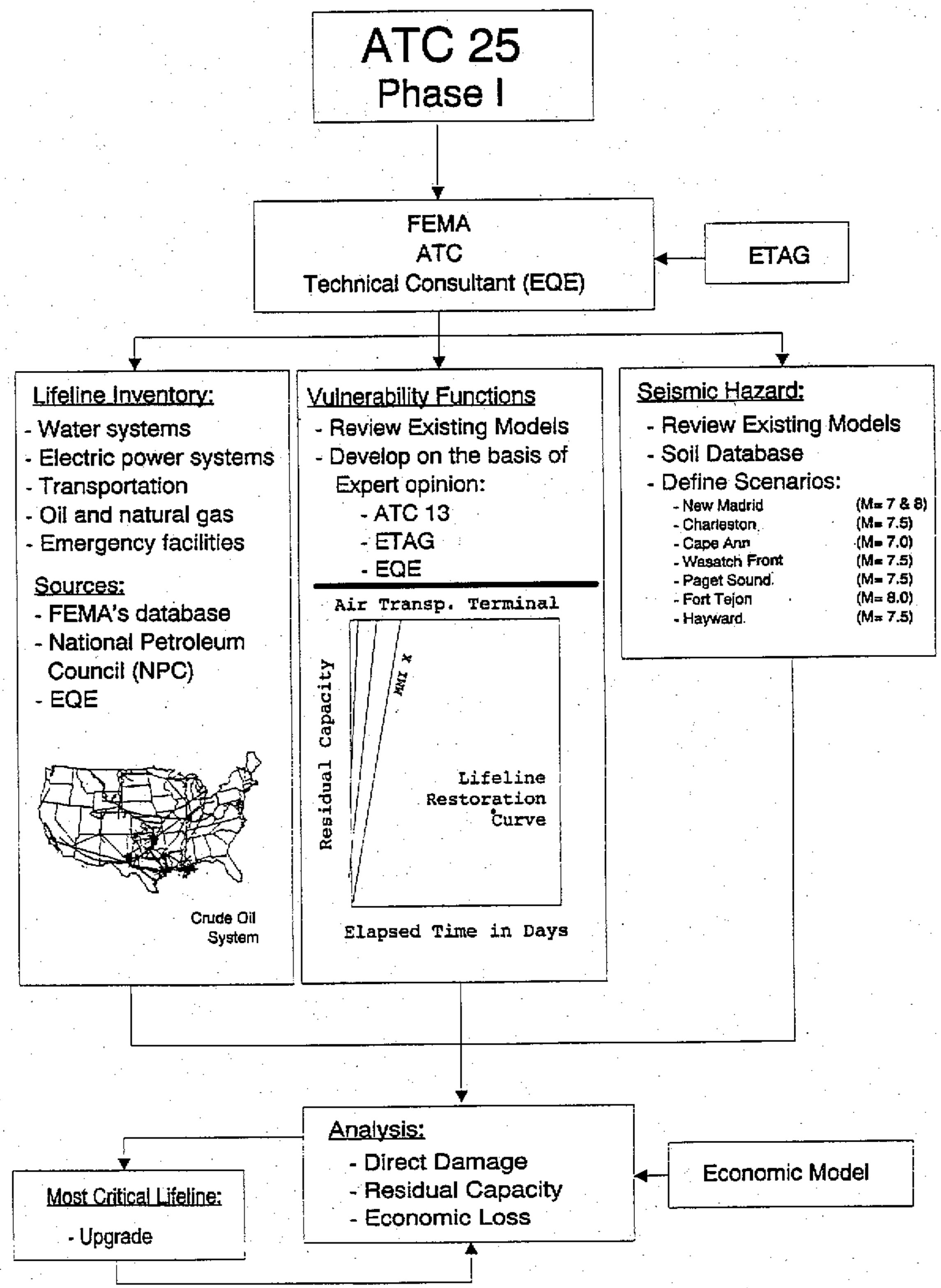
During development of this report and its supporting data, several problems were encountered that could not be resolved because of technical difficulties and lack of available data. For example, telecommunication systems, nuclear and fossil-fuel power plants, dams, and certain water, electric, and transportation 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.