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Technical Report NCEER-96-0011

August 16, 1996

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# NOTICE

NATIONAL CENTER FOR EARTHQUAKE ENGINEERING RESEARCH

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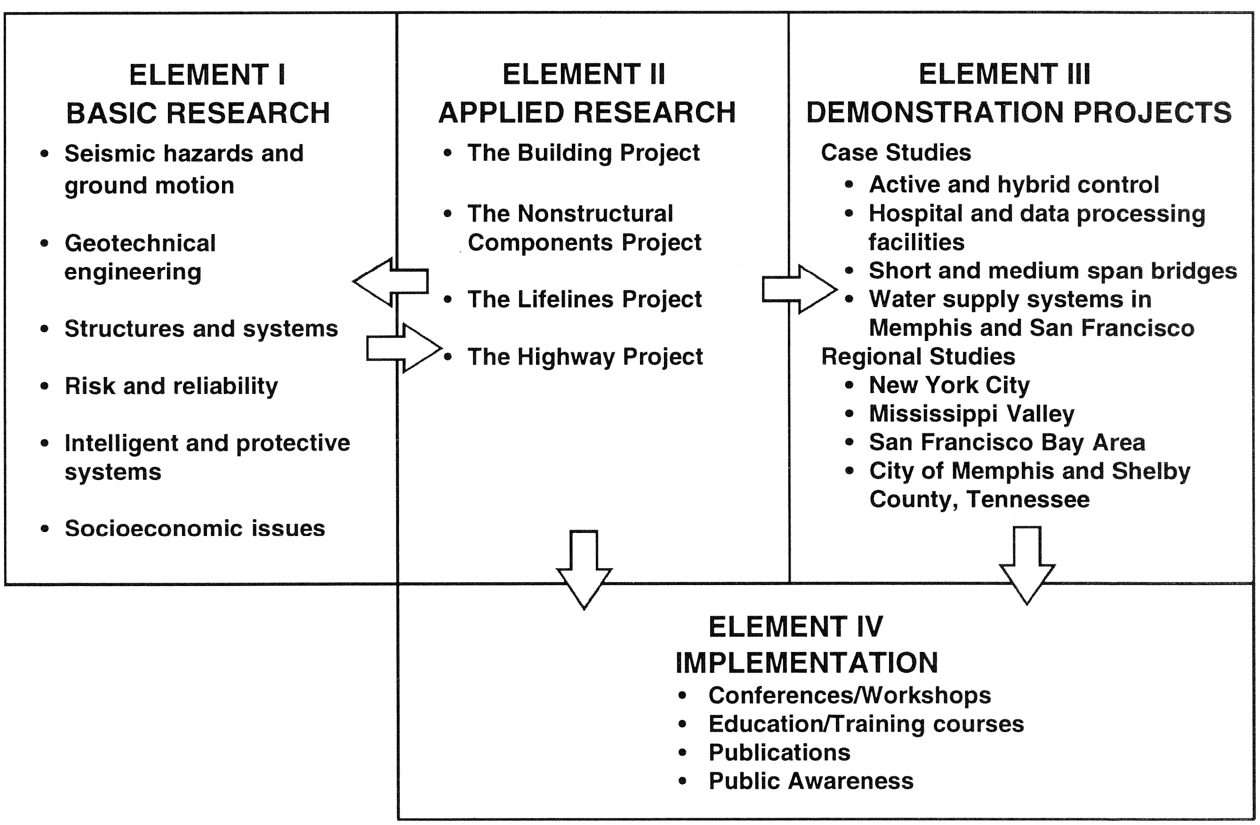
## PREFACE

The National Center for Earthquake Engineering Research (NCEER) was established in 1986 to develop and disseminate new knowledge about earthquakes, earthquake-resistant design and seismic hazard mitigation procedures to minimize loss of life and property. The emphasis of the Center is on eastern and central United States *structures*, and *lifelines* throughout the country that may be exposed to any level of earthquake hazard.

NCEER's research is conducted under one of four Projects: the Building Project, the Nonstructural Components Project, and the Lifelines Project, all three of which are principally supported by the National Science Foundation, and the Highway Project which is primarily sponsored by the Federal Highway Administration.

The research and implementation plan in years six through ten (1991-1996) for the Building, Nonstructural Components, and Lifelines Projects comprises four interdependent elements, as shown in the figure below. Element I, Basic Research, is carried out to support projects in the Applied Research area. Element II, Applied Research, is the major focus of work for years six through ten for these three projects. Demonstration Projects under Element III have been planned to support the Applied Research projects and include individual case studies and regional studies. Element IV, Implementation, will result from activity in the Applied Research projects, and from Demonstration Projects.



Research tasks in the **Lifeline Project** evaluate seismic performance of lifeline systems, and recommend and implement measures for mitigating the societal risk arising from their failures or disruption caused by earthquakes. Water delivery, crude oil transmission, gas pipelines, electric power and telecommunications systems are being studied. Regardless of the specific systems to be considered, research tasks focus on (1) seismic vulnerability and strengthening; (2) repair and restoration; (3) risk and reliability; (4) disaster planning; and (5) dissemination of research products.

The end products of the **Lifeline Project** will include technical reports, computer codes and manuals, design and retrofit guidelines, and recommended procedures for repair and restoration of seismically damaged systems.

The **societal and economic impact program** constitutes one of the important areas of research in the **Lifeline Project**. The program involves identifying, quantifying, and analyzing the impacts earthquakes and other natural disasters have on the populations and socio-economic systems of impacted regions. The primary focus of this program is on the interaction between the social and economic system and the built physical environment which accommodates it. The major tasks are as follows:

1. Fundamental research concerning the built physical environment system.
2. Fundamental research concerning the social and economic system, including investigations of macro-economic impact, epidemiology of casualties, and housing reconstruction.
3. Specific research concerning the social and economic system such as the economics of non-structural component and lifeline failures, and the social consequences of lifeline failures.
4. Knowledge utilization research focused on professional and private acceptance of research results.

*This is a comprehensive multidisciplinary study of the direct and indirect economic impact of electricity, gas, and water utility lifeline disruptions resulting from a major earthquake. It is based on a sound, and, at times innovative, methodology. The underlying assumptions are reasonable and it utilizes the best available data. Moreover, the authors have performed some sensitivity analyses. The report builds on the work of other NCEER researchers in both the areas of engineering and economics. It is a clear advance over other studies that have either limited their analyses to a single lifeline, or that have not used the proper economic definitions of direct and indirect effects. The authors have set forth a methodology that can readily be used by teams of engineers and economists to simulate the effects of hypothetical earthquakes, and, with some minor modifications, to estimate the lifeline-related impacts of actual events.*

## ABSTRACT

This technical report focuses on the estimation of economic losses from urban lifeline disruption in seismic events. A methodological approach is developed and applied to estimating losses that would be incurred in Memphis/Shelby County, Tennessee in the event of a large hypothetical seismic event in the New Madrid Seismic Zone (NMSZ). Disruption to the natural gas, electric power and water lifeline systems is considered. Economic loss is evaluated for each of the three lifelines individually, as well as for the case of multiple lifeline disruption. The scope includes evaluation of four types of economic loss: lifeline facility repair costs, revenue losses to the utility provider, direct economic loss suffered by utility customers, and the consequent indirect economic loss in the region. This study focuses on the development of methods for estimating direct economic loss and pays particular attention to inter-industry and intra-regional differentials in impact. As part of a larger NCEER coordinated project on Urban Seismic Risk Assessment, it utilizes results from associated NCEER studies on hazard assessment, lifeline damage and outage estimation, business impact assessment, GIS/business location mapping, and indirect economic impact analysis.

## TABLE OF CONTENTS

**TABLE OF CONTENTS (cont'd)**

## TABLE OF CONTENTS (cont'd)

**TABLE OF CONTENTS (cont'd)**

## LIST OF ILLUSTRATIONS

## LIST OF ILLUSTRATIONS (cont'd)

## LIST OF TABLES

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# SECTION 1

# INTRODUCTION

Recent earthquake disasters have vividly demonstrated the seismic vulnerability of lifeline systems and the severe socio-economic impact of lifeline service disruption. In the January 17, 1994 Northridge earthquake, for example, the M 6.7 event caused a complete blackout in the Los Angeles Department of Water and Power service area for the first time in the utility company's history. About 15 percent of its customers were left without water. Southern California Edison Company also suffered power loss to 25 percent of its customers, and Southern California Gas Company had service disruption to 3 percent of its customers (Eguchi 1995).

Lifeline disruption was even more severe in the Great Hanshin earthquake disaster that struck Kobe, Japan, one year later. The M 6.9 event caused severe damage to almost all of the major lifeline systems, including electric power, water, wastewater, natural gas, and transportation. About 2.6 million households lost electricity, 1.3 million lost water, 860,000 lost gas, and 300,000 lost telephone service. Three major highways, all of the major railroad transportation lines in the region, and the Port of Kobe were severely damaged. Restoration of electric power and telecommunications service was completed within a few days; however, full restoration of water and natural gas took much longer, requiring roughly two and a half to three months (Takada and Ueno 1995; Goltz 1996).

Despite the importance of lifeline disruption in the impact of earthquakes on urbanized areas, economic loss evaluation for seismically induced lifeline service disruption has only recently emerged as an area of research. It may be particularly indicative to note that while the standardized earthquake loss estimation methodology under development for the National Institute of Building Sciences (NIBS) does include a module for evaluating the direct and indirect economic impact of building damage, its treatment of lifeline impact is limited to an assessment of repair costs (RMS 1995). Similarly, an important study of the regional economic impact of the

Northridge earthquake conducted at the University of Southern California (Gordon and Richardson 1995) limits its scope to the effects of building damage.

A few recent studies have focused specifically on loss estimation for lifeline systems. An important reference in this area is ATC-25 (1991), "Seismic Vulnerability and Disruption of Lifelines in the Conterminous United States," which develops generalized lifeline damage, outage, restoration and direct economic impact models. A recent NCEER study provides an assessment of the potential economic losses from damage to crude oil transmission systems in a NMSZ earthquake (Wiggins 1994). Rose and Benavides (1996) and Rose et al. (1997) focus on estimating economic losses associated with electric power disruption. In terms of empirical studies, Rose and Lim (1996) apply an input-output modeling approach to evaluate the total direct and indirect economic impact of electric power outage in the Northridge earthquake. Chang (1996) and Chang and Taylor (1995) develop an empirical regression model to evaluate the contribution of lifeline disruption to total economic loss in the Great Hanshin earthquake.

This technical report summarizes the research conducted by EQE International, Inc. on urban seismic risk assessment for lifeline systems under NCEER grants number 926301A and 936301. The objectives of this research are (1) to develop a methodological approach for estimating economic losses from disruption of urban lifeline services in earthquake disasters, and (2) to demonstrate its application for a large postulated seismic event in the New Madrid Seismic Zone (NMSZ). The study evaluates several different types of economic loss including lifeline facility repair costs, revenue loss to the utility provider, direct economic loss suffered by utility customers, and the consequent indirect economic loss in the region. The scope is limited to the natural gas, electric power and water delivery lifeline systems, and the focus of the demonstration is Memphis/Shelby County, Tennessee.

This project concentrates on methodologies for estimating direct economic loss. In the past, this area has represented a critical yet weakly formed bridge between the engineering and social science dimensions of the earthquake impact assessment problem. For example, engineering modeling results of physical damage need to be translated into socioeconomic terms in order to be usable for economic impact analysis. This study addresses the need to develop a balanced and integrated multi-disciplinary earthquake loss estimation framework for lifeline systems. An earlier summary version of the direct economic loss estimation methodology can be found in Chang et al. (1995).

This research comprises one part of a larger NCEER coordinated effort on urban seismic risk assessment under the Lifelines Project. This effort, documented in a forthcoming monograph on the impact of electric power disruption in a scenario NMSZ earthquake on the economy of Memphis/Shelby County, has involved a multi-disciplinary team of investigators focusing on different aspects of the loss estimation problem (NCEER, 1996). Part of the current study is summarized in the monograph; however, this technical report also contains a substantial amount of material and detail that does not appear in the monograph. These include, most notably, assessment of repair costs and utility revenue loss, consideration of natural gas and water delivery systems, and loss estimation within a multiple lifeline disruption framework.

The successful completion of this study owes much to the cooperation and assistance of several individuals and institutions. In particular, the work of the following NCEER researchers provided critical input into this study: H. Hwang at the Center for Earthquake Research and Information at Memphis State University (hazard assessment); M. Shinozuka and S. Tanaka at Princeton University (lifeline damage and outage estimation); K. Tierney at the Disaster Research Center of the University of Delaware (business impact assessment); S. French at Georgia Tech University (GIS/business location mapping); and A. Rose at Pennsylvania State University (economic impact analysis). In addition, much valuable information was provided by Memphis Light Gas and Water Company (MLGW) on their facilities and operations. Finally, the authors are grateful to NCEER for supporting this project.

# SECTION 2

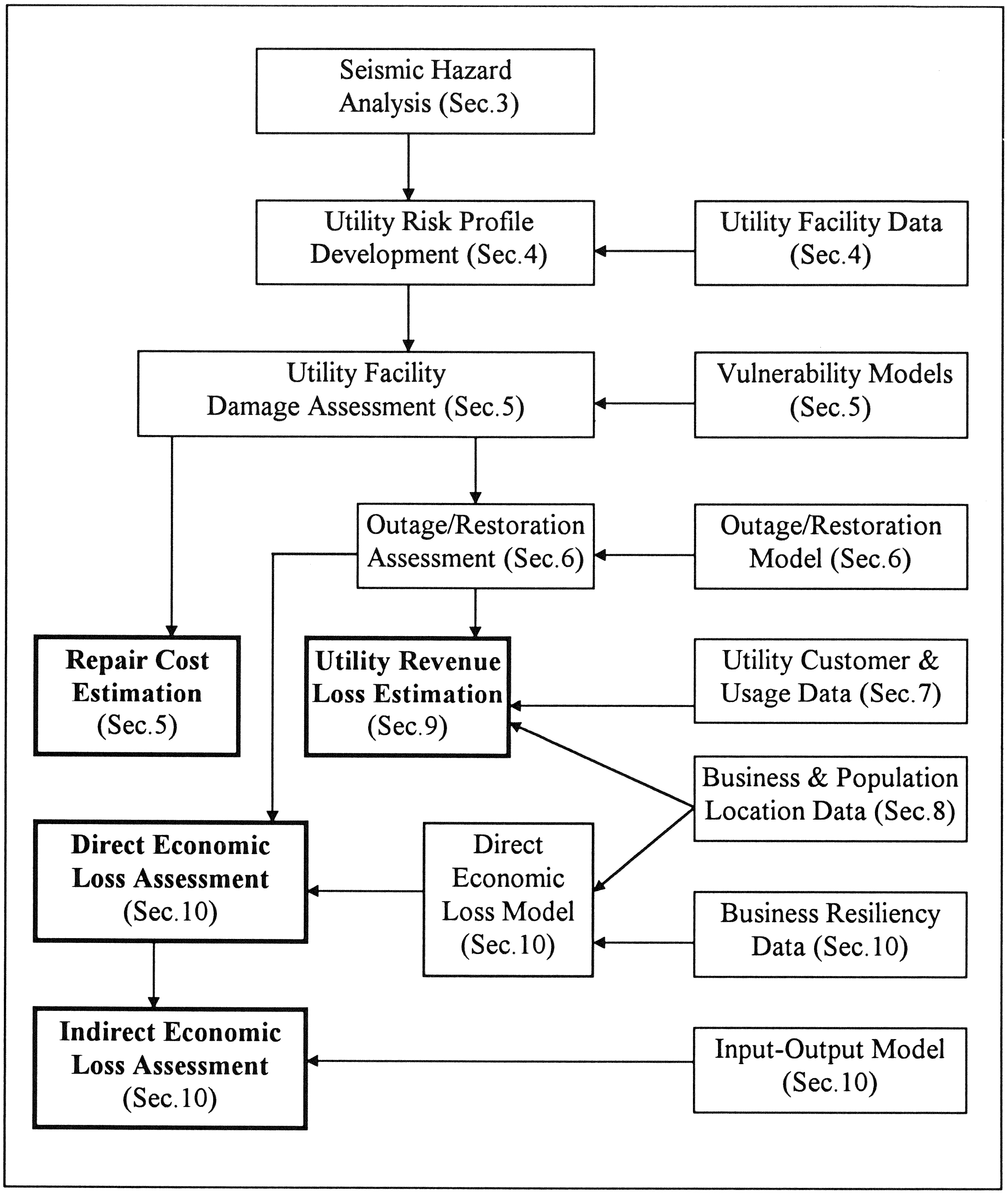
# METHODOLOGICAL APPROACH

The assessment of economic losses due to earthquake-induced utility disruption in an urban environment requires a multi-disciplinary approach. This study was conducted in coordination with a group of NCEER investigators representing a range of disciplines and utilizes results from their research as inputs into the loss estimation process. Because the focus of the study is the impact caused by lifeline disruption, other potential sources of economic loss in an earthquake such as building damage are not considered in the analysis. In order to demonstrate the application of such a loss estimation methodology, this study focuses on an assessment of economic losses related to the disruption of natural gas, electricity and water service provided by Memphis Light Gas and Water (MLGW) in the event of a large earthquake in the New Madrid Seismic Zone. MLGW serves Shelby County, Tennessee, including the city of Memphis.

The basic steps of the methodology developed in this study are shown in Figure 2-1. This approach is general and applicable to many urban utility networks, such as natural gas, water, electric power, and telecommunications. Boxes in boldface indicate the results of the analytical process, that is, the various components of total economic loss. Section numbers in parentheses indicate where each item is developed and discussed.

The first major step in the loss assessment, described in section 3, is the analysis of seismic hazard and liquefaction potential. This includes the development of earthquake scenarios and estimates of associated levels of ground shaking in terms of Modified Mercalli Intensity (MMI) throughout the affected area. For this study, seismic hazard analyses results from an NCEER study performed by Professor Howard Hwang and others at Memphis State University's Center for Earthquake Research and Information (CERI) are utilized directly.

Section 4 describes the next major step, the development of a utility risk profile. This profile combines the regional hazard information with data on utility facilities, such as pipeline and




notes: boxes in **boldface** indicate economic loss results

FIGURE 2-1 Flowchart of Economic Loss Estimation Methodology storage facility specifications and pipeline system maps, including locations of compressor stations. MLGW facility data have been collected by Professor Hwang.

The third step consists of utility facility damage assessment and is described in section 5. For the demonstration application, damage assessment was performed by various NCEER investigators and coordinated by Professor M. Shinozuka at Princeton University. Preliminary results of their damage assessment of the MLGW water delivery system were made available for use in the current study. Existing damage models or experience data were used to supplement this information for the other lifelines. Application of simple repair cost models yields an estimate of the first component of economic loss, the repair costs associated with utility facility damage in the earthquake.

Section 6 turns to the estimation of the damage-related utility service outage and the development of anticipated service restoration patterns. Initial outage results for the demonstration example were provided by Prof. Shinozuka and colleagues for the water and electric power utilities based upon probabilistic risk and reliability analysis. Restoration models are developed in this study based primarily upon experience in previous earthquakes.

Up until this point, analysis has focused on physical and engineering dimensions of damage and loss. In order to assess socio-economic impact, the methodology requires development of several additional databases. Section 7 describes the information on utility customers and their usage patterns for the various lifeline services. Most of this information was provided by MLGW and obtained through the assistance of Prof. H. Hwang. Section 8 describes geographic information on the locational patterns of the population and economic activity within Shelby County. Locational information, based on data collected from published and unpublished government sources, is important because loss estimation is conducted at the census tract level. A map identifying the census tracts in Shelby County is shown in Figure 2-2. Some of the locational information was provided by Profs. A. Rose and S. French. The census tract level of geographic disaggregation allows greater methodological refinement and analytical accuracy compared with, for example, county-level analysis. It permits the analysis of hazard variability,

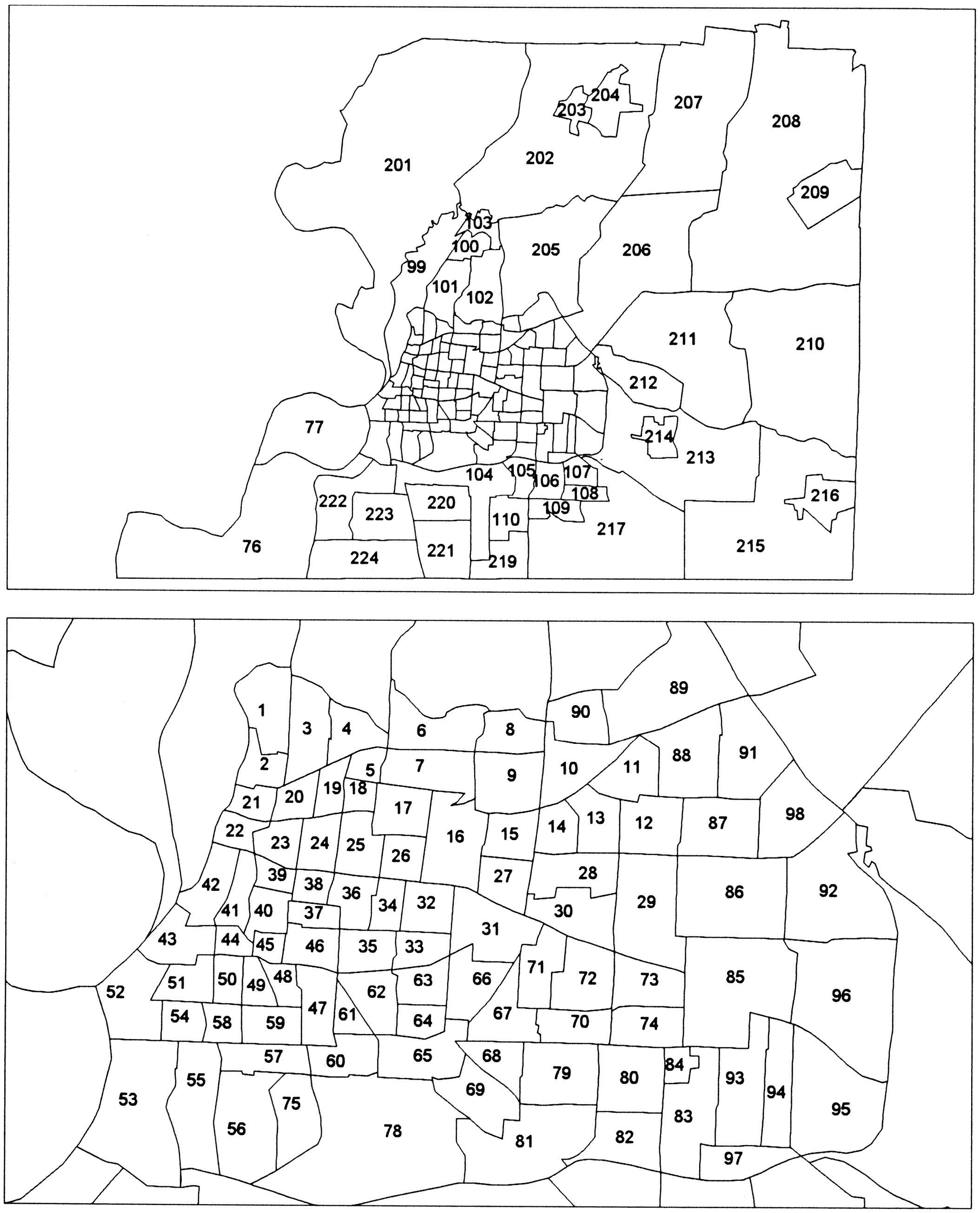



FIGURE 2-2 Census Tract Identification, Shelby County

for instance, throughout the study area. Furthermore, it provides a more useful picture of loss for potential end users such as local planners and public officials. Combining information on outage and restoration, utility service usage, and customer location patterns enables the estimation of revenue losses that the utility company might expect to experience due to loss of supply to its customers with natural gas, electric power, or water service. Estimation of utility revenue loss, the second component of total economic loss, is described in section 9.

Section 10 focuses on the final step in the methodology, estimation of the direct and indirect economic losses associated with lifeline service disruption. Direct economic losses are here defined as those business interruption losses suffered by utility customers because of lifeline service disruption at their place of production. Indirect economic losses consist of the multiplier effect of these direct economic losses, or the additional production losses that are suffered when reduced production by directly impacted businesses causes losses to their customers or suppliers who might not necessarily have suffered any direct impact.

In order to estimate direct economic losses, a model is developed based on existing methodologies in ATC-25 (1991), "Seismic Vulnerability and Disruption of Lifelines in the Conterminous United States." To implement the model, results are applied from a NCEER study conducted by Prof. K. Tierney on business disaster vulnerability and preparedness in Shelby County. Results from that study were used to develop a database on business resiliency to lifeline disruption. The direct loss model also requires information on customer location. Together with results on lifeline service outage and restoration, the model is used to estimate the direct economic losses associated with disruption of gas, electric power and water individually. Analysis of these results at the census tract level determines the direct economic loss when there is multiple lifeline disruption. Aggregation yields results on total direct economic loss. Note that the application to Shelby County utilized some unpublished data; for generality to cases where industry economic data may not be readily available, an alternative method for inferring this information is presented in Appendix A.

Finally, the indirect component of loss is estimated from the results on direct economic impact through application of an interindustry Input-Output analytical model. The indirect loss estimation methodology was developed by Prof. Rose and other researchers at Penn State, with input from EQE, for a related NCEER study and is described in Rose et al. (1997) and NCEER (1996). An input-output model of Shelby County developed for that study was applied here.

Section 11 summarizes the results presented in previous sections and provides a discussion of the significance of the findings, major methodological contributions of the study, and areas for further research.

# SECTION 3

# SEISMIC HAZARD ASSESSMENT

This section describes the seismic hazard modelling used in this study. Section 3.1 provides background to the hazards assessment, and section 3.2 describes the historic seismicity in the New Madrid Seismic Zone (NMSZ). A summary of data used for an earlier earthquake planning scenario is included for reference. Such information could be relevant for assessing the regional impacts of the scenario earthquake. Section 3.4 provides detailed seismic hazard data developed by other NCEER investigators for the scenario earthquake investigated in this study, a M 7.5 Marked Tree event, and the associated effects on Shelby County.

## 3.1 Background

The underlying assumption for most seismic hazard assessment methodologies is that the character of future seismic occurrences can be predicted from the history of past seismicity (Howell and Schultz, 1975). Seismic intensity, measured subjectively in terms of human response to shaking and associated damage, describes the degree of damage caused at a particular location. Intensity estimates are often used to characterize past seismicity rather than more precise instrumental measurements (e.g., peak ground acceleration) because the accumulated database for these physical quantities is small by comparison. Intensity estimates, in the form of intensity maps and reported maximum intensities ($I_O$), are available for many historic earthquakes. A condensed version of the most commonly used intensity scale in the United States, the Modified Mercalli Intensity (MMI) Scale, is presented in Table 3-1.

**TABLE 3-1 Modified Mercalli Intensity Scale**
(excerpt, abridged)

| | |
|---|---|
| I - V | Not significant to structures. |
| VI | Felt by all; many are frightened and run outdoors. Some heavy furniture moves; a few instances of fallen plaster or damaged chimneys. Damage slight. |
| VII | Everybody runs outdoors. Damage negligible to buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving motorcars. |
| VIII | Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Chimneys, factory stacks, columns, monuments and walls fall. Heavy furniture overturned. Disturbs persons driving motorcars. |
| IX | Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; damage great in substantial buildings with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken. |
| X | Some well-built wooden structures destroyed; most masonry and frame structures destroyed. along with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks. |

## 3.2 Historic Seismicity of the New Madrid Seismic Zone

Unlike most earthquakes, which occur along faults at the boundaries of rigid crustal plates, earthquakes originating in the New Madrid Seismic Zone are intraplate events located away from a plate boundary. The NMSZ forms a rough zigzag pattern; the southwestern extension begins at Marked Tree, Arkansas, and continues northeast to Caruthersville, Missouri; the middle stretch begins at Ridgely, Tennessee, and extends northwest to New Madrid, Missouri; and finally northeast to Cairo, Illinois (Metzger, 1974).

Johnston and Nava (1985) describe the NMSZ as follows:

> Geographically, the zone lies within the Mississippi embayment, a sediment-filled structural trough opening south to the Gulf Coastal Plain. Geophysically, it is contained within the Reelfoot Rift, thought to have formed in late Precambrian times and to be currently experiencing compressive reactivation of some structural features. Because the zone generated a series of great earthquakes in the winter of 1811 - 1812, because it is located in a tectonic feature of dimensions capable of supporting large earthquakes, and because it exhibits a relatively high level of present-day seismicity, it is considered the highest seismic hazard zone in the United States east of the Rocky Mountains.

A possible explanation for the seismic activity in this area is offered by the "zone of weakness model" (Braile et al., 1984), wherein "... contemporary earthquake activity is due to a reactivation of ancient faults buried within the crystalline crust which are presently subjected to an appropriately oriented stress field".

The most significant earthquakes occurring in this area were a series of four events in the winter of 1811 - 1812. It is estimated that at least three of these had magnitudes of 8.0 or greater. No earthquakes larger than these have occurred within the coterminous United States during historical times. The ground shaking from these events was felt over virtually the entire eastern U.S. (approximately 2.5 million square kilometers) with a maximum Modified Mercalli Intensity ranging from X to XII (Hopper, 1985). Ground failure, including fissures, sandblows, landslides and subsidence, occurred over a 48,000 square kilometer area. In addition, ground failure "... temporarily obstructed the flow of the Mississippi River in two places; and created innumerable navigational hazards on both the Mississippi and Ohio Rivers for hundreds of kilometers" (Street and Nuttli, 1984). Three smaller damaging earthquakes originating within the NMSZ have occurred since the 1812 series. Magnitudes and other information for these earthquakes are presented in Table 3-2.

Probability estimates for the recurrence of events similar to these are given in "Recurrence Rates and Probability Estimates for the New Madrid Seismic Zone" (Johnston and Nava, 1985), and are reprinted in Table 3-3.

**TABLE 3-2 Historical Earthquakes in the New Madrid Seismic Zone**
(Modified from Hopper, 1985)

| Date | Felt Area (km) | $M_s$ | $m_b$ | $I_o$ | General Epicentral Location |
|---|---|---|---|---|---|
| Dec 16, 1811* | 2,500,000 | 8.6 | 7.2 | XI | South of AR/MO border |
| Dec 16, 1811* | " | | 7.0 | | AR/MO border |
| Jan 23, 1812* | " | 8.4 | 7.1 | X-XI | Missouri Bootheel |
| Feb 7, 1812 | " | 8.7 | 7.3 | XI-XII | MO near KY/TN border |
| Jan 5, 1843 | 1,500,000 | -- | 6.0 | VIII | South end of NMSZ (TN) |
| Oct 31, 1895* | 2,500,000 | -- | 6.2 | IX | North end of NMSZ (MO) |
| Nov 9, 1968 | 1,500,000 | -- | 5.5 | VII | South-central Illinois |
| July 27, 1980 | --- | -- | 5.3 | VII | Northern Kentucky |

* Liquefaction observed

**TABLE 3-3 Recurrence Intervals and Probability Estimates for the New Madrid Seismic Zone**
(Johnston and Nava, 1985)

| Magnitude $M_s$ | $m_b$ | Recurrence Interval | Probability by the Year 2000 (15 year) | Probability by the Year 2035 (50 year) |
|---|---|---|---|---|
| ·6.3 | ·6.0 | 70 ± 15 | 40 - 63% (~50%) | 86 - 97% (~90%) |
| ·7.6 | ·6.6 | 254 ± 60 | 5.4 - 8.7% (~7%) | 19 - 29% (~25%) |
| ·8.3 | ·7.0 | 550 ± 125 | 0.3 - 1.0% | 2.7 - 4.0% |

### 3.3 Regional Earthquake Hazards in "Six Cities" Report

With the recognition of the NMSZ as a serious earthquake hazard has come comprehensive research, including placement of strong motion instrumentation, geologic and soils studies, and hazard assessments for use as planning tools. The Central United States Earthquake Preparedness Project (CUSEPP) prepared "An Assessment of Damage and Casualty Estimates for Six Cities in the Central United States Resulting from Earthquakes in the New Madrid Seismic Zone" (1985), also referred to as the "Six Cities report" as an emergency response planning tool for the Federal Emergency Management Agency (FEMA). The hazard data for the earthquake scenarios modelled (surface-wave magnitudes 7.6 and 8.6) were developed by the United States Geological Survey (USGS, 1985). The larger event, similar in size to the earthquakes of 1811 - 1812, was used for an assessment of the upper limits of damage, although the smaller event has a greater probability of occurrence and is considered "more appropriate for realistic risk assessment" (CUSEPP, 1985). In fact, the report notes that "... recent research has theorized that current strain in the New Madrid Seismic Zone would create a $M_S$ = 7.6 earthquake if it were released today..." (CUSEPP, 1985).

Regional strong ground shaking estimates for the affected midwestern region were developed by the U.S. Geological Survey (USGS) for the "Six Cities" report. The ground shaking estimates (Algermissen and Hopper, 1984) are in the form of regional isoseismal maps for the states of Arkansas, Illinois, Indiana, Kentucky, Mississippi, Missouri, and Tennessee. These maps are based on isoseismals developed by Algermissen and Hopper for the 1843 and 1895 earthquakes, because these events are the largest historic earthquakes in the NMSZ for which sufficient data are available to make reasonably detailed isoseismal maps. The "Six Cities" regional isoseismal maps were constructed by first scaling the 1843 and 1895 isoseismals up to the scenario earthquake's epicentral intensity to develop two maps - one with a northern epicenter, and one with a southern epicenter. Together, these two maps are assumed to represent the attenuation patterns for large earthquakes likely to occur throughout the NMSZ. The two maps were combined graphically, taking the maximum MMI at each point. The zone of maximum intensity along the NMSZ was extrapolated to cover the gap between the two epicentral areas, since large earthquakes are assumed possible anywhere within this zone. Actual isoseismal contours were drawn, and then generalized to follow county boundaries for ease of application over the broad study area. The resulting maps are considered to represent likely intensities for an event of the given magnitude occurring anywhere within the New Madrid Seismic Zone. The contoured regional MMI map for the $M_S$ 7.6 event is given in Figure 3-1. As shown in the figure, MMI X is the maximum MMI expected in this event, affecting a small area surrounding the NMSZ.

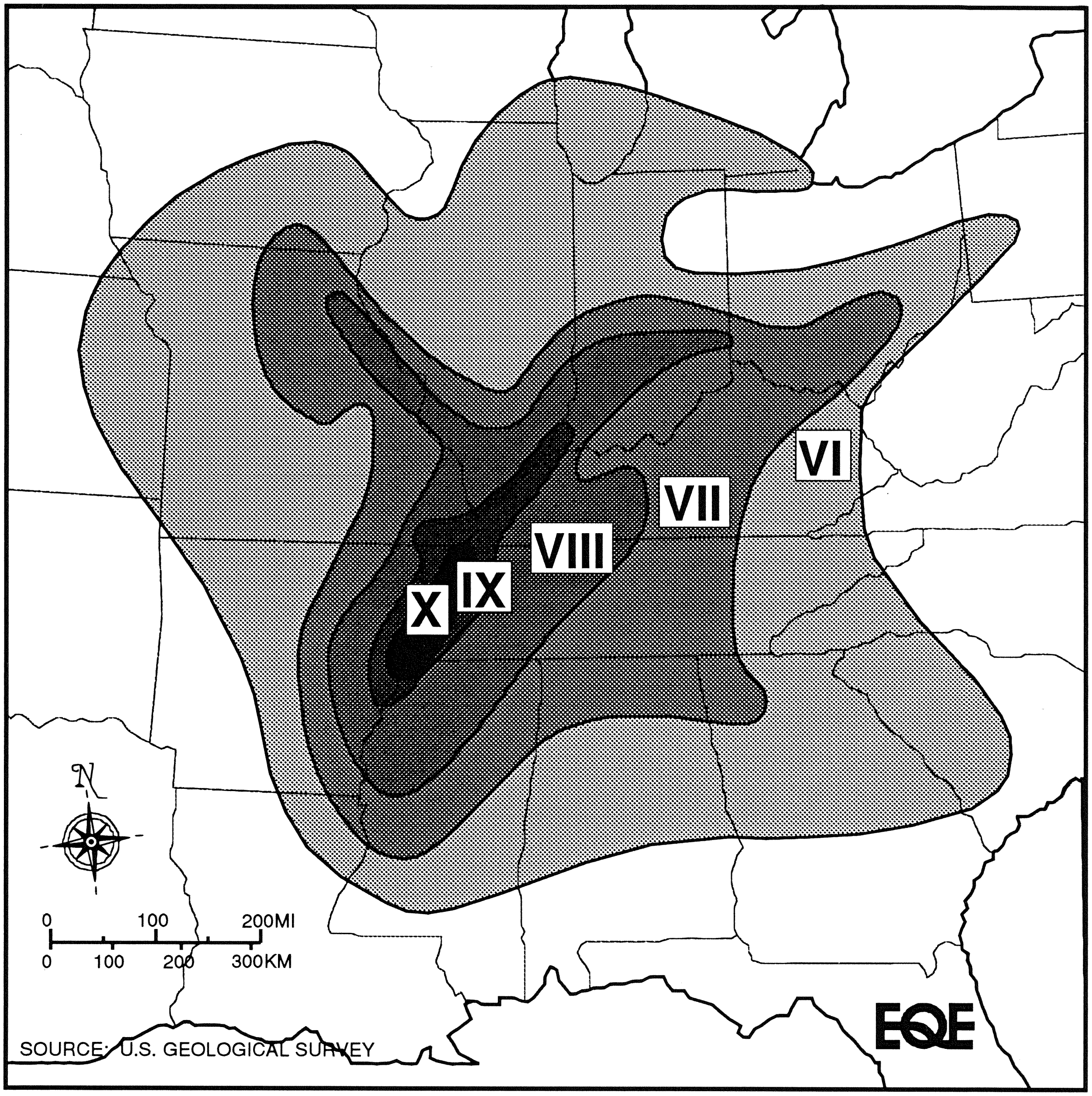



Figure 3-1: "Six Cities" Report MMI Map For Ms 7.6 NMSZ Earthquake

As part of the supporting models developed by the USGS for the "Six Cities" report, regional liquefaction potential maps for seven states in the larger scenario earthquake were generated (Obermeier and Wingard, 1985). These maps delineated areas of moderate to high liquefaction potential when subject to strong ground shaking from a recurrence of an 1811-1812 strength earthquake (M 8.6). While it is difficult to utilize these large scale maps directly for the smaller event and for a small-scale study area, some generalizations may be made from the supporting documentation (Obermeier, 1985).

Obermeier (1985) used historical reports of liquefaction to develop some generalized liquefaction threshold values for the area. In the 1811 - 1812 series of earthquakes, liquefaction-induced ground failure was "very commonplace and widespread" in the alluvial lowlands. Manifestations include sand blows, lateral spreads, ground fissures, and localized distortion and warping of the ground surface. Liquefaction was also commonplace, as evidenced by sand blows, in the 1895 earthquake. No liquefaction was reported in the 1843 or 1968 events. Generally, threshold values are as follows:

- A regional MMI VII is the liquefaction threshold for the very loose flood plain sands, i.e., modern flood plain deposits, regardless of earthquake magnitude.
- MMI VIII is the threshold for minor occurrences of liquefaction in very loose sediments.
- MMI IX is probably the intensity threshold at which damaging liquefaction becomes relatively commonplace in very loose to loose sands.

To summarize, liquefaction of very loose deposits may occur at levels as low as MMI VII, and become commonplace when shaking reaches MMI IX and greater.

The "Six Cities" report recognized the limitations of these large-scale, regional maps, for application to smaller study areas. As a result, damage estimates considered liquefaction only in a qualitative sense. It was noted that "Without specific knowledge of sub-surface conditions, nothing more than a categorical warning of such soil behaviors can be made." (CUSEPP, 1985)

The study did assume, however, that adverse soil conditions will exist along flood plains of existing rivers and streams. Ground failure was implicitly incorporated by increasing ground shaking intensities in areas thought to have vulnerable soils. In addition, for the Memphis area, several small zones of soil susceptible to liquefaction identified in other studies were presented.

The regional maps developed for the "Six Cities" study predict generalized ground shaking throughout Shelby County, Tennessee of MMI IX for the $M_S$ 7.6 event. In addition, Memphis was one of the six cities studied in the report, for which some additional, more detailed, hazard mapping was performed. This mapping predicted MMI VIII and IX for the city of Memphis in the scenario earthquake. MMI IX is expected to occur in the alluvial valleys, areas of high amplification, and areas susceptible to liquefaction.

## 3.4 NCEER Seismic Hazard Studies for Shelby County

### 3.4.1 Hazards Assessment

A detailed assessment of the seismic hazards facing Shelby County, Tennessee has been made by other NCEER investigators (Hwang, et al., 1989, 1990; Hwang, 1991; Hwang and Lee, 1991; Shinozuka et al., 1992). These publications represent the results of a multi-year effort to assess the seismic hazards of the Memphis water supply system operated by Memphis Light, Gas and Water (MLGW) Division.

The initial hazard assessment (Hwang et al., 1989) included calculation of peak bedrock accelerations throughout the County of Shelby for 2 NMSZ events: a $M_W$ 7.5 and a $M_W$ 6.5. The larger event "represents a major event to be considered for seismic risk assessment and emergency response planning". This event is similar in size to the $M_S$ 7.6 event used by the USGS in the "Six Cities" report. Two sources were postulated for each event; a single point source at Marked Tree, Arkansas; and the southern-most segment of the NMSZ. Results were presented in the form of peak bedrock acceleration contour maps.

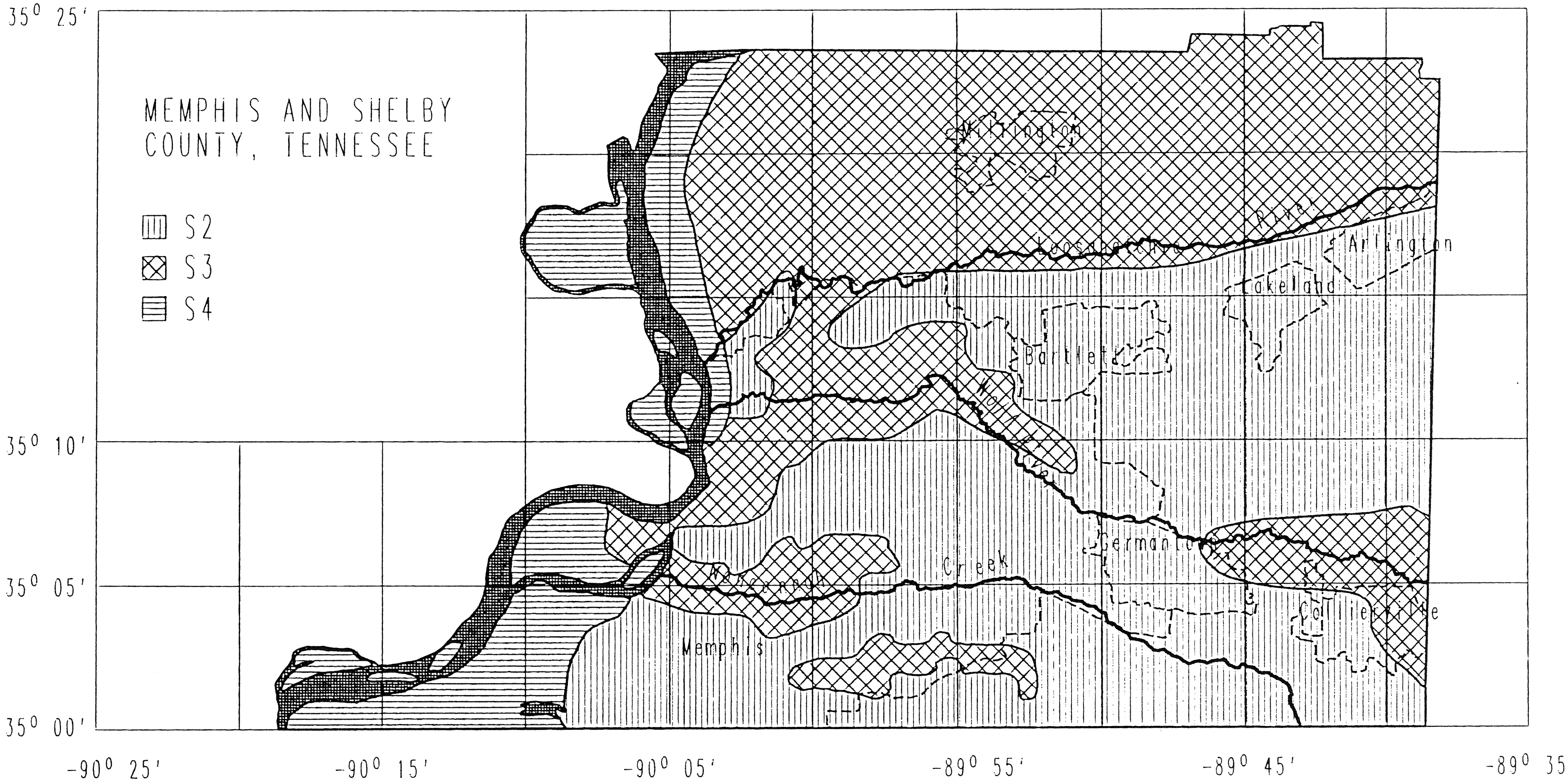
The next phase of work incorporated local soil effects into the hazard assessment (Hwang et al., 1990). For the $M_W$ 7.5 event at Marked Tree, 424 representative boring logs throughout the county were utilized to implement a site response analysis. Results include a generalized soil profile according to UBC soil classifications (Figure 3-2), and a map of peak ground acceleration shown in Figure 3-3. In general, the ground accelerations are smaller than the bedrock accelerations because the soil deposits appear to filter out a significant portion of the high frequency motion. Peak ground accelerations (PGAs) for the county in this event range from 0.09g to 0.23g. This data was later used to develop a Modified Mercalli Intensity map for Shelby County, described below.

In addition, a liquefaction potential analysis was performed, and a generalized liquefaction potential map developed for the Shelby County area (Hwang, 1991). Geotechnical data from the same representative boring logs were used to compute the expected severity of liquefaction in the scenario earthquake. The liquefaction potential map is reproduced in Figure 3-4. It was found that (Hwang, 1991):

- only a few isolated areas have major liquefaction potential;
- some areas along the Mississippi River, Wolf River and Loosahatchie River, plus a small zone near Millington are exposed to moderate liquefaction;
- minor liquefaction potential is expected in the Mississippi alluvial plain, and areas along the Wolf River;
- the majority of the Memphis/Shelby County area are subject to little or no liquefaction potential.

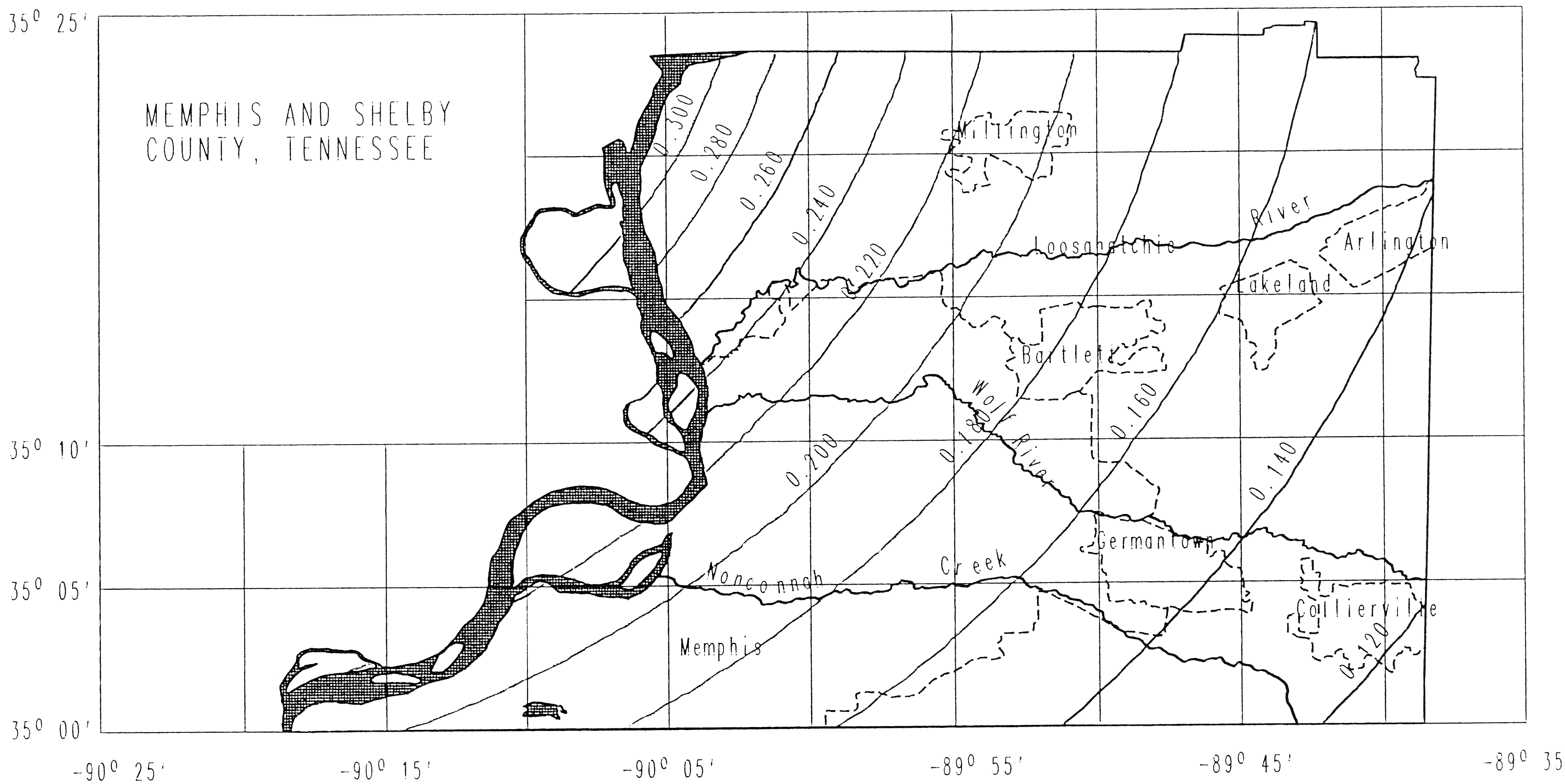
### 3.4.2 MMI Estimates for Scenario Earthquake

The current study focuses on the scenario $M_W$ 7.5 earthquake originating from a point source at Marked Tree, Arkansas, that has been studied in detail by several NCEER investigators. For



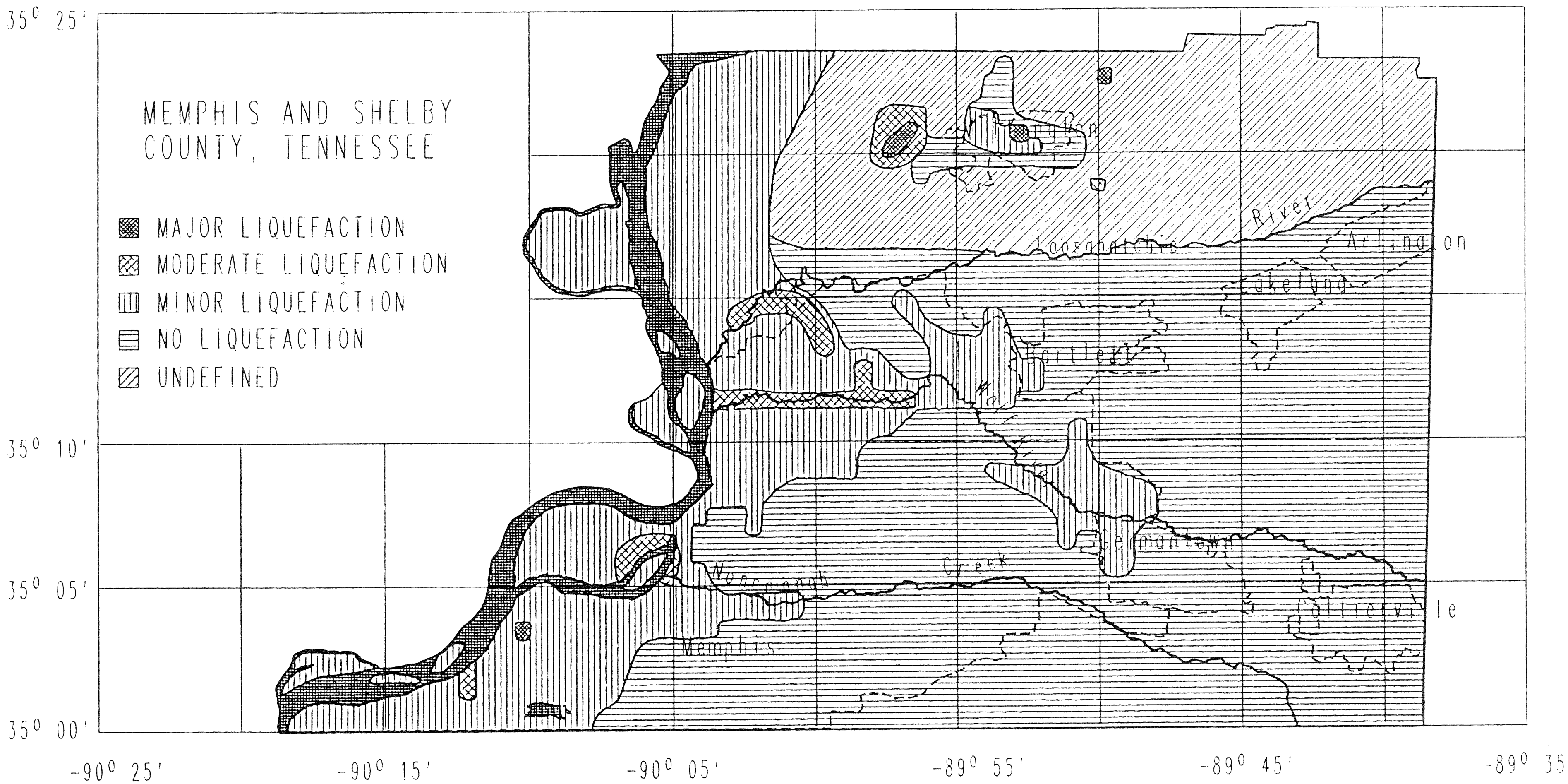
(Source: H. Hwang, CERI)

**FIGURE 3-2 Generalized Soil Classification Map**




(Source: H. Hwang, CERI)

**FIGURE 3-3 NCEER Contour Map of Horizontal Peak Ground Acceleration (M = 7.5, Marked Tree Event)**




(Source: H. Hwang, CERI)

**FIGURE 3-4 Generalized Liquefaction Potential Map**

purposes of damage and loss estimation, ground motion input was used in the form of Modified Mercalli Intensity. Prof. Hwang's estimates of MMI in Shelby County were presented in grid cell format. MMIs range from VII-1/2 to IX. However, the vast majority (99 percent) of the county is projected to experience either MMI VIII or VIII-1/2. In general, ground shaking intensity decreases as one moves from the northwest to the southeast of the county.

For purposes of estimating economic losses in this study, MMI levels for individual census tracts comprising Shelby County were estimated from intensity information from the grid cells. For those tracts which included grid cells of two or more different intensity levels, the MMI indicated for the majority of the land area was selected. The resulting MMI inferences for the census tracts are shown in Figure 3-5.

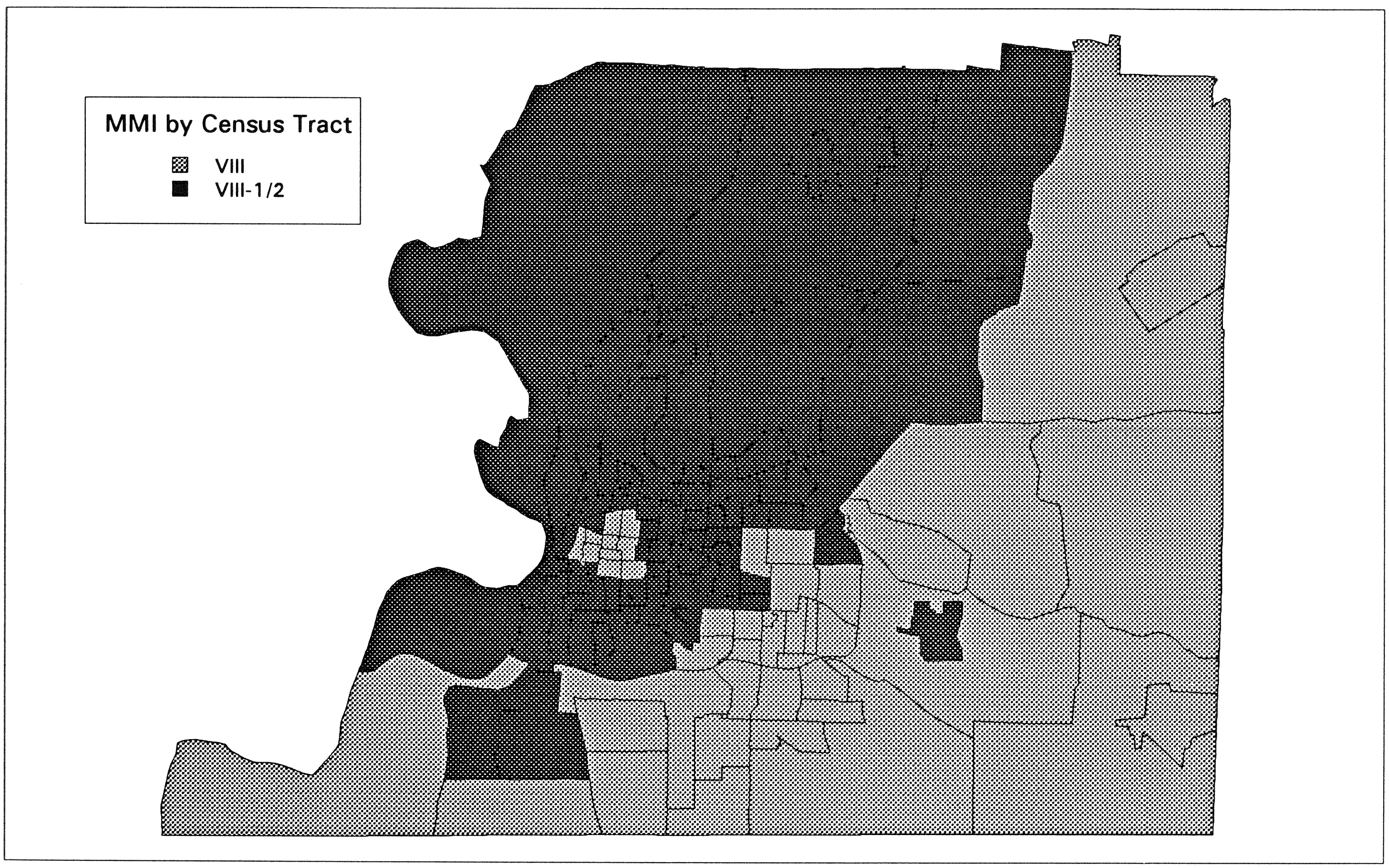



**FIGURE 3-6 MMI by Census Tract for Shelby County (M 7.5 Marked Tree Event)**

# SECTION 4

# MLGW FACILITIES AT RISK

Natural gas, electricity and water service is provided to the city of Memphis and Shelby County by Memphis Light, Gas and Water Division (MLGW). This section describes the facilities operated by MLGW and their exposure to the seismic hazards described in Section 3.

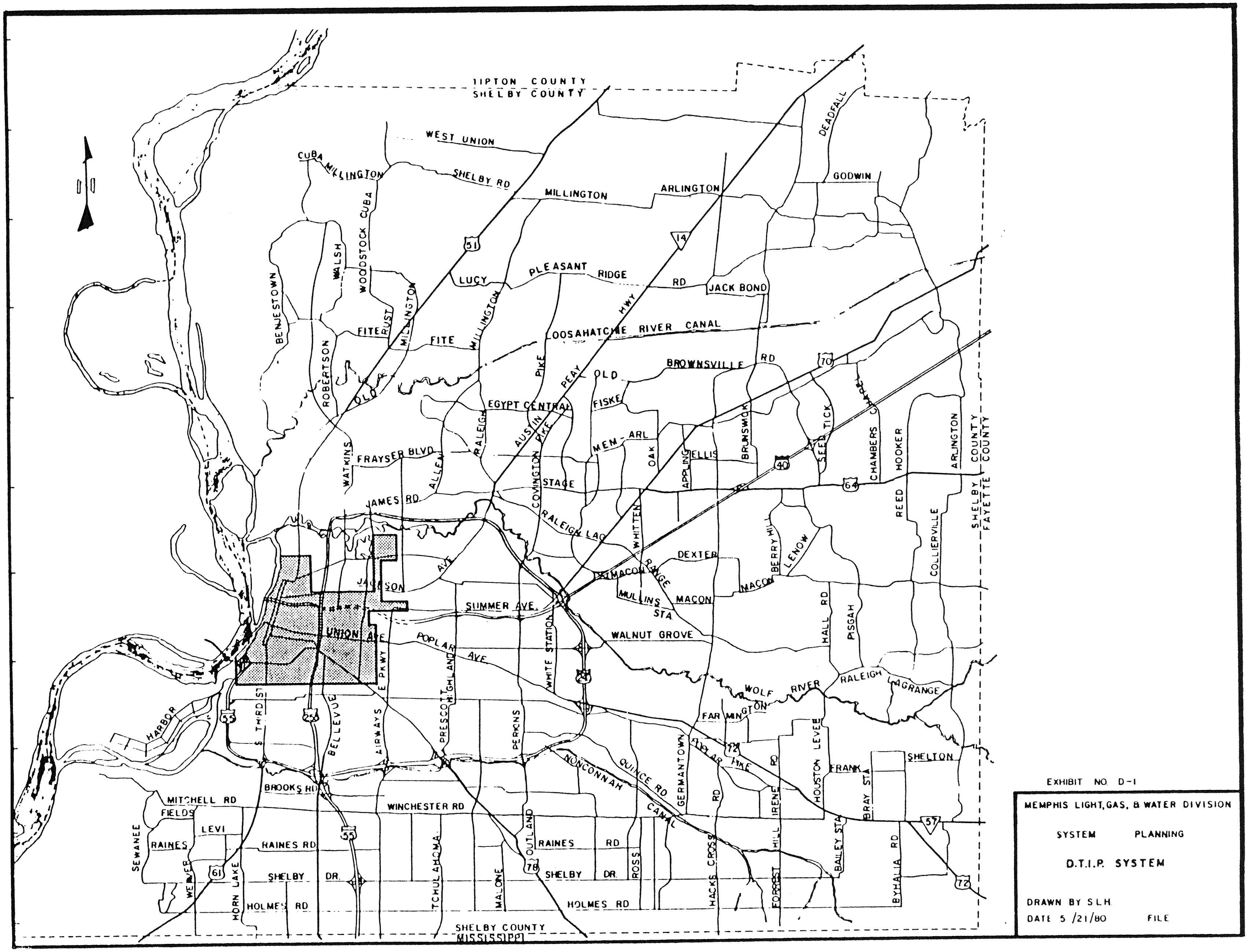
## 4.1 Natural Gas Facilities

Among Pipeline & Gas Journal's Top 300 Gas Distribution Utilities, MLGW ranked 52nd in terms of number of customers for 1991, when this study was undertaken. It services roughly 265,000 customers through more than 3,500 miles of main and 2,200 miles of services (P&GJ, 1992). As of November, 1991, it was reported that the distribution system consisted of approximately 73% steel pipe, ranging from 3/4 inch to 26 inches in diameter, 17% plastic pipe between 5/8 inch and 4 inches, and 10% cast iron pipe from 2 to 16 inches in diameter (P&GJ, 1991).

The 750,000 square mile service territory (Benson, 1992) includes five pressure systems, as follows (MLGW, 1992):

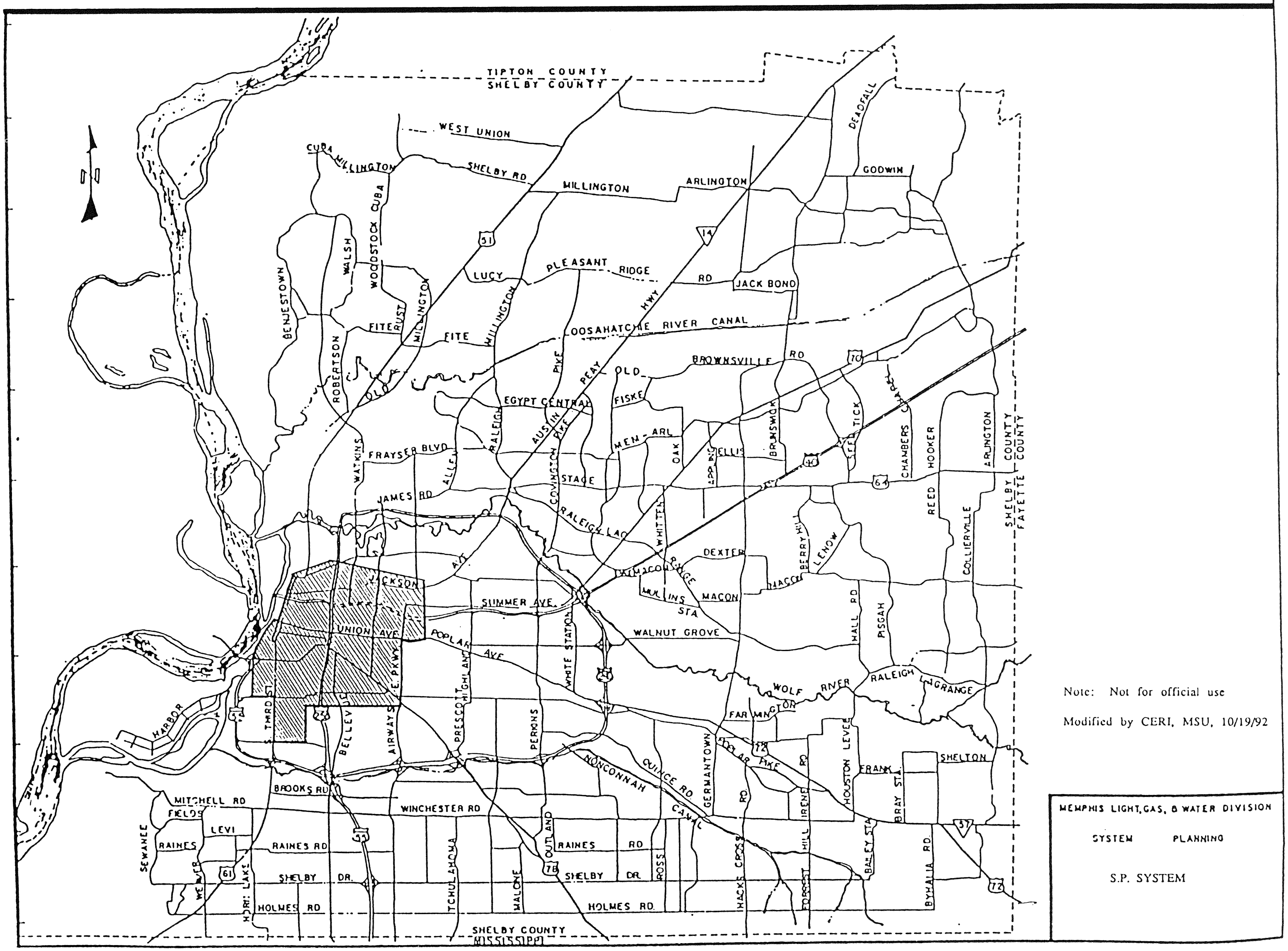
- Standard - 45,453 customers
- Inner Intermediate - 15,256 customers
- East Intermediate - 23,439 customers
- Medium (including Millington Medium) - 9,908 customers
- High - 170,510 customers

These pressure zones are delineated in Figures 4-1.*a* through *f*. The gas transmission network as modeled by H. Hwang at Memphis State University is shown in Figure 4-2.



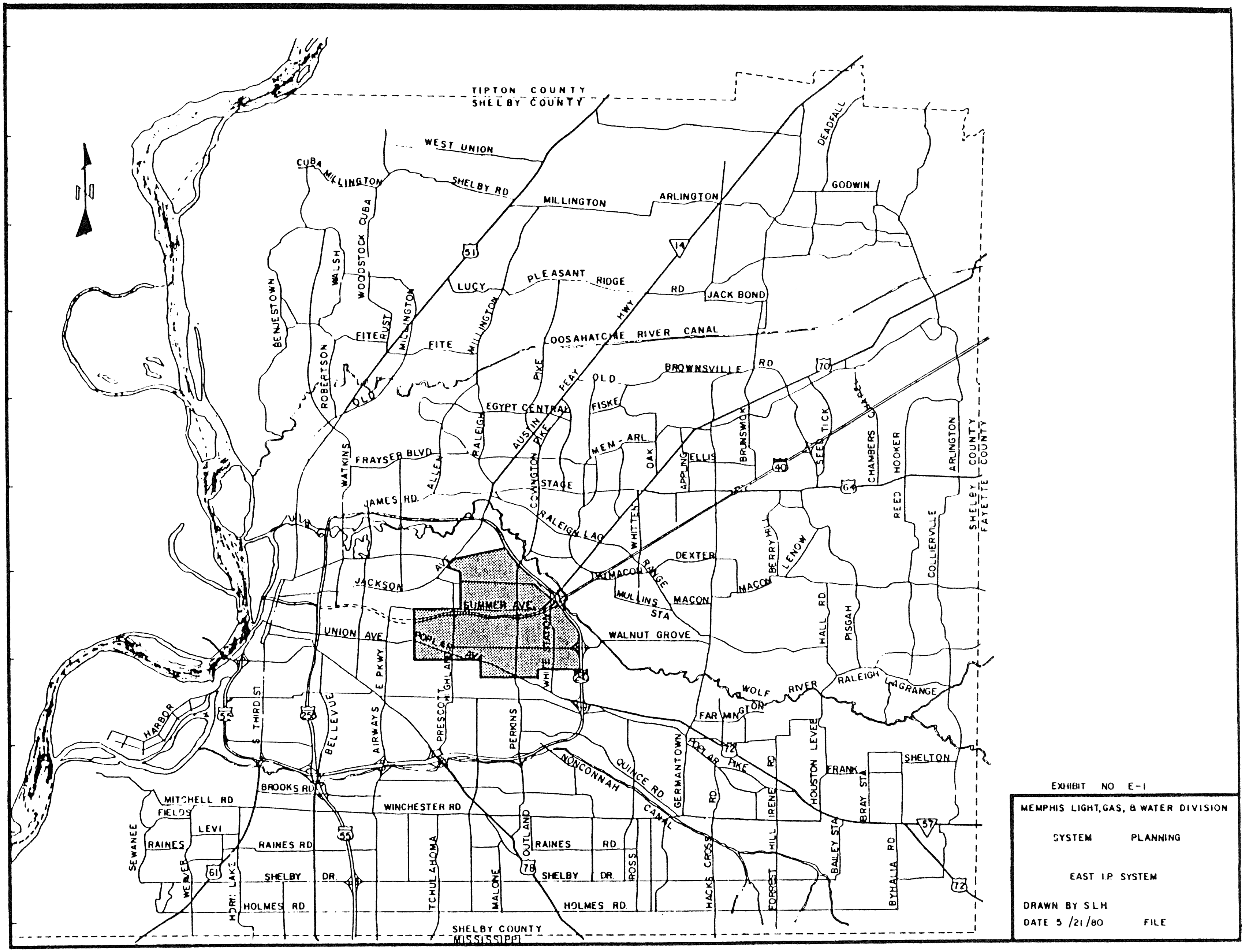

(Source: MLGW)

Figure 4-1a: MLGW Gas System: Inner Intermediate Pressure System



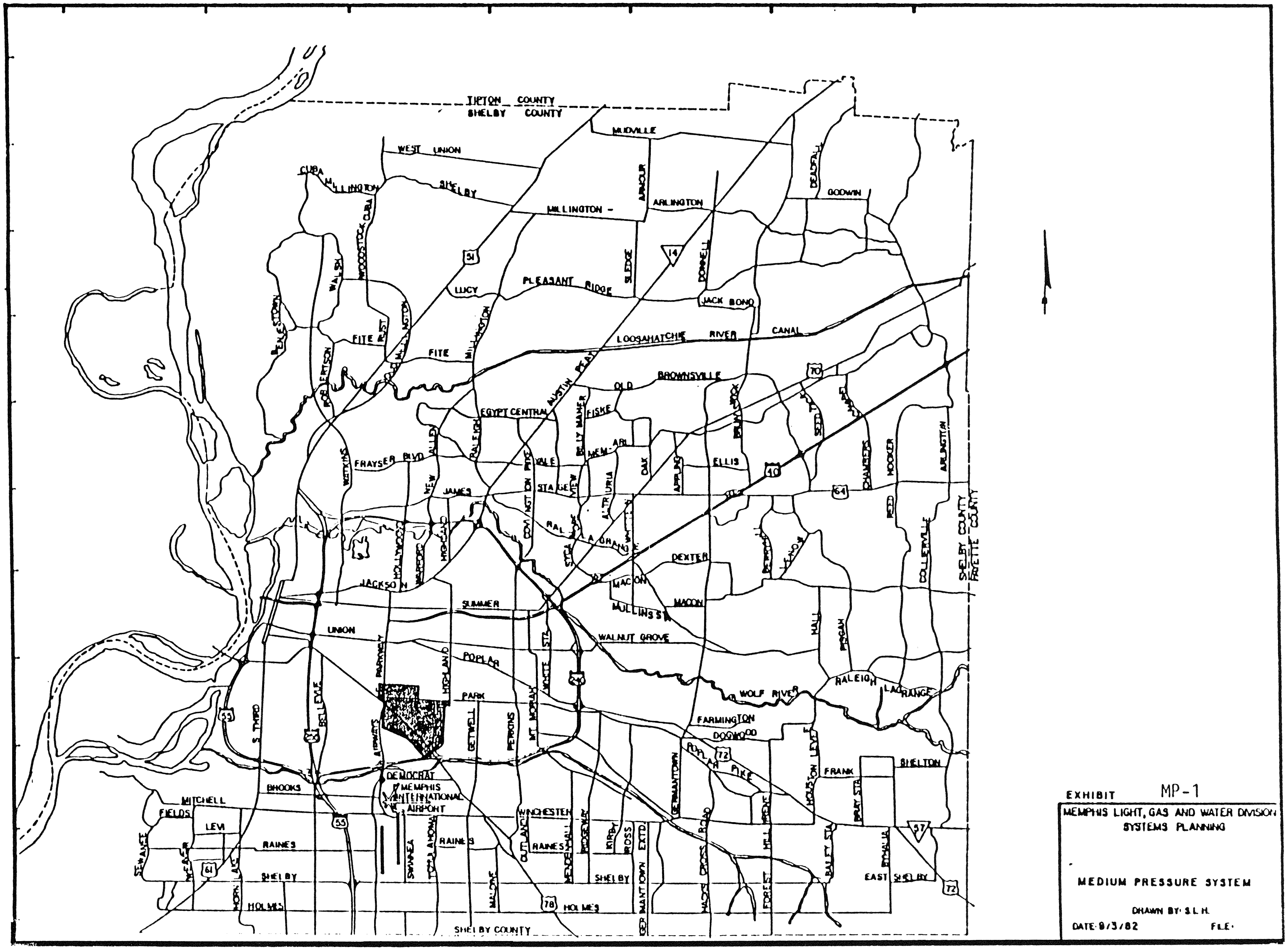

(Source: MLGW)

Figure 4-1b: MLGW Gas System: Standard Pressure System



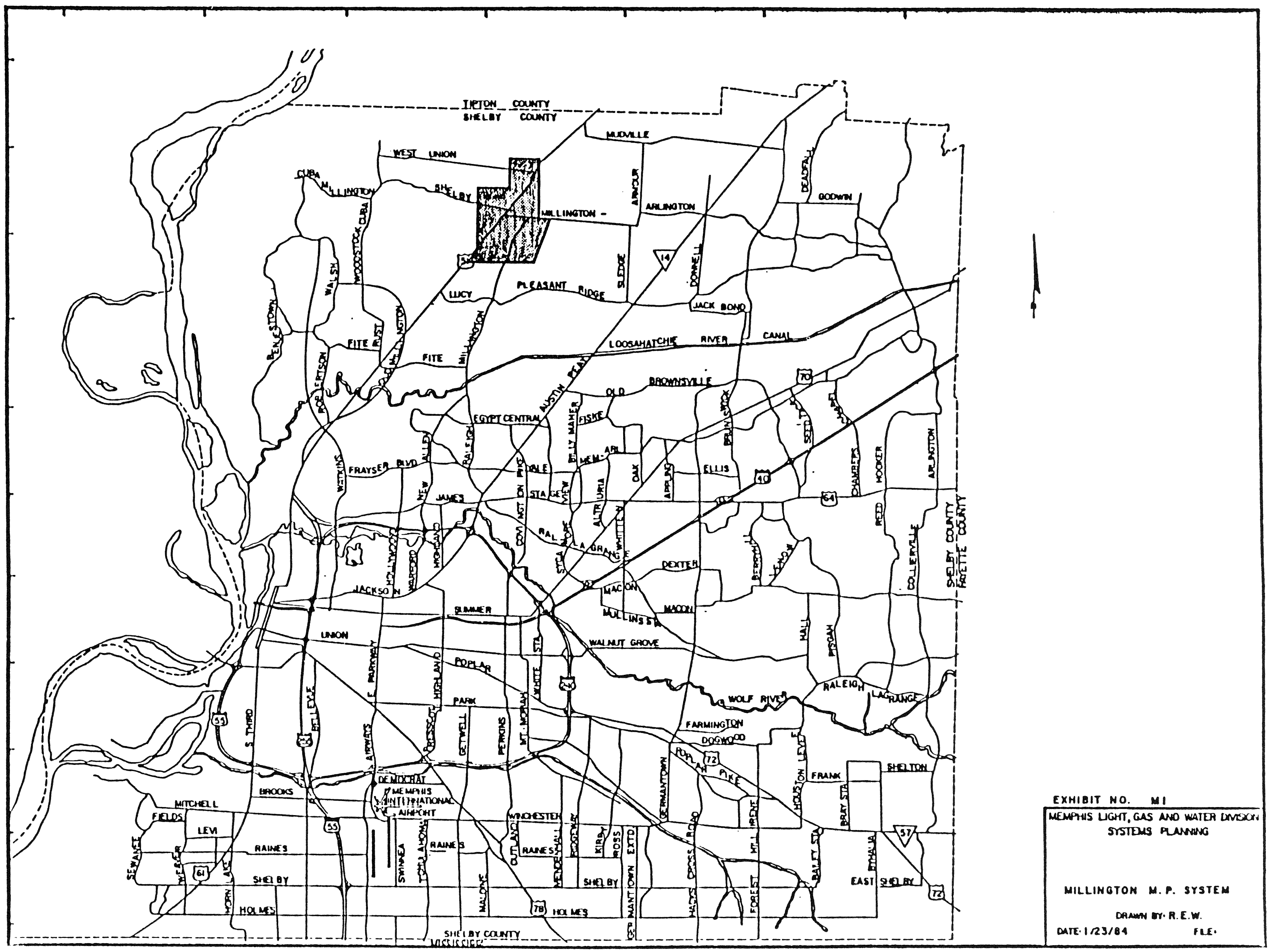

(Source: MLGW)

**Figure 4-1c: MLGW Gas System: East Intermediate Pressure System**



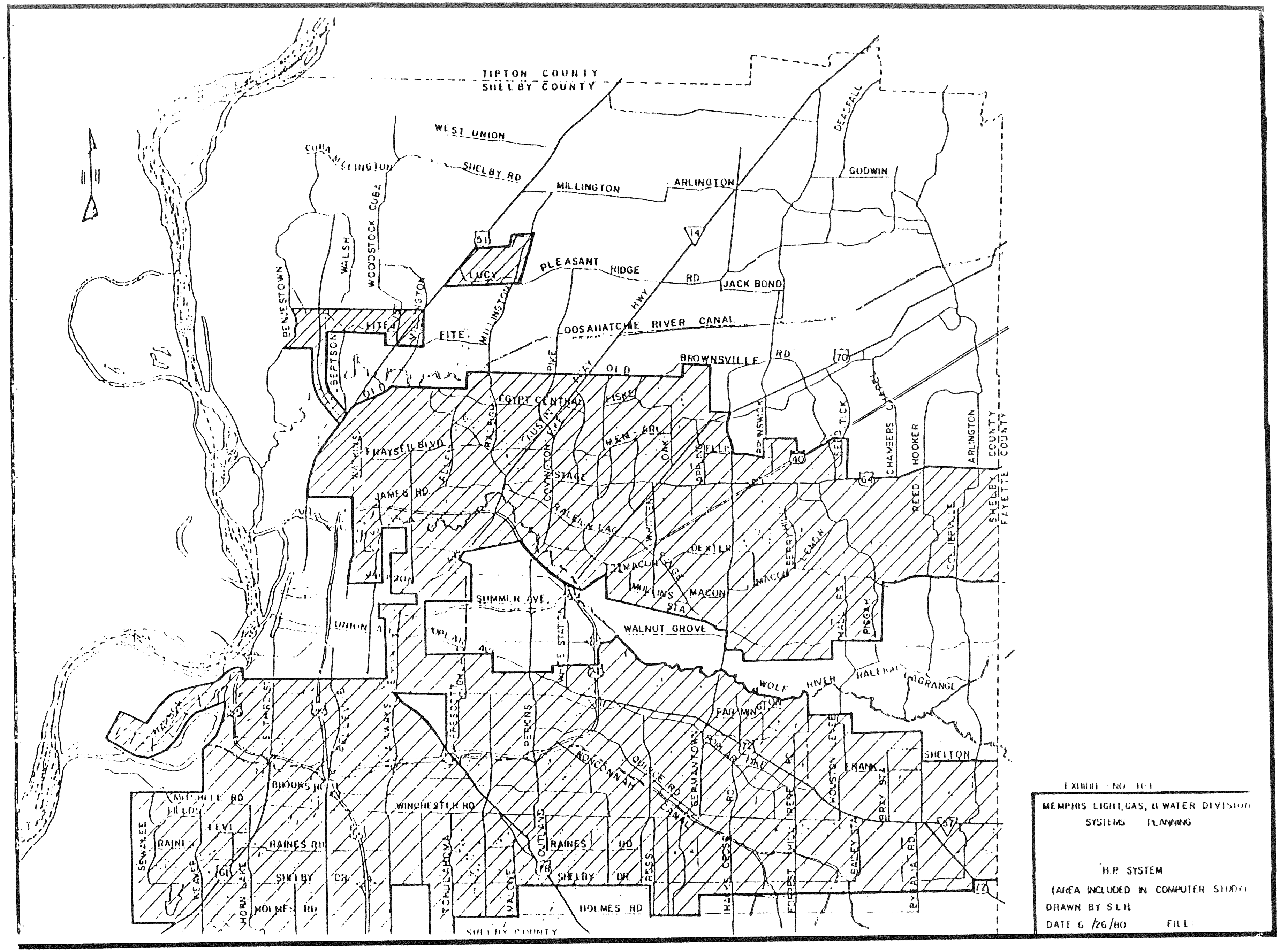

(Source: MLGW)

**Figure 4-1d: MLGW Gas System: Medium Pressure System**



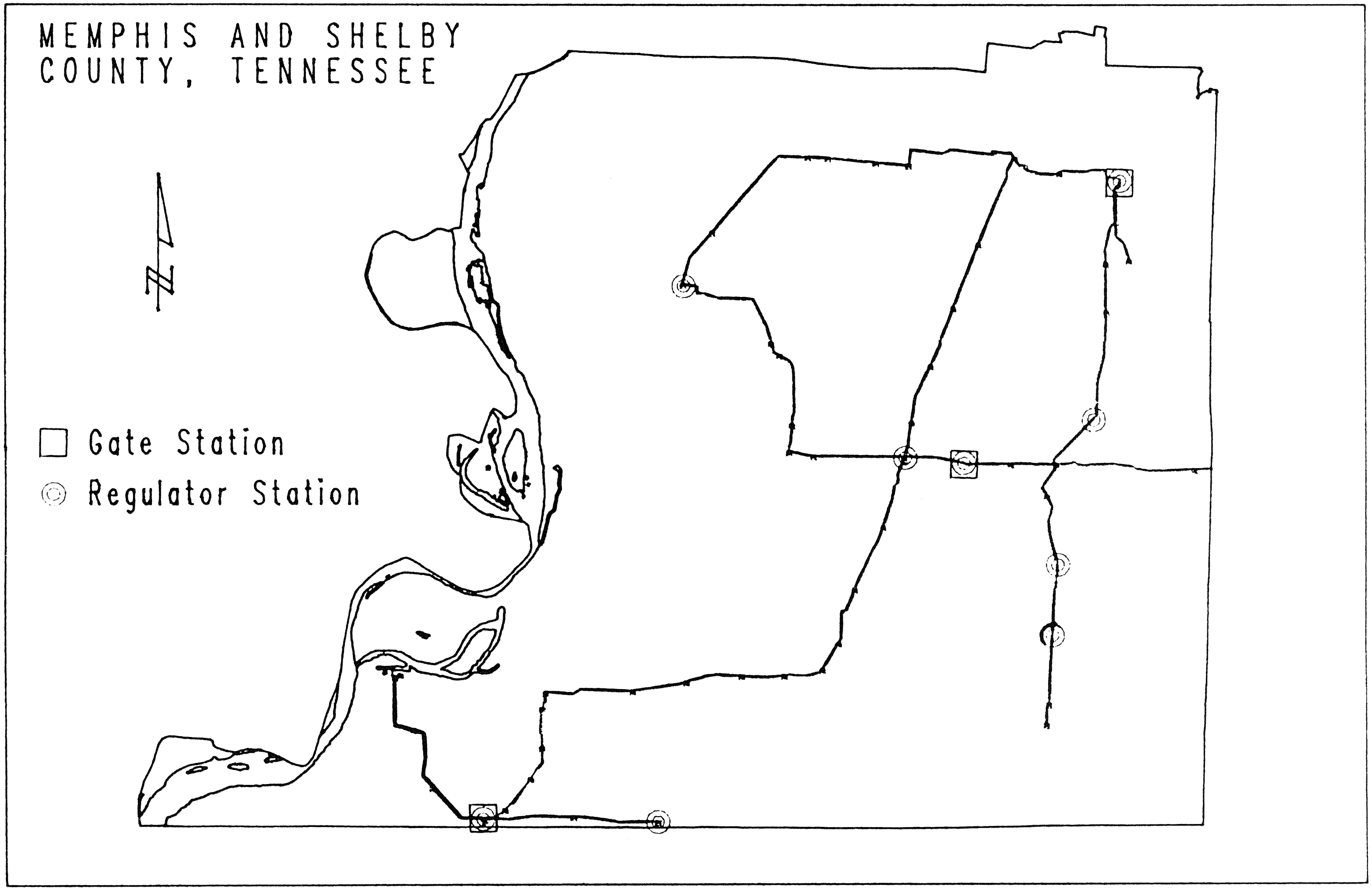

(Source: MLGW)

**Figure 4-1e: MLGW Gas System: Millington Medium Pressure System**




(Source: MLGW)

Figure 4-1f: MLGW Gas System: High Pressure System




(Source: H. Hwang)

**FIGURE 4-2 MLGW Gas Transmission System**

For the current study, no information was available on the exact location of the gas pipes comprising the distribution system. It is known, however, that the cast-iron pipes are concentrated in the standard pressure and downtown intermediate pressure systems (Hwang communication).

MLGW purchases gas from two pipeline transmission companies, the Texas Gas Transmission Corporation (TGT) and the Trunkline Gas Company (TGC). According to annual volumes for 1991, 46.4% of receipts totalling 64,030 million cubic feet came from TGT, while 53.6% came from TGC (MLGW, 1992). MLGW receives gas from TGT at six purchase points: Airways, Arlington, Germantown, Outland, Ridgeway and Weaver Gate Stations. All deliveries from TGC are received through the Fayette County Gate Station (MLGW, 1992).

The Texas Gas Transmission Corporation operates 6,100 miles of pipe from the Louisiana Gulf Coast to Ohio. Most of TGT's gas is received in Louisiana, while additional supplies are received in Texas and Arkansas. Underground storage facilities are located in Kentucky and Indiana. Deliveries are made to the nine states in which the pipelines operate: Texas, Louisiana, Arkansas, Mississippi, Tennessee, Kentucky, Illinois, Indiana and Ohio (DOE/EIA, 1992). According to the Pipeline & Gas Journal (Sept., 1992), TGT had a total throughput of more than 1 trillion cubic feet in 1991.

The gas fields of the Texas and Louisiana gulf coast serve as the natural gas sources for Trunkline Gas Company, which operates about 4,800 miles of pipe. While most of TGC's customers are local distribution companies in Illinois, Indiana and Michigan, deliveries are also made to resellers in Kentucky, Louisiana, and Tennessee. Trunkline Gas Company began transportation service of gas to Memphis in February of 1990 (DOE/EIA, 1992). The TGC pipeline route originates in Texas and passes through Louisiana, Arkansas and Mississippi before reaching Tennessee. The Trunkline Gas Company had a total throughput of 0.8 trillion cubic feet in 1991 (P&GJ, 1992). Gas delivered to MLGW represents less than 5% of total throughput for either supplier.

Given the observation that gas supplies to Shelby County originate from the south, it would be reasonable to expect that in the event of a major New Madrid Seismiz Zone earthquake, these supply routes would be subject to lower hazard than the MLGW network itself. Had the sources of gas been from the north, the supply might have been in jeopardy in such a disaster.

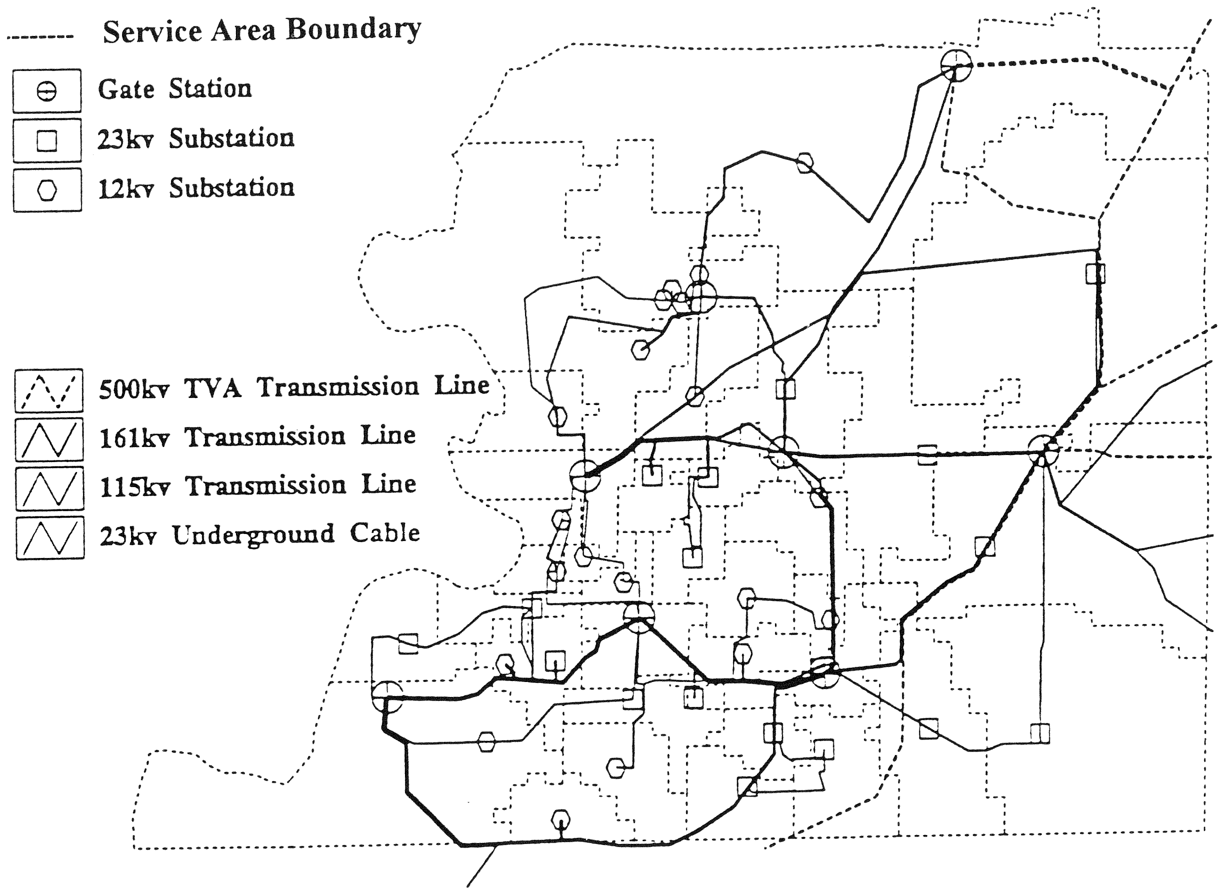
## 4.2 Electrical System Facilities

The electric power transmission system in Shelby County has been described in Tanaka (1995) and Shinozuka et al. (1994). The source of electric power in Shelby County is the Tennessee Valley Authority (TVA) and no electricity is generated within the County. Electric power is transmitted through 8 gate stations to 37 transmission substations. The transmission system consists of gate stations, 23kv and 12kv substations, and 500kv, 161 kv, 115 kv, and 23 kv transmission lines. TVA operates the gate stations and 500kv transmission lines. Other components of the system are operated by MLGW. In general, each of the transmission substations serves a single electric power service area (EPSA). Figure 4-3, reproduced from Tanaka (1995), depicts the electric power transmission system in Shelby County.

For the M 7.5 Marked Tree scenario, exposure of the transmission substations to ground shaking can be estimated based on hazard assessment in section 3 and facility locations shown in Figure 4-3. Table 4-1 summarizes the exposure by type of substation and ground shaking intensity.

**TABLE 4-1 Transmission Substation Exposure in Scenario Earthquake**

| Substation Type | MMI VIII | MMI VIII-1/2 | Total |
|---|---|---|---|
| Gate Station | 3 | 5 | 8 |
| 23kv Substation | 9 | 8 | 17 |
| 12kv Substation | 5 | 15 | 20 |
| Total Number of Substations | 17 | 28 | 45 |



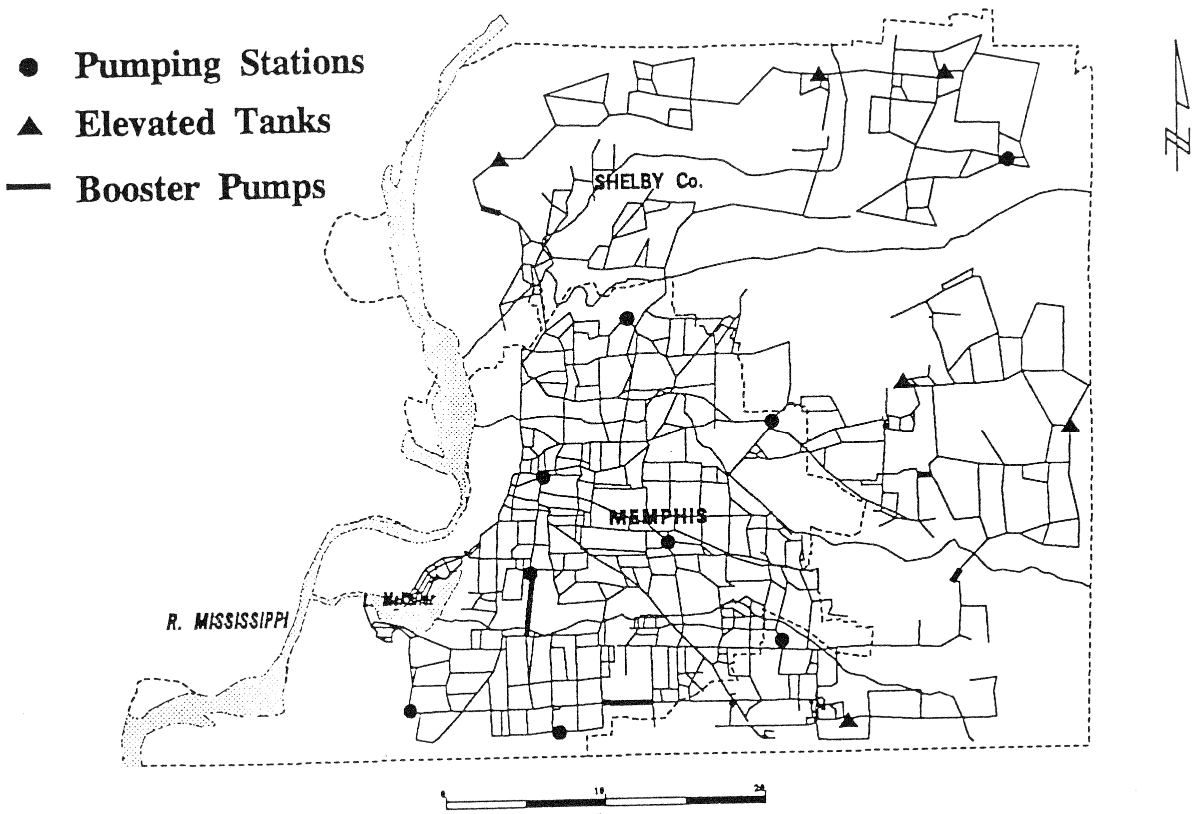

(Source: Adapted from Tanaka 1995)

Figure 4-3: MLGW Electric Power Transmission Network

### 4.3 Water Delivery System Facilities

The Memphis water delivery system, consisting primarily of MLGW facilities, has been described in Tanaka (1995) and Shinozuka et al. (1992). The MLGW water delivery system consists of two types of pressure systems: a large low-pressure system and several high-pressure systems located on the outskirts of the city of Memphis. The system includes about 1370 km of buried pipes. For pipes installed before 1975, the material was primarily unlined and cement-lined cast iron. Since 1975, primarily ductile iron pipes have been used. In addition, the water delivery system has nine pumping stations, six elevated tanks in the high-pressure system, and nine booster pumps that connect the low- and high-pressure systems. Figure 4-4, reproduced from Tanaka (1995), depicts the water delivery system in Shelby County.

MLGW is the primary supplier of water for Shelby County, with the exception of a few unincorporated municipalities. The source of the water is an underground aquifer accessed by wells (Shinozuka et al. 1992). The damage and loss evaluation in subsequent sections considers only the MLGW supply system.




(Source: Tanaka 1995)

**FIGURE 4-4 MLGW Water Delivery Network**

# SECTION 5

# DAMAGE AND REPAIR COST ASSESSMENT

This section focuses on the estimation of physical damage to MLGW's natural gas, electric power, and water delivery systems and associated repair costs. Estimates of physical damage were provided by Prof. Shinozuka and colleagues at Princeton University for the water delivery system. For gas and electric power, existing damage estimation methods were applied. Repair costs were estimated using simple cost models.

The scope of damage estimation depended on the lifeline system being studied. For natural gas, the damage assessment pertains to the distribution system. The transmission system is not included because more stringent material and maintenance requirements for high pressure systems result in lesser vulnerability for transmission than distribution systems. Loss and restoration of service is therefore expected to be governed by distribution system damage. For electric power and water, analysis pertains to transmission substation damage and the entire delivery system (both transmission and distribution, including elevated tanks and pump stations), respectively, as analyzed by Shinozuka et al.

## 5.1 Natural Gas System

Damage assessment for the scenario M 7.5 Marked Tree earthquake is limited in the current study to a rough estimation of pipe repairs in the distribution system due to ground shaking. Pipe repairs are estimated according to pipe material. As indicated in section 3, it is assumed that liquefaction will not present a major problem for the County as a whole, based on Hwang (1991).

Since a detailed analysis of gas distribution system performance is beyond the scope of this project, a rough estimation of damage is made based on existing methodologies. Relevant damage model parameters were derived based on results from Eguchi (1991) and are shown in Table 5-1.

**TABLE 5-1 Natural Gas Pipeline Damage Model**

| | Break (Repair) Rates Per 1000 Feet | |
|---|---|---|
| MMI | Cast Iron | Plastic/Steel |
| VI | .00046 | .00032 |
| VII | .0052 | .0036 |
| VIII | .058 | .040 |
| VIII 1/2 | .078 | .053 |
| IX | .12 | .082 |
| X | .24 | .17 |

source: based on Eguchi (1991)

These parameters are based upon empirical pipeline damage models using observations in the 1971 San Fernando, the 1969 Santa Rosa, the 1972 Managua, and the 1979 Imperial Valley earthquakes. Note that the damage rates for plastic and steel pipes are assumed to be the same, but those for cast iron are higher.

This information is used to estimate damage to the gas distribution system in the scenario M 7.5 Mårked Tree event. As mentioned in the previous section, available information is insufficient for determining the precise location and therefore the MMI breakdown of the gas distribution system. However, the shaking intensity estimates described in section 3 indicate that roughly half of Shelby County experiences an intensity VIII and the other half an intensity VIII-1/2 in this earthquake. Therefore, a mathematical average of the rates for these two intensity levels can be applied to derive a rough approximation of damage. This average repair rate (0.0678 for cast iron and 0.0466 for plastic and steel pipe) is used here.

In addition, the total length of pipe by material type is estimated based on information presented in section 4.1. Specifically, the total length of MLGW gas distribution system pipe is 3,500 miles (main only), with 73 percent being made of steel, 17 percent of plastic, and 10 percent of cast iron. Because the distribution of pipe material throughout the system is unknown, it was assumed to be uniformly distributed for each material.

Estimates of average costs per pipe repair were derived from expert judgment (McDonough communication). While average repair cost is lowest for plastic pipe ($400 per repair), it is also lower for cast iron than for steel pipe ($1500 versus $2000) because of differences in typical failure modes and the time to make repairs for each material. Cost estimates are based on the assumption that the utility company will choose to repair the pipe breaks rather than replace the entire pipe. Since MLGW is currently undergoing a phased pipe replacement plan (Hwang communication), it is reasonable to assume that in the event of an earthquake, the utility would repair or replace pipe rather than use pipe insertion methods to handle pipe damage. While recognizing that pipe replacement would be economical in cases of multiple breaks in a given pipe, because insufficient information is available regarding the locations and concentrations of damage, costs are estimated assuming all breaks are repaired in place.

Results are shown in Table 5-2. It is estimated that in the scenario earthquake, the gas distribution system would suffer roughly 900 pipe breaks, leading to total repair costs of roughly $1.5 million.

**TABLE 5-2 Damage and Repair Cost Estimates for Gas Distribution System**

| Pipe Material | Total Length (thou. feet) | Repair Rate (per thou. ft.) | Estimated No.Repairs | Average Cost per Repair ($)[a] | Estimated Repair Cost ($) |
|---|---|---|---|---|---|
| Steel | 13,490 | .0466 | 629 | $2,000 | $1,258,000 |
| Plastic | 3,142 | .0466 | 147 | $ 400 | $ 58,800 |
| Cast iron | 1,848 | .0678 | 125 | $1,500 | $ 187,500 |
| TOTAL | 18,480 | - | 901 | - | $1,504,300 |

note: (a) source: P. McDonough, communication.

Unfortunately, comparable figures are not available for previous earthquakes. In the Northridge earthquake, Southern California Gas Company estimated restoration costs between $53 and $68 million, of which $35 to $45 million were for operation and maintenance costs and $18 to $23 million for capital costs. Furthermore, it reported 752 pipe breaks, including those that were classified as "corrosion-related." (Schiff, ed., 1995) However, even though this $18-23 million capital cost estimate indicates an average repair cost substantially higher than figures used in

Table 5-2, it is difficult to make the comparison because while the MLGW analysis considers only distribution system damage, the SoCal Gas figures include 35 repairs to transmission system pipes which would be much more expensive. For purposes of this study, the figures in Table 5-2 can be considered as estimates on the low end of the possible range.

### 5.2 Electric Power System

Electric power outage due to transmission system failures in the scenario M 7.5 Marked Tree event was estimated by M. Shinozuka and colleagues at Princeton University and is described in section 6. However, their studies did not include an assessment of the damage levels in a form that could be used to evaluate the associated repair costs.

For purposes of repair cost estimation, a rough estimate of damage can nonetheless be made based on empirical models in ATC-25. Figures B-53 and B-60 in ATC-25 plot damage percent by MMI for electric transmission and distribution substations, respectively. Damage curves for regions outside of California are based on MMI intensity shifts applied to California functions. For Shelby County, mean damage figures as a percentage of replacement cost can be inferred from these figures and are indicated in Table 5-3. It should be noted that damage estimates in ATC-25 are based upon expert judgment and are not consistent with the detailed systems analysis performed by Shinozuka et al.

**TABLE 5-3 Electric Power Substation Damage Model**

| | Mean Damage (Percent of Replacement Cost) | |
|---|---|---|
| MMI | Transmission Substations | Distribution Substations |
| VI | 16 % | 9 % |
| VII | 27 % | 16 % |
| VIII | 43 % | 28 % |
| VIII 1/2 | 54 % | 35 % |
| IX | 68 % | 45 % |

source: ATC-25 (1991)

For purposes of applying these damage functions, the MLGW facilities were classified as "transmission" or "distribution" substations in accordance with definitions in ATC-25. Facilities identified as "gate stations" by MLGW (see Figure 4-3) receive power at 500 kv and 161 kv and are here considered as transmission substations according to ATC-25's definition as high voltage facilities receiving power at 220 kv or higher. Note that 161 kv facilities are expected to perform like high voltage substations in an earthquake even though the actual voltage is less than 220 kv. Other MLGW facilities, specifically the 23kv and 12kv substations shown in Figure 4-3, are considered as distribution substations, defined by ATC-25 as those receiving power at low voltages of 64 kv or less. The number of each of these facility types and the MMI zones in which they are located for the scenario earthquake were previously tabulated in Table 4-1.

In order to calculate repair costs associated with the damage, the damage factors or percentages shown in Table 5-3 were applied to estimated replacement costs for the MLGW facilities. Replacement values were approximated using information on electric power facilities in Los Angeles, for which detailed data are available. Data provided by the Los Angeles Department of Water and Power (LADWP) indicate the typical replacement costs for various types of facilities as shown in table 5-4.

**TABLE 5-4 Replacement Costs for Electric Power Substations**

| Facility Type | Voltage | Typical Replacement Cost |
|---|---|---|
| Major transmission substation | 500 kv | $ 300 million |
| Receiving station | 138/230 kv | $ 25 million |
| Distribution substation | 34.5 kv | $ 4 million |

note: based on information from LADWP (correspondence) and Lopez et al. (1994)

For repair cost estimation, some association of MLGW facilities with the categories in Table 5-4 is required. For the Shelby County gate stations, "major transmission substation" costs were applied to the 500 kv facilities and "receiving station" costs to the 161 kv facilities. For the 23 kv substations, "distribution substation" costs in Table 5-4 were used. Substations below 15 kv, such as the 12 kv facilities, would have different quantities and/or types of equipment than those above 15 kv. As a rough approximation, the replacement value for a 12 kv substation is estimated at half that of a 23 kv facility, or $2 million.

Using the assumptions outlined above, the estimated repair cost for MLGW electric power substations in the M 7.5 Marked Tree earthquake is $401,080,000. Of this total, $366.5 million or 91 percent of the cost is associated with repairing damaged gate stations, and only $34.58 million with the 23kv and 12 kv substations. This relative loss is consistent with experience in previous earthquakes, where little damage to low-voltage substations has been observed. The order of magnitude of the $401 million loss appears reasonable in light of the Northridge earthquake, in which "direct losses" to Los Angeles Department of Water and Power and Southern California Edison associated with electric power facilities were estimated at $183 million (Schiff, ed., 1995). A large concentration of this loss derived from damage to nine high-voltage (230 kV and 500 kV) substations.

### 5.3 Water Delivery System

Information on damage to the water delivery system was provided by Shinozuka et al. for the scenario M 7.5 event. Specifically, this damage data consisted of the expected number of breaks for each pipe (link) in the Shelby County water delivery system. The links were identified by link number and pipe material code. The expected number of breaks represents the average number of breaks over 100 simulations of network response to the seismic event. The damage data is summarized in table 5-5.

**TABLE 5-5 Water Delivery System Damage for Scenario Earthquake**

| Pipe Material | Expected No. Breaks (Repairs) |
|---|---|
| Unlined cast iron | 973 |
| Cement-lined cast iron | 3,440 |
| Cement-lined ductile iron | 93 |
| Not identified | 9 |
| Total | 4,514[a] |

note: (a) total may not add due to rounding error

To estimate the associated repair cost, dollar costs per repair were applied. Based on expert opinion (McDonough communication), a rough value of $1,500 per repair was used for lined and unlined cast iron, as well as for the "not identified" pipe material. As in the case of natural gas, because of the lack of information regarding the concentrations of pipe breaks throughout the system, it was assumed that each break would be repaired in place. In reality, for pipes with multiple breaks and areas of high break concentrations, it is likely that the utility company would choose to replace the pipes rather than repair them. The total repair cost for the water delivery system is estimated at $6,771,000. While comparable figures for previous earthquakes are difficult to obtain, it should be noted that in Northridge, water utility companies suffered about a $44 million loss associated with roughly 1200 repairs (Eguchi, 1995). This indicates a much higher per-repair cost than that assumed in this study. However, the definition and scope of the reported loss is unclear, and the number of repairs is also not certain. Thus for purposes of this study, as in the case of natural gas facilities, the estimated repair costs can be considered as representing the low end of the possible range.

# SECTION 6

# UTILITY OUTAGE AND RESTORATION MODELING

This section discusses the development of service outage and restoration models for the natural gas, water, and electricity lifelines in the study area. Results which comprise the inputs to the economic models described in the subsequent sections are also presented. Because this study represents part of a larger NCEER effort that involves multiple investigators, the development of the outage models for the various lifelines displays some differences in methodological approach. In particular, modeling water and electricity outage was conducted by Prof. M. Shinozuka and colleagues at Princeton University.

Sections 6.1 and 6.2 discuss model development for the transmission and distribution systems for the natural gas utility. A comparison is made between the expert opinion-based models suggested by ATC-25 (1991) and actual earthquake experience. The results are empirical models estimating the length of outage in areas of different seismic hazard levels. Section 6.3 compares these results to conclusions of other studies in the Midwest. Section 6.4 develops a natural gas service restoration model for different zones within the impacted urban area for the Shelby County case study. Sections 6.5 and 6.6 pertain to the electricity and water lifelines respectively, focusing on outage results from Shinozuka et al. and modeling of service restoration. Section 6.7 summarizes the results and provides a discussion of issues related to methodological development.

## 6.1 Natural Gas Outage Time Models: Transmission System

Natural gas transmission systems usually consist of high pressure, welded steel pipelines transporting gas long distances, often across many states, from the production source to the reseller. Local high pressure, or distribution supply lines, are usually considered to be part of the distribution system.

### 6.1.1 ATC-25 Restoration Estimates - California

The ATC-25 "Residual Capacity curves" for natural gas transmission lines in California - NEHRP Area 7 (considered to be the only region of the US with a significant history of lifeline seismic design for major earthquakes) predict restoration times as shown in Table 6-1.

**TABLE 6-1 ATC-25 Restoration Times for Natural Gas Transmission Pipelines in California**

| MMI | Time to Full Restoration |
|---|---|
| VI | --- |
| VII | 1.6 days |
| VIII | 1.6 days |
| IX | 3.7 days |
| X | 3.2 days |

These estimates have several major limitations. First, the inconsistency between the estimates for MMI IX and X is noted, while the specific cause is unknown. Intuitively, one would expect the outage at MMI X to exceed that of MMI IX. In addition, these curves are for damage related to ground-shaking only, but it is often difficult to separate damage due to shaking from damage due to ground failure at MMI IX and above.

### 6.1.2 California Earthquake Experience

These opinion-based estimates may be compared to actual experience in recent CA-NEHRP Area 7 earthquakes, beginning with the 1971 San Fernando earthquake. While damage to transmission pipeline systems has occurred in earlier California earthquakes (1933 Long Beach, 1952 Kern County), little documentation of the restoration process for these events exists.

In the 1971 San Fernando earthquake (M=6.4), significant damage to transmission pipelines occurred in areas of fault rupture and ground failure (more that 68 breaks), yet were repaired within 3 days (NOAA, 1973). These areas were assigned an MMI of IX. No substantial damage to transmission lines occurred outside these ground failure areas, although transmission pipelines did traverse areas of MMI VI and higher.

In the 1987 Whittier Narrows earthquake (M=5.9), no damage to transmission lines was reported, but exposure to ground shaking of MMI VII or higher was minimal (EERI, 1988).

The 1989 Loma Prieta earthquake (M=7.1) caused 2 leaks on a transmission line in Hollister, within the area of MMI VII, but no interruption resulted (Phillips and Virostek, 1990). A significant amount of transmission piping was exposed to shaking of MMI VII in this event, with a small amount extending into areas of MMI VIII.

Finally, in the 1992 Landers earthquake (M=7.4), no damage occurred to two transmission pipelines located just north (30" diameter) and just south (6" diameter) of the fault rupture area (EERI, 1992). These areas were rated MMI VIII.

### 6.1.3 Empirical Outage Model for California

Historic performance of transmission pipelines in earthquakes prompts the following observations:

- There has been considerable exposure of transmission pipelines to ground shaking of MMI VII, yet with a noticeable lack of damage and subsequent outage. This suggests that the ATC-25 estimate of 1.6 days outage for MMI VII is too long.
- No damage or outage has resulted in areas of MMI VIII, although the exposure of pipelines has been considerably less. Even though no damage or outage has been reported in these areas, there is probably not enough data to rule it out at this level of hazard. Any damage is expected to be limited, and could probably be repaired quickly, with a minimum of interruption. The ATC-25 estimate of 1.6 days may be used to generalize predicted outage to 1 or 2 days.

- The only noted occurrence of transmission line outage was due to ground failure, in an area rated MMI IX. Although damage in this case was attributed to ground failure, the definition of strong ground shaking of IX and above implicitly includes ground failure effects. Therefore, for the purpose of this outage assessment, outage due to ground failure will be grouped with outage due to strong ground shaking, because ground failure areas will likely be rated MMI IX or above. The 3 day outage in San Fernando generally confirms the ATC-25 3.7 day outage prediction at MMI IX.
- No recent historic earthquake experience includes transmission pipelines in areas of MMI X. It is expected that the outage will be similar to or greater than in MMI IX.

The empirical model for California is summarized in the Table 6-2.

**TABLE 6-2 Empirical Outage Time Model for Natural Gas Transmission Pipelines in California**

| MMI | Outage Time |
|---|---|
| VI | --- |
| VII | --- |
| VIII | 1 - 2 days |
| IX/ground failure | 3 - 4 days |
| X/ground failure | 4+ days |

### 6.1.4 Extrapolation of the Model Outside California

To utilize the ATC-25 restoration models for areas outside California, alternate curves are presented which essentially shift the damage curves back one MMI unit. This is based on the assumption that other areas of the US have no "significant history of lifeline seismic design for major earthquakes" (ATC, 1991). This model is summarized in Table 6-3.

While ATC-25 assumes that California construction is "a composite of older and more modern transmission lines", the same holds true for transmission systems in other parts of the country. In addition, the significant consequence of failure and the rigorous operating procedures for high pressure pipelines (including comprehensive monitoring programs) suggest that regional differences may be less conspicuous than suggested by the different ATC-25 models.

**TABLE 6-3 ATC-25 Restoration Times for Natural Gas Transmission Pipelines Outside California**

| MMI | Time to Full Restoration |
|---|---|
| VI | 1.1 |
| VII | 1.1 |
| VIII | 3.7 days |
| IX | 3.2 days |
| X | 8.4 days |

Unfortunately, recent experience data outside California is essentially limited to the 1980 Northern Kentucky earthquake (M 5.3) (EERI, 1980). This small event produced ground shaking up to MMI VII, but had no impact on regional natural gas transmission systems. While one data point is not enough to justify significant revisions to the model, it should be noted that pipeline performance is not dissimilar to that in California.

While this suggests that the threshold for transmission pipeline damage may be similar throughout the US, the extent of exposure will certainly be greater in a NMSZ event than in a similarly-sized California event. That is, because of the extensive area of felt-effects for NMSZ earthquakes, more of the regional transmission system will be exposed to ground shaking and ground failure hazards. The increased exposure is likely to increase the extent of damage, and correspondingly, the length of outage due to increased demand on personnel and resources. This increased demand on resources is not incorporated into ATC-25, which assumed unlimited resources for repair and restoration. This resource limitation is expected to be significant enough to adjust the outage models slightly upward. The refined outage model for application to the NMSZ is given below in Table 6-4:

**TABLE 6-4 Empirical Outage Time Model For Natural Gas Transmission Pipelines Outside California**

| MMI | Outage Time |
|---|---|
| VI | --- |
| VII | --- |
| VIII | 1 - 3 days |
| IX/ground failure | 4 - 6 days |
| X or above/ground failure | 7+ days |

## 6.2 Natural Gas Outage Time Models: Distribution System

Distribution systems receive gas from high pressure transmission systems, reduce the pressure and distribute it to the end-users through a highly netted, often redundant network of pipelines. These pipelines can be constructed of steel, cast iron, ductile iron or plastic of various diameters, at various pressures.

### 6.2.1 ATC-25 Restoration Estimates - California

The ATC-25 "Residual Capacity curves" for natural gas distribution systems in California - NEHRP Area 7 predict the restoration times as given in Table 6-5. As noted in Section 6.1.1, these figures have various limitations. Again, it can be seen that the ATC-25 estimate is inconsistent in the transition between MMI VIII and IX.

**TABLE 6-5 ATC-25 Restoration Times for Natural Gas Distribution Systems in California**

| MMI | Time to Full Restoration |
|---|---|
| VI | 2.8 days |
| VII | 2.8 days |
| VIII | 5.2 days |
| IX | 4.7 days |
| X | 10.9 days |

### 6.2.2 California Earthquake Experience

A comparison of the ATC-25 distribution system restoration time estimates to actual recent earthquake performance is instructive. In the 1971 San Fernando earthquake, four square miles of the distribution system in the area of ground failure (faulting, landslide, lurching, etc.) experienced close to 400 breaks. 17,000 customers were affected, and service was restored within 2 weeks (NOAA, 1973). No significant damage to the distribution system was noted outside this area.

The 1983 Coalinga earthquake (M 6.7) presents a special case. The entire municipally-owned distribution system was shut off immediately following the earthquake to reduce the risk of fire. Damage turned out to be relatively minor; 2 steel mains were damaged, 3 leaks were found on plastic pipe, and 39 services had to be cut and capped. 2,500 customers were affected, and restoration took 2 weeks. MMI VIII was estimated in this area (EERI, 1984; Tierney, 1985).

Damage caused by the 1987 Whittier Narrows earthquake caused no significant service interruptions, but over 16,500 customers needlessly shut off their own gas (an additional 4,500 turned off their gas following a major aftershock). Only one main leak was reported, and 1400 leaks were found on customer property (EERI, 1988). Distribution system exposure included MMI VI, VII and VIII.

The 1989 Loma Prieta earthquake caused over 1,000 leaks to the PG&E distribution system, including many to services. Three sections of the distribution system were so heavily damaged that they required replacement; the Marina (MMI IX/ground failure), Los Gatos (MMI VIII) and Watsonville (MMI VIII). 5,100 customers were affected in the Marina District, where the steel and cast iron system was heavily damaged by ground failure. Replacement was accomplished in one month. In Los Gatos, restoration affected 140 customers and required one month to complete. In Watsonville, the steel distribution system was replaced within 3 weeks, having impacted 166 customers (Phillips and Virostek, 1990). It is important to note that other areas subject to similar ground shaking did not suffer significant service interruptions, including Santa Cruz. More that 156,000 customers required service restoration, most due to unnecessary gas shut off. Restoration was accomplished within 10 days (Phillips and Virostek, 1990).

Finally, in the 1992 Landers earthquake, natural gas service to the communities of Joshua Tree and Yucca Valley (MMI VIII) were unaffected by the earthquake, although water systems in the epicentral area did suffer significant damage. Other communities (i.e., Landers) are not served by an underground natural gas distribution system (EERI, 1992).

### 6.2.3 Empirical Outage Time Model for California

The historic performance of natural gas distribution systems in recent California earthquakes generates the following observations:

- No appreciable service outage has been seen in MMI VI or VII.
- Portions of some distribution systems have suffered significant damage and subsequent outage in areas of MMI VIII, including Watsonville and Los Gatos (Loma Prieta). These outages have ranged from three weeks to one month for a limited number of customers (< 200). However, numerous examples of other communities in MMI VIII which have not suffered service disruption also exist, such as Santa Cruz (Loma Prieta), Whittier (Whittier Narrows), and Yucca Valley (Landers). It is likely that MMI VIII is the threshold for small areal service interruptions, but only a percentage of systems in these areas will actually suffer from interruption, depending on the age and condition of the systems. In the absence of an extensive historic database, we estimate that this proportion may be around 50%. A probabilistic assessment of likely outage may be estimated as follows: approximately half of communities subject to MMI VIII may suffer outage of as long as one month, so the probabilistic outage for areas of MMI VIII may be taken as two weeks.
- Damaged distribution systems in areas of ground failure/MMI IX have been shown to require between 2 weeks (San Fernando) and one month (Marina District) for restoration of service.

Affected areas have typically been larger than those for MMI VIII, including several thousand customers or more. Areas of X/ground failure may be expected to suffer similar or perhaps even more severe outages.

These observations may be translated into the empirical model described in Table 6-6.

**TABLE 6-6 Empirical Outage Time Model for Natural Gas Distribution Systems in California**

| MMI | Outage Time |
|---|---|
| VI | --- |
| VII | --- |
| VIII | 2 weeks |
| IX/ground failure | up to one month |
| X or above/ground failure | up to one month or more |

### 6.2.4 Extrapolation of the Model Outside California

As with transmission systems, alternate ATC-25 restoration curves are presented for areas outside California that essentially shift the damage curves back one MMI unit. The model for natural gas distribution systems is presented in Table 6-7. ATC-25 assumes that California construction is "a composite of older and more modern mains". In the older cities of the Midwest, less recent development is likely to have taken place, these systems can be expected to contain a greater proportion of older, vulnerable pipe, likely resulting in more widespread damage and increased outage in an earthquake.

Little experience data exists for distribution systems outside California. The 1980 Northern Kentucky earthquake produced ground shaking up to MMI VII, but no reports of damage to the local natural gas distribution systems were found (EERI, 1980).

As with transmission systems, the extent of regional exposure will be greater in a Mid-Western earthquake than in California. This means that more individual distribution systems will be exposed to damaging seismic hazards. While this may have little impact on resources internal to the individual distribution systems, it is likely to impact regional material resources, such as heavy equipment and replacement pipe, and make fewer personnel available for mutual aid. Distribution utilities may face a situation where they must be essentially self-reliant.

**TABLE 6-7 ATC-25 Restoration Times for Natural Gas Distribution Systems Outside of California**

| MMI | Time to Full Restoration |
|---|---|
| VI | 2.8 days |
| VII | 5.2 days |
| VIII | 4.7 days |
| IX | 10.9 days |
| X | 20.7 days |

Although the distribution systems in the Mid-West are potentially more vulnerable than those in California, there is no real evidence to support several days of outage in areas of MMI as low as VI. In addition, because resource limitations are not incorporated in the ATC-25 restoration estimates, their reliability when applied to non-California situations is questionable. Some adjustment of the California outage model as given in Table 6-6 is required, and it should qualitatively consider both the more extensive damage of older Midwestern systems and the likely resource limitations.

The approach taken to adjust the outage models has been to increase the expected outage, once the damage threshold has been reached. That is, a greater percentage of systems in MMI VIII are likely to be damaged, because of the prevalence of older pipe. In addition, general resource limitations are expected to increase outages at all hazard levels. The refined outage model for application to the NMSZ is given in Table 6-8.

**TABLE 6-8 Empirical Outage Time Model for Natural Gas Distribution Systems Outside California**

| MMI | Outage Time |
|---|---|
| VI | --- |
| VII | --- |
| VIII | 3 - 4 weeks |
| IX/ground failure | 4 - 6 weeks |
| X or above/ground failure | 6+ weeks |

## 6.3 Comparison to Previous Outage Estimates in the Midwest

These estimates may be compared to a previous planning effort for the Mid-west. In the 1985 "Six Cities" report, The Central United States Earthquake Preparedness Project estimated the impacts of two large NMSZ earthquakes on the following cities: Carbondale, Illinois; Evansville, Indiana; Little Rock, Arkansas; Memphis, Tennessee; Paducah, Kentucky; and Poplar Bluff, Missouri. Estimated impacts included an assessment of natural gas system disruption for each city in a M 8.6 NMSZ earthquake. Ground shaking effects were estimated for each city, and a review of natural gas facilities was performed. Table 6-9 summarizes each city's exposure and assessed impact for the scenario earthquake.

In all six of the cities, the report predicted immediate shut off of the entire natural gas system, regardless of the individual city's level of ground shaking. From past earthquake experience, this seems somewhat unrealistic. While some of the more significantly impacted areas will need to be isolated, it is unlikely that a utility would shut down the entire system. The only precedent for this is the City of Coalinga, which serves only 2,500 customers, significantly less than even the smallest of the six cities considered here.

Nevertheless, some generalizations regarding the report's restoration predictions can be made. In general, if no cast iron pipelines were present (cities 1, 3, and 6), 1 to 2 weeks were estimated for restoration of the small to medium systems, regardless of predicted ground shaking. This probably reflects a minimum of pipeline damage and repair, but includes time required to re-light customers. Again, this is consistent with the experience at Coalinga, as well as Loma Prieta.

For systems including cast iron pipe, outages were estimated to last 3 to 4 weeks for medium sized and smaller systems with exposure to MMI VIII and above. For the large Memphis system, which has cast iron pipe and severe ground shaking hazards (MMI IX and X), outages were expected to last 6 weeks or more. These estimates are roughly consistent with the outage model developed for this study, as given in Table 6-8.

**TABLE 6-9 Natural Gas Outage Assessment from 1985 "Six Cities" Report**

| | City | 1980 Population | Size of System[a] | Includes Cast Iron | Approximate Hazard Exposure (%) X | IX | VIII | VII | VI | Predicted Outage |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Carbondale, IL | 26,000 | S | No | | 100 | | | | 1-2 weeks |
| 2 | Evansville, IL | 130,000 | M | Yes | | 25 | 75 | | | 3-4 weeks |
| 3 | Little Rock, AR | 158,000 | M | No | | | 25 | | 75 | 1-2 weeks |
| 4 | Memphis, TN | 646,000 | L | Yes | 50 | 50 | | | | 6+ weeks |
| 5 | Paducah, KY | 42,000 | VS | Yes | 5 | 65 | 30 | | | 4 weeks |
| 6 | Poplar Bluff, MO | 17,000 | S | No | 40 | | 60 | | | 1-2 weeks |

(a) Size is categorized as follows: VS (very small) = <50 miles of pipe
S (small) = 50-150 mi.
M (medium) = 850-1000 mi.
L (large) = >1000 mi.

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## 6.4 Natural Gas Outage and Restoration: Memphis Study

Systems analysis of initial outage was beyond the scope of this project and, unlike the cases of electric power and water described below, estimates of initial outage for natural gas were not available from Shinozuka et al. Based on the above discussion, in the case of the M 7.5 Marked Tree earthquake scenario, it is assumed that complete restoration of natural gas service in Shelby County will take about 4 weeks. As described in section 3, roughly half the county experiences an intensity level VIII and roughly half an VIII 1/2. Table 6-8 indicates a 3-4 week restoration timeframe for distribution systems in areas with intensity VIII and 4-6 weeks for regions in IX and/or with ground failure. Since repair of the distribution system is likely to be the controlling factor in service restoration, 4 weeks represents a reasonable estimate of the timeframe for complete system restoration.

It is further assumed that immediately after the disaster, gas service is disrupted throughout the county. While more detailed systems analysis could be undertaken to verify this assumption, it is nonetheless a reasonable projection in view of experience in recent earthquakes. For example, in the M=6.9 Kobe earthquake, gas service was suspended to 860,000 customers and full restoration required almost 3 months (Oka, 1995). As a result of the 1994 M=6.7 Northridge earthquake, there were 151,000 customers impacted by outage, 123,000 of these resulting from customer shutoffs. Restoration of service to approximately 84,000 customers was accomplished within one week, and to 120,000 within one month (EERI, 1995).

It is also assumed that the greatest damage to distribution pipelines will be found in the area where cast-iron pipes are concentrated. Based on information provided by Prof. Hwang at CERI, cast-iron pipes are primarily located in MLGW's standard pressure (S.P.) system and, to a lesser extent, in the downtown intermediate pressure (D.T.I.P.) system. (Hwang communication) These systems cover approximately the same geographic area.

In addition, experience from previous earthquakes indicates that areas of least damage are restored more quickly than those with heavy damage. This was the case in the Kobe earthquake (DPRI, 1995). The S.P./D.T.I.P. service areas can be expected to both suffer greater pipeline damage and longer outage times than other areas in the county. Furthermore, since MLGW has for a number of years been implementing a phased upgrading plan for cast-iron pipes in which the upgrading method is pipe replacement rather than the faster method of pipe insertion (Hwang communication), it was assumed that in the event of an earthquake, damaged cast-iron pipes would similarly be replaced.

Based on these observations and assumptions, the county was divided into four gas outage "recovery zones." Criteria for these zones are indicated in Table 6-10. Within the context of a 4-week complete restoration timeframe, restoration times for the zones were assumed somewhat arbitrarily at weekly intervals.

**TABLE 6-10 Gas Restoration Zones**

| Restoration Zone | Distribution System | MMI | Restoration Time |
|---|---|---|---|
| A | S.P./D.T.I.P. | VIII 1/2 | 4 weeks |
| B | " | VIII | 3 weeks |
| C | All Other | VIII 1/2 | 2 weeks |
| D | " | VIII | 1 week |

Census tracts were used as the basic unit of analysis. Tracts were assigned to distribution systems on the basis of coverage maps from MLGW obtained through Prof. Hwang at CERI (see Figures 4.1*a* through *f*). Tracts were assigned to S.P./D.T.I.P. if over half the land area was included in one or both of these systems' service areas. Census tracts were assigned MMIs based on ground shaking information provided by Prof. Hwang as described in section 3.

Figure 6-1 shows the physical extent of the assumed gas restoration recovery zones. Zones A and B together comprise the S.P./D.T.I.P. distribution systems area. Note that the zone of greatest impact (A) actually encloses a zone of lesser impact (B). This relates directly to the ground shaking intensity map produced at CERI, in which a pocket of intensity VIII is located within the VIII 1/2 region.

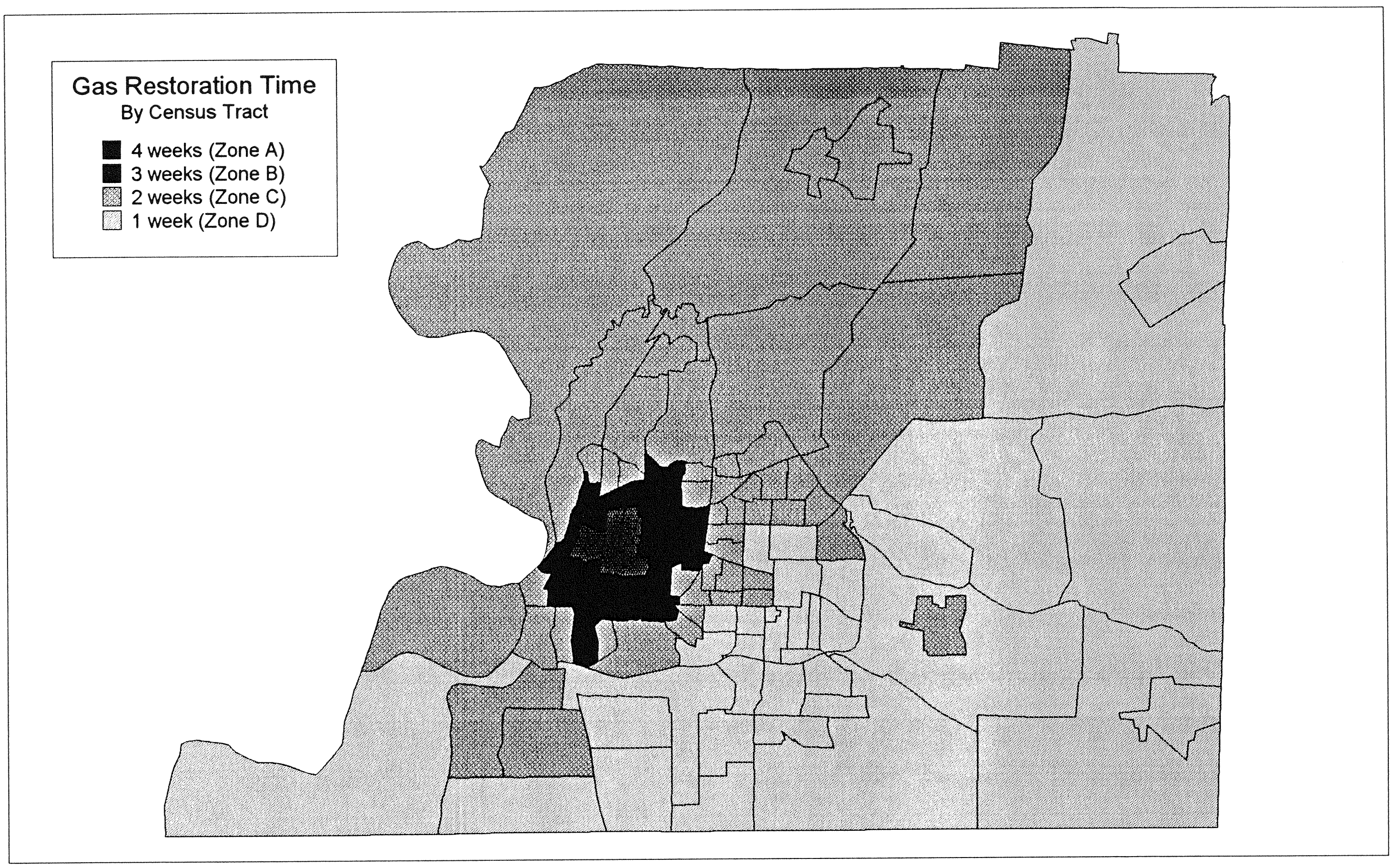



**FIGURE 6-1 Inferred Gas Restoration Pattern**

## 6.5 Electricity Outage and Restoration Models

### 6.5.1 Electricity Outage

Information on electricity outage after a major earthquake is derived from studies conducted by M. Shinozuka and colleagues at Princeton University (Shinozuka et al., 1994; Tanaka, 1995). These studies focus on the vulnerability of electric power transmission substations and consider three modes of failure: (i) failure of substation critical components, (ii) power imbalance, and (iii) loss of connectivity. It is assumed that power supply to the transmission substations is available after an earthquake. Compared to other components of electric power systems such as power lines and distribution substations, transmission substations are the most time-consuming to repair after an earthquake and therefore typically represent a controlling factor in the restoration of the entire system. For this reason, the functionality of transmission substations can be used to represent the availability of electric power in a given area.

Results from the reliability analysis conducted by Shinozuka et al. include, for a given scenario earthquake, estimates of ratios of "average post-earthquake availability" of electricity by electric power service area (EPSA). These ratios were derived by Monte Carlo simulation analysis, in which the particular earthquake event is repeatedly simulated to produce a series of lifeline disruption realizations. (Tanaka communication) Each of these simulations evaluates the functional status of a series of nodes within a particular transmission substation serving an EPSA. Node conditions, together with information on normal flows, are used to estimate the post-earthquake level of electricity in the EPSA. The simulation result, which can be interpreted as a scenario outcome, is combined with the other Monte Carlo simulations to produce the probabilistic "average post-earthquake availability" results.

In this study, results from the magnitude 7.5 scenario earthquake with epicenter at Marked Tree, Arkansas are applied. Results from Shinozuka et al. are based upon 100 simulations and are reported for the 36 EPSAs comprising Shelby County. The "average post-earthquake availability" ratio ranges from 0.11 to 0.57 in the EPSAs with the most and least severe expected disruption, respectively. Research by various NCEER investigators on electricity disruption and its socioeconomic impact in this scenario event is described in NCEER (forthcoming).

Here, in order to facilitate analysis of multiple lifeline disruption, the results are further disaggregated to the census tract level. Average post-earthquake electric power availability for the 133 census tracts in Shelby County was inferred by matching the tracts to the EPSA in which it was either contained or had the greatest territorial overlap.

### 6.5.2 Electricity Restoration Modeling

The restoration model for electric power is based on three main assumptions deriving from experience in past earthquakes. First, as in the case of the natural gas utility, restoration proceeds from areas of least to areas of heaviest damage. This is consistent with experience in the Northridge and Great Hanshin earthquakes (City of Los Angeles, 1994; Chang and Taylor, 1995). Second, restoration proceeds nonlinearly, with most customers having power restored quickly and proportionally fewer customers being restored as time elapses. This was observed in the two disasters mentioned previously and is also reflected in estimated restoration curves in ATC-25. The restoration percentage, in other words, increases at a decreasing rate with time after the disaster. Third, it is assumed that this empirical observation can be approximated using the following functional form for the restoration curve:

$$R=1-e^{-bct} \tag{6.1}$$

where $R$ is the percentage of customers with power restored, $e$ is the base of the natural logarithm, $t$ is a time index, $b$ is a constant, and $c$ is a scaling factor related to the estimated time to full restoration. This function was calibrated using data from the Northridge earthquake. Setting the scaling factor $c$ to 1, and noting that the full restoration time was 4 days (City of Los Angeles, 1994), the parameter $b$ is estimated to be 2.75. To derive a restoration function for the Memphis scenario, the scaling factor $c$ was adjusted to reflect the difference between full restoration time for Northridge and the corresponding estimate for the Memphis scenario. In other words, the restoration function is assumed to have the same shape as the Northridge curve, except that it is "stretched" to reflect the longer restoration time in the Memphis scenario.

One estimate of full restoration time for the Memphis scenario is available from ATC-25. ATC-25 indicates that for an area such as Memphis with MMI VIII, it would take approximately 15 weeks for damaged electric transmission substations to return to full capacity. This long restoration time is presumably due in part to the relative lack of earthquake experience and preparedness in the Central U.S. as compared to California. In addition, component parts of transmission substations are generally very specialized and spare parts are generally not stocked by each utility. In the event that they are damaged, it may take some time to obtain a replacement part. This situation is likely to be aggravated in the case of a major Central U.S. earthquake where many electric power systems across many states are likely to experience damage. However, even with these considerations, experience from past earthquakes indicates that 15 weeks probably represents an excessive estimate of outage time. Although it may take this long to repair the damage, electric power service is likely to be restored within a much shorter timeframe through the use of emergency measures such as bypassing usual protection measures, using jumpers, etc. Thus it is reasonable to assume that electric power service would be available within one to two weeks to any customer that could use it.

With these considerations in mind, full restoration was assumed to be two weeks. Substituting into equation 6.1 yields

$$R=1-e^{-(2.75*0.1905)t} \tag{6.2}$$

where $t$ is measured in days. The scaling parameter $c$ in the Memphis case was thus derived to be 0.1905. This indicates that 97.4 percent of customers are expected to have electric power service restored within 1 week of the disaster and 99.9 percent within 2 weeks.

This restoration curve, together with the initial outage pattern and the assumption that areas of least damage are repaired first, allows the estimation of restoration times for each of the census tracts in the county. Electric power service areas (EPSAs) were first ranked according to initial outage in descending order on the basis of their "average post-earthquake availability" ratios. It is assumed that electricity is restored to EPSAs in this order. The cumulative number of customers in the EPSAs therefore indicates the number of customers with power restored as successive EPSAs are brought "on-line". Information on the number of customers in each census tract was estimated (according to the methodology to be described later in section 8), and this information was obtained for EPSAs by summing over the constituent census tracts (see Table 8-2). Both residential and nonresidential customers are included. Restoration times were then inferred for each EPSA so that the resulting restoration curve would approach equation 6.2 as closely as possible. Finally, restoration times for census tracts were inferred based upon the time for the corresponding EPSAs. Figure 6-2 shows the resulting estimated restoration pattern across the county. Restoration information is summarized in Table 6-11.

**TABLE 6-11 Estimated Restoration of Electric Power Service**

| Restoration (days) | Number of EPSAs | Percent of Customers | Cumulative Percent |
|---|---|---|---|
| 1 | 10 | 39.9% | 39.9% |
| 2 | 10 | 23.1% | 63.0% |
| 3 | 5 | 16.0% | 79.0% |
| 4 | 3 | 7.9% | 86.9% |
| 5 | 2 | 4.5% | 91.4% |
| 6 | 3 | 2.6% | 93.9% |
| 8 | 1 | 4.2% | 98.2% |
| 14 | 2 | 1.8% | 100.0% |

Since the initial outage levels reflect a probabilistic average rather than a particular outcome scenario, the inferred restoration pattern can be interpreted as an "average" pattern. A more accurate approach would have been to first apply the restoration inference methodology outlined above separately to each of the 100 Monte Carlo simulations of outage produced by Shinozuka et al., then estimate the resulting economic losses for each and combine the results. However, such an approach exceeds the scope of the present study.

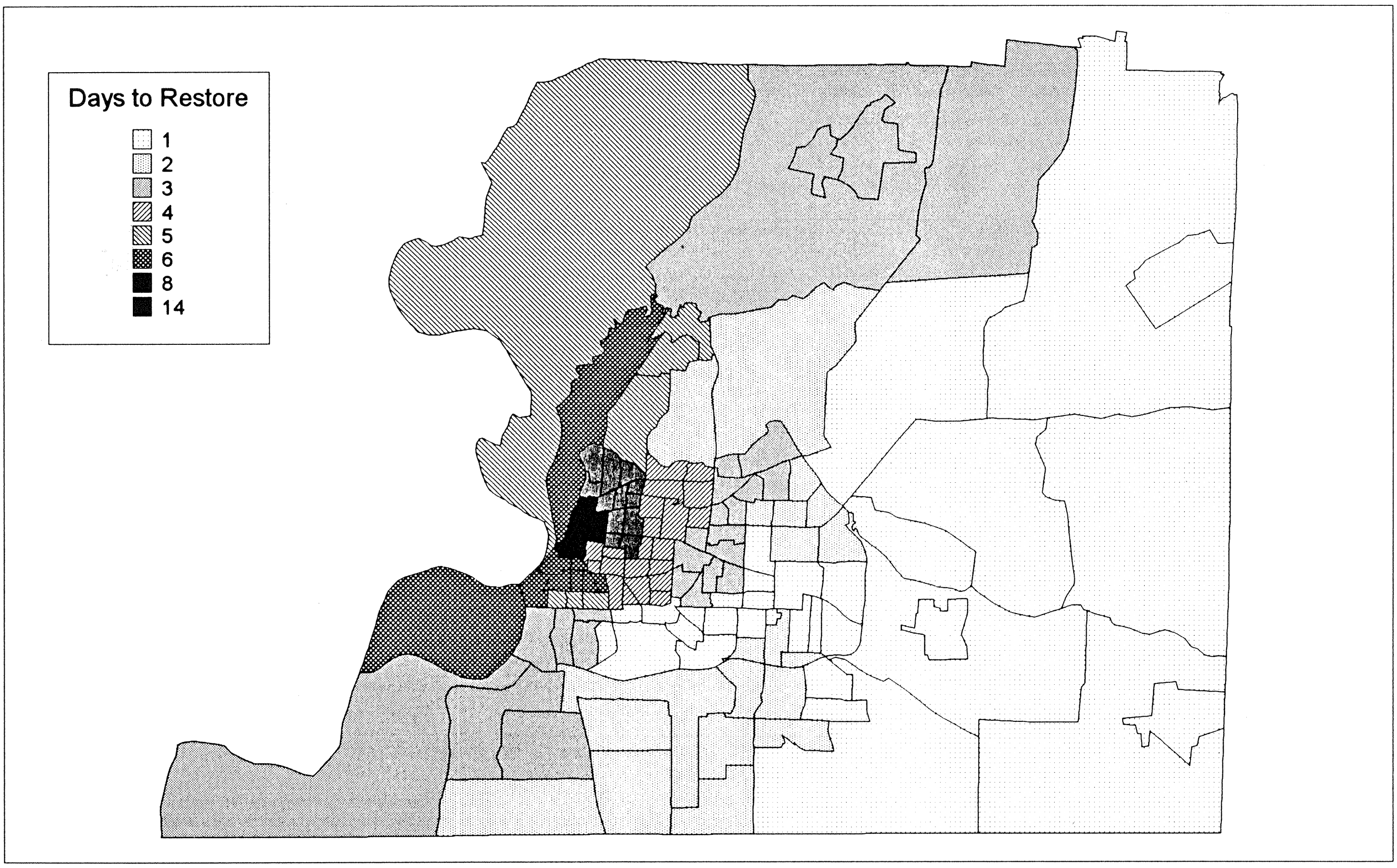



**FIGURE 6-2 Inferred Electric Power Restoration Pattern**

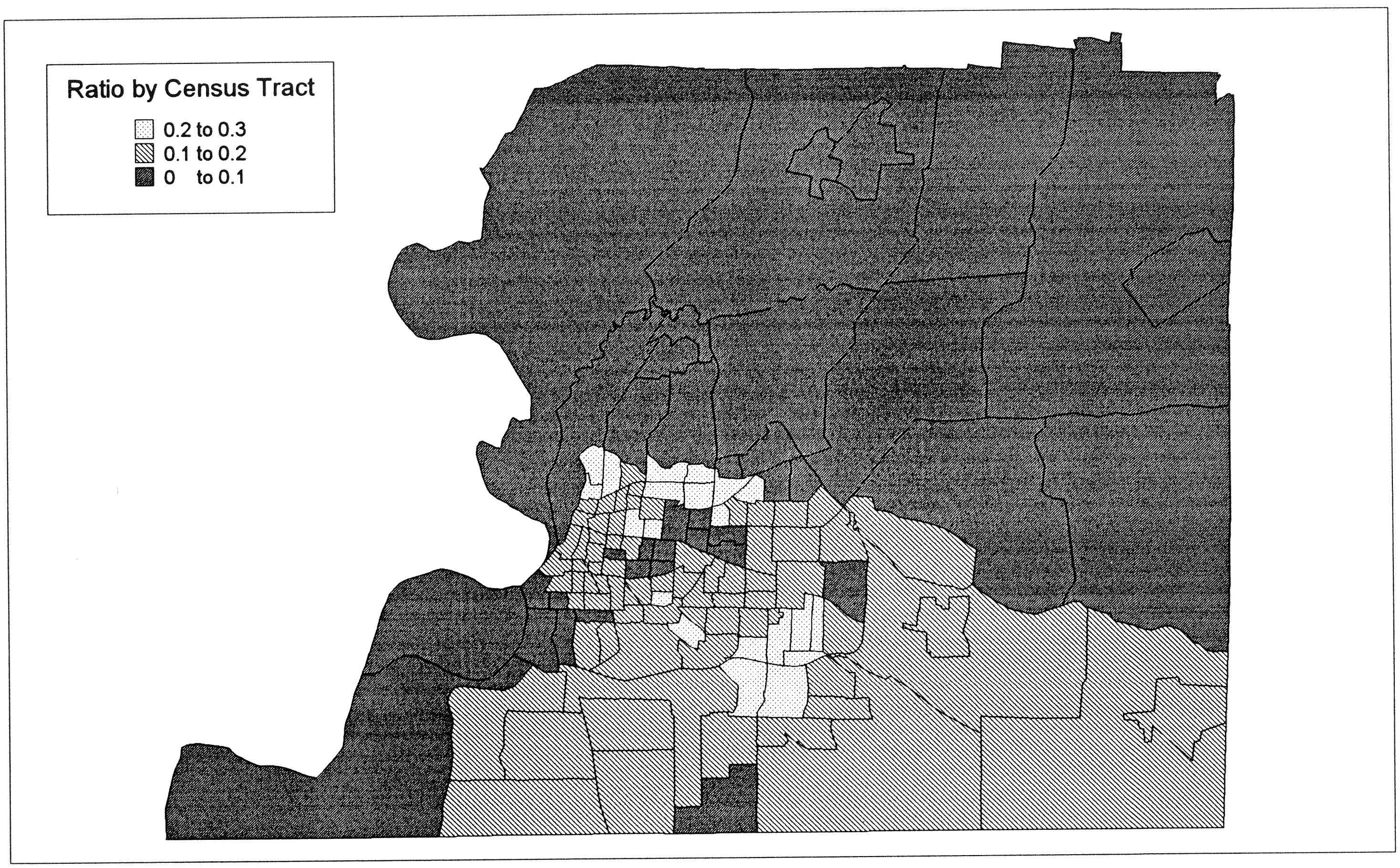
## 6.6 Water Outage and Restoration Models

### 6.6.1 Water Outage

Results for water outage were also adopted from models developed and applied to Shelby County by Shinozuka et al. at Princeton University. This model is implemented in a GIS-based computer code and consists of several principal steps. (Koiwa et al., 1993) These include flow analysis of the water delivery network under normal conditions (with no earthquake), estimation of the damaged state of the network for a given earthquake in terms of pipe breaks through Monte Carlo simulation, hydraulic analysis of the damaged network, and comparison of the results from the normal and seismic analyses.

In simulating the damaged state of the network, for a given earthquake scenario, the occurrence rate of pipe failures is first calculated. Monte Carlo simulation then yields the system damage state. Water flow parameters are then calculated, the new network topology is established through connectivity analysis, and flow analysis on the resulting network is performed. Results include simulation averages for number of pipe breaks, water head and flow output, as well as their corresponding ratios to the intact condition. These results are mapped onto census tracts for further analysis. As in the case of electricity outage, these results represent probabilistic averages rather than deterministic estimates.

Results from the study by Shinozuka et al. provided information on initial water outage, measured as the associated ratios of post-earthquake to pre-earthquake output by census tract. Initial outage across the county is shown in Figure 6-3. The average post-earthquake water availability ratio ranged from 0.0 to 0.28 in the census tracts with the most and least expected disruption, respectively.



source: based on information from Shinozuka et al.

**FIGURE 6-3 Ratio of Post-Earthquake Water Output Flow to Normal Demand**

### 6.6.2 Water Restoration

As in the case of electricity, the scope of the current project limited the estimation of water service restoration to the application of simplified models. The density of water pipe breaks was used to approximate the amount of time that would be required for work crews to restore water service in a given census tract. In a study of the San Fernando and Whittier earthquakes, Seligson et al. (1991) observed that areas with the least damage to water pipe breaks were restored first after the disasters. Using the raw data developed in that study for San Fernando, an empirical relationship was estimated between the number of breaks per square mile ($B$) and the number of days of water outage ($d$) where

$$d = \begin{cases} 2.18 + 2.51 \ln B & \text{if } B > .42 \\ 0 & \text{if } B \leq .42 \end{cases} \qquad (6.3)$$

The loglinear functional form is consistent with the expectation that in areas of high pipe break density, pipes may be replaced rather than repaired, indicating that incremental increases in pipe break density would not have much impact on total restoration time. For the Shelby County application, the density of breaks ($B$) was calculated by summing the number of pipe breaks in each census tract and dividing by its land area. Area estimates were produced automatically in MapInfo, the Geographic Information System (GIS) program used. Some aggregation was needed in order to estimate the number of pipe breaks in each tract. Shinozuka et al. provided information on the number of breaks occurring for each pipe and the census tract(s) within which the various pipes are located. In 366 of the 1321 cases, the pipes crossed census tract boundaries and were located in up to four different tracts. For these cases, the reported number of breaks was divided evenly among the associated census tracts. The density of damage ranged from 0.04 to 73.80 breaks per square mile for the various census tracts. The outage time estimates from applying equation 6.3, rounded up to the nearest full day, ranged from 0 to 13 days. Figure 6-4 shows the resulting water restoration pattern by census tract.

While equation 6.3 provides a first approximation of restoration time, several limitations with its application should be recognized. First, the experience in the San Fernando earthquake upon which the relationship is based may not provide an accurate indication of conditions after a major

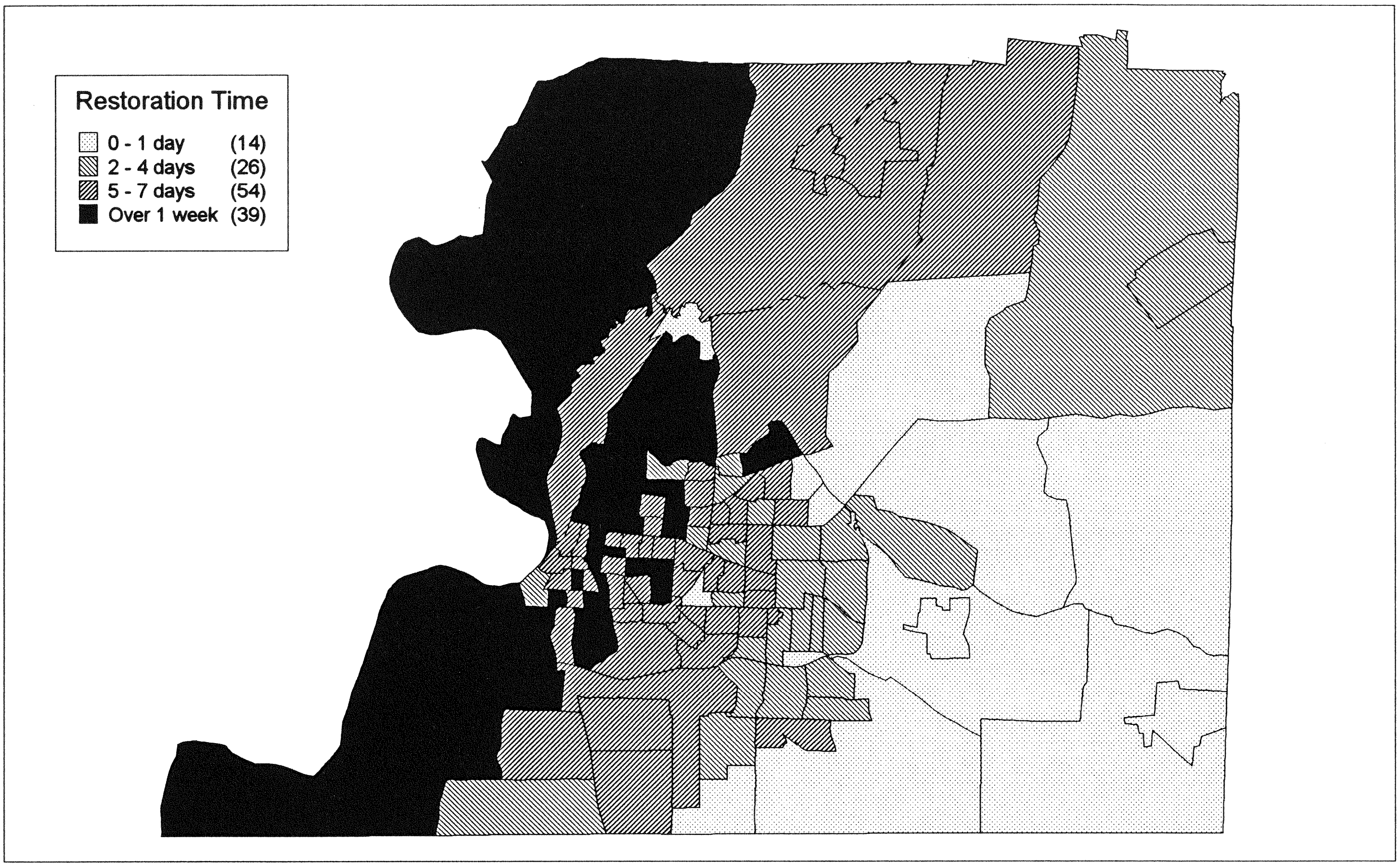



**FIGURE 6-4 Inferred Water Restoration Pattern**

Central U.S. earthquake. For example, the limited earthquake disaster experience of work crews, the possible insufficiency of readily available repair materials, as well as other factors such as transportation disruption, may lengthen restoration time. On a methodological level, the empirical relationship in equation 6.3 does not consider any systems effects in restoration of water throughout the county. A network analysis-based model of water service restoration is beyond the scope of this project. In addition, equation 6.3 was developed using data on grid cells of roughly 0.22 square miles each, whereas the census tracts to which the equation was applied in Shelby County average 5.9 square miles. This difference in scale may have introduced a nonconservative bias into the estimated restoration times.

Given these considerations, it is useful to compare the restoration pattern with the results that would have been obtained from applying an alternative methodology such as that described in ATC-25. ATC-25 suggests the following estimates of restoration timeframe for water delivery systems in the Central U. S., shown in Table 6-12:

**TABLE 6-12 ATC-25 Restoration Timeframes for Water Delivery Systems**

| | Restoration Timeframe (days) | |
|---|---|---|
| MMI | Water Supply Trunk Lines | Water Distribution Lines |
| VI | 2.2 | 4.4 |
| VII | 5.1 | 10.1 |
| VIII | 4.3 | 8.7 |
| IX | 11.5 | 23.1 |
| X | 24.2 | 48.3 |

Restoration times for distribution lines were derived by doubling those for trunk lines, as suggested in ATC-25. As in the case of natural gas, we note the apparent inconsistency between the MMI VIII estimates and those for intensities VII and IX. Recall that in Shelby County, MMI intensities are expected to range from VIII to VIII 1/2. Table 6-12 indicates an expected restoration time between 8 days for MMI VIII and 23 days for MMI IX. Applying equation 6.3 at the census tract level results in a full restoration time of 13 days with 89 percent of customers estimated to have water restored within 8 days. While it is difficult to make a clear comparison, these restoration estimates do not appear to be inconsistent with ATC-25.

## 6.7 Outage and Restoration Summary Results and Discussion

### 6.7.1 Summary Results

Based on the discussions above, initial outage and subsequent service restoration estimates were derived for the three lifeline systems on a census tract level. Numerical results, including outage and restoration time, are reported in Table 6-13.

In order to summarize and facilitate comparison of the disruption results, restoration curves for the three lifelines were developed for all of Shelby County. Outage and restoration results were combined with customer information (described in section 8) for each census tract. To develop a curve indicating the percentage of customers with lifeline service restored at particular point in time, it was assumed that customers in a given census tract could be considered "restored" when lifeline damage in that tract had been completely repaired. Thus the approach actually indicates the restoration pattern on a census tract rather than individual customer basis.

Figure 6-5 shows the restoration curves (percent of customers with lifeline service by day after the earthquake) for the three utilities that were inferred in this way. For reasons discussed above, these restoration curves should be interpreted as an average or expected pattern rather than as an actual outcome to a single deterministic scenario. The graph shows that at the end of the first week, while electric power is expected to be restored to almost all customers and water restoration is estimated at roughly 80 percent, gas service restoration is expected to proceed at a much slower rate. It is reassuring that both the shapes and relative positions of the three lifeline curves are consistent with actual experience in the Northridge and Kobe earthquakes.

### 6.7.2 Discussion

Particularly in comparison with other components of this study, the methodological approach discussed in this section is subject to a noticeable amount of ambiguity, unevenness, and internal inconsistency. Particularly significant issues in this regard include: (1) uneven and inconsistent treatment across lifelines, (2) at times independent estimation of outage and restoration, and (3) ambiguous utilization of probabilistic outage estimates and interpretation of restoration results. While these problems are recognized as limitations to the analysis, they do point to a number of areas for more detailed and rigorous further research.

The first issue consists of the uneven and inconsistent treatment of outage and restoration modeling across lifelines. In terms of outage estimation, because the results were utilized directly in the format in which they were produced in other related NCEER studies, the problem is one of coordination rather than methodological development. For example, the blanket assumption of complete natural gas disruption was made because specific outage results were unavailable. On the other hand, outage pertained to transmission system damage only in the case of electricity and to the entire delivery system damage in the case of water because of the scope of work defined in other studies. The difficulty in loss estimation arises from the need for consistent outage estimates across all of the lifelines. Similarly, disparate treatments of restoration modeling across lifelines derive, in part, from constraints related to outage information and the differential availability of empirical models from past earthquake experience. It is important to note, however, that systems operational considerations underlie the treatment of gas restoration on a distribution system basis, electric power on a substation basis and water on a total systems performance basis (with results aggregated by census tract). Furthermore, the principle that areas of least damage are generally restored first is maintained throughout. Thus the noted inconsistencies across lifelines do not seriously detract from the development and validity of the loss estimation methodology.

A second issue relates to the sometimes apparently independent treatment of outage and restoration estimation. Despite differences in implementation, the idea maintained in the treatment of all three lifelines is that restoration times directly relate to damage levels in each subarea of the County. For example, in the case of electric power, restoration modeling is tied directly to initial outage levels; for natural gas, it is related to the expected pipe damage in different areas on a pressure system basis. In the case of water delivery, it may seem that initial outage (Figure 6-3) is only loosely correlated with inferred restoration times (Figure 6-4) in the various census tracts. In fact, outage and restoration are connected through the physical damage levels or pipe breaks throughout the network. However, restoration relates to expected repair time, indicated by pipe break density in a given census tract, while initial outage considers the topology and hydraulic analysis of the entire water delivery network.

The third issue, concerning ambiguous utilization of probabilistic outage estimates and interpretation of restoration results, is perhaps the principal problem needing further methodological development. While initial outage is represented in terms of probabilistic average service availability in a given area, derived from 100 simulations of the same seismic event, restoration across census tracts is inferred as a single sequence corresponding to the average initial outage pattern. Thus it is not a deterministic restoration pattern because the initial outage pattern is not an actual outcome corresponding to a single simulation. However, neither is it a probabilistic restoration pattern corresponding to the probabilistic outage setting. In further research, perhaps the most viable approach would be to develop a fully probabilistic methodology. This could be based upon treating each of the 100 simulations as a deterministic outcome for which restoration patterns are developed and economic impacts (discussed in subsequent sections) are estimated. Average restoration times and losses could then be computed which would be fully consistent with the probabilistic damage and outage results and which could be interpreted without ambiguity.

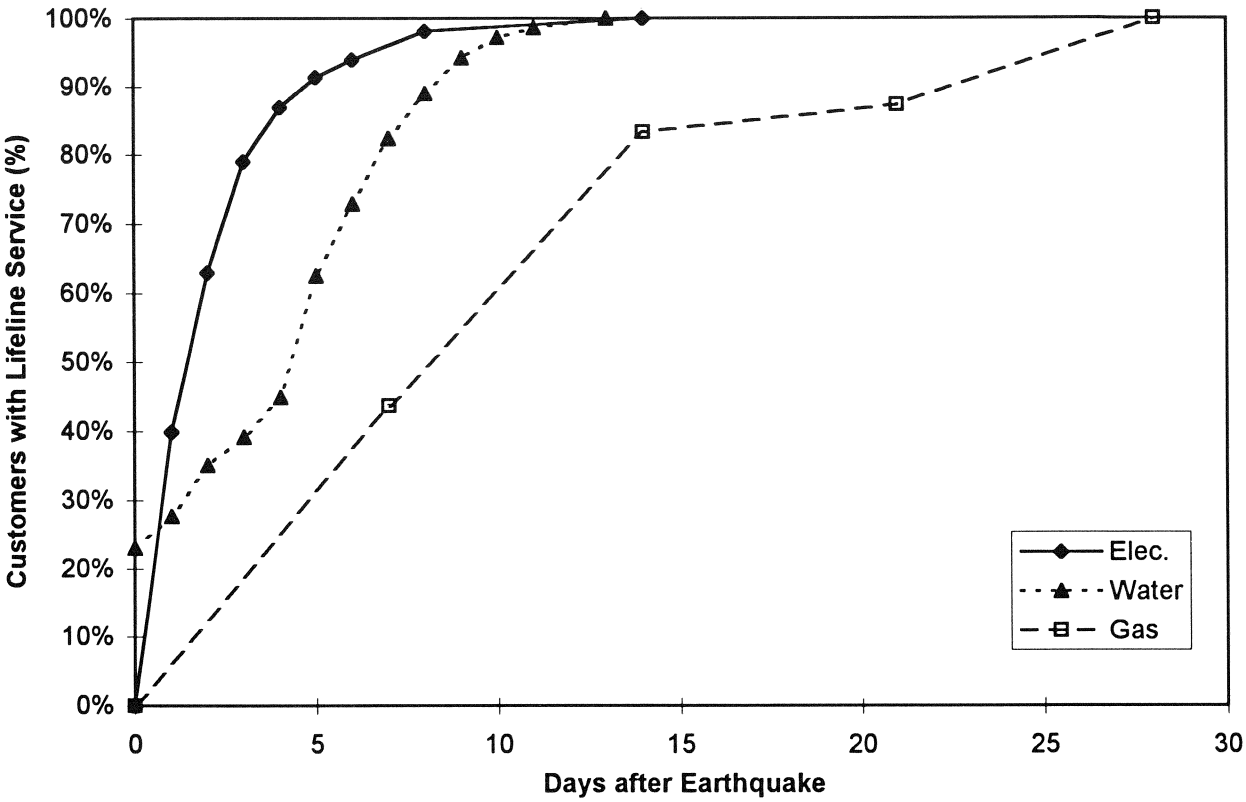



**FIGURE 6-5 Inferred Restoration Curves**

| TABLE 6-13 Outage and Restoration Estimates by Census Tract | | | | | | |
|---|---|---|---|---|---|---|
| Census | Restoration Time (days) | | | Outage (% Available) | | |
| Tract | Gas | Elec. | Water | Gas | Elec. | Water |
| 1 | 14 | 8 | 8 | 0% | 18% | 25% |
| 2 | 28 | 8 | 8 | 0% | 18% | 25% |
| 3 | 14 | 8 | 8 | 0% | 18% | 25% |
| 4 | 14 | 8 | 8 | 0% | 18% | 14% |
| 5 | 28 | 8 | 9 | 0% | 18% | 14% |
| 6 | 28 | 4 | 3 | 0% | 34% | 21% |
| 7 | 28 | 4 | 9 | 0% | 34% | 21% |
| 8 | 14 | 4 | 6 | 0% | 34% | 21% |
| 9 | 14 | 4 | 7 | 0% | 34% | 21% |
| 10 | 14 | 3 | 3 | 0% | 42% | 21% |
| 11 | 14 | 3 | 7 | 0% | 42% | 21% |
| 12 | 14 | 2 | 4 | 0% | 50% | 10% |
| 13 | 14 | 3 | 5 | 0% | 50% | 15% |
| 14 | 14 | 3 | 7 | 0% | 40% | 25% |
| 15 | 28 | 4 | 6 | 0% | 40% | 0% |
| 16 | 28 | 4 | 8 | 0% | 34% | 5% |
| 17 | 28 | 4 | 7 | 0% | 34% | 17% |
| 18 | 28 | 8 | 11 | 0% | 18% | 17% |
| 19 | 28 | 8 | 11 | 0% | 18% | 17% |
| 20 | 28 | 8 | 10 | 0% | 14% | 15% |
| 21 | 28 | 14 | 10 | 0% | 18% | 15% |
| 22 | 28 | 14 | 8 | 0% | 14% | 18% |
| 23 | 28 | 14 | 8 | 0% | 18% | 18% |
| 24 | 21 | 8 | 10 | 0% | 18% | 18% |
| 25 | 21 | 8 | 10 | 0% | 18% | 20% |
| 26 | 28 | 4 | 5 | 0% | 32% | 20% |
| 27 | 28 | 3 | 3 | 0% | 40% | 10% |
| 28 | 14 | 3 | 5 | 0% | 40% | 10% |
| 29 | 7 | 1 | 5 | 0% | 50% | 14% |
| 30 | 14 | 3 | 2 | 0% | 40% | 2% |
| 31 | 28 | 3 | 5 | 0% | 40% | 11% |
| 32 | 28 | 4 | 6 | 0% | 32% | 4% |
| 33 | 28 | 4 | 9 | 0% | 32% | 9% |
| 34 | 28 | 4 | 7 | 0% | 32% | 6% |
| 35 | 21 | 4 | 8 | 0% | 32% | 10% |
| 36 | 21 | 8 | 6 | 0% | 18% | 16% |
| 37 | 21 | 4 | 9 | 0% | 32% | 7% |
| 38 | 21 | 8 | 5 | 0% | 32% | 16% |
| 39 | 21 | 14 | 9 | 0% | 14% | 16% |
| 40 | 21 | 4 | 9 | 0% | 32% | 17% |
| 41 | 21 | 14 | 5 | 0% | 23% | 11% |
| 42 | 28 | 14 | 5 | 0% | 14% | 11% |
| 43 | 28 | 6 | 6 | 0% | 23% | 15% |
| 44 | 28 | 6 | 6 | 0% | 23% | 15% |
| 45 | 28 | 4 | 9 | 0% | 32% | 16% |
| 46 | 21 | 4 | 7 | 0% | 32% | 13% |
| 47 | 28 | 4 | 6 | 0% | 32% | 16% |
| 48 | 28 | 6 | 11 | 0% | 32% | 14% |

| TABLE 6-13 (Cont'd) | | | | | | |
|---|---|---|---|---|---|---|
| Census | Restoration Time (days) | | | Outage (% Available) | | |
| Tract | Gas | Elec. | Water | Gas | Elec. | Water |
| 49 | 28 | 6 | 5 | 0% | 23% | 14% |
| 50 | 28 | 6 | 11 | 0% | 23% | 16% |
| 51 | 28 | 6 | 7 | 0% | 23% | 16% |
| 52 | 14 | 6 | 4 | 0% | 23% | 8% |
| 53 | 14 | 3 | 8 | 0% | 43% | 8% |
| 54 | 28 | 5 | 9 | 0% | 26% | 8% |
| 55 | 14 | 3 | 6 | 0% | 43% | 9% |
| 56 | 28 | 3 | 8 | 0% | 43% | 12% |
| 57 | 28 | 3 | 9 | 0% | 43% | 9% |
| 58 | 28 | 5 | 6 | 0% | 26% | 16% |
| 59 | 28 | 5 | 8 | 0% | 26% | 16% |
| 60 | 28 | 1 | 5 | 0% | 55% | 11% |
| 61 | 28 | 4 | 7 | 0% | 34% | 16% |
| 62 | 28 | 4 | 6 | 0% | 34% | 14% |
| 63 | 28 | 4 | 8 | 0% | 34% | 13% |
| 64 | 28 | 4 | 8 | 0% | 34% | 23% |
| 65 | 28 | 1 | 7 | 0% | 55% | 19% |
| 66 | 14 | 3 | 5 | 0% | 40% | 14% |
| 67 | 14 | 3 | 0 | 0% | 40% | 14% |
| 68 | 14 | 1 | 7 | 0% | 55% | 13% |
| 69 | 14 | 1 | 5 | 0% | 55% | 23% |
| 70 | 14 | 1 | 2 | 0% | 55% | 10% |
| 71 | 14 | 3 | 5 | 0% | 40% | 13% |
| 72 | 14 | 3 | 5 | 0% | 40% | 12% |
| 73 | 14 | 1 | 5 | 0% | 55% | 11% |
| 74 | 14 | 1 | 5 | 0% | 55% | 13% |
| 75 | 14 | 1 | 8 | 0% | 43% | 10% |
| 76 | 7 | 3 | 9 | 0% | 44% | 0% |
| 77 | 14 | 6 | 13 | 0% | 26% | 0% |
| 78 | 14 | 1 | 7 | 0% | 55% | 12% |
| 79 | 7 | 1 | 7 | 0% | 55% | 15% |
| 80 | 7 | 1 | 5 | 0% | 55% | 14% |
| 81 | 7 | 1 | 7 | 0% | 53% | 10% |
| 82 | 7 | 2 | 2 | 0% | 53% | 28% |
| 83 | 7 | 2 | 4 | 0% | 53% | 28% |
| 84 | 7 | 1 | 6 | 0% | 55% | 14% |
| 85 | 7 | 1 | 3 | 0% | 55% | 13% |
| 86 | 7 | 2 | 2 | 0% | 50% | 13% |
| 87 | 14 | 2 | 5 | 0% | 50% | 12% |
| 88 | 14 | 3 | 5 | 0% | 42% | 6% |
| 89 | 14 | 3 | 8 | 0% | 42% | 6% |
| 90 | 14 | 3 | 2 | 0% | 42% | 6% |
| 91 | 14 | 2 | 1 | 0% | 50% | 6% |
| 92 | 14 | 2 | 2 | 0% | 50% | 15% |
| 93 | 7 | 1 | 4 | 0% | 55% | 22% |
| 94 | 7 | 1 | 2 | 0% | 55% | 22% |
| 95 | 7 | 1 | 3 | 0% | 55% | 20% |
| 96 | 7 | 1 | 4 | 0% | 55% | 9% |

| TABLE 6-13 (Cont'd) | | | | | | |
|---|---|---|---|---|---|---|
| Census | Restoration Time (days) | | | Outage (% Available) | | |
| Tract | Gas | Elec. | Water | Gas | Elec. | Water |
| 97 | 7 | 2 | 0 | 0% | 55% | 22% |
| 98 | 14 | 2 | 0 | 0% | 50% | 15% |
| 99 | 14 | 6 | 7 | 0% | 14% | 3% |
| 100 | 14 | 5 | 9 | 0% | 27% | 2% |
| 101 | 14 | 5 | 10 | 0% | 18% | 2% |
| 102 | 14 | 2 | 9 | 0% | 51% | 6% |
| 103 | 14 | 5 | 1 | 0% | 11% | 2% |
| 104 | 7 | 2 | 5 | 0% | 45% | 13% |
| 105 | 7 | 2 | 4 | 0% | 53% | 24% |
| 106 | 7 | 2 | 4 | 0% | 53% | 21% |
| 107 | 7 | 1 | 4 | 0% | 56% | 20% |
| 108 | 7 | 1 | 2 | 0% | 56% | 18% |
| 109 | 7 | 2 | 5 | 0% | 53% | 18% |
| 110 | 7 | 2 | 2 | 0% | 45% | 10% |
| 201 | 14 | 5 | 8 | 0% | 14% | 0% |
| 202 | 14 | 3 | 7 | 0% | 35% | 2% |
| 203 | 14 | 3 | 5 | 0% | 35% | 2% |
| 204 | 14 | 3 | 5 | 0% | 35% | 2% |
| 205 | 14 | 2 | 6 | 0% | 48% | 5% |
| 206 | 14 | 1 | 0 | 0% | 48% | 5% |
| 207 | 14 | 3 | 7 | 0% | 35% | 2% |
| 208 | 7 | 1 | 2 | 0% | 57% | 3% |
| 209 | 7 | 1 | 2 | 0% | 57% | 3% |
| 210 | 7 | 1 | 0 | 0% | 56% | 3% |
| 211 | 7 | 1 | 1 | 0% | 57% | 5% |
| 212 | 7 | 1 | 2 | 0% | 57% | 11% |
| 213 | 7 | 1 | 0 | 0% | 56% | 13% |
| 214 | 14 | 1 | 0 | 0% | 56% | 13% |
| 215 | 7 | 1 | 0 | 0% | 56% | 15% |
| 216 | 7 | 1 | 0 | 0% | 56% | 15% |
| 217 | 7 | 1 | 0 | 0% | 56% | 18% |
| 219 | 7 | 2 | 0 | 0% | 53% | 0% |
| 220 | 7 | 2 | 6 | 0% | 45% | 15% |
| 221 | 7 | 2 | 5 | 0% | 52% | 17% |
| 222 | 14 | 3 | 13 | 0% | 43% | 12% |
| 223 | 14 | 3 | 5 | 0% | 43% | 16% |
| 224 | 7 | 2 | 3 | 0% | 55% | 15% |

# SECTION 7

# UTILITY USAGE DATA

This section presents information related to the usage of natural gas, electricity and water. This data will be used to estimate revenue losses to the utility provider in the event of an earthquake. Basic statistics include the number of customers served and the price of the utility service. As in previous sections, natural gas is explored in greatest detail because of the development history of this project.

## 7.1. Natural Gas Data Sources

Data on regional and national natural gas utilization are available from two sources: the American Gas Association (AGA) and the Department of Energy's Energy Information Administration (DOE/EIA). The American Gas Association annually publishes *Gas Facts*, a statistical record of the gas utility industry. *Gas Facts* contains data on energy reserves, natural gas supply, underground storage, energy consumption, customers, sales, revenues and prices. Relevant data is presented for the U.S. as a whole, for census divisions, and for individual states. *The Natural Gas Annual*, published by DOE/EIA, presents similar information, and includes a set of summary statistics for each state. In addition to data on natural gas deliveries by utilities, the DOE/EIA statistics include natural gas purchased directly from producers and delivered to end users through transportation agreements with pipeline companies. These "transportation volumes" or "deliveries for the accounts of others" are, by definition, not included in the gas utility industry figures presented by the AGA. Furthermore, they are not relevant to the current study -- while damage to the pipeline companies will impact these transportation volumes and deliveries, this study is concerned with the impact of natural gas utility disruption on an urban area. Therefore, the AGA statistics (1991) will be utilized here to characterize gas usage at the state level.

Data on local natural gas usage were obtained from Memphis Light, Gas and Water Division (MLGW), which provides natural gas service to Shelby County and the city of Memphis.

Statistics on MLGW's customers, consumption, revenue and supply (MLGW, 1992) were obtained through the assistance of Prof. H. Hwang at Memphis State University's Center for Earthquake Research and Information.

### 7.2 Natural Gas Supply and Disposition in Tennessee

There are several features of the natural gas supply and disposition within Tennessee which distinguish the state from the remainder of the region.

- Tennessee has no underground storage reservoirs, unlike the remainder of the East South Central Division which has a storage capacity of about 315,000 million cubic feet (MMcf), with 180,000 MMcf in storage at the end of 1990 (AGA, 1991).
- According to AGA data, net interstate imports of natural gas into Tennessee in 1989 totalled 182,573 MMcf. No 1990 data or breakdown by source are given. In the 1990 Natural Gas Annual (DOE/EIA, 1991), detailed data on interstate transfers for 1990 are available. Total net movement into Tennessee for 1989 and 1990 were reported as 187,111 and 104,733 MMcf, respectively. The net amount remaining in state in 1990 is significantly lower than of 1989, even though consumption remained relatively constant. This discrepancy is attributed to quantities lost and data reporting problems. While the actual quantities of the deliveries will not equate to consumption, the relative movement of natural gas from state to state is of interest. The detailed breakdown of data by source provides an indication of the primary sources of supply for the state. Net movement of natural gas into and out of Tennessee in 1990 was as follows (DOE/EIA, 1991):

| | |
|---|---|
| + | 2,382,952 MMcf from Mississippi |
| + | 1,007,942 MMcf from Alabama |
| + | 8,079 MMcf from Georgia |
| + | 2,174 MMcf from Virginia |
| - | 3,296,414 MMcf to Kentucky |
| = | 104,733 MMcf net in state |

- In 1990, Tennessee had only 690 producing natural gas wells, which yielded 2,067 MMcf, compared to 15,350 producing gas wells in the East South Central region, which produced 300,009 MMcf in the same year (DOE/EIA, 1991).

The significant conclusion from this data is that the state of Tennessee does not produce its own natural gas in significant quantities, nor does it store significant quantities underground. Natural gas supply within the state, therefore, is almost entirely dependent upon interstate imports, 70% of which comes from Mississippi, and 30% from Alabama.

### 7.3 Natural Gas Usage Patterns

The basic statistics of importance for this loss assessment are the number of customers served by natural gas utilities, and the price of the natural gas. This data will be combined with outage estimates to determine the impacted households and commercial and industrial enterprises, and the subsequent economic impact in terms of loss of revenue for the utility. Other data, such as on gas consumption, are important to complete the overall picture of regional natural gas usage. Four sets of data representing various levels of the regional analysis will be presented here when available, including Shelby County, the State of Tennessee, the East South Central census division (which includes Alabama, Kentucky, Mississippi, and Tennessee), and the entire U.S.

#### 7.3.1 Natural Gas Customers and Consumption

Customers are categorized by the gas utility industry into five groups: residential, commercial, industrial, electric generation, and other. Table 7-1 presents a breakdown of available customer information for 1990 natural gas usage. The distribution of customers in Shelby County according to the major categories is shown to be similar to that of the larger regions. In Shelby County, residential customers represent 92.8 percent of the total while commercial and industrial customers make up the remaining 7.2 percent.

**TABLE 7-1 1990 Natural Gas Utility Customers[a]**
(Thousands and Percent of Customers)

| Region | Residential | Commercial | Industrial | Electric Generation | Other | Total |
|---|---|---|---|---|---|---|
| U.S. | 49,830.2<br>(91.8%) | 4,248.5<br>(7.8%) | 165.6<br>(0.3%) | .4<br>- | 47.9<br>(.09%) | 54,292.6<br>(100%) |
| East South Central Census Division | 2,258.0<br>(89.9%) | 239.1<br>(9.5%) | 6.7<br>(0.2%) | --[b] | 9.4<br>(0.4%) | 2,513.2<br>(100%) |
| Tennessee | 595.6<br>(87.2%) | 82.6<br>(12.1%) | 2.2<br>(0.3%) | 0.0 | 2.9<br>(0.4%) | 683.3<br>(100%) |
| Shelby County (MLGW) | 245.6<br>(92.8%) | 18.6[c]<br>(7.0%) | 0.4[d]<br>(0.2%) | --- | --- | 264.6<br>(100%) |

Notes:
a) Source: Gas Facts, AGA (1991), except for Shelby County, which is 1991 data from MLGW (1992).
b) less than 0.05
c) MLGW "general services" customers are assumed to represent mostly commercial customers
d) MLGW "demand" customers are assumed to represent mostly industrial customers

However, although the majority of customers are residential, the quantity of natural gas consumed per customer is much greater in the industrial and electric generating categories. Table 7-2 shows the average annual natural gas consumption for each customer type.

Table 7-2 shows that users generating electric power consume a significant amount of natural gas; however, there are no such users in Tennessee. The table also shows that while the East South Central Census Division has average per customer commercial usage lower than the national average, such usage in Tennessee and Shelby County exceeds the national average. In addition, the East South Central, Tennessee, and Shelby County in particular all have average industrial usage significantly higher than the national average.

**TABLE 7-2 1990 Average Annual Natural Gas Consumption Per Gas Utility Customer** (Million BTUs)

| Region | Residential | Commercial | Industrial | Electric Generation | Other |
|---|---|---|---|---|---|
| U.S. | 89.7 | 516.3 | 11,416.7 | 2,545,669.5 | 3,570.8 |
| East South Central Census Division | 79.5 | 456.3 | 22,152.9 | 144,516.7 | 1,034.4 |
| Tennessee | 81.3 | 537.1 | 29,542.3 | 0.0 | 211.5 |
| Shelby County[a] (MLGW) | 81.6 | 694.8 | 89,296.0 | --- | --- |

Notes: a) source: for Shelby County, derived from 1991 consumption data from MLGW (1992); for all other, Gas Facts (AGA, 1991)

**TABLE 7-3 Total 1990 Natural Gas Utility Sales[a]** (Trillion BTUs and Percent)

| Region | Residential | Commercial | Industrial | Electric Generation | Other | Total |
|---|---|---|---|---|---|---|
| U.S. | 4,471.4 (45%) | 2,193.3 (22%) | 1,890.4 (19%) | 1,120.1 (11%) | 171.1 (2%) | 9,846.3 (100%) |
| East South Central Census Division | 179.5 (40%) | 109.1 (24%) | 149.4 (33%) | 0.9 (0%) | 9.8 (2%) | 448.7 (100%) |
| Tennessee | 48.4 (30%) | 44.4 (28%) | 65.4 (41%) | --[b] | 0.6 (0%) | 158.8 (100%) |
| Shelby County (MLWG) | 20.0 (31%) | 12.9 (20%) | 31.6 (49%) | --- | --- | 64.5 (100%) |

Notes:

a) excludes transportation volumes and sales of gas for resale

b) less than 0.05 trillion BTU

c) source: for Shelby County, derived from 1991 consumption data from MLGW (1992); for all other, Gas Facts (AGA, 1991)

These trends are reflected in total sales figures for natural gas by user category, presented in Table 7-3. At the national level, residential users consumed almost half of all natural gas sold by utilities in 1990, while industrial sales accounted for about 20 percent. In Tennessee, over 40 percent of utility sales were to industrial users, with residential customers accounting for about 30 percent of 1990 sales. In Shelby County, industrial users account for almost 50 percent of gas sales, while residential users represent another 30 percent.

### 7.3.2 Natural Gas Usage Data by Standard Industrial Classification

The customer types indicated in the previous section represent highly aggregate categories, and it would be desirable to be able to further break down the commercial and industrial group information by detailed industry group. Only limited information is available, however, on natural gas sales or consumption by Standard Industrial Classification (SIC) code. The 1991 edition of *Gas Facts* includes tables tallying volume sold by 1- or 2-digit SIC classifications for industrial and electric generation users and for commercial and other users. Such information would be excellent for modelling gas usage in a form compatible with many economic indicators. However, the available data has certain limitations that make its use less than advantageous.

One limitation of this tabulation is that the data has been compiled at the national and Census Division levels only. Tabulations at the state level are not available through the AGA, nor are data for Shelby County. In addition, no customer or revenue data for each SIC are given. The sales figures presented in these tables are based on company reports, but combine actual data with projections or estimates. For the U.S. figures, actual reported data accounts for at most about 60% of the total projected figures. Similarly, for the East South Central figures, actual data is at most 55% of the total. Because the final numbers represent projections, these bottom line figures do not precisely match other sales data as presented in *Gas Facts*. An additional drawback associated with these figures results from the fact that a significant portion of the data has not been classified. For national figures, up to 55% of the data has not been assigned to a SIC, while for the East South Central data, as much as 69% of the data is similarly unassigned.

Because of these limitations, natural gas usage will be modelled in this study according to the generalized user groups as presented in tables above, for which customer, sales, and cost figures are available. The usage data by SIC is useful, however, in that it provides information on which SIC groups are considered by the gas utility industry to be commercial and industrial customers. Table 7-4 identifies SIC codes with the major customer type classification used by the gas utility industry.

**TABLE 7-4 Natural Gas Customer Category for SIC Codes**

| SIC Division | SIC Code | Description | Customer Type |
|---|---|---|---|
| A | 01-09 | Agriculture, Forestry, Fishing | Commercial |
| B | 10-14 | Mining | Industrial |
| C | 15-17 | Construction | Commercial |
| D | 20-39 | Manufacturing | Industrial |
| E | 40-48, 49 (except 491,493) | Transportation and Utilities other than electric generation | Commercial |
| E | 491,493 | Electric Generation | Electric Generation |
| F | 50-51 | Wholesale Trade | Commercial |
| G | 52-59 | Retail Trade | Commercial |
| H | 60-67 | Finance, Insurance & Real Estate | Commercial |
| I | 70-89 | Services | Commercial |
| J | 91-97 | Public Administration | Commercial |
| K | 99 | Non-Classifiable | Commercial |

### 7.3.3 Natural Gas Cost and Revenue Data

In order to estimate the utility's revenue losses following an earthquake, information is needed on the average daily revenues from each type of customer. This information can be derived from sales figures, average prices and the number of customers. Table 7-5 presents total 1990 gas utility industry revenues.

National revenue patterns, as shown in Table 7-5, indicate that about 55 percent of all gas utility industry revenues come from residential customers, 23 percent from commercial customers, 13 percent from industrial customers, and 7 percent from electric generation. Focussing in on the East South Central region, the residential contribution to revenues declines to 48 percent, while commercial and industrial increases to 26 and 24 percent, respectively. In Tennessee, the distribution of revenues from the three major user groups levels out even further, with residential, commercial and industrial revenues accounting for 36, 31 and 33 percent of the total, respectively. The revenue breakdown in Shelby County, however, is 56, 29 and 12 percent for residential, commercial, and industrial customers, respectively. Thus even though volume sales to industrial customers comprise a much higher share of all sales in Shelby County as compared with the nation as a whole (Table 7-3), revenue source patterns are very similar.

**TABLE 7-5 Total 1990 Gas Utility Industry Revenues[a]**
(Thousands of Dollars)

| Region | Residential | Commercial | Industrial | Electric Generation | Other | Total |
|---|---|---|---|---|---|---|
| U.S. | 25,013,880 (55%) | 10,609,970 (23%) | 6,034,227 (13%) | 2,962,516 (7%) | 553,308 (1%) | 45,173,901 (100%) |
| East South Central Census Division | 942,604 (48%) | 497,135 (26%) | 467,829 (24%) | 3,047 (0%) | 37,409 (2%) | 1,948,024 (100%) |
| Tennessee | 229,998 (36%) | 200,249 (31%) | 211,669 (33%) | 123 (0%) | 2,564 (0%) | 644,603 (100%) |
| Shelby County (MLGW) | 88,389 (56%) | 46,508 (29%) | 24,245 (15%) | --- | --- | 159,142 (100%) |

Notes:
a) Source: Gas Facts, AGA (1991), except for Shelby County, which is 1991 data from MLGW (1992).

This derives from the differential in prices charged to different types of customers. Table 7-6 lists average gas prices and shows that average prices in Shelby County are less than both the East South Central states and national average for all customer types. This difference is especially great in the case of industrial customers. This observation is consistent with the expectation that large-volume customers would be charged lower per unit prices and with the observation from

Table 7-2 that average annual gas consumption per customer is almost 8 times higher in Shelby County than in the nation as a whole. Furthermore, the differential between average residential and industrial prices is much higher in Shelby County than in the the nation, the region, and even the state.

**TABLE 7-6 Average 1990 Gas Utility Industry Prices[a]**
(Dollars per Million BTU)

| Region | Residential | Commercial | Industrial | Electric Generation | Other |
|---|---|---|---|---|---|
| U.S. | 5.59 | 4.84 | 3.19 | 2.65 | 3.24 |
| East South Central Census Division | 5.25 | 4.56 | 3.13 | 3.51 | 3.83 |
| Tennessee | 4.75 | 4.51 | 3.24 | --[b] | 4.13 |
| Shelby County (MLGW) | 4.41 | 3.60 | 0.77 | --- | --- |

Notes:
a) Source: Gas Facts, AGA (1991), except for Shelby County, which is 1991 data from MLGW (1992).
b) less than 0.05 trillion BTU in sales

### 7.3.4 Derivation of Seasonal Average Daily Revenues

In developing average daily revenues per customer for each user group, it is important to consider seasonal fluctuations in natural gas usage. An examination of U.S. quarterly sales volumes (AGA, 1991) over the past 5 years (1986 - 1990) reveals a consistent pattern of significantly greater usage in the winter months (1st and 4th quarters, October through March) than in the summer months (2nd and 3rd quarters, April through September). The extent of this fluctuation varies among the different user groups, as follows:

- Residential Users
  - summer usage accounts for approximately 25% of annual sales by volume
  - winter usage accounts for approximately 75% of annual sales by volume
- Commercial Users
  - summer usage accounts for approximately 30% of annual sales by volume
  - winter usage accounts for approximately 70% of annual sales by volume
- Industrial Users - seasonal fluctuation in usage is negligible

It is assumed that these national figures, representing typical seasonal fluctuation patterns, are sufficient to capture the average seasonal variation in the current study area. This information may be used to calculate two average daily sales volume figures from total annual sales for each user group - one for summer and one for winter. From the average daily sales figures, average price data allows calculation of average daily revenues, which, when combined with customer data, yields average daily revenues per customer. Table 7-7 lists seasonal average daily revenues per customer derived for Shelby County.

**TABLE 7-7 Average Daily Revenue per Gas Utility Customer for Natural Gas Sales in Shelby County, Tennessee**

| Customer Group | Winter | Summer |
|---|---|---|
| Residential | $1.48 | $0.49 |
| Commercial | $9.63 | $4.10 |
| Industrial | $188.16 | $187.13 |

### 7.4 Electricity Usage Patterns

For electricity, information on usage patterns was obtained from MLGW through the assistance of Prof. Hwang. Table 7-8 summarizes data for 1990.

**TABLE 7-8 Electricity Usage Patterns, Shelby County, 1990**

| | Residential | Commercial | Industrial | Total |
|---|---|---|---|---|
| Number of customers | 310,241<br>(90%) | 34,213<br>(10%) | 177<br>(0%) | 344,631<br>(100%) |
| Average annual consumption per customer (Kwh) | 14,026 | 139,659 | 9,733 | 31,490 |
| Total sales (Mwh) | 4.351,567<br>(40%) | 4,778,158<br>(44%) | 1,722,748<br>(16%) | 10,852,473<br>(100%) |
| Total Revenues ($) | 252,584,989<br>(42%) | 272,647,590<br>(45%) | 75,551,724<br>(13%) | 611,784,303<br>(100%) |
| Average Price ($/Kwh) | $0.058 | $0.057 | $0.044 | $0.055 |
| Average daily revenue per customer ($) | $2.23 | $21.83 | $1,169.44 | $4.78 |

Source: MLGW communication (1995)

As in the case of natural gas usage, residential customers account for the vast majority of electricity customers but a much smaller share of sales volume and revenue. The average daily revenue per customer is much higher for electricity than for natural gas across all customer groups. It is interesting to note that there are more electricity customers than gas customers. One reason may be that not all residences or business sites use gas, whereas almost all use electricity. Insufficient information was available to make seasonal adjustments.

### 7.5 Water Usage Patterns

Similar information on water usage was also provided by MLGW for 1990. This data is shown in table 7-9. Unfortunately, MLGW was unable to break down non-residential customers by type. These are therefore reported together under the “commercial/ industrial” heading.

**TABLE 7-9 Water Usage Patterns, Shelby County, 1990[a]**

| | Residential | Commercial/ Industrial | Total |
|---|---|---|---|
| Number of customers | 189,012 (92%) | 17,288 (8%) | 206,300 (100%) |
| Average annual consumption per customer (ccf)[(b)] | 141 | 1,628 | 265 |
| Total sales (ccf) | 26,568,349 (49%) | 28,138,764 (51%) | 54,707,113 (100%) |
| Total revenues ($) | 18,210,554 (56%) | 14,343,949 (56%) | 32,554,503 (44%) |
| Average price ($/ccf) | $0.685 | $0.510 | $0.595 |
| Average daily revenue per customer ($) | $0.26 | $2.27 | $0.43 |

Notes: a) data from MLGW correspondence (1995)
b) ccf=100 cubic feet

Similar patterns can be observed in the case of water. Residential users constitute 92 percent of the users but only 49 percent of sales and 56 percent of revenues. Average daily revenue per customer is lower for water than for either gas or electricity. Indeed, total annual revenue for water ($33 million) is much lower than that for natural gas ($159 million) or electricity ($612 million). In addition, it is also interesting to note that there are fewer water customers than gas customers. This may be due in part to multi-family residential buildings or complexes being considered together for water billing purposes but individually for gas billing. Other reasons may also apply. Insufficient information was available to make seasonal adjustments; however, in contrast to natural gas and electricity which are used for energy, seasonal variations in water consumption are expected to be relatively minor.

# SECTION 8

# CUSTOMER LOCATION PATTERNS

In addition to usage data, information on customer location patterns is required for evaluating revenue and other economic loss. Results from section 6 indicated that the extent of lifeline service disruption and restoration will vary across the County. The associated economic impact will derive from how this disruption pattern relates to the location of utility customers within the county. Severe lifeline service disruption in a rural area would have less impact, for example, than the same level of disruption in a central urban district. This section presents information related to the location of customers of natural gas, electricity and water service in Shelby County.

## 8.1 Data

Customer location information will be used to estimate both revenue losses to the utility provider and economic or business interruption losses to the utility service user. In both cases, information is needed on the number of customers by customer type in each census tract within the County. Although data on the actual location of MLGW customers was not available, other data sources can be used to infer this information.

For residential customers, population data by census tract from the *1990 Census of Population* was used. The total resident population in Shelby County was 826,271 persons. Assuming that each of MLGW's residential customers represents the same number of persons regardless of location within the county, the locational pattern of persons can be used to represent the locational pattern of residential customers within the county.

Similarly, for nonresidential customers, information on employment distribution can be used to approximate the locational pattern of utility customers. Standard Census publications, however, tabulate employment by place of residence rather than by place of work. In this study, information from an unpublished data source of employment by place of employment was obtained for a related NCEER study and made available to us by Prof. A. Rose at Pennsylvania State University. This data source consists of a special Census Bureau study undertaken for the Memphis and Shelby County Office of Planning and Development. It includes information on number of jobs in 1990 by detailed industry for over 500 Traffic Analysis Zones (TAZs) that comprise the County.

Data from this study was condensed into major industries and regrouped by assigning TAZs to census tracts through GIS overlay. In the vast majority of cases, TAZs fell primarily or entirely within census tracts. However, in a few cases, very small census tracts were not assigned any employment data because the overlapping TAZ was assigned to an adjacent census tract. The resulting inaccuracies are very minor.

The total number of private-sector jobs in the County, as indicated by this special Census study, is 390,220. The distribution among nine major industries is shown in Table 8-1. About one-third of jobs in the county are in the services industry.

**TABLE 8-1 Industry Composition of Employment, Shelby County**

| Industry | Employment | Percent of County |
|---|---|---|
| Agriculture | 4,459 | 1.1% |
| Mining | 264 | 0.1% |
| Construction | 23,306 | 6.0% |
| Manufacturing | 53,613 | 13.7% |
| TCU[a] | 52,389 | 13.4% |
| Wholesale Trade | 26,889 | 6.9% |
| Retail Trade | 69,111 | 17.7% |
| FIRE[b] | 26,261 | 6.7% |
| Services | 133,928 | 34.3% |
| Total | 390,220 | 100.0% |

notes: (a) transportation, communications and utilities
(b) finance, insurance and real estate

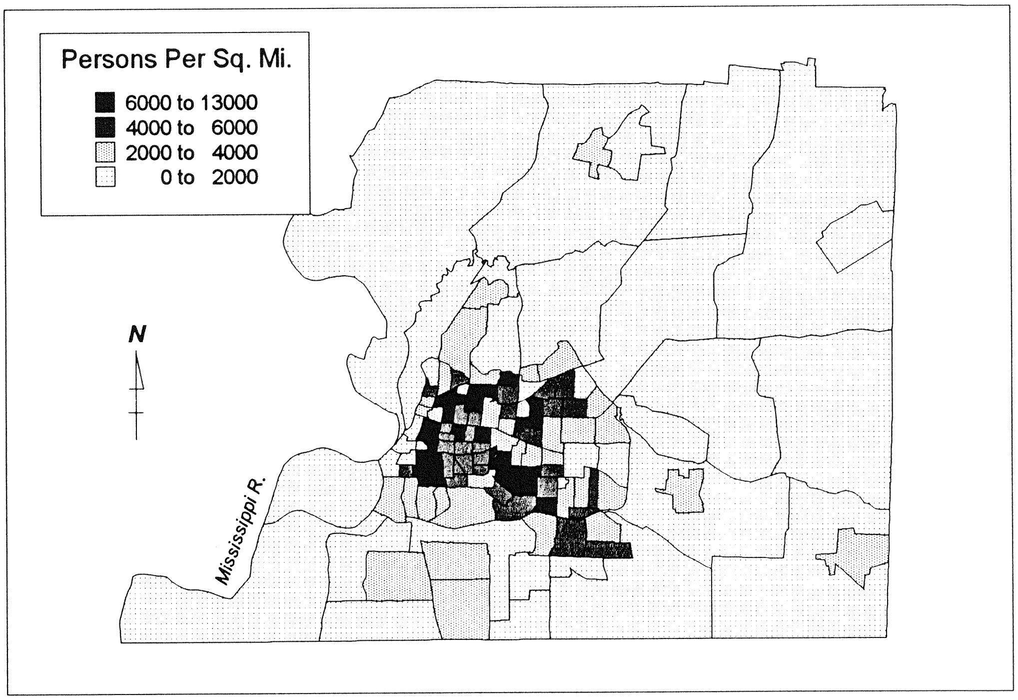
If it is assumed that for a given industry the average number of employees per MLGW utility customer is the same regardless of location within the county, then the pattern of employment location can be used to represent the pattern of nonresidential customer location. This information can be used to estimate utility revenue losses following an earthquake. If it is further assumed that there is regional uniform labor productivity within each industry, then the information can also represent the pattern of production in the county and be used to estimate business interruption losses in a disaster. These simplifying assumptions can be refined in further study.

## 8.2 Residential Location Patterns

Population in Shelby County is concentrated in the City of Memphis. Figure 8-1 plots population and employment density by census tract. The upper map, showing population density, identifies the built-up area in the county, which consists primarily of Memphis and a few small towns located to the north and southeast. Population density ranges from under 2000 persons per square mile in the rural areas to about 13000 in the most densely populated urban census tract. Most of the densely populated area falls within the MMI VIII-1/2 region as indicated in Figure 3-6.

## 8.3 Industry Location Patterns

Industry location patterns based on census tract employment data indicate that the location of business customers and economic activity differs notably from that of population. The lower map in Figure 8-1 shows the density of employment by census tract. The number of jobs per square mile ranges from under 500 in rural parts of the county to over 60,000 in the census tract with highest employment density. In comparing the two maps in Figure 8-1, differences between population and employment distribution can be clearly seen. Certain census tracts with high population density but low employment density can be seen to be primarily residential, whereas those with the opposite pattern can be inferred to be primarily commercial or industrial areas. For



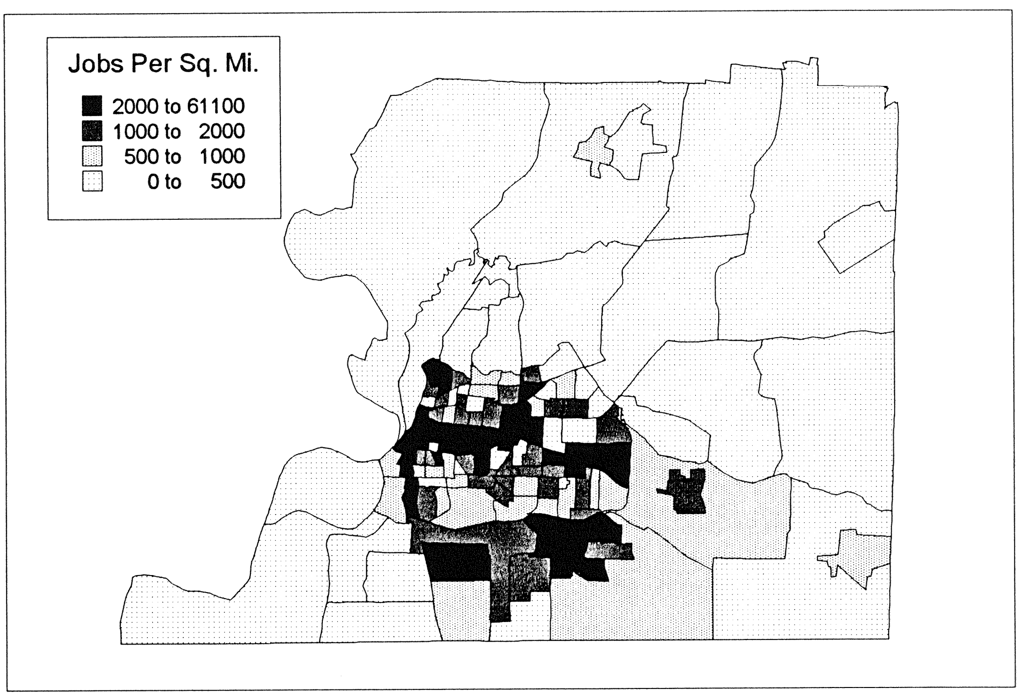




**FIGURE 8-1 Population and Employment Density by Census Tract Shelby County**

example, the "T"-shaped census tract in the south-central portion of the county encompasses Memphis International Airport, where there is considerable employment but few residences.

It is anticipated that the locational patterns of businesses will vary between industries because of differential needs for space, transportation access, etc. Some industries, for example, will be much more concentrated geographically than others. These locational differences will lead to variations in the exposure of an industry to seismic hazard.

To investigate this issue, a series of maps (Figures 8-2 through 8-10) were produced. The maps plot the difference between a census tract's share of total county employment in a given industry versus the corresponding share for all industries combined. Census tracts shaded dark are those where the difference is positive; for example, where a census tract might account for 10 percent of county jobs in the agriculture industry but only 5 percent of jobs overall ("agr. ≥ total"). The regions shaded dark therefore give a rough indication of where within the county a given industry is concentrated. The figures in parentheses in the legend indicates the number of census tracts in the positive (dark shading) and negative (light shading) categories. Generally speaking, the fewer the number of census tracts in the positive category, the more concentrated is employment in that industry relative to employment in all industries.

The series of maps shows that the locational pattern of economic activity differs significantly from industry to industry. Figure 8-2 shows, for example, that agricultural employment is concentrated in the fringe areas in the northern and eastern areas of the county. Figure 8-3 shows that mining is also primarily located in fringe areas of the county; however, it is more concentrated than agricultural activity. Construction is more evenly distributed (Figure 8-4) while most manufacturing takes place in the southern half of the County (Figure 8-5). Transportation, communications, and utilities (TCU) employment (Figure 8-6) is concentrated along the Mississippi waterfront areas, near the airport, and in the southeastern areas of the county. The pattern for wholesale trade bears partial ressemblance to that of TCU (Figure 8-7) and presents a notable contrast to that of retail trade (Figure 8-8). Finance, insurance and real estate (FIRE) employment is highly concentrated (Figure 8-9) while services is very dispersed (Figure 8-10).

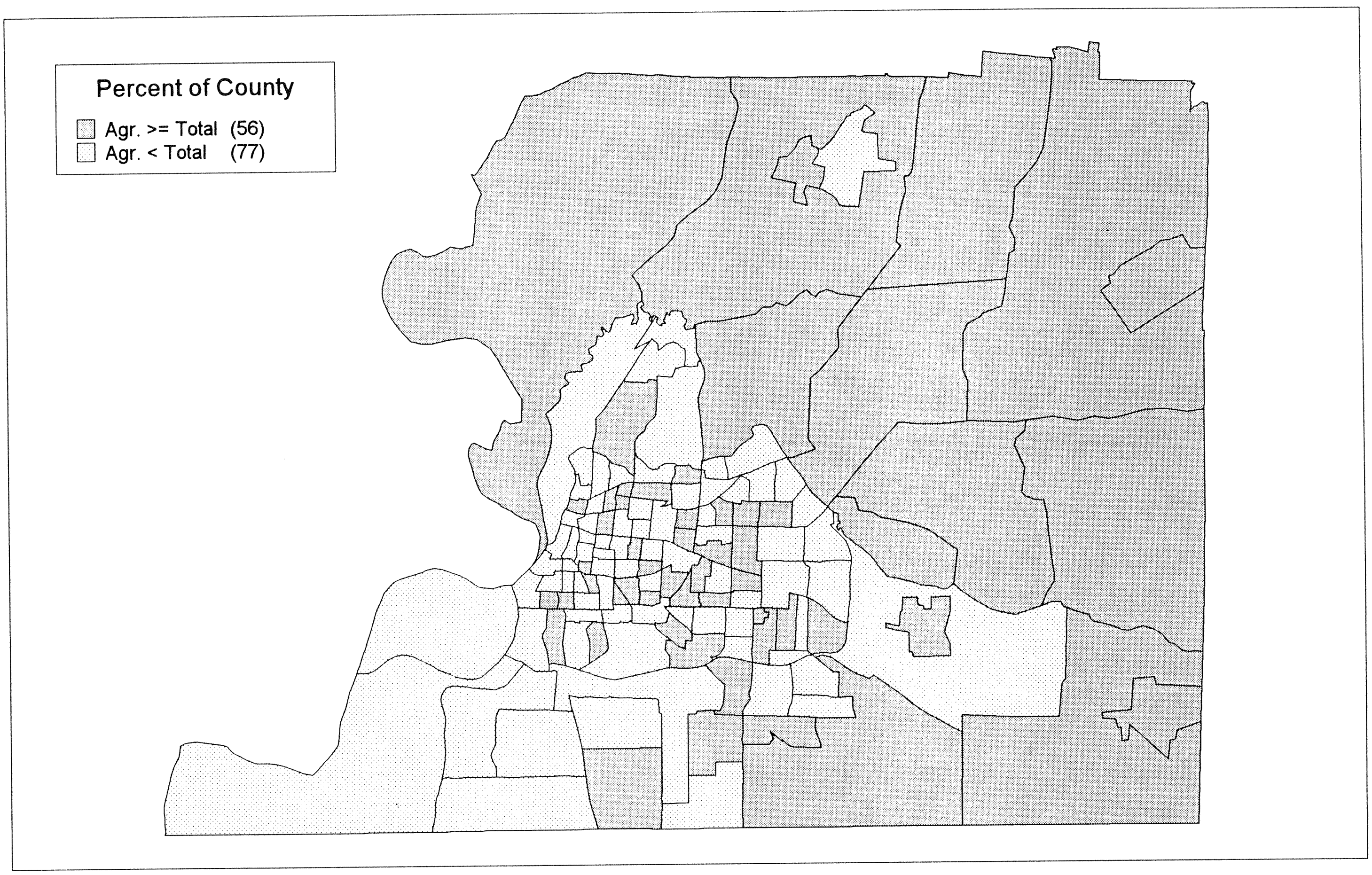



**FIGURE 8-2 Agricultural v. Total Employment, Shares by Census Tract**

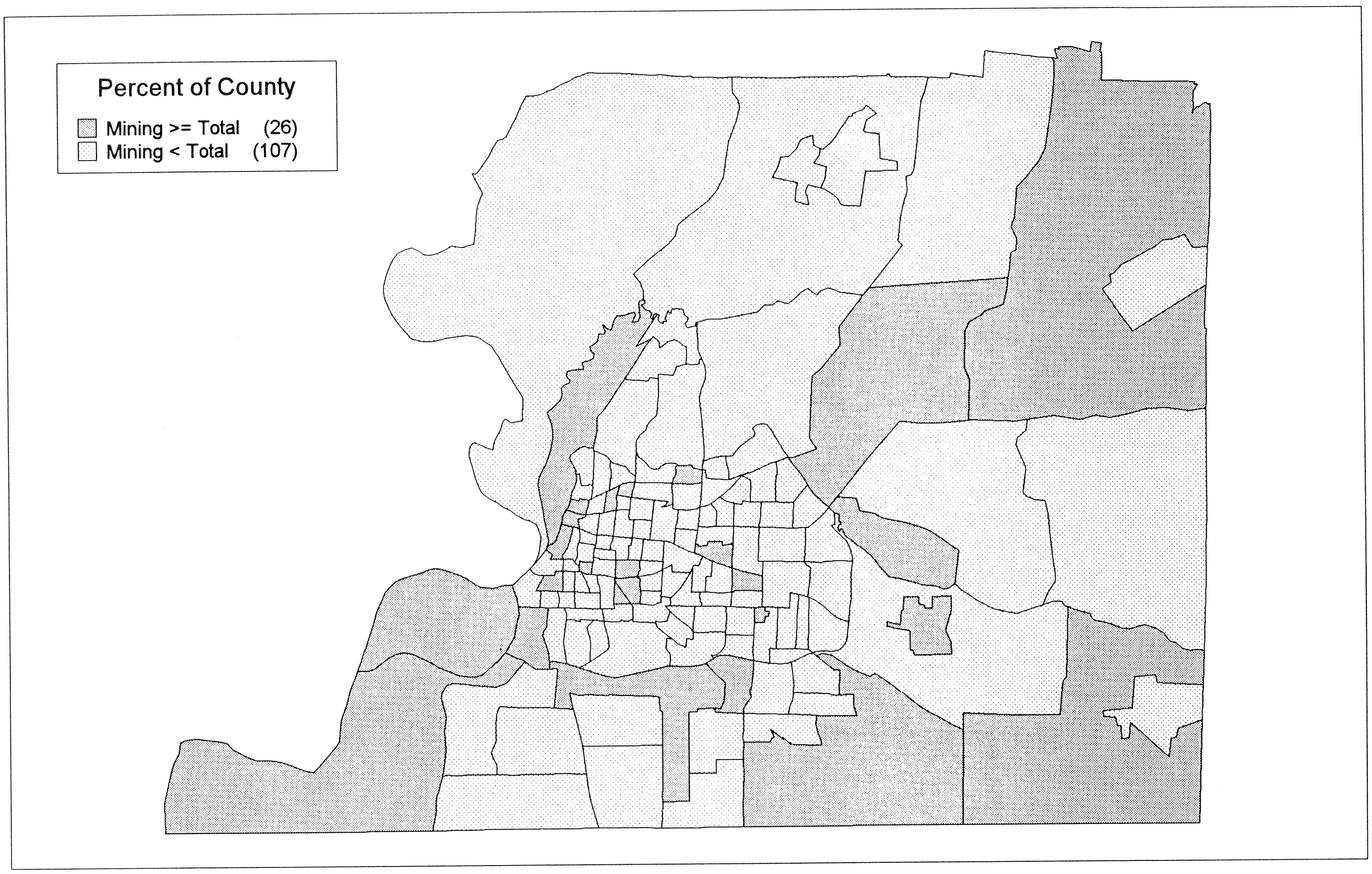



**FIGURE 8-3 Mining v. Total Employment, Shares by Census Tract**

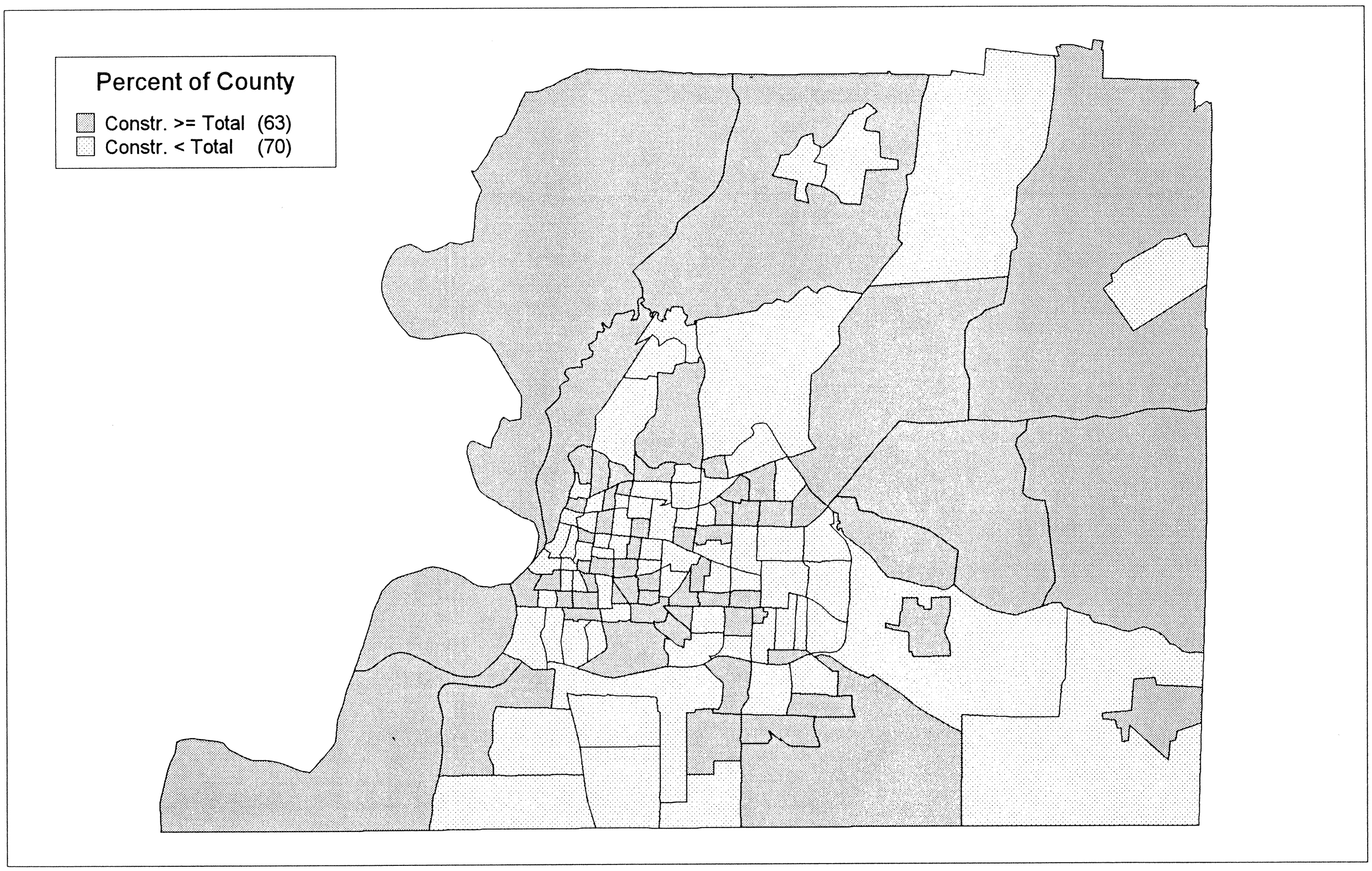



**FIGURE 8-4 Construction v. Total Employment, Shares by Census Tract**

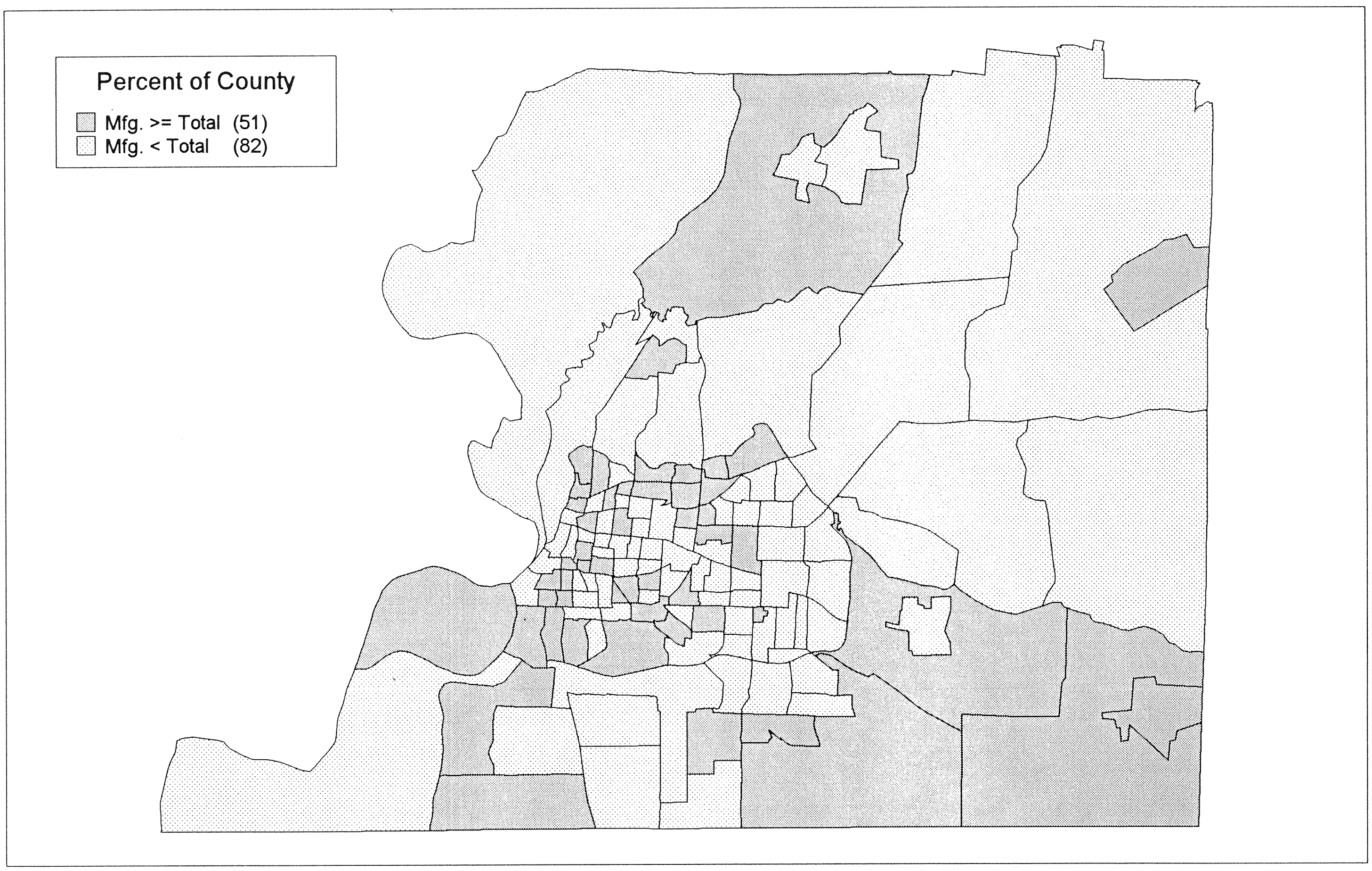



**FIGURE 8-5 Manufacturing v. Total Employment, Shares by Census Tract**

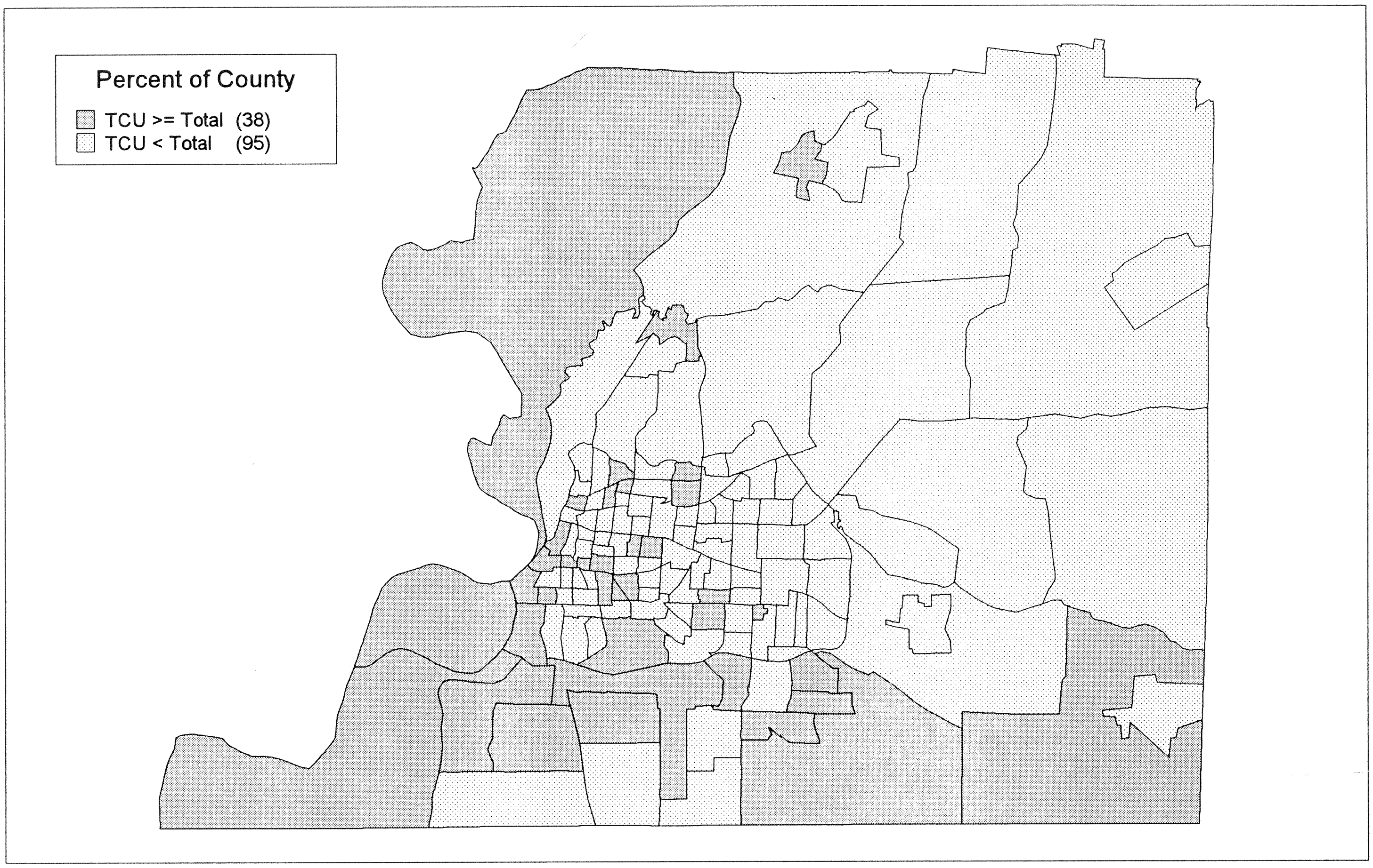



**FIGURE 8-6 TCU v. Total Employment, Shares by Census Tract**

| TABLE 8-2 Inferred Number of Customers by Type and Census Tract, Shelby County | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | GAS | | | ELEC | | | WATER | |
| | Res. | Comm. | Ind. | Res. | Comm. | Ind. | Res. | Comm./Ind. |
| COUNTY | 245,600 | 18,600 | 400 | 310,241 | 34,213 | 177 | 189,012 | 17,288 |
| Tract | | | | | | | | |
| 1 | 380 | 56 | 12 | 480 | 103 | 5 | 292 | 114 |
| 2 | 647 | 31 | 2 | 817 | 57 | 1 | 498 | 36 |
| 3 | 975 | 75 | 7 | 1,232 | 138 | 3 | 751 | 99 |
| 4 | 851 | 32 | | 1,075 | 59 | | 655 | 26 |
| 5 | 273 | | | 344 | | | 210 | |
| 6 | 1,164 | 33 | 2 | 1,470 | 61 | 1 | 896 | 39 |
| 7 | 1,916 | 19 | 3 | 2,421 | 34 | 1 | 1,475 | 32 |
| 8 | 1,283 | 26 | 1 | 1,620 | 48 | | 987 | 27 |
| 9 | 1,396 | 56 | 3 | 1,764 | 103 | 1 | 1,074 | 60 |
| 10 | 216 | 149 | 17 | 273 | 274 | 8 | 166 | 221 |
| 11 | 1,033 | 15 | | 1,305 | 28 | | 795 | 13 |
| 12 | 1,072 | 54 | | 1,354 | 100 | | 825 | 45 |
| 13 | 1,257 | 34 | | 1,587 | 63 | | 967 | 28 |
| 14 | 560 | 39 | 4 | 708 | 71 | 2 | 431 | 54 |
| 15 | 761 | 89 | 3 | 962 | 163 | 1 | 586 | 91 |
| 16 | 940 | 92 | 1 | 1,188 | 169 | | 724 | 78 |
| 17 | 1,362 | 11 | | 1,720 | 19 | | 1,048 | 9 |
| 18 | 672 | 14 | | 849 | 25 | | 517 | 13 |
| 19 | 779 | | | 984 | | | 599 | |
| 20 | 1,171 | 28 | | 1,479 | 52 | | 901 | 24 |
| 21 | 334 | | | 422 | | | 257 | |
| 22 | 272 | 181 | 2 | 344 | 332 | 1 | 210 | 154 |
| 23 | 459 | 33 | 1 | 580 | 60 | 1 | 353 | 34 |
| 24 | 1,229 | 25 | | 1,552 | 46 | | 946 | 21 |
| 25 | 954 | 58 | 1 | 1,205 | 107 | 1 | 734 | 55 |
| 26 | 649 | 44 | 1 | 820 | 81 | | 500 | 38 |
| 27 | 573 | 143 | 2 | 724 | 264 | 1 | 441 | 129 |
| 28 | 1,655 | 115 | 2 | 2,091 | 211 | 1 | 1,274 | 107 |
| 29 | 1,404 | 33 | 1 | 1,773 | 61 | | 1,080 | 31 |
| 30 | 1,083 | 219 | 2 | 1,367 | 403 | 1 | 833 | 185 |
| 31 | 1,027 | 141 | 1 | 1,298 | 260 | | 791 | 118 |
| 32 | 1,187 | 105 | 1 | 1,499 | 193 | | 913 | 90 |
| 33 | 692 | 151 | 1 | 874 | 277 | 1 | 533 | 129 |
| 34 | 659 | 232 | 2 | 832 | 427 | 1 | 507 | 198 |
| 35 | 949 | 104 | 1 | 1,199 | 192 | | 730 | 90 |
| 36 | 943 | 223 | 1 | 1,191 | 410 | | 725 | 185 |
| 37 | 437 | 63 | | 552 | 115 | | 336 | 53 |
| 38 | 490 | 962 | 2 | 619 | 1,770 | 1 | 377 | 786 |
| 39 | 611 | 130 | 3 | 772 | 239 | 1 | 470 | 120 |
| 40 | 888 | 118 | 9 | 1,122 | 218 | 4 | 684 | 146 |
| 41 | 1,020 | 429 | 5 | 1,288 | 789 | 2 | 785 | 374 |
| 42 | 352 | 581 | 6 | 445 | 1,069 | 3 | 271 | 501 |
| 43 | 84 | 127 | 1 | 106 | 233 | | 65 | 108 |
| 44 | 153 | 58 | 2 | 193 | 106 | 1 | 118 | 58 |
| 45 | 529 | | | 669 | | | 407 | |
| 46 | 730 | 102 | 3 | 922 | 187 | 1 | 562 | 102 |

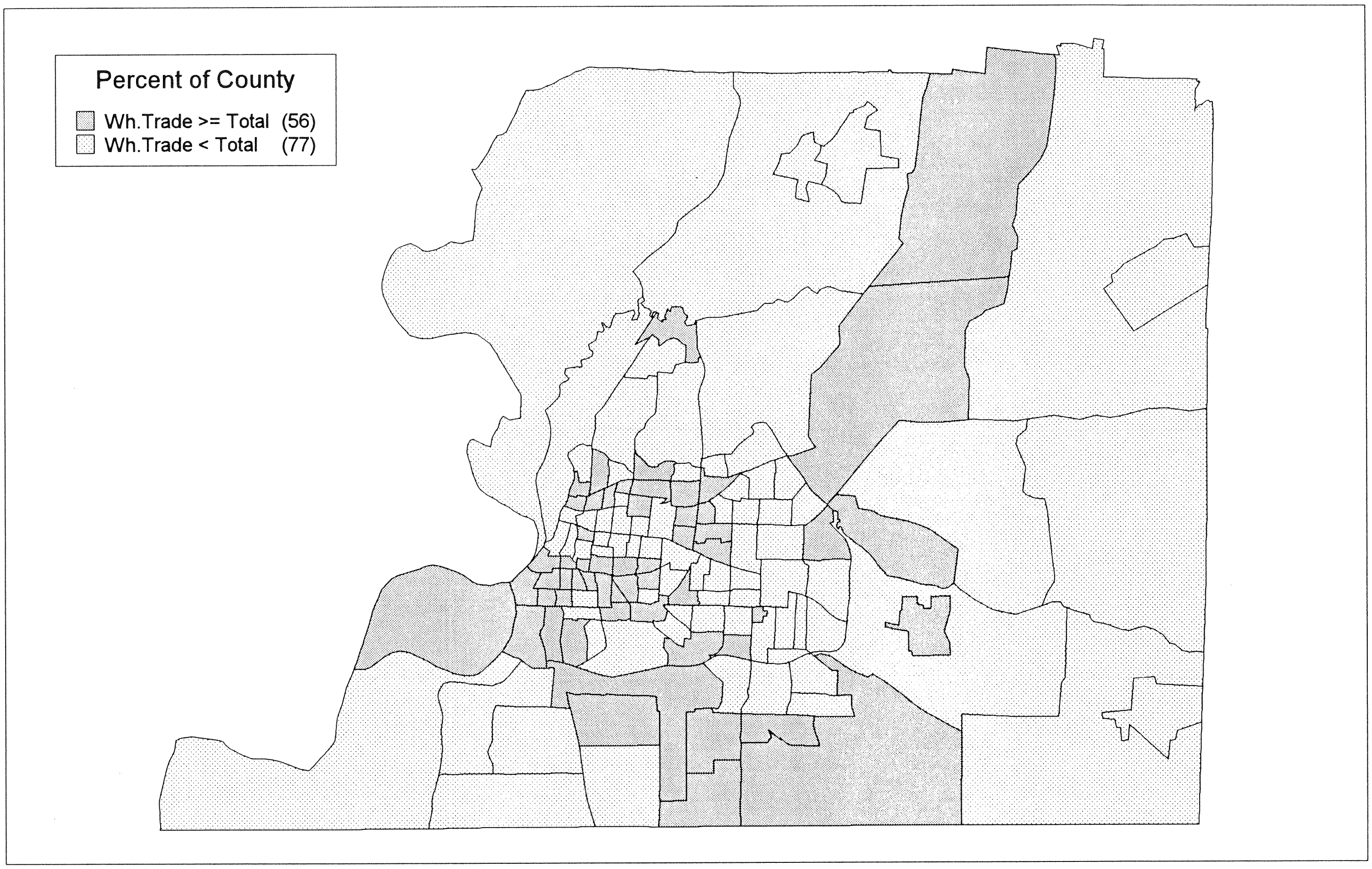



**FIGURE 8-7 Wholesale Trade v. Total Employment, Shares by Census Tract**

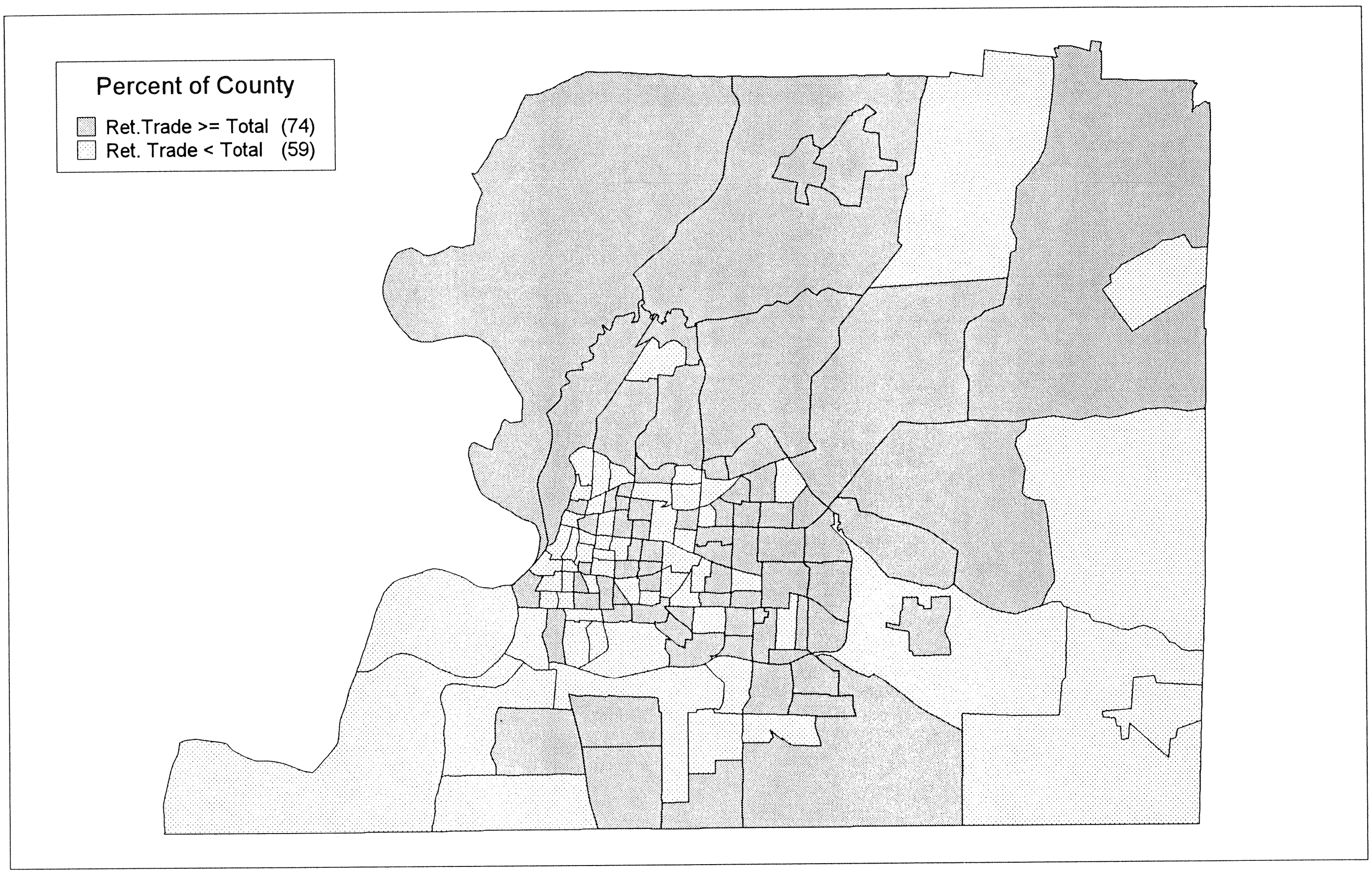



**FIGURE 8-8 Retail Trade v. Total Employment, Shares by Census Tract**

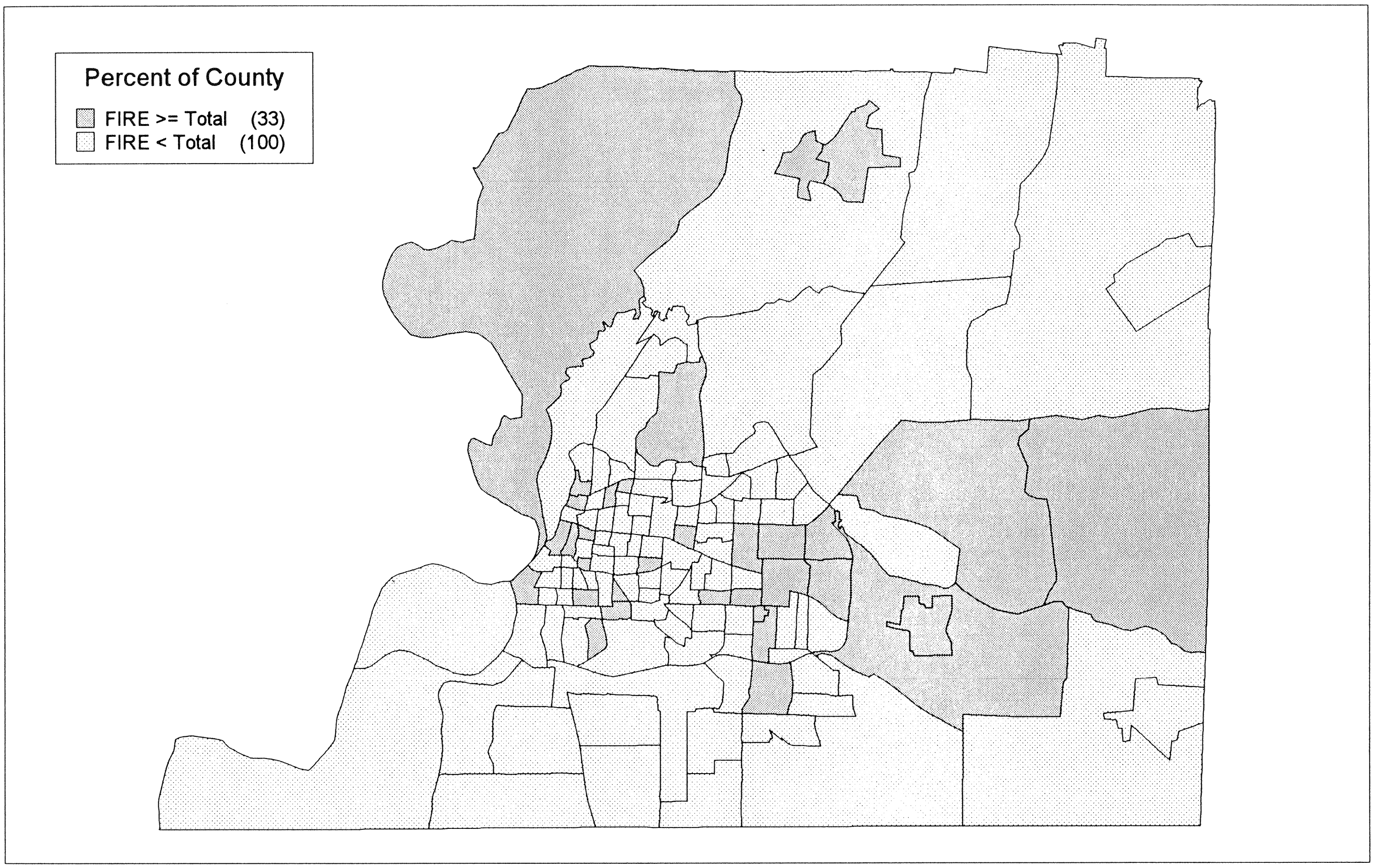



**FIGURE 8-9 FIRE v. Total Employment, Shares by Census Tract**

Because the locational patterns are very different across industries, it is expected that this may contribute to significant differences between industries in the extent of lifeline disruption suffered and the subsequent economic impact.

### 8.4 Utility Service Consumption Patterns

Information on the total number of customers for each utility service by aggregate category (residential, commercial and industrial) was presented in section 7. The distribution of population and of employment in various industries described above was used to infer how these customers are distributed throughout the county. For the "industrial" category of users, data from the mining and manufacturing industries were used (see Table 5-4); all other industries are classified under "commercial". It is assumed that the average number of employees per utility customer is consistent across census tracts within the county. This may not be an entirely realistic assumption because there may be certain users accounting for a large number of jobs which are concentrated in a few census tracts. However, accounting for this factor exceeds the scope of the present study and represents a potentially important topic for more detailed further investigation. Table 8-2 lists the estimated number of customers for each utility service by customer type according to census tract. Recall that nonresidential customer information is not broken down further for water consumption. Although figures in the table are shown rounded to the nearest whole number, fractional values are used in further analysis. Thus numbers in the table may not sum to the total due to rounding error.

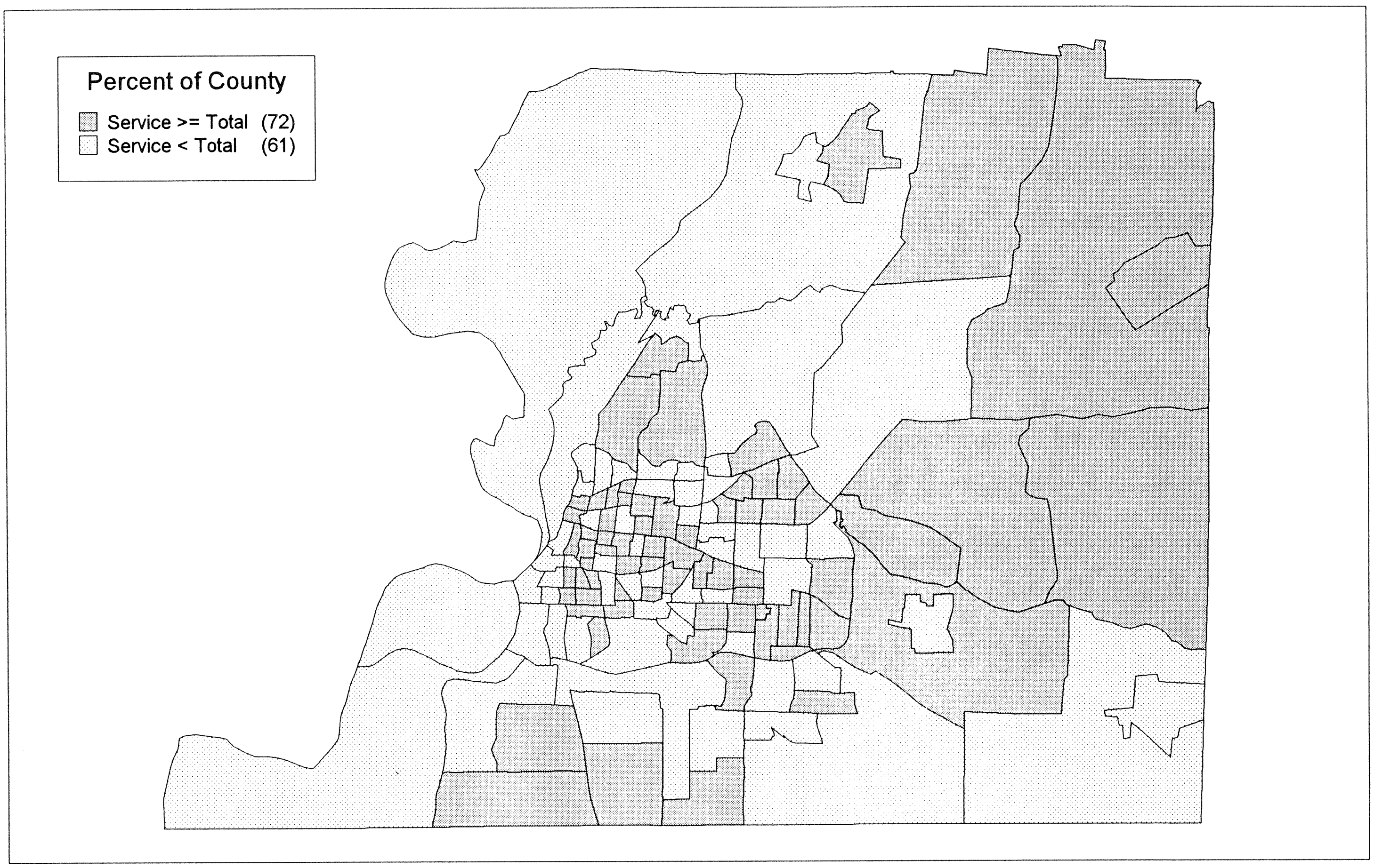



**FIGURE 8-10 Services v. Total Employment, Shares by Census Tract**

| TABLE 8-2 (Cont'd) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | GAS | | | ELEC | | | WATER | |
| | Res. | Comm. | Ind. | Res. | Comm. | Ind. | Res. | Comm./Ind. |
| 47 | 927 | 18 | | 1,171 | 34 | | 713 | 15 |
| 48 | 1,163 | 65 | | 1,469 | 120 | | 895 | 55 |
| 49 | 864 | 22 | | 1,091 | 40 | | 665 | 19 |
| 50 | 968 | 27 | 1 | 1,222 | 50 | | 745 | 26 |
| 51 | 120 | 107 | 7 | 151 | 196 | 3 | 92 | 129 |
| 52 | 188 | 43 | 1 | 237 | 79 | | 144 | 38 |
| 53 | 1,920 | 52 | 3 | 2,426 | 97 | 1 | 1,478 | 62 |
| 54 | 547 | 60 | 4 | 691 | 110 | 2 | 421 | 75 |
| 55 | 1,333 | 116 | 6 | 1,684 | 213 | 3 | 1,026 | 130 |
| 56 | 1,616 | 70 | 6 | 2,042 | 129 | 3 | 1,244 | 95 |
| 57 | 1,208 | 6 | | 1,526 | 10 | | 930 | 5 |
| 58 | 708 | 14 | | 895 | 26 | | 545 | 14 |
| 59 | 1,354 | 17 | | 1,710 | 32 | | 1,042 | 15 |
| 60 | 780 | 19 | | 985 | 34 | | 600 | 15 |
| 61 | 381 | | | 482 | | | 293 | |
| 62 | 1,169 | 44 | 2 | 1,477 | 81 | 1 | 900 | 49 |
| 63 | 886 | 58 | 2 | 1,119 | 106 | 1 | 682 | 56 |
| 64 | 622 | 43 | 1 | 785 | 79 | | 479 | 38 |
| 65 | 918 | 49 | 3 | 1,160 | 90 | 1 | 707 | 58 |
| 66 | 1,352 | 19 | | 1,708 | 35 | | 1,041 | 15 |
| 67 | 1,654 | 64 | 2 | 2,089 | 117 | 1 | 1,273 | 63 |
| 68 | 1,066 | 42 | 1 | 1,347 | 77 | | 821 | 39 |
| 69 | 1,180 | 57 | 3 | 1,491 | 105 | 1 | 908 | 62 |
| 70 | 1,171 | 36 | | 1,479 | 65 | | 901 | 30 |
| 71 | 810 | 15 | | 1,024 | 28 | | 624 | 12 |
| 72 | 723 | 80 | 1 | 913 | 146 | | 556 | 68 |
| 73 | 729 | 284 | 2 | 920 | 522 | 1 | 561 | 237 |
| 74 | 947 | 61 | 1 | 1,197 | 112 | | 729 | 54 |
| 75 | 620 | 26 | | 783 | 48 | | 477 | 22 |
| 76 | | 29 | | | 53 | | | 26 |
| 77 | | 182 | 12 | | 336 | 5 | | 217 |
| 78 | 4,080 | 190 | 5 | 5,154 | 349 | 2 | 3,140 | 183 |
| 79 | 2,232 | 30 | 1 | 2,819 | 56 | | 1,717 | 28 |
| 80 | 1,401 | 63 | 1 | 1,770 | 116 | | 1,078 | 55 |
| 81 | 3,359 | 82 | 2 | 4,243 | 150 | 1 | 2,585 | 75 |
| 82 | 1,651 | 32 | | 2,086 | 58 | | 1,271 | 27 |
| 83 | 1,443 | 41 | | 1,823 | 76 | | 1,111 | 35 |
| 84 | 90 | | | 114 | | | 70 | |
| 85 | 1,192 | 522 | 6 | 1,505 | 961 | 3 | 917 | 457 |
| 86 | 1,742 | 47 | | 2,200 | 87 | | 1,340 | 40 |
| 87 | 1,336 | 74 | 1 | 1,687 | 136 | | 1,028 | 62 |
| 88 | 1,842 | 36 | | 2,326 | 67 | | 1,417 | 31 |
| 89 | 1,478 | 36 | 1 | 1,868 | 66 | | 1,138 | 34 |
| 90 | 721 | 34 | 3 | 911 | 63 | 1 | 555 | 43 |
| 91 | 711 | 16 | | 898 | 29 | | 547 | 13 |
| 92 | 1,861 | 188 | 2 | 2,350 | 346 | 1 | 1,432 | 162 |
| 93 | 1,379 | 75 | 1 | 1,743 | 138 | | 1,062 | 63 |
| 94 | 1,037 | 34 | | 1,310 | 63 | | 798 | 29 |

| TABLE 8-2 (Cont'd) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | GAS | | | ELEC | | | WATER | |
| | Res. | Comm. | Ind. | Res. | Comm. | Ind. | Res. | Comm./Ind. |
| 95 | 2,073 | 60 | 1 | 2,619 | 110 | | 1,596 | 51 |
| 96 | 1,494 | 426 | 3 | 1,887 | 783 | 1 | 1,150 | 358 |
| 97 | 765 | 55 | | 966 | 102 | | 589 | 47 |
| 98 | 898 | 8 | | 1,134 | 15 | | 691 | 7 |
| 99 | 2,399 | 85 | 1 | 3,030 | 156 | | 1,846 | 73 |
| 100 | 2,053 | 19 | 1 | 2,593 | 34 | | 1,580 | 21 |
| 101 | 4,099 | 124 | 1 | 5,178 | 228 | | 3,155 | 105 |
| 102 | 4,137 | 68 | 1 | 5,226 | 125 | | 3,184 | 60 |
| 103 | 668 | 1 | | 844 | 2 | | 514 | 1 |
| 104 | 284 | 1,040 | 17 | 359 | 1,914 | 8 | 219 | 936 |
| 105 | 1,484 | 337 | 4 | 1,874 | 620 | 2 | 1,142 | 293 |
| 106 | 4,264 | 377 | 2 | 5,387 | 693 | 1 | 3,282 | 317 |
| 107 | 2,117 | 382 | 3 | 2,674 | 703 | 1 | 1,629 | 325 |
| 108 | 2,624 | 98 | 1 | 3,314 | 180 | | 2,019 | 83 |
| 109 | 970 | 518 | 32 | 1,226 | 952 | 14 | 747 | 607 |
| 110 | 2,206 | 191 | 6 | 2,786 | 351 | 3 | 1,698 | 187 |
| 201 | 2,337 | 34 | 1 | 2,953 | 63 | | 1,799 | 31 |
| 202 | 3,017 | 178 | 12 | 3,811 | 328 | 6 | 2,322 | 217 |
| 203 | 2,013 | 103 | 1 | 2,542 | 189 | | 1,549 | 89 |
| 204 | 2,875 | 3 | | 3,632 | 5 | | 2,213 | 3 |
| 205 | 11,185 | 444 | 3 | 14,129 | 817 | 1 | 8,608 | 373 |
| 206 | 13,032 | 576 | 9 | 16,462 | 1,059 | 4 | 10,029 | 516 |
| 207 | 514 | 10 | | 649 | 18 | | 396 | 8 |
| 208 | 2,410 | 117 | 2 | 3,044 | 214 | 1 | 1,855 | 103 |
| 209 | 465 | 60 | 6 | 588 | 110 | 3 | 358 | 87 |
| 210 | 1,087 | 39 | 1 | 1,373 | 71 | | 837 | 36 |
| 211 | 10,922 | 236 | 4 | 13,796 | 435 | 2 | 8,405 | 213 |
| 212 | 1,370 | 149 | 2 | 1,731 | 274 | 1 | 1,054 | 134 |
| 213 | 13,985 | 891 | 21 | 17,666 | 1,638 | 9 | 10,763 | 836 |
| 214 | 2,869 | 327 | 2 | 3,624 | 601 | 1 | 2,208 | 273 |
| 215 | 1,533 | 859 | 25 | 1,937 | 1,580 | 11 | 1,180 | 840 |
| 216 | 3,668 | 151 | 9 | 4,633 | 277 | 4 | 2,823 | 173 |
| 217 | 15,496 | 973 | 27 | 19,575 | 1,789 | 12 | 11,926 | 938 |
| 219 | 1,817 | 2 | | 2,296 | 3 | | 1,399 | 2 |
| 220 | 5,756 | 694 | 7 | 7,271 | 1,277 | 3 | 4,430 | 601 |
| 221 | 8,133 | 321 | 3 | 10,273 | 590 | 1 | 6,259 | 272 |
| 222 | 3,306 | 79 | 2 | 4,177 | 145 | 1 | 2,545 | 74 |
| 223 | 7,170 | 73 | | 9,057 | 135 | | 5,518 | 61 |
| 224 | 4,553 | 41 | 1 | 5,751 | 75 | 1 | 3,504 | 40 |

# SECTION 9

# REVENUE LOSS MODEL

This section focuses on the estimation of revenue losses that would be suffered by the utility industry due to lifeline service disruption in the disaster. There have been few studies published on this subject, and actual utility company experiences in previous disasters are often not available for public release. Wiggins and Eguchi (1993) estimate revenue losses in the event of a crude oil spill due to a hypothetical major earthquake in the New Madrid Seismic Zone. Expected revenue loss is calculated as the product of the number of barrels of crude oil lost and the price per barrel.

In the event of an actual disaster, many factors besides service disruption could potentially influence revenue loss. For instance, the utility company may decide as a matter of policy to forgive customer debts for some period after the disaster. Customers may default on their payments because of other losses suffered in the earthquake. Utility meters might themselves be damaged, hampering efforts to charge according to the volume of water, gas, or electric power delivered. Even if customers did pay according to service volume, pre-earthquake usage volumes and prices may change in response to the disaster. For example, customers may change their usage patterns, substituting energy sources if gas or electricity were unavailable or requiring less utility service if businesses were temporarily closed for cleanup and reconstruction.

Consideration of these factors is beyond the scope of the current project. Instead, the purpose is to establish a rough approximation of the expected revenue losses insofar as they can be related to the lifeline outage and restoration estimates presented in section 6. For this purpose, information on customer usage and location patterns presented in sections 7 and 8 is utilized. Section 9.1 describes the revenue loss model and section 9.2 presents results for the M 7.5 Marked Tree scenario earthquake.

## 9.1 Model

As in Wiggins and Eguchi (1993), the revenue loss model is based upon the volume of utility product that is lost, that is to say not delivered to the customer, in the disaster. Lost product is related to the outage and restoration patterns described in section 6.

$$R_i = \sum_g d_{i,g} \cdot (\sum_t \sum_k l_{i,k,t} \cdot C_{i,k,g}) \tag{9.1}$$

where $R_i$ = total revenue loss for lifeline *i*

$d_{i,g}$ = average daily revenue per customer for lifeline *i*, customer type *g*

$l_{i,k,t}$ = percent loss of lifeline *i* service in census tract *k* at time *t* in days

$C_{i,k,g}$ = number of customers for lifeline *i* in census tract *k* of type *g*

Customer types include residential, commercial and industrial. Information on average daily revenue for different customer types (*d*) was presented in section 7, while customer location patterns (*C*) were described in section 8. Time *t* is evaluated on a daily basis.

While outage and restoration results were derived in section 6, some further assumptions are required in order to establish a time series of lifeline service loss (*l*). For example, suppose that for the *k*th census tract, estimated available electric power immediately after the earthquake (or restoration ratio, as a percentage of normal service) was $a_0$ and the estimated time to restore service was $T_k$.. Initial outage $l_0$ would then be $1-a_0$. To estimate revenue loss, the daily volume restoration curve within the census tract would need to be inferred. Figure 9-1 shows a couple of possible scenarios.

One possibility would be to assume for purposes of revenue loss estimation that initial outage levels are maintained in the census tract until full restoration at time $T_k$. For utilities such as natural gas where restoration typically proceeds on a system rather than component basis, it may be reasonable to assume that the entire census tract is restored at once. The daily loss factor until time $T_k$ would then be $1\text{-}a_0$, and the total revenue loss in that tract would then be the area ABCD in Figure 9-1 multiplied by average daily revenue. This case can be referred to as a "step" restoration function.

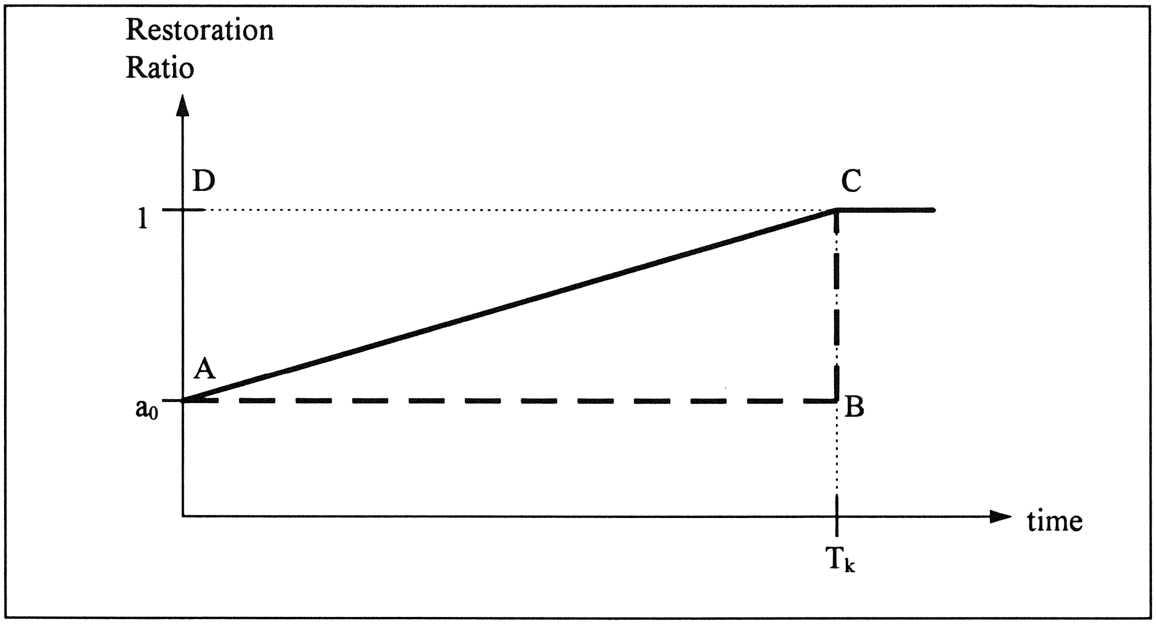



**FIGURE 9-1 Alternative Volume Loss Assumptions**

Another possibility would be to assume that restoration of utility service volume proceeds proportionally over time in a "linear" restoration function, as indicated by the line AC in Figure 9-1. This may be a more realistic assumption for utilities such as water or electric power where restoration typically proceeds on a pipe-by-pipe or customer-by-customer basis. The total revenue loss in tract $k$ would then be the area ACD multiplied by average daily revenue. Since total revenue loss is the sum of revenue loss in all of the census tracts, it can be seen that the linear restoration assumption yields a revenue loss exactly one-half as large as the step restoration assumption. Note that in reality, restoration is likely to fall somewhere between the "step" and "linear" restoration functions. In the case of electric power, for example, service at a given substation may be restored in phases.

## 9.2 Results

Revenue loss estimates for the Memphis event were first made using equation 9.1 with the "step" restoration function for each of the three utilities. Division by two yields results for "linear" restoration. Because information on seasonal usage of natural gas was available, winter and summer scenarios as well as an annual average were calculated. In the case of water and electricity, seasonal information was not available, but results can be interpreted to represent an annual average. Usage information described in section 7 was available for three customer types (residential, commercial and industrial) for natural gas and electricity. However, for water, MGLW did not distinguish between commercial and industrial usage.

Table 9-1 presents the revenue loss results for the natural gas utility. Assuming a step restoration pattern, the total revenue loss is estimated at $5.9 million for the seasonal average. With linear restoration, revenue loss would be $2.9 million. Table 9-1 shows that revenue losses would vary substantially depending upon the season in which the disaster struck. Losses for a winter scenario, when natural gas usage is at a peak, would be $8.1 million assuming step restoration. This amounts to about 2.3 times expected losses in a summer scenario. In each case, revenue losses associated with residential customers account for 54 percent of the total, while commercial losses are 29 percent and industrial 17 percent.

**TABLE 9-1 Revenue Loss from Natural Gas Disruption**

| | Step Restoration | | | Linear Restoration | | |
|---|---|---|---|---|---|---|
| | Summer | Winter | Average | Summer | Winter | Average |
| Residential | $1,560,016 | $4,711,886 | $3,135,951 | $ 780,008 | $2,355,943 | $1,567,976 |
| Commercial | $1,029,536 | $2,418,155 | $1,723,845 | $ 514,768 | $1,209,077 | $ 861,923 |
| Industrial | $ 988,974 | $ 994,417 | $ 991,696 | $ 494,487 | $ 497,209 | $ 495,848 |
| TOTAL | $3,578,526 | $8,124,458 | $5,851,492 | $1,789,263 | $4,062,229 | $2,925,746 |

Table 9-2 shows expected revenue losses from electric power disruption. Total losses would be $3.3 million assuming step restoration and $1.7 million assuming linear restoration. In contrast to natural gas, however, most of the losses (53 percent) derive from service disruption to commercial customers. Residential and industrial customers account for 34 and 13 percent of revenue loss, respectively. The difference in the customer type composition of revenue losses derives from different patterns of disruption and customer location, as well as contrasts in average daily revenue per customer for residential, commercial, and industrial users.

**TABLE 9-2 Revenue Loss from Electric Power Disruption**

| | Step Restoration | Linear Restoration |
|---|---|---|
| Residential | $1,119,074 | $ 559,537 |
| Commercial | $1,758,478 | $ 879,239 |
| Industrial | $ 445,851 | $ 222,926 |
| TOTAL | $3,323,403 | $1,661,702 |

Table 9-3 shows the expected revenue losses from water service disruption. Total losses are estimated at roughly $154,000 and $77,000 for the step and linear restoration assumptions, respectively. Water revenue losses are thus an order of magnitude smaller than those for the other two utilities. As with natural gas, slightly over half of the losses (57 percent) are from residential customers, while the remainder (43 percent) is related to nonresidential customer outage.

**TABLE 9-3 Revenue Loss from Water Disruption**

| | Step Restoration | Linear Restoration |
|---|---|---|
| Residential | $ 188,567 | $ 94,283 |
| Commercial/Industrial | $ 146,607 | $ 73,303 |
| TOTAL | $335,173 | $167,587 |

To summarize, Table 9-4 provides an overview of expected revenue loss based on the results that are considered the "best estimate" for each of the three utilities. As mentioned previously, step restoration was considered more plausible for natural gas and linear restoration for water and electricity.

Table 9-4 shows that in terms of overall revenue losses, natural gas accounts for 67 to 82 percent, depending upon the season, electricity between 31 and 17 percent, and water about 1 percent. These differences derive from several principal factors. First, the expected duration of service disruption was greatest in the case of natural gas. As shown in Figure 6-5, restoration of over 90 percent of customers was expected to take roughly 5-7 days for water and electricity but between 3 and 4 weeks for gas. Second, as indicated in Tables 7-5, 7-8 and 7-9, normal revenue levels are much lower for water than for other utilities. Annual revenues for 1990 were $159 million for gas, $612 million for electricity, and only $33 million for water. The relative magnitudes of these figures would, of course, also be reflected in average daily revenue per customer.

Total revenue losses range from $5.3 million for a summer scenario to $9.9 million for a winter event, reflecfing seasonal usage patterns for natural gas only. The average loss is estimated at $7.6 million. Using the average results for natural gas, expected revenue loss from this scenario earthquake would amount to 4 percent of annual revenue for that utility. For electric power and water, the corresponding shares are 0.3 percent and 0.2 percent, respectively.

The results presented above represent a rough approximation of expected revenue losses in the scenario earthquake. As discussed, a number of simplifying assumptions were applied and potentially significant factors were not considered. An important area for further research would be to investigate utility company revenue losses in actual disasters such as the 1994 Northridge earthquake and the 1993 Midwest floods. The extent to which factors such as metering problems and debt forgiveness play a role in determining actual revenue losses could provide insights for developing future models of utility company revenue loss.

**TABLE 9-4 Summary of Expected Revenue Losses**

| | Summer[a] | | Winter[a] | | Average | |
|---|---|---|---|---|---|---|
| | Dollars | Percent of total[b] | Dollars | Percent of total[b] | Dollars | Percent of total[b] |
| | | | *Natural Gas* | | | |
| Residential | $1,560,016 | | $4,711,886 | | $3,135,951 | |
| Comm. | $1,029,536 | | $2,418,155 | | $1,723,845 | |
| Industrial | $ 988,974 | | $ 994,417 | | $ 991,696 | |
| Total | $3,578,526 | 66% | $8,124,458 | 82% | $5,851,492 | 76% |
| | | | *Electricity* | | | |
| Residential | $ 559,537 | | $ 559,537 | | $ 559,537 | |
| Comm. | $ 879,239 | | $ 879,239 | | $ 879,239 | |
| Industrial | $ 222,926 | | $ 222,926 | | $ 222,926 | |
| Total | $1,661,702 | 31% | $1,661,702 | 17% | $1,661,702 | 22% |
| | | | *Water* | | | |
| Residential | $ 94,283 | | $ 94,283 | | $ 94,283 | |
| Comm./Ind. | $ 73,303 | | $ 73,303 | | $ 73,303 | |
| Total | $ 167,587 | 3% | $ 167,587 | 2% | $ 167,587 | 2% |
| | | | *All Utilities* | | | |
| Residential | $2,213,837 | | $5,365,707 | | $3,789,772 | |
| Comm./Ind. | $3,193,978 | | $4,588,040 | | $3,891,009 | |
| Total | $5,407,815 | 100% | $9,953,746 | 100% | $7,680,781 | 100% |

notes: (a) average figures are used for electricity and water
(b) figures may not add due to rounding error.

# SECTION 10

# ECONOMIC LOSS MODELS

This section describes the estimation of direct and indirect economic losses associated with lifeline disruption in earthquakes. In contrast to sections 5 (Repair Cost) and 9 (Revenue Loss), which focused on losses that would be suffered by the utility service provider, this section concentrates on business interruption losses that would be suffered by all sectors of the impacted economy. Direct economic losses are those that are suffered by the utility customers who must reduce productive activities (e.g., manufacturing steel) due to the disruption of lifeline services. Indirect economic losses are "downstream" or "upstream" effects that accrue to other businesses (e.g., purchasers of steel or providers of raw materials needed to produce steel) because the direct losses entail reductions in both the availability of and demand for intermediate inputs for production.

Section 10.1 describes the conceptual framework and development of the economic loss model in this study. Section 10.2 presents the application of this model to the scenario M 7.5 Marked Tree earthquake and the resulting estimates of direct economic loss in Shelby County. Section 10.3 presents results on indirect economic losses in the County.

## 10.1 Lifeline Disruption Impact Model

The economic loss models developed in this study are based upon existing methodologies described in the ATC-13 and ATC-25 reports. However, several refinements were made that take advantage of results from other NCEER studies focusing on Shelby County. These include (1) utilization of newly available empirical data on business dependency on lifelines, (2) modification of the methodology to consider duration effects associated with lifeline outage, (3) evaluation at a geographically disaggregate (i.e., census tract) level, (4) consideration of multiple lifeline disruption, and (5) evaluation of indirect economic losses.

### 10.1.1 ATC-13 Model

As part of the ATC-13 *Earthquake Damage Evaluation Data for California* report, "importance factors" were presented that indicate the extent to which each Social Function Classification (e.g., residential, commercial, industrial, agricultural uses) will be affected by the failure of main and distribution systems for various lifeline systems. A sample of natural gas importance factors are presented in Table 10-1. Main components are defined as including transmission lines and distribution components as including distribution feeder mains.

**TABLE 10-1 Selected Natural Gas Importance Factors from ATC-13**

| Social Function Class | Importance Factors | |
|---|---|---|
| | Main | Distribution |
| Permanent Dwelling | 0.0 | 0.2 |
| Group Institutional Housing | 0.0 | 0.5 |
| Retail Trade | 0.0 | 0.1 |
| Wholesale Trade | 0.0 | 0.1 |
| Industrial - Heavy Fabrication and Assembly | 0.4 | 0.4 |
| Industrial - Light Fabrication and Assembly | 0.2 | 0.2 |
| Industrial - High Technology | 0.1 | 0.5 |
| Construction | 0.0 | 0.0 |

These importance factors were developed under the following assumptions (ATC-13, 1985):

1) the importance factors are based on judgment and are prescribed for California conditions only;

2) water main and gas main components were not regarded as important except for high-water and high-gas consumption facilities. This is based upon the presumption that for low consumption facilities, e.g., residences, the distribution system is of primary importance and failures in the main system would or could be repaired before the distribution system was depleted.

The importance factors were used to develop functionality curves for each social function classification of facilities that relate economic functionality to the extent of lifeline disruption.

### 10.1.2 ATC-25 Model

In the ATC-25 study, modified ATC-13 importance factors were utilized. Importance weights for main and distribution systems were averaged for each lifeline, and social functions were correlated to a 36 economic sector classification scheme. Judgement was used to further modify the ATC-13 factors "to reflect the difference between the importance of the lifeline and its impact on the economy if it were totally disrupted". It is assumed that some of these modifications were made to allow application of the ATC-13 importance factors to areas outside of California, as ATC-25 examined losses across the United States. Maximum impact estimates were developed for each economic sector in terms of percent value added lost due to total lifeline disruption. These maximum impacts were presented as importance weights, and are summarized for natural gas in Table 10-2.

Several assumptions were made in ATC-25 for the purpose of developing a first approximation of the economic effects of lifeline interruption. These are important to recognize in using these factors in the current study.

First, ATC-25 assumed that lifeline elements were independent. "Interruptions in elements of one lifeline do not produce interruptions in other lifelines elements." This allows us to utilize the natural gas factors, for example, apart from the analysis of other lifelines.

**TABLE 10-2 ATC-25 Importance Weights for Natural Gas**

| | ATC-25 Economic Sector | Importance Weight |
|---|---|---|
| 1 | Livestock | 0.10 |
| 2 | Agr. Prod. | 0.30 |
| 3 | AgServ For. Fish | 0.30 |
| 4 | Mining | 0.10 |
| 5 | Construction | 0.00 |
| 6 | Food Tobacco | 0.25 |
| 7 | Textile Goods | 0.20 |
| 8 | Misc. Text. Prod. | 0.20 |
| 9 | Lumber & Wood | 0.20 |
| 10 | Furniture | 0.20 |
| 11 | Pulp & Paper | 0.40 |
| 12 | Print & Publish | 0.20 |
| 13 | Chemical Drugs | 0.90 |
| 14 | Petrol Refining | 0.50 |
| 15 | Rubber & Plastic | 0.50 |
| 16 | Leather Prods. | 0.20 |
| 17 | Glass Stone Clay | 0.50 |
| 18 | Prim. Metal Prod. | 0.50 |
| 19 | Fab. Metal Prod. | 0.50 |
| 20 | Mach. Exc. Elec. | 0.50 |
| 21 | Elec. & Electron. | 0.50 |
| 22 | Transport Eq. | 0.50 |
| 23 | Instruments | 0.75 |
| 24 | Misc. Manufact. | 0.50 |
| 25 | Transp & Whse. | 0.00 |
| 26 | Utilities | 0.40 |
| 27 | Wholesale Trade | 0.10 |
| 28 | Retail Trade | 0.20 |
| 29 | F.I.R.E. | 0.20 |
| 30 | Pers./Prof. Serv. | 0.20 |
| 31 | Eating Drinking | 0.40 |
| 32 | Auto Serv. | 0.05 |
| 33 | Amuse & Rec. | 0.40 |
| 34 | Health Ed. Soc. | 0.20 |
| 35 | Govt & Govt Ind. | 0.20 |
| 36 | Households | 0.35 |
| | TOTAL | 0.32 |

Second, ATC-25 examined only first order economic losses of the type under study in the current project. Impacts of one industry's losses on another -- or what are defined in this study as “indirect” impacts -- were not considered.

The range of impacts were calculated based on estimated maximum impacts, as follows (ATC-25, 1991):

> 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 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 maximum effect, as mentioned previously, is indicated by the importance weights for each sector/lifeline combination. The linearity assumption mentioned above assumes that remaining lifeline capacity could be used productively. That is, limited lifeline damage would not cause a complete cessation of economic activity in the sector. Following these assumptions, impacts for various levels of utility disruption may be derived.

### 10.1.3 Conceptual Framework

The conceptual framework developed in this study for estimation of direct and indirect economic losses from lifeline disruption is illustrated in Figure 10-1. The methodological framework consists of first developing a direct economic loss model that essentially depicts industry vulnerability to lifeline outage (or loss factors) based upon the geographic location pattern of businesses in that industry (see section 8) as well as the resiliency of the industry to temporary lifeline service disruption. For the Memphis application, resiliency factors are developed based upon an NCEER study of businesses in Shelby County conducted by Prof. K. Tierney at the Disaster Research Center of the University of Delaware. Results from the lifeline outage and restoration assessment (see section 6) are fed into the direct economic loss model to estimate direct economic loss. Indirect economic losses are then evaluated using the procedure described in Rose et al. (forthcoming). The approach is based on input-output methodologies and focuses on bottleneck effects in the post-earthquake economy.

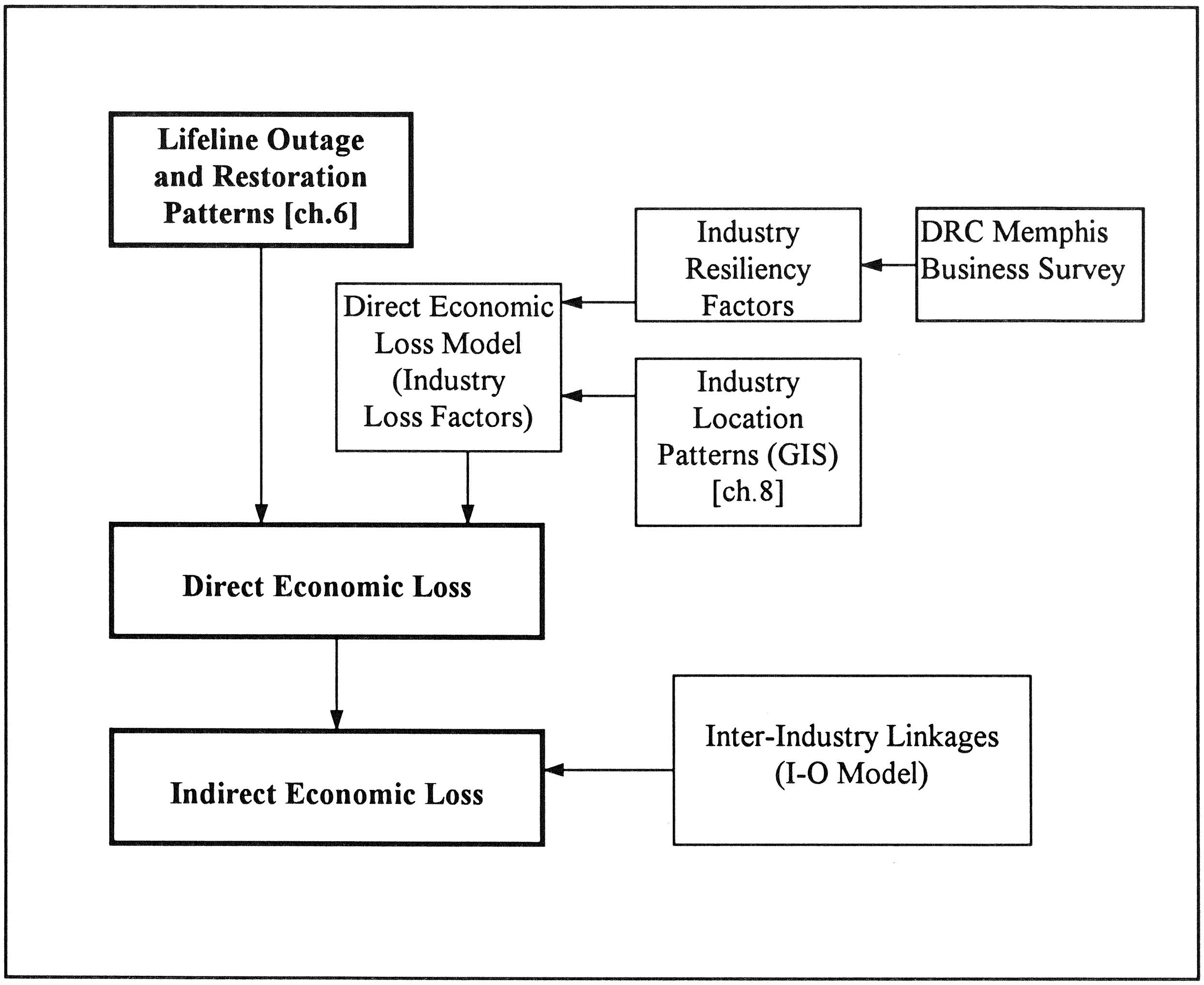



**FIGURE 10-1 Economic Loss Model Framework**

### 10.1.4 Economic Loss Model

The first step in the economic loss model, the estimation of loss factors, is based upon the ATC-25 methodology. Specifically,

$$
\begin{aligned}
l_{ijt}^{s} &= \frac{(1-r_{ijt})}{0.95}\cdot(d_{it}^{s}-0.05) && \text{if } d_{it}^{s} > 0.05 \\
&= 0 && \text{if } d_{it}^{s} \le 0.05
\end{aligned}
\tag{10.1}
$$

where $l_{ijt}^{s}$ $(0 \le l_{ijt}^{s} \le 1)$ is the loss factor associated with lifeline $i$ disruption for industry $j$ in subarea (e.g., census tract) $s$ in time period $t$ after the disaster, $r_{ijt}$ $(0 \le r_{ijt} \le 1)$ is a "resiliency" factor, and $d_{it}^{s}$ $(0 \le d_{it}^{s} \le 1)$ is the percent of lifeline service disruption. Economic loss is expressed relative to normal economic production levels.

As in ATC-25, it is assumed that the first 5 percent of lifeline service disruption can be absorbed without economic loss, beyond which economic loss increases in proportion to extent of lifeline service disruption up to some maximum. In ATC-25, the "importance" factor indicated the maximum percent of production loss that would be associated with complete lifeline disruption. Here, we define a "resiliency" factor $r$ as the percent of remaining production in the event of complete lifeline outage, or equivalently, one minus the importance factor. This resiliency factor is specific to lifeline $i$ and industry $j$ and reflects lifeline usage characteristics and dependency. The empirical calibration of this resiliency factor is discussed in the section 10.2.1 below.

In contrast to ATC-25, the current methodology accounts for possible changes in the resiliency factor over time. That is, as lifeline service disruption is sustained over a period of days or weeks, some of the initial resiliency "cushion" would be gradually worn away. Stored energy reserves, as an example, may be depleted. On the other hand, it is also possible that in the course of the recovery process, resiliency may increase due, for example, to businesses setting up new temporary electric generators. In general, however, we would expect the resiliency factor to decrease over time. This is schematically illustrated in Figure 10-2. The y-intercept of the solid line, $r_0$, indicates the resiliency factor immediately after the disaster; one week later, resiliency decreases to $r_1$.

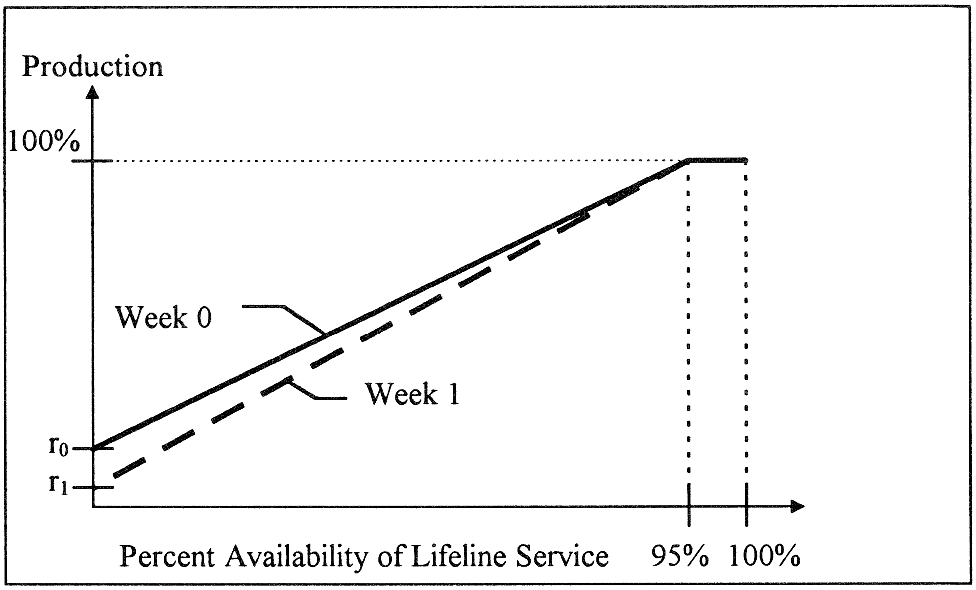



**FIGURE 10-2 Direct Economic Loss Model and Changes over Time**

In other words, the resiliency factor $r_{ijt}$ serves to modify the impact of lifeline service disruption. A resiliency factor of 0 indicates that industry $j$ has no flexibility in dealing with lifeline service disruption beyond the initial 5 percent outage that can be absorbed without loss. In this case, based on equation 10.1, 100 percent lifeline outage would lead to 100 percent loss in production. A resiliency factor of 0.1 would mean that 100 percent outage would lead to 90 percent loss in production.

Over the course of the repair and restoration period, in a particular subarea $s$, we would expect both the disruption factor $d$ and the resiliency factor $r$ to decrease. These produce opposite effects, so that the net impact on the loss factor $l$ in equations 10.1 may be either an increase or decrease at any point in time.

For a given lifeline $i$, the loss model represented by equation 10.1 indicates the direct economic impact for a particular industry $j$ in a particular subarea $s$. Total direct economic impact depends upon the locational distribution of economic activity among all subareas in the impacted region. At time $t$, the total direct economic impact for industry $j$ can be evaluated as a weighted sum over all service areas:

$$L_{ijt} = \sum_{s} l_{ijt}^{s} W_{j}^{s} \tag{10.2}$$

$$\text{where } W_j^s = \frac{Q_j^s}{Q_j}$$

$L_{ijt}$ ($0\leq L_{jt} \leq 1$) is the percent loss of production in industry $j$ due to disruption of lifeline service $i$ at time $t$, and $l_{ijt}^{s}$ is the loss factor for subarea $s$ defined in equation 10.1. $Q$ represents production output, and the area weights $W_j^s$ are indicated by the share of total industry $j$ production in the study area that is accounted for by subarea $s$. Total direct economic loss for the impacted region in dollar terms ($\Delta X_t$) due to lifeline $i$ disruption at time $t$ is then derived as:

$$\Delta X_{it} = \sum_{j} \Delta X_{ijt} = \sum_{j} L_{ijt} \cdot X_{j} \tag{10.3}$$

where $X_j$ is the normal production level for industry $j$ in the impacted region. Equation 10.3 yields the direct economic impact in terms of regional gross output.

To translate gross output loss into the decrease in gross regional product (GRP), a modification to the standard input-output relationship can be used, as described in Rose et al. (forthcoming):

$$\Delta \overline{Y}_{it} = (\boldsymbol{I} - \boldsymbol{A}^*)\Delta \overline{X}_{it} \tag{10.4}$$

where $\Delta \overline{Y}_{it}$ represents the vector of changes to industry final demand at time $t$ due to lifeline $i$ disruption, $\Delta \overline{X}_{it}$ represents the vector of changes to industry gross output, $\boldsymbol{I}$ is the identity matrix, and $\boldsymbol{A}^*$ is a modified version of the input-output matrix of inter-industry technical coefficients. The modification consists of multiplying the lifeline service input coefficient in each sector by the corresponding importance factor. Total change in GRP at time $t$ after the disaster would then be the sum of final demand changes in each industry:

$$\Delta Y_{it} = \sum_{j} \Delta Y_{ijt} \tag{10.5}$$

Final direct economic loss results can be evaluated in gross output terms as

$$\Delta X_{i} = \sum_{t} \Delta X_{i,t} \tag{10.6}$$

or in GRP terms as

$$\Delta Y_i = \sum_t \Delta Y_{i,t} \tag{10.7}$$

However, as shown below, it is necessary to retain the time series of direct losses for purposes of indirect economic loss estimation.

The estimation of indirect economic losses is based upon a methodology developed by Prof. A. Rose and colleagues at Pennsylvania State University (Rose et al., 1997; Rose and Benavides, 1996). Briefly, the direct losses in equation 10.3 represent changes in gross output due to lifeline outages at the site of production. In some cases, indirect economic impacts such as downstream or multiplier effects due to supply shortages are already embodied in this estimate of direct loss. To utilize these direct loss estimates as exogenous final demand shocks in a conventional input-output application, that is to apply input-output multipliers to the output changes, would therefore be inappropriate and lead to double-counting of losses. Indeed, the gross output changes in equation 10.3 represent the final demand or GRP changes in equation 10.4 multiplied by appropriate input-output or indirect loss multipliers. This implies that in some cases, there may be no additional "indirect" losses over and above the "direct" losses estimated in equation 10.3. This is especially likely to hold when the direct losses are very similar across all industries.

To illustrate this observation, suppose that a particular business *Z* may suffer 50 percent production loss if water service is completely disrupted; furthermore, disruption of water service to the business *Z*'s suppliers might independently cause a 30 percent production curtailment on business *Z*'s part. In a post-earthquake situation where water service is disrupted to both this *Z* and its suppliers, it may be conservatively assumed that business *Z* will suffer a 50 percent rather than an 80 percent loss of production. Thus the indirect impacts (30 percent) on business *Z* in this example are already subsumed under the direct losses (50 percent) that it is estimated to incur.

However, indirect losses over and above direct losses in equations 10.3 through 10.5 will arise when the direct impact is much higher in some sectors than in others. Such a significant impact differential might arise, for example, when a particular industry is heavily concentrated in a few subareas within the impacted region or when an industry is much more dependent than others on a particular lifeline service. In these situations, heavily impacted sectors may create "bottlenecks" in the overall economy that lead to indirect effects arising from inter-industry linkages or dependencies.

Rose et al. propose that to model these situations, the initial vector of gross output losses should be examined to identify the bottleneck sector, or that associated with the constraining input. Post-earthquake gross output for the constraining sector, or $\Delta X_{j*t}$, is then applied to all other sectors to model the bottleneck effect. This leads to a new set of gross output changes which, when run through equation 10.4 and 10.5, yield a new set of final demand and GRP changes. Note that at different points in time $t$ in the recovery process, the identity of the constraining sector may change. Rose et al. (forthcoming) presents an application of this methodology to electricity disruption in a scenario earthquake for Memphis, Tennessee.

So far, the methodology has been developed without consideration for effects that take place when more than one lifeline suffers outage in the disaster. However, in the event of multiple lifeline disruption, there may be interaction in an operational sense; for example, disruption of electric power may further impede water delivery over and above the effect of water system damage alone. Treatment of this type of lifeline interaction is beyond the scope of this study. In terms of economic impact, however, two extreme possibilities can be posed. First, the direct losses may be additive across lifelines (up to a maximum of 100 percent loss). That is, for any given industry $j$ located in subarea $s$,

$$1 \geq l^s_{jt} = \sum_i l^s_{ijt} \tag{10.8}$$

For example, if the loss factors were hypothetically 0.3 for natural gas, 0.3 for electricity, and 0.4 for water, the combined loss factor would be 1.0, indicating complete loss of production. However, this approach will probably and perhaps substantially overestimate economic losses.

An alternative, conservative approach would be to assume that the lifeline service with the most impact will be the controlling lifeline. Thus

$$l_{jt}^{s} = \max_{i} \, (l_{ijt}^{s}) \tag{10.9}$$

so that
$$L_{jt} = \sum_{s} l_{jt}^{s} \cdot W_{j}^{s} \tag{10.10}$$

and
$$\Delta X_{t} = \sum_{j} L_{jt} \cdot X_{j} \tag{10.11}$$

and
$$\Delta \overline{Y}_{t} = (\boldsymbol{I} - \boldsymbol{A}^{**})\Delta \overline{X}_{t} \tag{10.12}$$

where $\boldsymbol{A}^{**}$ is similar to $\boldsymbol{A}^{*}$ except that the modification factors are applied with respect to all of the lifelines. Recall that the rationale for developing the modified matrix $\boldsymbol{A}^{*}$ was to take into account the significance of the resiliency factor -- a non-zero resiliency factor for electricity, for example, indicates that less electricity is needed per unit of output than in the standard case, so that the electricity input coefficient should be decreased from the standard input-output matrix. Following this rationale, in the event of multiple lifeline disruption, the $\boldsymbol{A}^{**}$ matrix should account for nonzero resiliency factors applicable to all the lifelines. If the input-output model is sufficiently disaggregated so that each lifeline (natural gas, electricity, and water) is modeled as a separate sector, the application is unambiguous. If they are modeled as one sector, e.g. "public utilities", then the modification should consist of a weighted average of the respective lifeline importance factors that might as an example be based upon relative sales volumes.

### 10.2 Direct Economic Loss Estimation for Shelby County

This section describes the implementation of the direct economic loss estimation methodology to the Shelby County case study. As previously noted, this involved the development of empirical resiliency factors, outlined in section 10.2.1. Section 10.2.2 provides an overview of the loss estimation application and section 10.2.3 describes the resulting direct economic loss and recovery patterns. Section 10.2.4 covers the conversion of gross output loss results into GRP terms and the development of the input-output model necessary for this purpose.

### 10.2.1 DRC Business Survey and Resiliency Factor Estimation

Although resiliency factors could have been inferred from data in ATC-25, this information is generic and based upon expert opinion rather than actual empirical study. Fortunately, for this study, an alternative source of data was available. In a study undertaken as part of the broader NCEER "Urban Seismic Risk Assessment" Project, Prof. K. Tierney at the Disaster Research Center of the University of Delaware focused on "Assessing Earthquake Impacts on Business Activity in the Greater Memphis Area." (NCEER Project No. 926301B) This study implemented a survey of businesses in Shelby County that included questions on the likely impact of disruption to various lifeline services (Tierney and Nigg, 1995; Tierney, forthcoming).

Results from the DRC survey were made available to researchers at EQE and provided an empirical basis for calibrating resiliency factors to business conditions in Shelby County. Specifically, responses on how long a particular business could operate without each of the major utilities were used to infer a cumulative distribution of temporary business closures according to the duration of the disruption. These distributions were calculated for each of nine major industries and for electricity, water, and natural gas independently. Businesses that reported not using natural gas were included in the analysis. Using the simplifying assumption of uniform output across business establishments in an industry, the percent of business closures at a particular point in time can be assumed to represent the loss of production in that industry due to complete loss of the utility service or, in other words, the ATC-25 "importance" factor. One minus the importance factor then yielded the resiliency factor *r*. Table 10-3 presents the estimated resiliency factors by lifeline and industry at weekly intervals for the first 4 weeks after the disaster.

Table 10-3 shows that in general, as would be expected, the impact of electricity disruption is the most severe, while water has a lesser effect and natural gas has the least effect. For all industries combined, the immediate (week 0) impact of complete electricity outage is an 86 percent loss of output, which corresponds to a resiliency factor of 0.14. In comparison, for water and natural gas, the resiliency factors are 0.34 and 0.65 respectively, corresponding to losses of 66 and 35

**TABLE 10-3 Resiliency Factors for Shelby County by Industry**

| WEEKS | ALL | AGR | MIN | CON | MFG | TCU | WHS | RET | FIR | SVC |
|---|---|---|---|---|---|---|---|---|---|---|
| **ELECTRICITY** | | | | | | | | | | |
| 0 | 0.14 | 0.25 | 0.67 | 0.26 | 0.07 | 0.26 | 0.12 | 0.10 | 0.11 | 0.11 |
| 1 | 0.08 | 0.13 | 0.33 | 0.15 | 0.03 | 0.14 | 0.06 | 0.08 | 0.07 | 0.08 |
| 2 | 0.08 | 0.13 | 0.33 | 0.15 | 0.03 | 0.13 | 0.05 | 0.08 | 0.07 | 0.06 |
| 3 | 0.08 | 0.13 | 0.33 | 0.15 | 0.03 | 0.13 | 0.05 | 0.08 | 0.07 | 0.06 |
| 4 | 0.06 | 0.13 | 0.00 | 0.15 | 0.02 | 0.09 | 0.04 | 0.07 | 0.02 | 0.06 |
| **WATER** | | | | | | | | | | |
| 0 | 0.34 | 0.20 | 0.67 | 0.56 | 0.27 | 0.51 | 0.39 | 0.30 | 0.35 | 0.26 |
| 1 | 0.23 | 0.13 | 0.33 | 0.30 | 0.17 | 0.35 | 0.31 | 0.23 | 0.21 | 0.18 |
| 2 | 0.20 | 0.13 | 0.33 | 0.30 | 0.16 | 0.30 | 0.26 | 0.22 | 0.20 | 0.15 |
| 3 | 0.20 | 0.13 | 0.33 | 0.30 | 0.16 | 0.30 | 0.26 | 0.22 | 0.20 | 0.15 |
| 4 | 0.15 | 0.07 | 0.00 | 0.22 | 0.14 | 0.20 | 0.16 | 0.19 | 0.12 | 0.12 |
| **GAS** | | | | | | | | | | |
| 0 | 0.65 | 0.69 | 1.00 | 0.76 | 0.58 | 0.76 | 0.68 | 0.65 | 0.61 | 0.62 |
| 1 | 0.59 | 0.56 | 1.00 | 0.64 | 0.48 | 0.66 | 0.61 | 0.61 | 0.51 | 0.59 |
| 2 | 0.56 | 0.56 | 1.00 | 0.64 | 0.48 | 0.61 | 0.57 | 0.58 | 0.51 | 0.57 |
| 3 | 0.56 | 0.56 | 1.00 | 0.64 | 0.48 | 0.61 | 0.55 | 0.57 | 0.51 | 0.57 |
| 4 | 0.51 | 0.56 | 0.67 | 0.56 | 0.45 | 0.54 | 0.51 | 0.51 | 0.43 | 0.55 |

percent of production, respectively. The magnitude of these effects varies quite substantially, however, by industry. For example, the immediate resiliency factor for water in the construction industry 0.56 while that for services is only 0.26.

Table 10-3 also shows the deterioration of industry resiliency as the duration of lifeline outage increases. For example, the resiliency factor for the services industry to disruption of water service is 0.26 in week 0 immediately after the earthquake. One week after the disaster, resiliency decreases to 0.18 and by the fourth week, this has further deteriorated to 0.12. Thus the same amount of water service disruption causes greater direct economic loss as the outage is sustained over time.

It is interesting to compare these empirical results based on the DRC survey with the corresponding expert opinion-based estimates from ATC-25. This comparison is shown in Table 10-4. Resiliency factors for ATC-25 are calculated as one minus the reported "importance" factor. For comparability, ATC-25 figures have been aggregated to a nine-industry classification through averaging over more detailed industries. The ATC-25 model was meant to apply to economic analysis conducted on a monthly basis. To facilitate comparison, therefore, parameters based on the DRC study are expressed for the first month following the earthquake by averaging factors over the first 4 weeks.

**TABLE 10-4 Comparison of ATC-25 and Shelby County Resiliency Factors**

| | **Electricity** | | **Water** | | **Natural Gas** | |
|---|---|---|---|---|---|---|
| **Industry** | ATC-25 | Shelby[a] | ATC-25 | Shelby[a] | ATC-25 | Shelby[a] |
| Agriculture | 0.50 | 0.15 | 0.47 | 0.13 | 0.77 | 0.59 |
| Mining[b] | 0.10 | 0.33 | 0.85 | 0.33 | 0.90 | 0.93 |
| Construction | 0.60 | 0.17 | 0.50 | 0.33 | 1.00 | 0.65 |
| Manufacturing | 0.02 | 0.04 | 0.36 | 0.18 | 0.58 | 0.50 |
| TCU | 0.45 | 0.15 | 0.70 | 0.33 | 0.80 | 0.64 |
| Wholesale Trade | 0.10 | 0.06 | 0.80 | 0.28 | 0.90 | 0.58 |
| Retail Trade | 0.10 | 0.08 | 0.80 | 0.23 | 0.80 | 0.58 |
| FIRE | 0.10 | 0.07 | 0.80 | 0.21 | 0.80 | 0.51 |
| Services | 0.16 | 0.07 | 0.54 | 0.17 | 0.75 | 0.58 |

Notes: (a) based on results from the DRC survey, averaged over first 4 weeks
(b) mining sample for Shelby County is only 3 businesses

The table reveals that while the expert-based judgments of the resiliency factor in ATC-25 are somewhat consistent with the survey-based results for electricity, they severely overestimate business resiliency to water and natural gas disruption and hence underestimate the associated business interruption losses. Many factors probably influence these differences: in addition to contrasts in methodology, aggregation and sampling factors probably have some impact. Generally, however, the empirical results suggest that previous models of business impact may substantially underestimate the economic losses from lifeline disruption.

### 10.2.2 Direct Economic Loss Estimation

Based on the methodology and data described above, estimates were made of direct loss of total gross output for Shelby County in the scenario M 7.5 earthquake. Equation 10.1 was first implemented to derive loss factors (*l*) associated with disruption to each of the three lifelines independently. These loss factors were calculated for each of the 133 census tracts, 9 major industries, and 27 days of lifeline disruption as consistent with outage estimates described in section 6. Recall that the longest time to full restoration, which applied to the gas system, consisted of 4 weeks or 28 days.

Equation 10.1 estimates loss factors based on disruption factors (*d*) and resiliency factors (*r*). Disruption factors were calculated on a daily basis using initial outage and restoration time results presented in Table 6-13. As explained in section 9 in the context of revenue loss estimation, a "step" restoration pattern was assumed in the case of natural gas and a "linear" restoration pattern in the case of water and electric power. Resiliency factors from Table 10-3 were used. It was judged appropriate to vary resiliency factors on a weekly rather than daily basis, given considerations of the nature of the raw data, as well as computational efficiency.

Based on the results for the individual lifelines, loss factors associated with multiple lifeline disruption were also estimated. It was assumed that for a given industry $j$ in a given census tract $s$ at any time $t$, the applicable loss factor in the event of multiple lifeline disruption would be the greatest of the loss factors for the individual lifelines $i$, as indicated in equation 10.9. This assumption is conservative because it does not account for reduced resiliency when more than one lifeline service is disrupted. For example, some portion of business resiliency to gas disruption alone may be due to ability to use electricity as a substitute energy source. Thus if both are disrupted, the loss factor would be greater than the maximum of the individual lifeline loss factors. Note that this type of economic interaction differs from lifeline interaction in the engineering sense (e.g., the use of electric power to operate components of the water delivery system), which could be handled by developing appropriate disruption factors ($d$) for use in equation 10.1.

Using the loss factors ($l$) thus developed for individual and multiple lifeline disruption, weighted loss factors ($L$) pertaining to the entire County rather than the census tracts individually were estimated using equation 10.2. Weights indicating each census tract's share of economic activity were applied. As a proxy to economic activity, data on employment by census tract were used (see section 8). These figures pertain to employment by place of work. Employment provides a reasonable proxy for production to the extent that it is accurate to assume uniform labor productivity within an industry across all census tracts of the county. Weighted loss factors were developed for each industry/time period and for individual as well as multiple lifeline disruption.

Estimates were then made of daily loss in gross output by industry and for the entire County economy as indicated in equation 10.3. This consisted of multiplying the weighted loss factors by normal (1991) levels of daily output by industry. (In other studies, industry economic data for the study area may not always be readily available. An alternative procedure for inferring this data is thus presented in Appendix A.)

In the process, the "transportation, communications and utilities" (TCU) industry was disaggregated into four industries: electric power, gas, water distribution, and other TCU. Because electric power is completely imported from outside the County, the industry is considered an extra-regional one and any losses it suffers would accrue outside of Shelby County. This is described further in section 10.2.4 below in the context of input-output modeling for the County. Total direct losses of gross output in the TCU industry were distributed among the gas, water, and "other TCU" industries. For lack of more detailed information, it was assumed that losses among these TCU sub-industries accrued in proportion to their normal output levels.

### 10.2.3 Loss and Recovery Patterns

Resulting estimates of gross output losses associated with multiple lifeline disruption are presented in Table 10-5. Total direct output loss is estimated at $434 million (in 1991 dollar terms). Of this total, about one-third or $147 million consists of loss suffered by the manufacturing industry while 20 percent or $85 million accrues to the services industry. The remaining industries together account for slightly less than half of total gross output losses. These proportions reflect both the severity of loss suffered by each industry as well as the relative size of the industry in the pre-earthquake economy.

**TABLE 10-5 Direct Loss from Multiple Lifeline Disruption, Gross Output Terms**

| Industry | Direct Loss of Gross Output (1991 $ million) | Loss as Percent of Total Loss | Loss as Percent of Annual Output |
|---|---|---|---|
| Agriculture | $ 2.49 | 0.57 % | 1.23 % |
| Mining | $ 0.09 | 0.02 % | 0.21 % |
| Construction | $ 25.77 | 5.94 % | 1.05 % |
| Manufacturing | $ 147.03 | 33.87 % | 1.60 % |
| TCU | $ 47.38 | 10.91 % | 0.96 % |
| Wholesale Trade | $ 27.37 | 6.30 % | 1.28 % |
| Retail Trade | $ 36.37 | 8.38 % | 1.25 % |
| FIRE | $ 62.72 | 14.45 % | 1.59 % |
| Services | $ 84.92 | 19.56 % | 1.55 % |
| TOTAL | $ 434.13 | 100.00 % | 1.39 % |

The impact of these dollar losses on the various industries will depend upon the severity of the losses in comparison with normal output levels. The last column in Table 10-5 shows the loss as a percentage of normal (1991) annual production levels, the data for which derive from the IMPLAN system (U.S. Forest Service, 1993). The $434 million output loss for the entire county amounts to 1.39 percent of annual gross output. Since one week or seven days is 1.92 percent of a year, this loss is equivalent to slightly under one full week of production. Most industries suffer a loss of about 1 percent of annual output. The primary exception is the mining industry, which suffers only a 0.2 percent loss. This effect results from a combination of high resiliency to lifeline disruption and geographic concentration in less damaged areas of the county, as can be seen by inspecting Table 10-3 and Figures 3-6 and 8-3.

Table 10-6 compares the estimated direct output losses associated with individual versus multiple lifeline disruption. It shows that the losses due to natural gas disruption alone ($419 million) would have amounted to almost as great a loss as in the multiple lifeline disruption case ($434 million). With only electric power or water outage, gross output losses were estimated at $60 and $80 million, respectively. These results imply that for the most part, the constraining lifeline insofar as loss factors are concerned is natural gas. This result is consistent with the observation that in this scenario disaster, gas outage is generally higher and of longer duration than disruption to water or electric power, as shown by the restoration curves in Figure 6-5.

**TABLE 10-6 Direct Economic Loss for Single v. Multiple Lifeline Disruption, Gross Output Terms** (1991 $ million)

| | | Single Lifelines | | |
|---|---|---|---|---|
| Industry | Multiple Lifelines | Natural Gas | Electric Power | Water |
| Agriculture | $ 2.5 | $ 2.3 | $ 0.2 | $ 0.5 |
| Mining | $ 0.1 | $ 0.0 | $ 0.0 | $ 0.1 |
| Construction | $ 25.8 | $ 24.7 | $ 3.5 | $ 4.2 |
| Manufacturing | $ 147.0 | $ 143.4 | $ 16.8 | $ 28.3 |
| TCU | $ 47.4 | $ 44.6 | $ 7.4 | $ 9.9 |
| Wholesale Trade | $ 27.4 | $ 26.4 | $ 3.4 | $ 4.9 |
| Retail Trade | $ 36.4 | $ 35.0 | $ 4.1 | $ 7.7 |
| FIRE | $ 62.7 | $ 60.6 | $ 11.3 | $ 8.5 |
| Services | $ 84.9 | $ 81.7 | $ 13.1 | $ 16.2 |
| TOTAL | $ 434.1 | $ 418.7 | $ 59.7 | $ 80.4 |

Figure 10-3 shows the pattern of direct output losses over time, up until full restoration of all lifelines 4 weeks (28 days) after the earthquake. Losses are shown for the individual lifelines and for the multiple lifeline disruption case. On the first day after the earthquake, estimated losses are roughly $29 million due to water outage alone, $20 million in the case of electric power disruption, and $30 million from gas outage alone. Recall that there is complete gas outage throughout the county but only partial water and electric power outage. Considering disruption

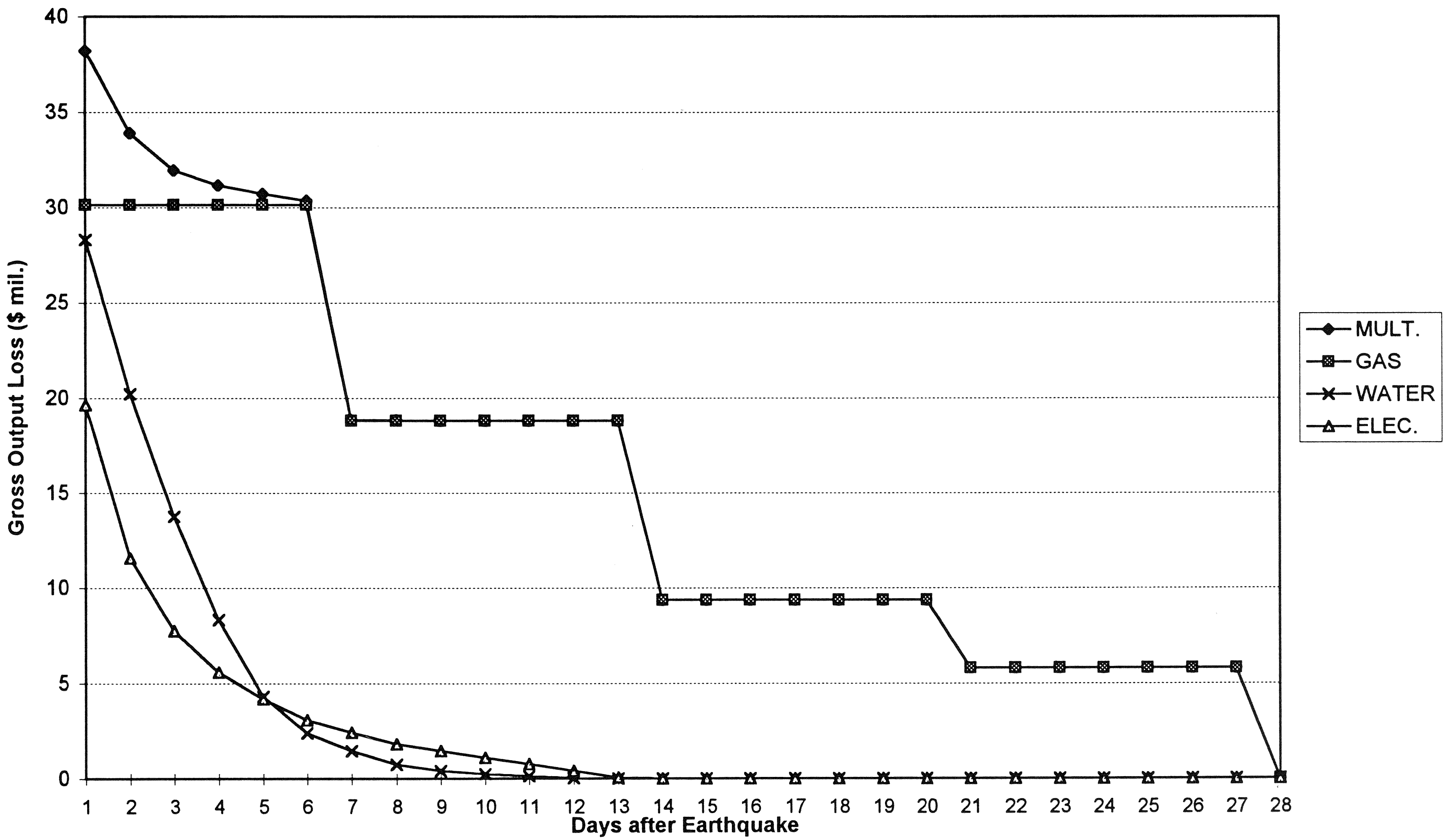



FIGURE 10-3 Timeline of Direct Economic Loss, Gross Output Terms

to all three lifelines, total losses are $38 million, or somewhat higher than in the case of any one of the lifelines alone. This indicates that at time $t=1$, even though gas service disruption is the highest in the entire county, for some industries in some census tracts, disruption to water or electric power is the controlling factor in terms of economic loss.

Losses from water or electric power disruption alone dissipate rapidly in the first week after the earthquake in conjunction with anticipated restoration patterns. Losses in the case of gas outage alone are much more substantial throughout the recovery period. It can be seen that after the first week, the loss timeline in the multiple lifeline case closely follows the case of gas disruption alone.

### 10.2.4 Input-Output Model and GRP Loss

In order to convert gross output losses to gross regional product (GRP) losses, as indicated in equation 10.12, information is needed on the matrix ***(I-A**)***. This matrix was derived based on information on the input-output (I-O) structure of the Shelby County economy as described in Rose and Szesniak (forthcoming). The 21-sector I-O transactions matrix used in that study was first aggregated to 12 sectors and government classified as a final demand sector. Table 10-7 shows the transactions matrix and Table 10-8 the associated direct coefficients matrix. Note that the electricity industry (no. 5) is actual an extra-regional one because electric power is imported into Shelby County from TVA. Thus the row corresponding to industry 5 actually represents imported electricity, and the intra-regional inputs column for industry 5 consists of zero entries.

The coefficients matrix was modified to obtain matrix $A^{**}$ in equation 10.12. Resiliency factors from Table 10-3 were used to derive modification factors $m$, taking into account the 5 percent lifeline disruption that could be absorbed without loss:

$$m_{ijt} = \frac{1 - r_{ijt}}{0.95} \qquad (10.13)$$

These factors were applied to the corresponding lifeline input coefficients in the direct coefficients matrix to obtain $A^{**}$. Separate matrices were estimated for each week. Finally, a series of matrices ***(I-A**)*** for each week was obtained by subtracting the $A^{**}$'s from the identity matrix. The matrix for week 0 (days 1-6) is shown in Table 10-9.

**TABLE 10-7 Shelby County Input-Output Transactions Table (1991 $ mil.)**

| Industry | | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *1* | Agric. | 19.2 | 0.0 | 8.7 | 14.0 | 0.0 | 0.0 | 0.0 | 0.6 | 0.1 | 1.0 | 11.5 | 4.7 |
| *2* | Mining | 0.0 | 1.5 | 0.6 | 2.1 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| *3* | Constr. | 3.3 | 0.4 | 4.8 | 31.1 | 0.0 | 0.0 | 1.1 | 57.8 | 2.0 | 12.8 | 103.2 | 48.8 |
| *4* | Mfg. | 12.4 | 0.9 | 141.0 | 1012.5 | 0.0 | 0.0 | 6.2 | 222.6 | 9.8 | 81.2 | 13.1 | 170.7 |
| *5* | Elec. | 1.6 | 0.5 | 4.7 | 63.3 | 0.0 | 0.0 | 0.0 | 9.3 | 1.4 | 16.6 | 1.6 | 13.2 |
| *6* | Gas | 0.1 | 0.0 | 0.2 | 3.5 | 0.0 | 0.0 | 0.3 | 0.1 | 0.1 | 0.3 | 0.0 | 0.7 |
| *7* | Water | 0.4 | 0.1 | 1.2 | 13.2 | 0.0 | 0.0 | 2.5 | 1.5 | 0.1 | 0.6 | 0.8 | 1.1 |
| *8* | OTCU[a] | 3.9 | 0.3 | 102.9 | 231.1 | 0.0 | 0.0 | 2.2 | 450.4 | 10.5 | 45.6 | 41.4 | 85.4 |
| *9* | Whs.Tr. | 5.2 | 0.2 | 108.8 | 211.4 | 0.0 | 0.0 | 1.2 | 47.8 | 3.6 | 19.2 | 1.9 | 34.3 |
| *10* | Ret.Tr. | 0.9 | 0.1 | 83.4 | 24.6 | 0.0 | 0.0 | 0.3 | 90.4 | 5.8 | 23.3 | 18.8 | 40.1 |
| *11* | FIRE | 15.8 | 1.2 | 40.3 | 69 | 0.0 | 0.0 | 1.7 | 118.9 | 12.2 | 93.5 | 276.0 | 194.3 |
| *12* | Services | 9.4 | 1.0 | 279.3 | 302.6 | 0.0 | 0.0 | 2.3 | 227.4 | 48.3 | 152.5 | 139.5 | 472.5 |

**TABLE 10-8 Shelby County Input-Output Direct Coefficients Table**

| Industry | | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *1* | Agric. | .095 | .000 | .004 | .002 | .000 | .000 | .000 | .000 | .000 | .000 | .003 | .001 |
| *2* | Mining | .000 | .038 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 |
| *3* | Constr. | .016 | .010 | .002 | .003 | .000 | .000 | .021 | .012 | .001 | .004 | .026 | .009 |
| *4* | Mfg. | .061 | .023 | .057 | .110 | .000 | .000 | .116 | .048 | .005 | .028 | .003 | .031 |
| *5* | Elec. | .008 | .013 | .002 | .007 | .000 | .004 | .001 | .002 | .001 | .006 | .000 | .002 |
| *6* | Gas | .000 | .000 | .000 | .000 | .000 | .000 | .005 | .000 | .000 | .000 | .000 | .000 |
| *7* | Water | .002 | .002 | .000 | .001 | .000 | .000 | .048 | .000 | .000 | .000 | .000 | .000 |
| *8* | OTCU[a] | .019 | .008 | .042 | .025 | .000 | .000 | .041 | .097 | .005 | .016 | .011 | .016 |
| *9* | Whs.Tr. | .026 | .005 | .044 | .023 | .000 | .000 | .022 | .010 | .002 | .007 | .000 | .006 |
| *10* | Ret.Tr. | .004 | .003 | .034 | .003 | .000 | .000 | .006 | .019 | .003 | .008 | .005 | .007 |
| *11* | FIRE | .078 | .030 | .016 | .008 | .000 | .000 | .032 | .026 | .006 | .032 | .070 | .035 |
| *12* | Services | .046 | .025 | .114 | .033 | .000 | .000 | .043 | .049 | .023 | .052 | .035 | .086 |

**TABLE 10-9 Matrix (I-A**) for Shelby County, Week 0**

| Industry | | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *1* | Agric. | .905 | .000 | -.004 | -.002 | .000 | .000 | .000 | .000 | .000 | .000 | -.003 | -.001 |
| *2* | Mining | .000 | .962 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 | .000 |
| *3* | Constr. | -.016 | -.010 | .998 | -.003 | .000 | .000 | -.021 | -.012 | -.001 | -.004 | -.026 | -.009 |
| *4* | Mfg. | -.061 | -.023 | -.057 | .890 | .000 | .000 | -.116 | -.048 | -.005 | -.028 | -.003 | -.031 |
| *5* | Elec. | -.006 | -.004 | -.001 | -.007 | 1.00 | -.003 | -.001 | -.002 | -.001 | -.005 | .000 | -.002 |
| *6* | Gas | .000 | .000 | .000 | .000 | .000 | 1.00 | -.001 | .000 | .000 | .000 | .000 | .000 |
| *7* | Water | -.002 | -.001 | .000 | -.001 | .000 | .000 | .975 | .000 | .000 | .000 | .000 | .000 |
| *8* | OTCU[a] | -.019 | -.008 | -.042 | -.025 | .000 | .000 | -.041 | .903 | -.005 | -.016 | -.011 | -.016 |
| *9* | Whs.Tr. | -.026 | -.005 | -.044 | -.023 | .000 | .000 | -.022 | -.010 | .998 | -.007 | .000 | -.006 |
| *10* | Ret.Tr. | -.004 | -.003 | -.034 | -.003 | .000 | .000 | -.006 | -.019 | -.003 | .992 | -.005 | -.007 |
| *11* | FIRE | -.078 | -.030 | -.016 | -.008 | .000 | .000 | -.032 | -.026 | -.006 | -.032 | .930 | -.035 |
| *12* | Services | -.046 | -.025 | -.114 | -.033 | .000 | .000 | -.043 | -.049 | -.023 | -.052 | -.035 | .914 |

note: (a) OTCU = other transportation, communications and public utilities

Equation 10.12 was then used to obtain the industry final demand losses associated with the gross output loss results. Direct economic loss in terms of reduction in gross regional product (GRP) was then evaluated as the sum of final demand losses over all the industries. Results for the individual and multiple lifeline disruption cases are shown in Table 10-10. GRP loss for the multiple lifeline disruption case was estimated at $349.6 million, or 1.3 percent of GRP in 1991. This is again slightly less than one week's production in GRP terms.

**TABLE 10-10 Direct Economic Loss Estimates, Final Demand Terms**

| | Multiple Lifeline Disruption ($ mil.) | Single Lifelines | | |
|---|---|---|---|---|
| | | Natural Gas | Electric Power | Water |
| Agriculture | $ 1.7 | $ 1.5 | $ 0.1 | $ 0.4 |
| Mining | $ 0.0 | $ 0.0 | $ 0.0 | $ 0.1 |
| Construction | $ 22.0 | $ 21.0 | $ 2.9 | $ 3.6 |
| Manufacturing | $ 122.9 | $ 120.0 | $ 13.8 | $ 23.7 |
| TCU | $ 35.0 | $ 32.8 | $ 5.5 | $ 7.5 |
| Wholesale Trade | $ 21.4 | $ 20.7 | $ 2.7 | $ 3.8 |
| Retail Trade | $ 32.9 | $ 31.6 | $ 3.6 | $ 7.0 |
| FIRE | $ 51.1 | $ 49.4 | $ 9.5 | $ 6.5 |
| Services | $ 62.6 | $ 60.3 | $ 10.0 | $ 12.0 |
| TOTAL[(a)] | $ 349.6 | $ 337.3 | $ 48.2 | $ 64.6 |

note: (a) total may not add due to rounding error.

### 10.3 Indirect Economic Loss Estimation for Shelby County

Finally, total direct plus indirect economic losses were estimated for the scenario earthquake using the methodology described in section 10.1.4 above. This entailed estimating the additional losses over and above direct losses that would be associated with "bottleneck" effects and their multiplier impact. Following the methodology developed by Rose et al. (forthcoming), bottleneck industries were identified from the gross output loss results at each time period. It turned out that in the first two weeks, the manufacturing industry constituted the bottleneck industry and in the third and fourth weeks, the services and FIRE industries respectively were the constraints. While the disruption of certain types of services such as entertainment or personal services might not be considered critical in the sense of causing bottleneck effects, curtailment of other types such as business services could very well represent a real constraint on upstream or downstream economic activity. A revised vector of gross output losses was estimated and the associated final demand losses were calculated in the same manner as before.

Table 10-11 compares the results for the case without bottleneck effects ("direct" losses) and with these constraints (total "direct" plus "indirect" losses) for multiple lifeline disruption. The table shows that while direct loss to GRP or total final demand loss amounted to $350 million, when indirect effects are included, this impact rises to $420 million. The latter figure amounts to 1.5 percent of GRP. In gross output terms, adding indirect effects increases losses from $434 to $524 million. The table also shows that the significance of indirect losses differs substantially by industry. For instance, direct losses represent only 7 percent of total losses for the mining industry but 97 percent for the manufacturing, FIRE and services industries. Conversely, indirect losses represent 93 percent of the total for mining and 3 percent for manufacturing, FIRE and services. Indeed, the pattern is directly related to the severity of direct output losses as indicated in the last column of Table 10-5. This stands to reason because the industry that represents the bottleneck in a given time period will suffer no indirect losses, whereas an industry with relatively low direct losses will suffer high indirect losses due to the bottleneck effect imposed on it.

**TABLE 10-11 Direct and Total Economic Loss Estimates, Multiple Lifeline Disruption**

| | *Final Demand Loss* | | | *Gross Output Loss* | |
|---|---|---|---|---|---|
| Industry | Direct ($ mil.) | Total ($ mil.) | Direct / Total (%) | Direct ($ mil.) | Total ($ mil.) |
| Agriculture | $ 1.7 | $ 2.4 | 69 % | $ 2.5 | $ 3.4 |
| Mining | $ 0.0 | $ 0.6 | 7 % | $ 0.1 | $ 0.7 |
| Construction | $ 22.0 | $ 36.9 | 60 % | $ 25.8 | $ 41.4 |
| Mfg. | $ 122.9 | $ 126.5 | 97 % | $ 147.0 | $ 154.7 |
| TCU | $ 35.0 | $ 62.7 | 56 % | $ 47.4 | $ 79.5 |
| Whs. Trade | $ 21.4 | $ 28.8 | 74 % | $ 27.4 | $ 36.1 |
| Retail Trade | $ 32.9 | $ 44.2 | 74 % | $ 36.4 | $ 49.1 |
| FIRE | $ 51.1 | $ 52.6 | 97 % | $ 62.7 | $ 66.5 |
| Services | $ 62.6 | $ 64.8 | 97 % | $ 84.9 | $ 92.4 |
| TOTAL | $ 349.6 | $ 419.6 | 83 % | $ 434.1 | $ 523.7 |

## SECTION 11

## CONCLUSIONS

As outlined in the flowchart in Figure 2-1, this study has applied a multi-disciplinary framework for estimating economic losses associated with seismically-induced damage to lifeline systems in urban areas. Previous sections included detailed descriptions of the methodological approach and loss estimation results. This section provides, in section 11.1, a summary and discussion of the key economic loss estimation results for the case study of the impact of the M 7.5 Marked Tree (New Madrid Seismic Zone) earthquake scenario on Memphis/Shelby County, Tennessee. Section 11.2 discusses the significance of the results, the major methodological contributions of this study, and important areas for further research.

### 11.1 Summary of Findings

An overview of the economic loss results in this case study can provide useful insights into how losses compare across different lifelines, the relative significance of different types of loss, and the overall magnitude of the impact.

Table 11-1 summarizes results for the three lifelines considered in this study -- natural gas, electric power, and water delivery. The revenue loss figure for natural gas is the average of estimates produced for the winter and summer disaster scenarios; however, because revenue losses are small compared with other types of loss, seasonal variations in that component make little difference to the total picture of impact. Note that the direct economic loss figures in Table 11-1 represent results for the applicable lifeline alone, in the absence of damage to the other utilities. The figures for the three lifelines therefore do not add to the final estimate of total direct loss which considers the redundant impacts of multiple lifeline disruption. Indirect economic losses are not shown because they were only computed for the case of multiple lifeline disruption and could not be unambiguously apportioned among the three utilities.

**TABLE 11-1 Comparison of Economic Losses for Individual Lifelines**

| | *Natural Gas* | | *Electric Power* | | *Water* | |
|---|---|---|---|---|---|---|
| Type of Loss | Million $ | Percent | Million $ | Percent | Million $ | Percent |
| Repair Cost | $ 1.5 | 0.4 % | $401.1 | 88.9 % | $ 6.8 | 9.5 % |
| Revenue Loss[a] | $ 5.9 | 1.7 % | $ 1.7 | 0.4 % | $ 0.2 | 0.2 % |
| Direct Econ.[b] | $337.3 | 97.9 % | $ 48.2 | 10.7 % | $ 64.6 | 90.3 % |
| Sum[c] | $344.7 | 100.0 % | $450.9 | 100.0 % | $ 71.5 | 100.0 % |

notes: (a) average of winter and summer estimates where applicable
(b) in final demand terms; considers each utility independently; does *not* represent apportionment of losses in multiple lifeline outage case.
(c) may not add due to rounding error.

The table shows that the economic loss pattern varies quite significantly between the three lifelines. In terms of the sum of repair cost, utility revenue loss and direct economic loss to utility customers, natural gas disruption impacts are the most severe, totalling $344.7 million. The comparable total for electric power is $450.9 million; however, for water, it is only a fraction of this magnitude at $71.5 million.

Much of the contrast between the utilities is related to the fact that, as shown by the inferred restoration curves in Figure 6-5, estimated outage times are much longer for natural gas than for the other two lifelines. Full restoration is anticipated to take approximately 4 weeks for natural gas and 2 weeks for water and electric power. Thus for natural gas, the vast majority (98 percent) of the losses shown in Table 11-1 are directly related to the long outage times and the high direct economic losses imposed on customers. Revenue losses, which are also related to disruption time, are higher for natural gas than for either electric power or water. Indeed, for the category of loss that is not related to disruption time, repair costs, the loss is actually lowest for natural gas among the three lifelines.

In the case of electric power, by contrast, the vast majority of the losses shown in Table 11-1 (89 percent) consists of physical repair costs. Although outage times were relatively brief, the estimated revenue loss is still higher than those for water disruption because of the higher per-customer cost of the utility service. In terms of business interruption or direct economic loss, even though electricity is more critical for business operation, losses from water disruption are higher because of the slower service restoration throughout the recovery period. Criticality was measured in this study in terms of the extent to which business production could be resilient to disruption of the lifeline (see Table 10-3).

Losses in Table 11-1 associated with water service disruption consist primarily of direct economic loss (90.3 percent), although repair costs to broken pipes (9.5 percent) are also significant. The relatively low losses overall derive from a combination of the relatively rapid anticipated restoration pattern (compared to natural gas) and low repair costs and cost of service per customer (compared to electric power).

To the extent possible, it is useful to make order-of-magnitude comparisons between results in Table 1 and estimated losses in the benchmark ATC-25 (1991) study on "Seismic Vulnerability and Impact of Disruption of Lifelines in the Conterminous United States." In the scenario NMSZ M 7.0 earthquake used in that study, the ratio of direct economic loss to repair costs (referred to in ATC-25 as "indirect" and "direct" losses, respectively) for electric power transmission systems in the entire impacted area is about 3.0. Results in Table 11-1 indicate that in the current study, the comparable ratio is about 0.1. This disparity probably derives in large part to the difference in expected restoration times -- 2 weeks in the current study and about 14 weeks (for Tennessee) in ATC-25. In view of past earthquake experience, the shorter time period is expected to better reflect the time to restore electricity *service*. Service restoration time may be significantly less than the time required to complete repairs because in a disaster, emergency measures can be used to temporarily restore service while repairs are under way. In the case of water, the ratios, at 2.0 in ATC-25 and 9.5 from Table 11-1, are more comparable. It was not possible to make the comparison for natural gas because distribution system losses were not evaluated in ATC-25.

Another factor that may contribute to the difference between results of this study and ATC-25, insofar as direct economic loss is concerned, consists of the assumptions regarding business resiliency to lifeline disruption. As shown in Table 10-4, the ATC-25 resiliency factors, which were developed for California based on expert opinion, generally overestimate business resiliency relative to the empirical survey-based factors derived from an NCEER study of business vulnerability in Shelby County. To test the sensitivity of the results to resiliency factor values, direct economic losses were estimated using ATC-25 resiliency factors as shown in Table 10-4. The resulting estimate of direct economic loss for multiple lifeline disruption was $231 million, compared to the $350 million estimated using the empirical resiliency factors. In other words, while the resiliency factors in this study were on average about 29 percent smaller than those from ATC-25 (based on Table 10-4), the associated direct loss results were 51 percent larger. This indicates that the outcome is highly sensitive to the assumed business resiliency factors.

For the case of multiple simultaneous lifeline disruption, Table 11-2 shows the relative significance of different types of loss, including indirect economic loss. Revenue loss is separated out in the table because including it with indirect losses would amount to double-counting. Direct and indirect losses are evaluated here on the sales side, and it would be inappropriate to add losses from the revenue side in determining total loss. In other words, revenue loss to the utility company has already been implicitly considered in the process of estimating indirect economic losses throughout the county.

**TABLE 11-2 Economic Loss for Multiple Lifeline Disruption by Type of Loss**

| Type of Loss | Dollar Loss | Percent of Total | Ratio to Repair Cost |
|---|---|---|---|
| Repair Cost | $ 409,355,000 | 49.4 % | 1.00 |
| Direct Economic Loss[a] | $ 349,632,000 | 42.2 % | 0.85 |
| Indirect Economic Loss[a] | $ 69,991,000 | 8.4 % | 0.17 |
| TOTAL[b] | $ 828,978,000 | 100.0 % | 2.03 |
| Revenue Loss[c] | $ 7,681,000 | - | 0.02 |

notes: (a) in terms of loss to GRP.
(b) total may not add due to rounding error.
(c) average of summer and winter estimates where applicable.

Total losses within Shelby County amount to $829 million. Repair costs are estimated at $409 million, with the vast part of this consisting of repairs to the electric power system as shown previously. Repair costs account for about half of total loss. Direct economic loss imposed on the utility customers comprises another 42 percent of total loss, or $350 million. Indirect economic loss suffered in the County, evaluated as production losses over and above direct economic loss due to bottleneck effects, makes up the remaining 8 percent of the total. The final column of Table 11-2 expresses the dollar losses for each item relative to repair costs and shows that total losses are roughly double repair costs alone.

It is useful to consider the loss results in relation to levels of normal economic activity in Shelby County. The total $829 million loss associated with the lifeline disruption represents about 3 percent of annual gross regional product (GRP) for the County, or the equivalent of completely shutting down the economy for roughly a week and a half. In terms of losses suffered by the utility provider itself, repair costs and revenue losses together sum to a $417 million loss. Although figures on the annual profits of the utility provider are unavailable, a comparison can be made relative to annual revenues. Based on Tables 7-5, 7-8 and 7-9, total annual revenues for Memphis Light Gas and Water (MLGW) deriving from sales of natural gas, electric power and water in 1990 amounted to $803.5 million. Repair costs and utility revenue losses therefore represent about 52 percent of this annual revenue figure. On a profits basis, that is, after deducting operating costs from revenues, the loss would be of an even more devastating magnitude.

## 11.2 Discussion

The results of this study yield a number of insights into both the expected economic impact of lifeline systems damage in earthquakes, particularly the losses to Memphis/Shelby County in a major NMSZ seismic event, and the process of estimating this impact.

While the numerical loss results are specific to the Memphis case, certain general conclusions can be made. First, the results demonstrate that economic losses deriving from lifeline damage alone in an earthquake -- neglecting building damage, casualties, etc. -- can be substantial. Second, in the case of multiple lifeline disruption, direct plus indirect economic loss (i.e., loss to GRP), represents roughly the same magnitude of loss as repair costs in this scenario event. Since the loss to GRP (but not the repair cost) is highly dependent upon the speed with which service is restored, the generalizability of these relative magnitudes will depend upon factors such as the severity of the disaster, the relationship between increasing repair costs and increasing service disruption, and the extent to which post-earthquake lifeline service restoration varies from event to event. Third, indirect economic losses amounted to only about one-fifth of direct economic losses in the case of multiple lifeline disruption. This result reflects the extent to which disparities in the direct losses across economic sectors caused bottleneck effects to reverberate in the economy. Finally, the relative significance of repair costs, revenue loss, and economic impact differs substantially between lifelines. Repair costs, for example, are especially high in the case of electric power systems, whereas because of long disruption times, direct economic losses comprise the vast majority of loss related to natural gas outage and, to a lesser extent, water service disruption. Restoration patterns were found to critically influence the ultimate economic impact resulting from lifeline damage.

The study has also led to several significant methodological improvements and insights into the loss estimation process. At the most basic level, it has demonstrated that integrated problem-solving multi-disciplinary research is possible and can be fruitful. The process of implementing a complete lifeline loss estimation exercise has also identified the types of information necessary for the loss estimation and shown the importance of utilizing detailed local data on both engineering and socioeconomic systems. For example, in order to analyze vulnerability and loss at the census tract level, detailed information was needed on the expected ground shaking intensity patterns, lifeline systems, and urban settlement and economic activity patterns. Finally, the study has developed a preliminary methodology for evaluating losses associated with multiple as opposed to single lifeline disruption in an earthquake, leading to more realistic modeling of the economic impact of earthquake disasters.

Based on findings from and problems encountered in the course of this study, the following issues are recommended for further research:

- *Development of fully probabilistic economic loss model* - As noted in section 10, the Memphis application utilized a hybrid approach, combining deterministic economic modeling with probabilistic engineering analysis of lifeline disruption. A fully probabilistic economic model would have the important benefit of being consistent with not only probabilistic outage estimates but also probabilistic hazard assessments for a given region.

- *Refinement of consideration of economic resiliency* - The modeling of economic resiliency in this study can be improved by taking into account such factors as deferability of production (i.e., ability to make up lost production at a later time), as well as empirical data from actual disasters such as the 1994 Northridge earthquake or the 1993 Midwest floods.

- *Restoration processes and priorities* - Restoration times were shown to exert substantial influence upon total economic loss. Further research is needed to develop more sophisticated lifeline restoration models that explore the impacts of alternative restoration priorities. Since outage times were shown to significantly influence economic loss, lifeline restoration optimization represents a potentially important policy option that should be explored further.

- *Economic analysis of mitigation options* - Mitigation of lifeline system vulnerability before an earthquake represents another important option for reducing anticipated impact. The economic loss results from this and similar studies could be used to assist in developing cost-benefit types of analyses for investigating mitigation options.

- *Exploration of actual experience in past earthquakes* - This would be especially important for developing more accurate revenue loss and restoration models that could take into account the variety of complicating factors in actual disasters.

- *Sensitivity analysis and development of generalized economic loss patterns* - Application of the methodological framework to a series of earthquake scenarios, for example as part of a structured sensitivity analysis study, could yield general "rules of thumb" regarding economic impact. Key issues to investigate in this regard would include the magnitude of direct and indirect economic impact relative to damage, the relationship between restoration time and economic loss, and the relative impact of disruption to different lifelines.

- *Combination with other sources of impact to produce complete loss estimate* - The lifeline disruption impact methodology developed here can be combined with considerations of transportation disruption, building damage, casualties, reconstruction, and other significant sources of impact to produce a complete model of urban losses from earthquake disasters.

# SECTION 12

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71. Wiggins, J.H., (1994), "Estimating Economic Losses Due to an Interruption in Crude Oil Deliveries Following an Earthquake in the New Madrid Seismic Zone," Proceedings of the Fifth U.S. National Conference on Earthquake Engineering, Vol. III, pp. 1077-1086.

## APPENDIX A

## ALTERNATIVE ECONOMIC SCALERS

The applicability of the methodology developed in this report to other seismically vulnerable regions of the country depends to a large extent on the availability of the requisite data. For example, the analysis of economic losses depended upon information on economic activity by industry for Shelby County. As described in sections 8 and 10, this information was inferred from unpublished data on county employment patterns by industry. In the event that this unpublished data had not been available, other means for inferring industry economic data would have been required. Similarly, if the study area had comprised a non-standard geographic region (e.g., "the MMI VIII+ region" in the scenario earthquake) for which data are not compiled, the relevant data would have to be inferred based on other known economic information.

This appendix presents one possible inference procedure for industry-level economic information that may be useful as an alternative in cases where data are not readily available. Its application is demonstrated for the case of natural gas outage in Shelby County.

### A.1 Data Sources

Various data on the national and state economies are collected and published by the Bureau of Economic Analysis (BEA) and the Bureau of the Census (BOC) in the U.S. Department of Commerce. Economic censuses are performed by the BOC every five years, most recently in 1992. Seven censuses collect data on various sectors of the economy, including: manufactures, wholesale trade, retail trade, service industries, mineral industries, construction industries, and transportation industries. Various other economic data are published monthly by the BEA in the *Survey of Current Business*.

The loss estimation methodology presented in this study uses information on the product or output levels among major industries in the economy. Industry output data are available at the state level from BEA's statistics on gross state product (GSP) by industry. GSP, the state counterpart of the national gross domestic product (GDP), is defined as the market value of goods and services produced by labor and property in a state. Each industry's share of GSP represents its Value Added, or the total value of its products less the value of intermediate goods and services purchased from other industries. This definition avoids double-counting of intermediate products. Henceforth, industry "product" will be used synonymously with the term "value added".

Data for GSP by industry are published according to Standard Industrial Classification (SIC) codes, summarized in Table A-1. The most recent estimates, for 1989, were presented in the December 1991 issue of *Survey of Current Business* (Trott et al., 1991).

**TABLE A-1 Standard Industrial Classification (SIC)**

| Division | Code Group | Description |
|---|---|---|
| A | 01-02 | Farms |
| | 07-09 | Agricultural services, forestry, and fisheries |
| B | 10-14 | Mining |
| C | 15-17 | Construction |
| D | 20-39 | Manufacturing |
| E | 40-49 | Transportation and Public Utilities |
| F | 50-51 | Wholesale Trade |
| G | 52-59 | Retail Trade |
| H | 60-67 | Finance, Insurance and Real Estate |
| I | 70-89 | Services |
| J | 91-96 | State and Local Government |
| --- | --- | Federal civilian government |
| --- | --- | Federal military |

Table A-2 presents 1989 GSP figures for the State of Tennessee and for the U.S. as a whole.

**TABLE A-2 1989 Gross State Product Data**
(Millions of Dollars)

| SIC Division & Major Group | | Tennessee | United States |
|---|---|---|---|
| A | Farms | 1,426 | 88,587 |
| A | Agricultural services, forestry, and fisheries | 312 | 24,896 |
| B | Mining | 354 | 80,254 |
| C | Construction | 4,013 | 247,721 |
| D | Manufacturing | 22,161 | 965,997 |
| E | Transportation and Public Utilities | 7,326 | 460,863 |
| F | Wholesale Trade | 6,271 | 339,468 |
| G | Retail Trade | 9,903 | 485,979 |
| H | F.I.R.E. | 13,981 | 896,652 |
| I | Services | 15,494 | 970,539 |
| J | State and Local Gov't. | 6,772 | 413,123 |
| -- | Fed. Civilian Gov't. | 3,716 | 125,481 |
| -- | Fed. Military | 537 | 65,111 |
| | TOTAL | 92,267 | 5,164,671 |

### A.2 County-Level Economic Activity

Product data by industry are not, however, readily available at the county or city level. Where data is unavailable for a given study area, it is possible to infer the information from other related statistics which are published. One such inference method, based on comparing state and county economic activity, is illustrated below for Shelby County.

The first step in deriving county-level estimates of product by industry is to compare economic indicators for the county to those of the state, and identify any differences that will be important to capture in the resulting model. *County Business Patterns 1989*, published by the Bureau of the Census (1991), presents estimates of employment, payroll, and number of establishments by detailed industry category. Table A-3 presents summary statistics for Tennessee and Shelby County. As shown in the table, Shelby County accounts for about 22% of the state's payroll, 20% of the state's employees, and 18% of the state's of business establishments. The number of establishments (19,888) compares favorably with the total number of MLGW commercial and industrial customers for natural gas (19,000) and water (17,288), as presented in section 7. However, it is rather less than the number of commercial and industrial customers (34,390) for electricity. Differences may be due to definitional and reporting variation; for example, the difference between plants and establishments (a single establishment may have several locations or plants within the county).

**TABLE A-3 1989 Business Patterns for Tennessee and Shelby County**
(Source: County Business Patterns, 1989; Tennessee, BOC, 1991)

| | Tennessee | Shelby County |
|---|---|---|
| Number of Establishments | 112,337 | 19,888 |
| Number of Employees | 1,829,371 | 364,349 |
| Annual Payroll ($1,000) | 34,792,660 | 7,620,976 |

Detailed data on the business indicators listed in Table A-3 are available for the following private sector SIC industry groups:

- A Agriculture, forestry and fishing
- B Mining
- C Construction
- D Manufacturing
- E Transportation and other Utilities
- F Wholesale Trade
- G Retail Trade
- H Finance, Insurance and Real Estate
- I Services
- K Non-classified Establishments

Figure A-1 shows the contribution of each industry, in percent, to the overall total number of establishments, for Shelby County and the state of Tennessee. Figures A-2 and A-3 show similar information for the total number of employees, and total annual payroll, respectively.

Figure A-1 shows that the distribution of business establishments by industry in Shelby county is similar to that of the entire state. In Figure A-2, some clear disparities between the county and state data are shown. A greater percent of the state's employees are involved in manufacturing (SIC Division D - 28% vs. 15%), while Shelby County has a higher proportion of employees engaged in transportation and utilities (SIC Division E -11% vs. 6%), wholesale trade (SIC Division F - 7% vs. 10%), and services (SIC Division I - 31% vs. 26%). Similar patterns are evident in Figure A-3, where the percent of annual payroll in manufacturing in Tennessee far exceeds the percentage in Shelby County (32% vs. 17%). Additionally, the payroll percentage for Transportation and utilities, and Wholesale trade in Shelby County exceed similar percentages for the state (16% vs. 8%, and 13% vs. 9%, respectively). These differences are expected to impact the distribution of county product by industry.

To determine which economic indicator provides the most appropriate scaling factor for estimating county-level product by industry, we first compare industry product shares to the various economic indicators for the state of Tennessee. Figure A-4 compares industry shares of Tennessee GSP to industry shares of the total number of business establishments in the state. Similarly, Figure A-5 compares GSP composition to the employment composition by industry, while Figure A-6 makes the same comparison for annual payroll. It should be noted that GSP estimates are given for local and federal government (not shown on figures), whereas no employment or payroll information is available.

Figure A-4 indicates that the percentage of establishments by industry does not follow the pattern for GSP. Figure A-5, however, shows that the percentage of employees by industry closely follows that of GSP for all industry categories except Retail Trade (G), Finance, Insurance, and Real Estate (H), and Services (I). Similarly, the pattern for payroll shows even better agreement with industry composition of GSP, with significant variances for FIRE and Services only.

FIGURE A-1  Share of Business Establishments by SIC Division
Shelby County and the State of Tennessee, 1989

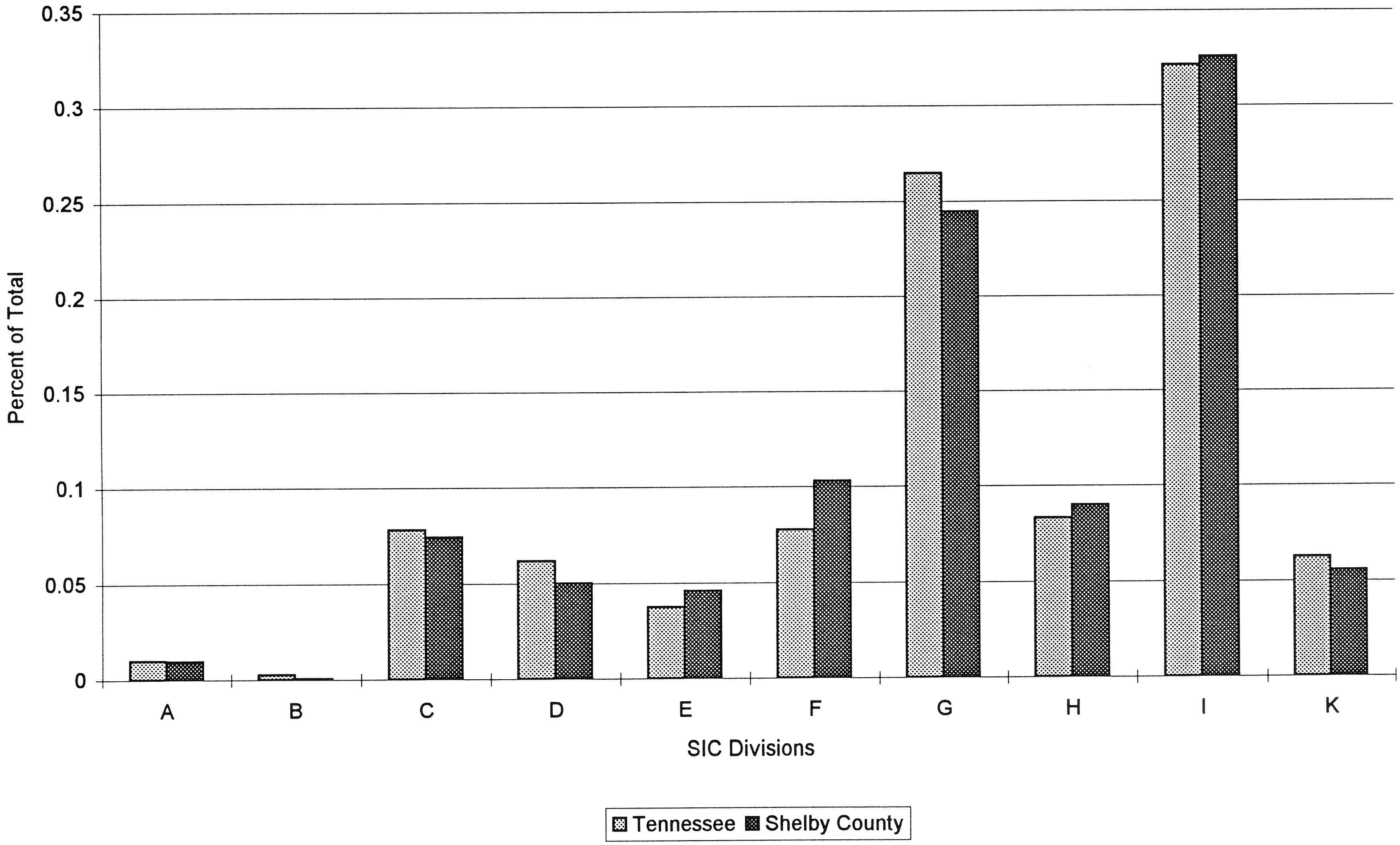


**FIGURE A-2 Share of Employment by SIC Division**
**Shelby County and the State of Tennessee, 1989**

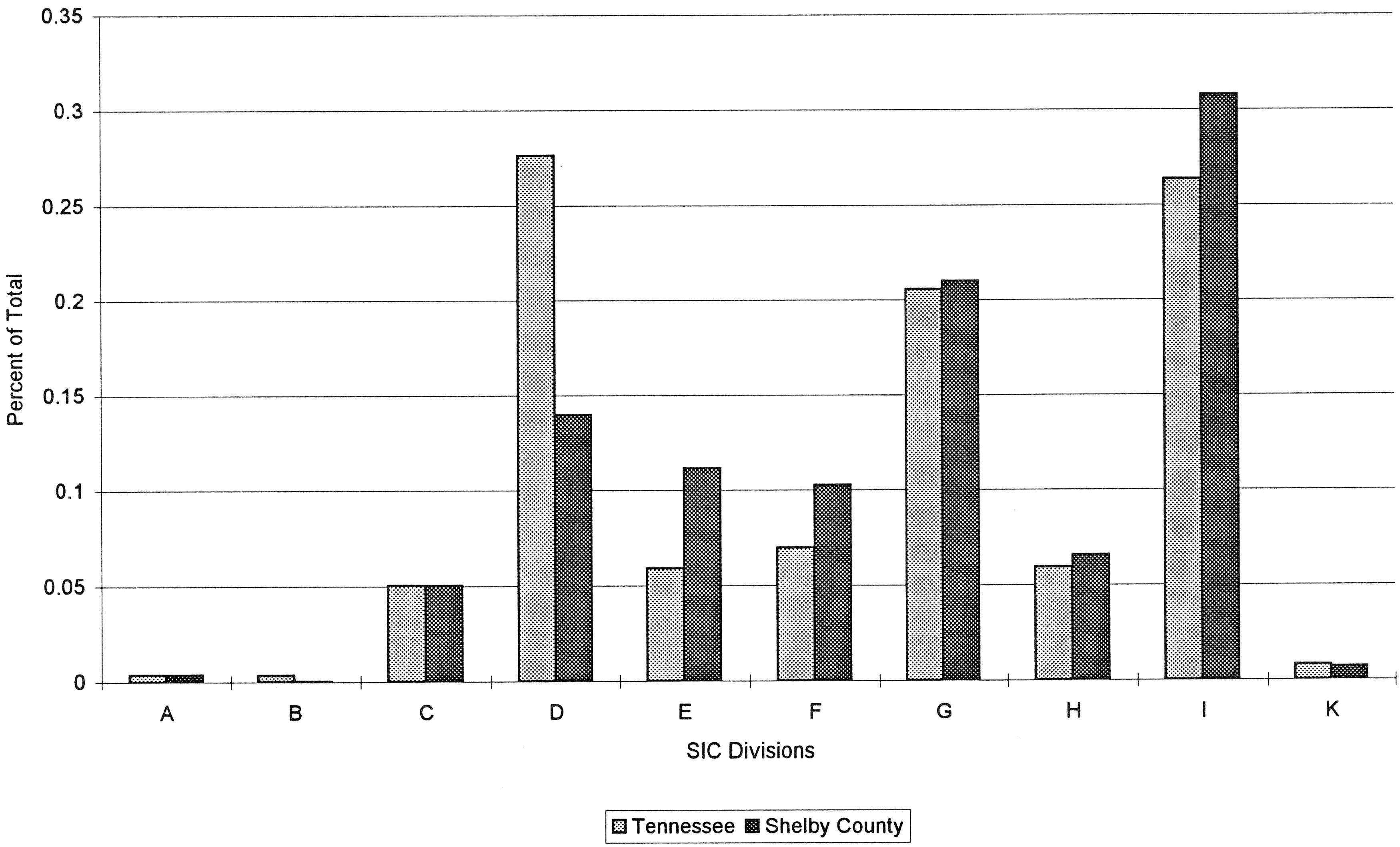


**FIGURE A-3 Share of Total Annual Payroll by SIC Division**
**Shelby County and the State of Tennessee, 1989**

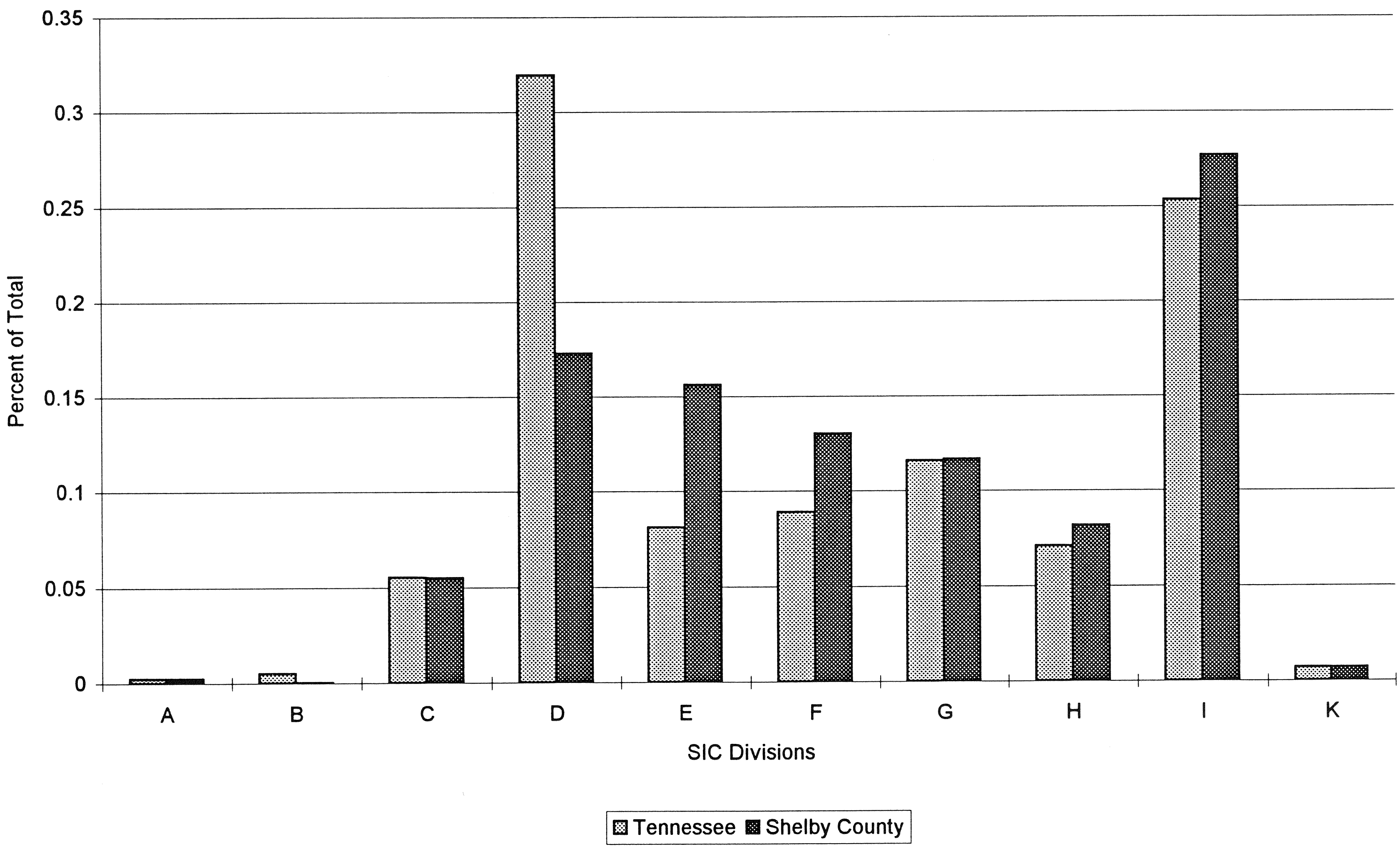


**FIGURE A-4 Share of GSP and Number of Establishments by SIC Division, State of Tennessee, 1989**

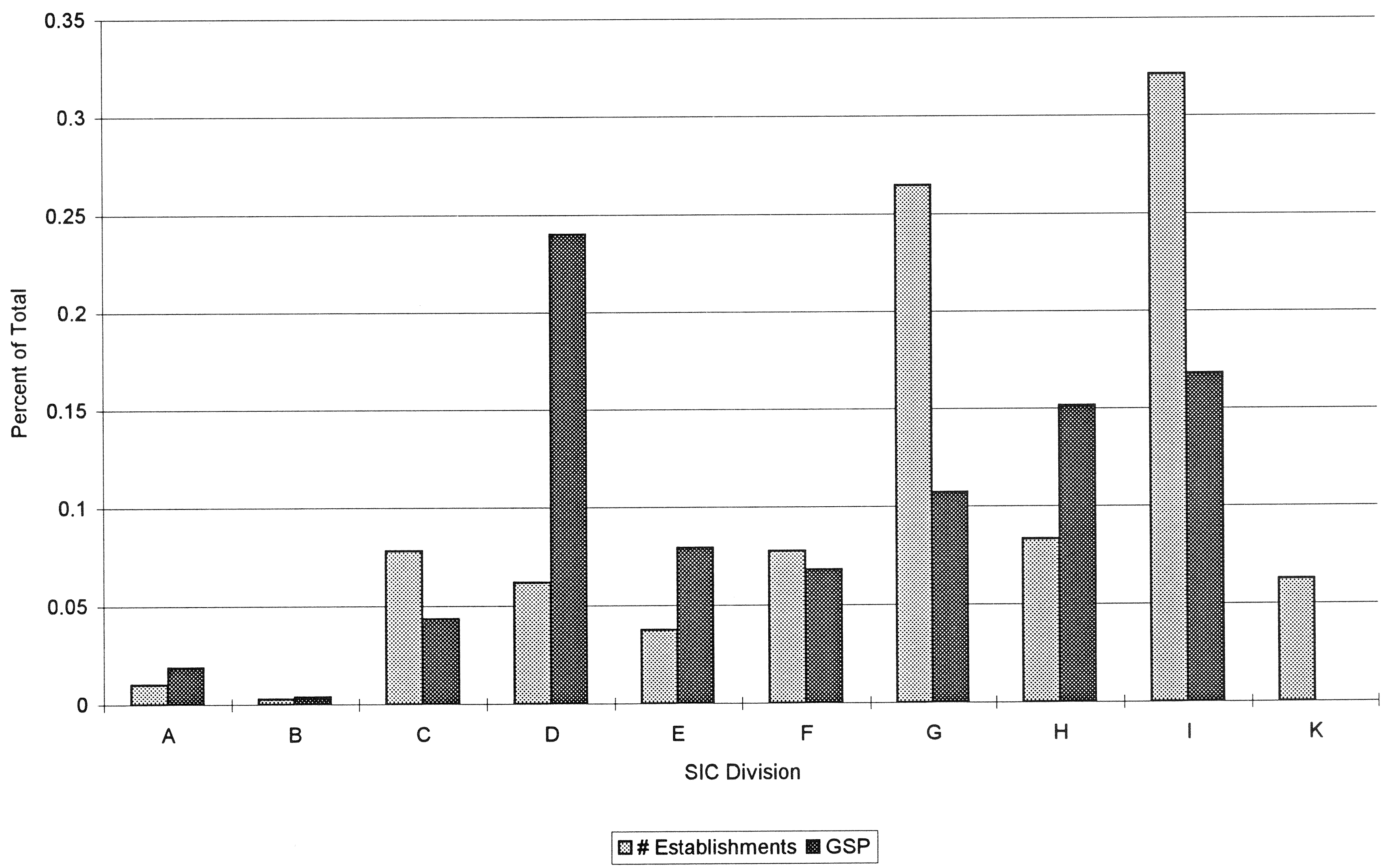


FIGURE A-5 Share of GSP and Number of Employees by SIC Division
State of Tennessee, 1989

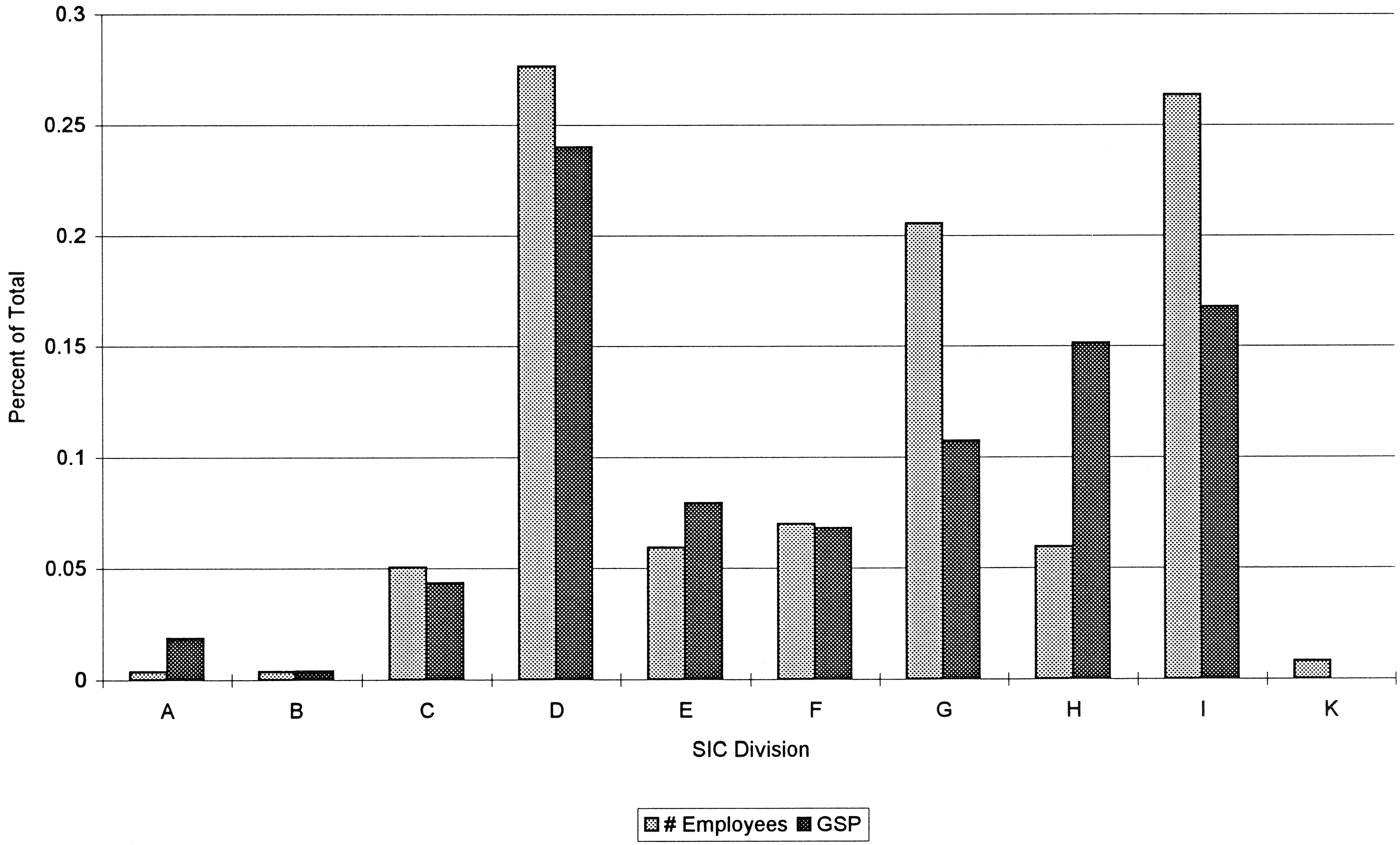


**FIGURE A-6 Share of GSP and Annual Payroll by SIC Division**
**State of Tennessee, 1989**

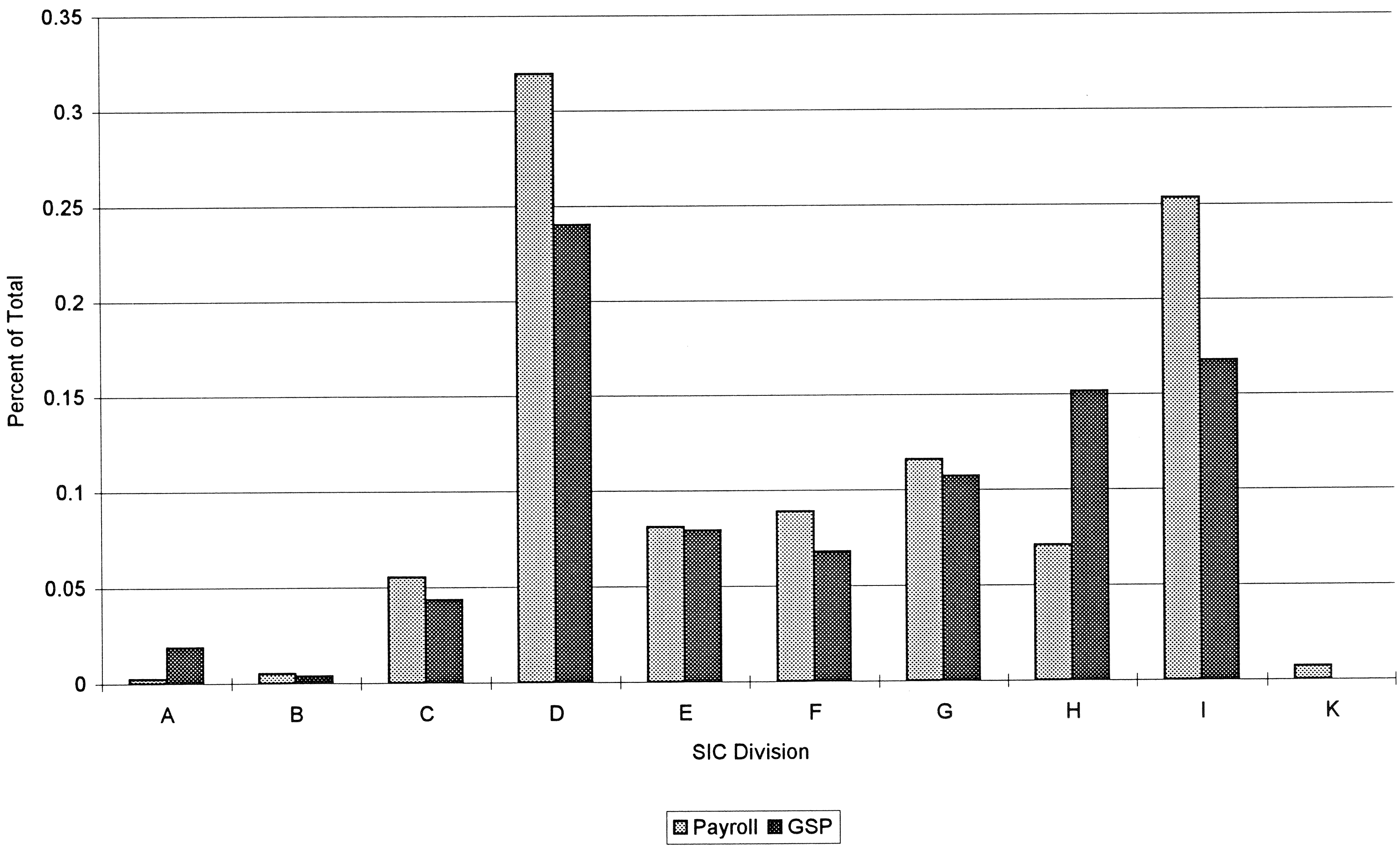
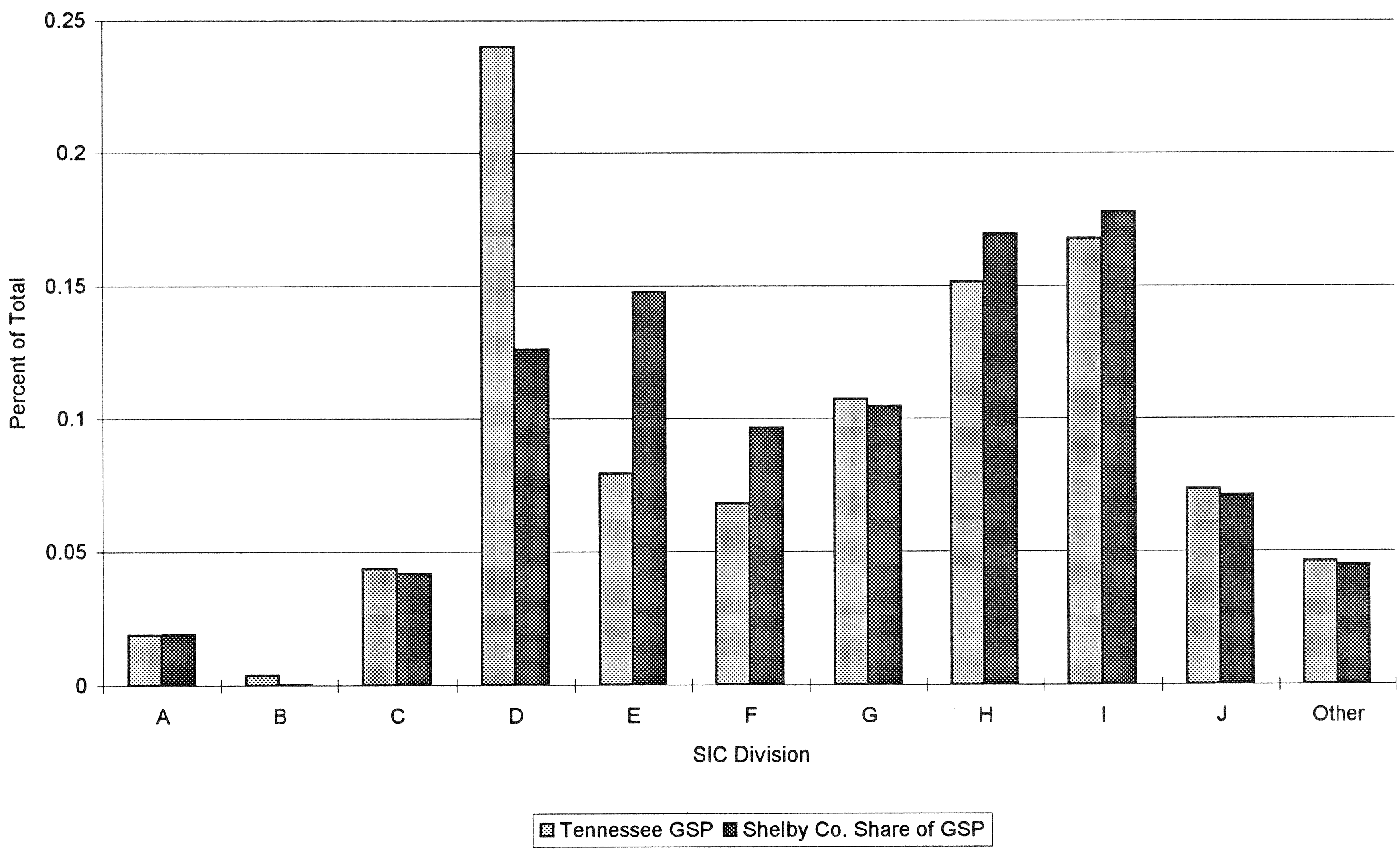


**FIGURE A-7 Share of GSP by SIC Division
State of Tennessee and Shelby County, 1989**



To model county-level product, it is important to know how product at the state level (GSP) is calculated. GSP is composed of four components, of which the major component, employee compensation, accounts for about 60 percent of the total (Trott et al., 1991). The other components are proprietor's income, indirect business tax and non-tax liability, and other capital-related charges.

Because employee compensation accounts for about 60 percent of GSP, and because the state payroll composition by industry follows the pattern for GSP by industry, the ratio of county to state payroll was selected as the means for scaling Tennessee GSP by industry to Shelby County.

Shelby County product by industry was estimated by combining Tennessee GSP by industry with the County's share of State payroll by industry. These figures are presented in Table A-4.

**TABLE A-4 Calculation of Shelby County Product by Industry**

| SIC Division | 1989 GSP[a] (million $) | Shelby Co. 1989 payroll (% of state) | Shelby Co. share of GSP (million $) |
|---|---|---|---|
| A | 1,738 | 22.9% | 399 |
| B | 354 | 1.3% | 5 |
| C | 4,013 | 21.7% | 871 |
| D | 22,161 | 11.9% | 2,629 |
| E | 7,326 | 42.1% | 3,084 |
| F | 6,271 | 32.1% | 2,014 |
| G | 9,903 | 22.0% | 2,183 |
| H | 13,981 | 25.3% | 3,539 |
| I | 15,494 | 23.9% | 3,709 |
| J | 6,772 | --[b] | 1,483 |
| Other[c] | 4,253 | --[b] | 932 |
| TOTAL | 92,266 | 21.9% | 20,847 |

Notes: a) No GSP estimates are presented for SIC Division K (Unclassified), which accounts for less than 1% of the state's and county's payroll, and will be omitted from further analysis.

b) No payroll estimates are given for local, state, or federal government or the military. Overall average percent contribution (21.9%) was used to compute county's share of GSP for these categories.

c) Federal government, military

Figure A-7 compares the resulting industry shares of County product to industry shares of GSP. This figure shows that manufacturing contributes more to product at the state level than at the county level, while Transportation and Utilities, and Wholesale trade contribute more at the County level. These differences reflect employment and payroll patterns as noted previously.

County contribution to GSP by industry may be evaluated in terms of dollars per day, as well as average dollars per day per business establishment. These figures are presented in Table A-5.

To utilize the economic data described above in the assessment of economic impacts of lifeline disruption, the economic activity of each industry group needs to be assigned to a customer category. This designation was presented in section 7 and is repeated here as Table A-6. Two basic business customer types exist within the State of Tennessee, and Shelby County - Commercial and Industrial. Electric generation customers have been omitted from Division E because virtually no gas utilities serve such customers within Tennessee. Table A-7 summarizes State and County GSP estimates by customer category. This data may be combined with outage estimates to quantify economic losses due to natural gas disruption in the absence of more detailed information on distribution of product.

**TABLE A-5 Shelby County Product by Industry**

| SIC Division | Annual Product (million $) | Product per day (million $) | Product per day, per establishment[a] ($) |
|---|---|---|---|
| A | 399 | 1.1 | 5,630 |
| B | 5 | 0.01 | 1,150 |
| C | 871 | 2.4 | 1,610 |
| D | 2,629 | 7.2 | 7,220 |
| E | 3,084 | 8.4 | 9,230 |
| F | 2,014 | 5.5 | 2,690 |
| G | 2,183 | 6.0 | 1,230 |
| H | 3,539 | 9.7 | 5,410 |
| I | 3,709 | 10.2 | 1,570 |
| J | 1,483 | 4.1 | --[b] |
| Other[c] | 932 | 2.6 | --[b] |
| TOTAL | 20,848 | 57.1 | |

Notes: a) Calculated using the 1989 estimates of the number of establishment by SIC for Shelby County (County Business Patterns, 1989; Tennessee, BOC, 1991).
b) no estimates for the number of government and military establishments are available.

**TABLE A-6**
Customer Category for Industry Groups

| SIC Division & Major Group | | Category |
|---|---|---|
| A | Agriculture, forestry, and fisheries | Commercial |
| B | Mining | Industrial |
| C | Construction | Commercial |
| D | Manufacturing | Industrial |
| E | Transportation and Public Utilities | Commercial |
| F | Wholesale Trade | Commercial |
| G | Retail Trade | Commercial |
| H | F.I.R.E. | Commercial |
| I | Services | Commercial |
| J | State and Local Gov't. | Commercial |
| -- | Other | Commercial |

**TABLE A-7**
1989 Product Estimates by Customer Category

| | Shelby County | State of Tennessee |
|---|---|---|
| Total Product | | |
| (million $) | 20,848 | 92,266 |
| Commercial | 18,214 | 69,751 |
| Industrial | 2,634 | 22,515 |
| Total Daily Product | | |
| (million $/day) | 57.1 | 252.8 |
| Commercial | 49.9 | 191.1 |
| Industrial | 7.2 | 61.7 |
| Total Number of Establishments | 19,888 | 112,337 |
| Commercial | 18,879 | 105,087 |
| Industrial | 1,009 | 7,250 |
| Average Daily Product per | | |
| Establishment ($/day/est.) | 2,870 | 2,250 |
| Commercial | 2,640 | 1,820 |
| Industrial | 7,150 | 8,510 |

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