EARTHQUAKE-INITIATED HAZARDOUS MATERIALS RELEASES: LESSONS FROM THE NORTHRIDGE EARTHQUAKE

Michael K. Lindell
George Washington University

and

Ronald W. Perry
Arizona State University

10 August, 1995

This research was supported by the National Science Foundation under Grant CMS 9415728. None of the conclusions expressed here necessarily reflects the views of the sponsoring organization.

PROJECT SUMMARY

Modern society has become increasingly reliant on materials that have extremely beneficial uses, but also pose significant health and safety hazards for unprotected exposures. These hazardous materials, commonly referred to as *hazmat,* are found in homes and commercial businesses. The potential for catastrophic hazmat releases has received increasing attention in recent years from government, industry, and professional groups. These groups have attempted to develop programs that will limit the likelihood and severity of environmental releases and provide a capability for responding effectively to any releases that do occur.

Hazmat poses a problem of great significance for earthquake hazard reduction because a severe earthquake could initiate hazmat releases at many locations at the same time. The increased magnitude of the hazmat threat could be compounded by obstacles to emergency response such as loss of communications to emergency responders, loss of warning systems for the public, and impediments to protective actions such as sheltering in-place and evacuation. This would be a significant problem because conventional hazmat emergency planning is based upon the assumption that releases would occur at only one location at a time, and that these releases would not take place concurrently with other hazards such as earthquakes.

Earthquake-initiated hazmat releases (EIHRs) also have received little attention from earthquake responders, planners, and researchers. One possible explanation for the lack of reported EIHRs is that California's strict construction codes and standards mandate seismic resistant structural design that prevents them from occurring. That is, this line of argument would suggest that no EIHR problem exists because the structures and containment systems in which they are stored do, in fact, protect them from seismic impacts. However, this explanation overlooks the lack of seismic standards for nonstructural mechanical or electrical components in hazmat facilities. It also overlooks three other important facts about building codes: a) many structures predate the current code revisions, b) inadequate building inspections can allow substandard structures to be built in spite of code restrictions, and c) even the most recent codes have been called into question by the performance of some structures in the Northridge earthquake. Finally, the stringency of

codes in California does nothing to protect structures in the Central and Eastern United States where jurisdictions have not adopted seismic elements. Even if seismic construction is part of the explanation for the unobtrusiveness of EIHRs, there are other important reasons for the lack of attention to this problem. One of these is underreporting due to hazmat handlers' concerns about company confidentiality, and the lack of clear assignment of responsibility to any governmental organization for systematically collecting and analyzing data on EIHRs. An even more compelling reason is statistical in nature. Moderate and severe earthquakes are infrequent events that were relatively rare in Southern California during major increases in the production and transportation of hazmat from 1930 to 1970. This temporal increase in hazmat hazard has been compounded by a geographical concentration of acutely hazardous chemical facilities in areas that have been unaffected by recent significant earthquakes. For example, the southern portion of the Los Angeles metropolitan area—which has the second largest concentration of chemical facilities in the country—has not been affected since the 1933 Long Beach earthquake. This problem of infrequent seismic impacts on hazmat facility clusters is even more true of hazmat facilities in seismic zones, such as the New Madrid Seismic Zone, that have even longer recurrence intervals. Geographical concentration of hazmat facilities decreases the likelihood of a significant EIHR, but would be expected to increase the catastrophe potential when a moderate or severe earthquake does strike the area where they are located.

Unfortunately, the potential for major EIHRs has received little attention from earthquake researchers and planners, probably because recent major earthquakes (1971 San Fernando, 1983 Coalinga, 1987 Whittier Narrows, 1989 Loma Prieta) struck areas that had structural vulnerability—many times manifested in noteworthy structural collapses—that substantially exceeded their hazmat vulnerability. These seismic events did, however, provide evidence of EIHRs that justifies greater concern. This concern has not been manifest in most studies of earthquake loss estimation, where the potential for EIHRs has been addressed only in the context of damage to lifelines (e.g., pipelines and port facilities) when it has been addressed at all. The one analytic study that addressed fixed-site hazmat facilities did provide support for the contention that EIHRs could cause significant casualties and economic consequences.

Evidence of the significance of EIHRs has been provided by the events of the Northridge earthquake. As was the case with previous earthquakes, the highest shaking intensities occurred in areas with relatively few hazmat facilities. Moreover, the facilities that were located in these areas tended to be ones that would generate environmental threats (e.g., soil and groundwater contamination) and occupational threats (e.g., workplace contamination), rather than acute public health hazards resulting from airborne release of acutely toxic gases or volatile liquids. Post-incident inspections reported by the Los Angeles County Fire Department Health Hazardous Materials Division revealed that hazmat releases occurred in approximately 20% of the industrial and 5% of the commercial facilities in the high impact areas (Modified Mercalli Intensity Zones VII-IX). There were significant hazmat problems at fixed-site facilities (ranging from university science laboratories to an aerospace industrial facility) and in hazmat transportation (including a train derailment involving sulfuric acid, a major petroleum pipeline spill, and natural gas pipeline releases and fires). Response to many of these problems was complicated by impacts on lifelines, critical facilities, but was facilitated by effective incident command in the impact area.

Comparison of the events of the Northridge earthquake with those of previous incidents and analyses shows that there were more EIHRs identified at Northridge than any other earthquake, although it is not clear to what degree this higher level of reported incidence is attributable to the magnitude of the earthquake, the nature of the soils, the number and structural characteristics of the hazmat facilities, the seismic resistance of the chemical containment/control systems and other building contents, or the completeness of incident reporting. The available data do confirm the potential for significant future problems in the areas of pipelines/pumping stations, fixed-site chemical facilities and, to a lesser extent, rail lines/yards. There were no data bearing on the potential for problems in highways/warehouses or ships/barges/port facilities. The evidence from the Northridge earthquake also points to a continued vulnerability of hazmat emergency response infrastructure to seismic impacts. There appear to have been no EIHR deaths or injuries, although it is important to note that the lack of reported casualties at Northridge would not necessarily generalize to areas having large concentrations of hazmat facilities, especially those handling toxic gases or highly volatile toxic liquids. Moreover, the overall level of disruption and damage attributable to EIHRs was only a small portion of the overall impacts, although they were quite significant for some hazmat handlers.

Any conclusions drawn from the data on the Northridge earthquake necessarily must be qualified by a careful delineation of the context of Southern California's EIHR vulnerability. First, EIHR vulnerability is determined by the extent to which hazmat handlers have adopted state-of-the-art measures to assess, mitigate, and prepare for EIHRs, but little is known currently either about the extent to which firms have adopted these measures, or about the legal, political, economic, or social factors that lead them to adopt these measures. Second, EIHR risks are influenced by a variety of federal and state seismic safety activities such as the National Earthquake Hazard Reduction Program and California requirements for structural safety. Other regulations, directed at hazmat safety, include the federal Superfund Amendments and Reauthorization Act (SARA Title III), Oil Pollution Act, the Department of Transportation's requirements for Transportation of Hazardous Liquids by Pipeline (49 CFR 195), and the Occupational Safety and Health Administration's Process Safety Management Rule (20 CFR 1910.119). The most important state requirement is California Health and Safety Code Chapter 6.95 (HSC 6.95). This legislation anticipates many important provisions of the federal Clean Air Act Amendments Section 112(r) requirement for the development Risk Management Plans by owner/operators of facilities handling large quantities of the most hazardous chemicals. Southern California jurisdictions implementing HSC 6.95 have adopted a supplementary seismic element that has not yet been addressed in the Environmental Protection Agency's proposed rule (40 CFR 68) on Risk Management Plans and, consequently, would not be extended to other seismic prone areas of the country. Similarly, local structural codes and standards in California are significantly more stringent than those in other seismic zones, while local Toxic Gas Ordinances appear to be unique to this state.

Industry initiatives, such as the Chemical Manufacturers Association's Responsible Care program, also are likely to have had a positive impact in enhancing EIHR risk reduction. Because programs such as Responsible Care are implemented nationwide, one would expect them to have similar impacts in other seismic hazard areas of the country.

Examination of the events that occurred during the Northridge earthquake, together with a review of previous research, suggests that significant efforts should be made to conduct comprehensive EIHR loss estimation studies for different seismic zones throughout the country, especially for faults near clusters of hazmat facilities. The current lack of information about EIHR casualties and damage means that existing seismic loss estimation studies *systematically underestimate* total casualties and damage to be expected in some future earthquakes. Research also is needed to identify and evaluate the effectiveness of alternative hazard mitigation and emergency preparedness measures for reducing EIHR threats to health, safety, and the environment. Studies of these effectiveness of these measures need to be followed up with studies of hazmat facility owner/operators' awareness, adoption, implementation, and evaluation of these measures. Efforts also need to be directed toward the development of hazard awareness materials for local policy makers, analytic tools and training for local emergency planners, and training and job aids for local emergency responders.

A number of EIHR hazard management actions also can be recommended. First, support should be mobilized for EIHR risk reduction by developing hazard awareness programs that recognize the differences in knowledge, resources, and decision processes of different stakeholders such as hazmat handlers, emergency planners, elected officials, and local residents. Moreover, the lack of adequate information about hazmat inventories and the potential consequences of hazmat releases necessitates the completion of hazard assessments that must be conducted before an earthquake occurs. In addition, thorough post-impact EIHR assessments need to be included as routine elements of earthquake disaster damage assessments to overcome the significant degree of underreporting of EIHRs associated with previous earthquakes. Moreover, significant hazard mitigation activities appear to be warranted for pipelines (especially petroleum pipelines), fixed-site facilities handling toxic gases or highly volatile toxic liquids, and emergency response infrastructure. In addition, petroleum pipelines and toxic gas facilities also appear to be in need of enhancements to their emergency preparedness. Finally, changes should be made to the implementation of some government regulations and programs, such as increasing the consistency of routine enforcement of regulated industries to ensure that they do not allow concerns about day-to-day costs obscure their obligations regarding environment, safety, and health.

TABLE OF CONTENTS

Introduction

Modern society has become increasingly reliant on materials that have extremely beneficial uses, but also pose significant health and safety hazards for unprotected exposures. These hazardous materials, commonly referred to as *hazmat*, are substances or combinations of substances that because of quantity, concentration, physical, chemical or infectious characteristics may either: a) cause, or significantly contribute to an increase in deaths or serious illness; or b) pose a substantial present or potential hazard to humans or the environment (California Governor's Office of Emergency Services, 1982).

These include substances that can be classified as explosive, flammable, toxic, corrosive, or highly reactive (Federal Emergency Management Agency, no date). In addition, there are nonchemical threats from radioactive and etiologic (biological) hazard agents. All of these substances can become dangerous when exposure occurs through inhalation into the lungs, ingestion into the digestive tract, or contact with the skin. Inhalation hazards can arise from gases such as chlorine, highly volatile liquids such as bromine, or solid particles such as asbestos, while ingestion hazards can come from low volatility liquids like petroleum. Skin contact can lead to chemical burns, transdermal absorption (e.g., some pesticides), or injection through the skin's surface as a result of some penetrating wound.

Many types of hazmat are found in homes and commercial businesses. Pesticides, automotive products, painting materials, and household cleaners are commonly encountered materials that are responsible for many poisonings every year (Grieshop & Stiles, 1989). While such exposures are of concern, greater attention has been devoted to the potential for hazmat exposures from industrial sources at fixed-site facilities or in transportation. Fixed-site facilities include such sources as chemical production plants and petroleum refineries, as well as manufacturers in the electronics, plastics, pharmaceuticals, aerospace, metal plating, agriculture, and food processing industries (see Perkins & Wyatt, 1991, for an extensive list of industries in which hazardous chemicals are handled). Transportation hazards can arise from hazmat shipments via rivers and ports, rail lines and yards, highways and warehouses, and pipelines and pumping facilities. Concerns about these industrial sources arise because of the large quantities of material that are involved and, in some cases, the presence of materials that are considerably more hazardous than those encountered in routine household and retail commercial use.

The path by which important targets such as workers, the environment, and the general public, can receive hazmat exposures is illustrated in Figure 1. This figure indicates that hazardous materials ordinarily are isolated by means of containment systems that include storage tanks, reactor vessels, and pipes. As indicated by the arrow with the solid line, a *release* occurs when hazmat escapes from the *containment systems* into the *immediate environment*. Depending upon the ambient environmental conditions and the characteristics of the hazardous material (especially volatility and solubility), *dispersion* transports the hazardous material out into the *extended environment* where it results in the exposure of a *target population*. The nature of the dispersion process is determined by the environmental medium into which the hazmat is released: air, surface waters, or ground (and, ultimately, ground water). Atmospheric dispersion is affected by meteorological conditions (especially temperature and wind speed). Dispersion into surface water is affected by hydrological conditions such as flow rate and turbulence, while dispersion into ground water is affected by conditions such as soil permeability and water table depth (National Fire Academy, no date). Categories of receptors include workers (who tend to be healthy adults), the general public (which also includes the very young, the very old, and the sick), and environmental flora and fauna. The target population can experience a variety of health effects such as minor injury or illness, long term effects such as cancer and birth defects, or death. Although not explicitly depicted in the figure, these adverse health effects can be addressed by medical responses ranging from self-administered first aid through definitive care in hospitals.

The consequences of this chain of events can be avoided by a timely and effective emergency response having four principal components. First, information about the emergency is assessed by an incident command system. The flow of information, which can be obtained from the status of containment systems, the immediate environment, the extended environment, or the target populations, is represented by dotted lines coming from these states to the incident command

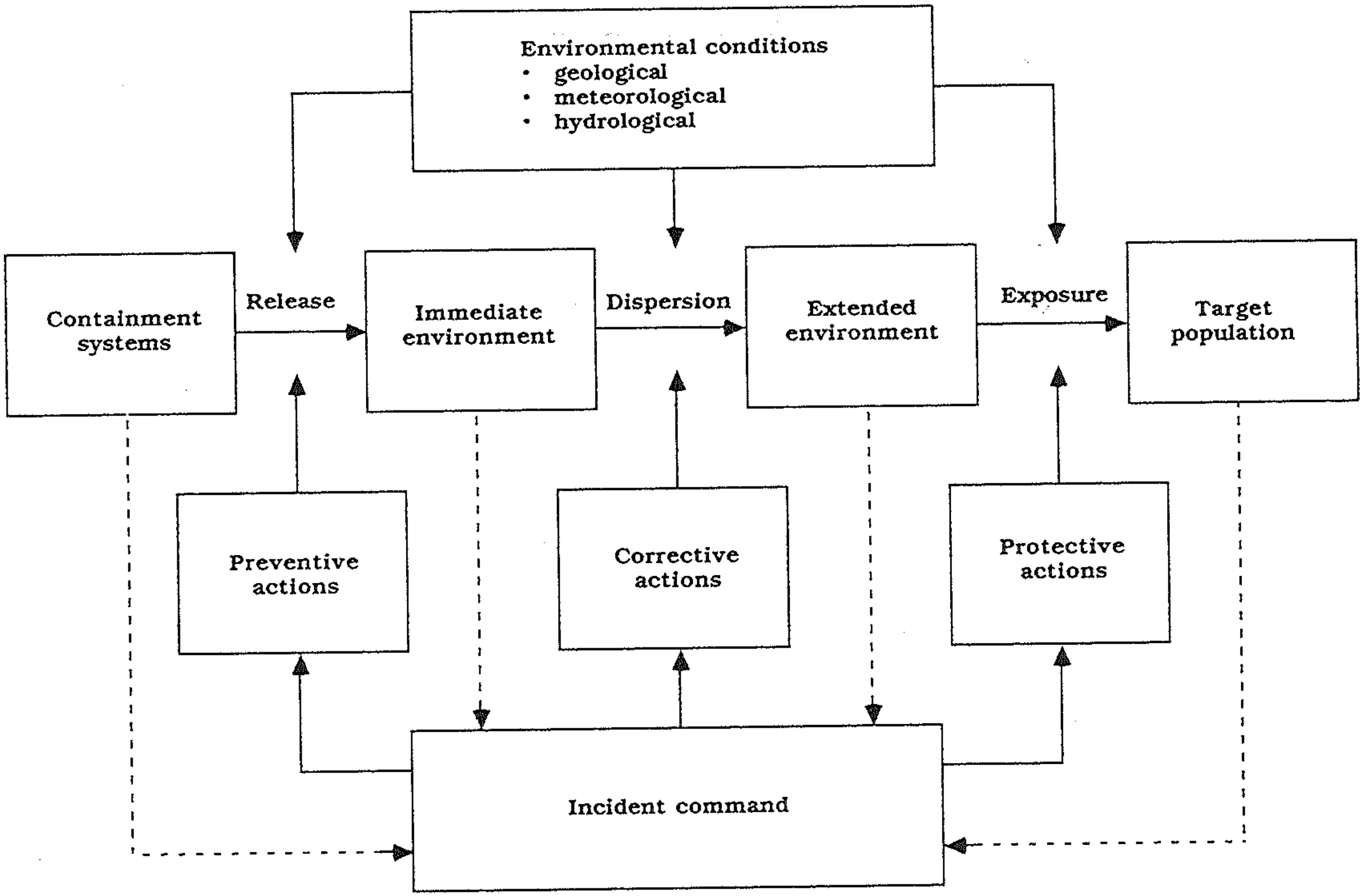

Figure 1: Chain of events for hazmat release

system. In response to this incoming information, the incident command system can implement any of three different types of emergency responses—preventive, corrective, or protective actions (Lindell, 1994). *Preventive* actions are taken to reduce the likelihood and magnitude of releases to the immediate environment; that is, to ensure that hazmat remains within a containment system. If these preventive actions are unsuccessful, *corrective* actions must be taken to prevent or limit dispersion of the release. This can be achieved by confinement, incineration, neutralization, dilution or precipitation. As a last resort, *protective* actions can be taken to protect the target populations by means of time (reducing the duration of exposure), distance (taking advantage of natural processes of aquatic or atmospheric dilution), or shielding (interposing barriers to exposure). Assurance of timely and effective implementation of these emergency response actions requires hazmat handlers to adhere to, and their surrounding communities to maintain, conscientious programs of emergency preparedness (see Drabek, 1986; Lindell & Perry, 1992; U.S. Environmental Protection Agency, 1987).

Although there are many different ways in which hazmat releases could be categorized, four principal types of problems can be classified by the type of receptor; the severity, immediacy, and scope of the threat; and the feasibility of countermeasures. These four types of releases can be labelled the *household threat*, the*occupational threat*, the *chronic environmental threat*, and the *acute public health threat*. The household threat typically is a small spill of a solid or liquid (e.g., a few pints of pesticides, automotive products, painting materials, or household cleaners) that is hazardous only to those in the immediate vicinity of the spill. It can involve acute hazards, but is more likely to result in chronic health effects such as those resulting from asbestos exposure. The occupational threat is similar in many ways to the household threat, but typically involves hundreds of gallons of material spilled into a workplace. The quantity and hazardousness of the material requires extensive cleanup by environmental contractors prior to resumption of business operations. The chronic environmental threat generally involves very large spills (tens or hundreds of thousands of gallons) of a low volatility liquid into surface waters (either inland or marine) or into soils where it can eventually reach ground water. Chronic environmental threats most immediately affect the human population through their potential impact on sources of drinking water. However, they also can pose an acute risk to the immediate survival of fish and game as well as a long term threat to these species as contamination of soil and vegetation moves up through the food chain. The acute public health threat involves a large release of an extremely hazardous gas or highly volatile liquid presenting an immediate inhalation hazard to workers in the facility and residents of surrounding areas—sometimes as far as five or more miles away (see, for example, U.S. Department of Transportation, 1993).

Hazmat risk reduction has received increasing attention in recent years as government regulation of hazardous materials has increased along with the industrial utilization of these materials. The most notable federal legislation includes the Clean Water Act, Clean Air Act, Resource Conservation and Recovery Act, Toxic Substances Control Act, and Comprehensive Environmental Response, Compensation Liability Act (CERCLA, or "Superfund"), Oil Pollution Act, and Occupational Safety and Health Act. Especially important are some recent amendments to this legislation, such as the Superfund Amendments and Reauthorization Act, which initiated community-right-to-know at the federal level, and the Clean Air Act Amendments, which instigated the Occupational Safety and Health Administration's Process Safety Management rule (29 CFR 1910.119) and the Environmental Protection Agency's proposed rule for hazardous facility Risk Management Programs (40 CFR 68). In general, this legislation is designed to limit the exposure of workers, the natural environment, and the general public to hazardous materials. Many federal agencies have active roles in the management of hazardous materials (14 agencies are members of the National Response Team), but the primary responsibilities fall upon the Environmental Protection Agency, Department of Transportation, Federal Emergency Management Agency, and Occupational Safety and Health Administration. In addition to imposing regulatory requirements, these agencies provide guidance, technical assistance, and funding to state and local governments. These agencies also are involved in developing programs for hazard assessment, hazard mitigation and emergency preparedness. For example, federal guidance on hazmat emergency planning includes publications by the National Response Team (1987), U.S. Environmental Protection

Agency (1989), Federal Emergency Management Agency (no date), Occupational Safety and Health Administration (1992), and U.S. Department of Transportation (1993), .

Additional programs come from relevant industry and professional groups. The Chemical Manufacturers' Association has sponsored the Responsible Care program (Chemical Manufacturers Association, no date), while the American Institute of Chemical Engineers' has sponsored a series of publications addressing chemical hazard issues (e.g., Center for Chemical Process Safety, 1989a, 1989b, 1989c). The National Fire Protection Association (1988), International City/County Management Association (Drabek & Hoetmer, 1990) and the National Governors' Association (Finegold & Solyst, 1994) also have been active in this area.

The fundamental purpose of these programs is to reduce hazmat risks by ensuring that hazmat handlers provide safeguards to limit the likelihood of environmental releases and establish a capability for responding effectively to any releases that do occur. In addition, these programs are intended to ensure that local governments are aware of the chemical hazards in their communities, can respond effectively if a release occurs, and establish mechanisms for coordination with industry to ensure the protection of workers, the environment, and the general public.

Earthquake-initiated hazmat releases

Hazmat poses a problem of great significance for earthquake hazard reduction because a severe earthquake could rupture the containment systems that hold these materials, thus exposing vulnerable populations. Even though significant casualties from hazmat releases have not been recorded in previous earthquakes, compelling scenarios can be constructed to describe how such events could occur and reasons offered as to why these scenarios have not *yet* occurred. Hazmat can be released from fixed site facilities through failure of storage tank foundations, valve rupture, or pipe connections (Perkins & Wyatt, 1990). Failure of these plant components could be caused directly by ground motion or ground failure (e.g., surface fault rupture, soil liquefaction, or landsliding) or indirectly by means of structural collapse of the buildings housing them.

Earthquake-initiated hazmat releases (EIHRs) also could occur in transportation if seismic forces cause pipeline rupture, train derailment, or tank truck accidents.

Earthquakes are a particularly significant threat to hazmat storage, processing, and transportation because they can cause simultaneous failure of what are normally independent systems for hazard management. Specifically, an earthquake's ability to destroy structures can initiate a release from containment by overstressing storage vessels, pipes and valves, while the destruction of offsite electric power and water systems can initiate releases by failing mixing and cooling systems needed to control chemical reactions, and thwart preventive response by failing backup control systems. In addition, an earthquake can collapse the structures in which corrective response resources are stored and, through the loss of communications equipment (due to destruction of telephone ground lines and microwave transmission towers, and overload of available radio frequencies), could delay or prevent onsite personnel from summoning offsite assistance. Loss of electric power could cause a loss of the lighting systems needed by emergency responders, and cut off the electricity that local residents' televisions and radios need to receive emergency warnings. At the same time, broken windows would preclude nearby residents from using their homes for in-place protection while waiting for a toxic plume to disperse. Evacuation routes could be blocked by collapsed street overpasses and debris from damaged buildings, while damage to hospitals and destruction of pharmacies could prevent chemical exposure victims from receiving adequate treatment. The end result could be thousands of casualties from chemical exposures in addition to those resulting from the collapse of other buildings such as residential, commercial, and other structures.

Earthquakes are especially formidable threats because they have the potential to produce releases from many locations at the same time. Concurrent releases constitute a significant problem for offsite emergency responders because hazmat emergency planning typically is based upon the implicit assumption that releases would occur at only one location at a time (e.g., Noll, Hildebrand & Yvorra, 1988). Under ordinary circumstances, this assumption is appropriate because releases from different facilities are rare and independent events. Thus, their joint occurrence would be expected to be the product of the probabilities of the separate events. That is, if the annual probability of a release from each of two sites were 10^{-3}, then the likelihood of both occurring *in the same year* would be 10^{-6}. Of course, the probability of the two releases occurring *on the same day* would be vanishingly remote. EIHRs, by contrast, would not be independent events because of their common cause.

Plausibility of a significant EIHR threat

Despite the fact that scenarios can be constructed to show that major impacts of EIHRs *could occur*, there has been relatively little attention paid to such indirect (or secondary) hazards in the earthquake planning literature (Federal Emergency Management Agency, 1994). For example, the incidence of EIHRs and the implementation of preimpact actions for their management (hazard assessment, hazard mitigation and emergency preparedness) largely have been neglected by previous social science research focussed upon building safety (Olson & Olson, 1993), insurance purchase (Kunreuther, Ginsberg, Miller, Sagi, Slovic, Borkan & Katz, 1978), hazard awareness (Mileti & Fitzpatrick, 1993; Nigg, 1982; Turner, 1987), emergency preparedness networks (Gillespie & Colignon, 1993; Gillespie, Colignon, Banerjee, Murthy & Rogge, 1993), and recovery (Bates & Peacock, 1992, 1993; Peacock, Killian & Bates, 1987). Broader treatments of policy implementation (Drabek, Mushkatel & Kilijanek, 1983; Lambright, 1985; May, 1988; Palm, 1987; Seigel, 1989; Wyner, 1984), emergency preparedness (Committee on Preparedness, Awareness & Education, 1993) and hazard mitigation (Godschalk, 1991) also have largely overlooked this issue.

Research on the impacts of earthquakes in Southern California also has neglected this issue. For example Toppozada, Bennett, Borchardt, Saul, and Davis's (1988) assessment of the impacts of a major earthquake on the Newport-Inglewood fault addressed the failures of oil and gas pipelines, and briefly discussed the potential for storage tank failures in Los Angeles-Long Beach port facilities, but ignored the potential for releases from the many chemical facilities in the Los Angeles metropolitan area. One possible reason for this oversight is that those addressing EIHRs as a "lifelines" problem, which would include oil and gas pipelines, have not made it sufficiently clear that they consider EIHRs as a "critical facilities" problem to be beyond the scope of their analyses. Yet another explanation is that it is only with the recent passage of federal and state community right-to-know legislation that it has been possible to identify potential EIHR sites and assess their hazards, let alone mitigate or prepare for them. Another possibility is that earthquakes tend to be perceived as a problem geographically limited to California, and chemical hazards as a problems for the Central and Eastern United States. This perception could be explained by Beavers, Hall & Nyman's observation (1993) that hazardous industrial facilities were constructed in the central and eastern regions before widespread recognition of their seismic hazards. Conversely, it is not widely recognized that Southern California has the second largest concentration of chemical facilities in the country (McCarthy, 1985).

The paucity of EIHR reports quite reasonably raises the question as to whether a significant level of risk actually exists. In particular, one might assume that incidents have occurred infrequently at fixed-site facilities because of seismic resistant structural design mandated by California's strict construction codes and standards. However, this explanation overlooks a number of factors. First, seismic design is well specified in connection with its application to buildings, but less well so in connection with nonstructural components such as chemical storage tanks, pipes, valves, and reactor vessels, or for control systems such as agitators, heaters, and refrigerators. Indeed, some observers contend that damage to nonstructural components can occur at seismic intensities significantly lower than those considered hazardous to structural integrity (Lama, 1993). Second, the existing building stock has been constructed under a wide variety of codes, in some cases predating the code devised after the destructive 1933 Long Beach earthquake. Many other structures predate later code revisions adopted following the 1971 San Fernando, 1983 Coalinga, 1987 Whittier, and 1989 Loma Prieta earthquakes (Martin, 1993). Thus, only an unknown fraction of the existing building stock housing hazmat storage and processing was designed according to the current code. Similar problems of outdated construction methods apply to pipelines, where pipe materials and welding techniques have changed significantly over the years. Third, structures designed to a given code have not necessarily been built to that code because understaffing of building inspection departments often has allowed substandard construction to pass undetected. In fact, substandard construction is recognized as a significant source of structural failure in earthquakes (Scawthorn, 1994). Fourth, unexpected structural failures during the Northridge and Kobe earthquakes have cast doubt on some of the design principles underlying even the current code (Arnold, 1995). Finally, California's sixty years of seismic experience and the codes resulting from that experience have made structures in that state quite dissimilar from those in other earthquake-prone states. The prevalence of unreinforced masonry structures in the Central and Eastern United States makes the argument of structural sufficiency particularly irrelevant in those regions.

A more likely reason for inattention to EIHRs is that historical data show most earthquake casualties have been a result of structural collapse (Durkin & Thiel, 1993; Stratton, 1989). Moreover, there is limited recognition of the extent to which hazmat releases *have occurred* during past earthquakes. Post-impact assessments of such recent California earthquakes as Whittier Narrows (Andrews, 1988; Tierney, 1988) and Loma Prieta (Holzer, 1994) have reported few hazmat releases of any significance. However, reliance on the number of *reported* releases in *previous* earthquakes can substantially underestimate the magnitude of the problem that could occur in more severe earthquakes. As a recent report indicates, "because of the massive overall destruction of an earthquake, the actual number of hazardous material incidents may go unreported" (Association of Bay Area Governments, 1990a, p. 22).

In fact, data collected by the Association of Bay Area Governments (ABAG) shows convincing evidence that EIHRs have been substantially underreported. In contrast to the data collection procedures used in previous earthquakes, which are of unknown quality, ABAG's investigation of the 1989 Loma Prieta earthquake was quite comprehensive. EIHRs were identified through direct project staff contacts with businesses, hospitals, schools, environmental contractors, and local governments. The total number of hazmat releases documented by the project staff for Loma Prieta (184) is only slightly less than the total number for all of the other 14 earthquakes in the database combined (220). One cannot rule out the possibility that the disproportionately large number of hazmat releases caused by Loma Prieta was due to greater numbers of hazmat facilities in the San Francisco Bay area. However, the fact that the most thorough investigation uncovered almost three times as many incidents during Loma Prieta as in the average earthquake suggests that the more likely explanation is a significant degree of underreporting of EIHRs in previous earthquakes.

There are a number of reasons for concluding that the number of hazardous materials releases reported in previous earthquakes seriously underestimates the actual incidence of EIHRs. Specifically, underreporting is most likely to take place in the category of occupational threats at fixed-site facilities when releases are not required to be reported because they do not meet a legal threshold reporting quantity or do not involve chemicals under the jurisdiction of regulatory agencies. Underreporting also is likely when the responsible party chooses to underestimate the quantity in an effort to avoid the legal and financial consequences of reporting a release, or when the spill can be cleaned up readily without the assistance of public agencies. Underreporting is less likely for chronic environmental threats when the affected areas are public property—for instance, when a transportation incident results in a release on public streets or highways—which are readily accessible to nearby residents and newsmedia reporters. Underreporting also is unlikely when acute public health threats at fixed-site facilities produce readily detectable sensory cues such as sights (visible fires, smoke or vapor plumes, floating oil, or dead animals), sounds (explosions), smells (pungent odors), or immediate physical symptoms in exposed populations (difficulty breathing), or if their mitigation requires offsite assistance. Such events are almost certain to be detected by nearby residents, reported by the newsmedia, and documented extensively in after-action reports by the cognizant regulatory agencies. Thus, agency records of reported releases are likely to be reasonably accurate in estimating the number of severe incidents but are likely to underestimate the actual number of other releases. In turn, systematic underreporting of EIHRs in moderate earthquakes will lead to significant underestimation of the hazards of EIHRs in great earthquakes.

The significance of the problem of EIHRs is underscored because recent data show that the likelihood of such events is increasing (Showalter & Myers, 1994), and that there are a number of reasons for explaining why this might be so. First, the production and transportation of hazardous materials is increasing throughout the country. Table 1 shows the U.S Department of Commerce's (1994) figures for the volume of production (in thousands of tons) from 1970 to 1994 for the 12 leading chemicals from the EPA's list of Extremely Hazardous Substances (EHSs).

Rank in top 50	Chemical name	Year				% increase 1970-1994
		1970	1980	1990	1994	
1	Sulfuric acid	29,525	44,157	44,337	44,599	51
8	Ammonia	13,824	19,653	17,003	17,965	30
10	Chlorine	9,764	11,421	11,809	12,098	24
13	Nitric acid	7,603	9,232	7,931	8,824	16
23	Formaldehyde	2,214	2,778	3,360	4,277	93
25	Ethylene oxide	1,933	2,810	2,678	3,391	75
31	Phenol	854	1,284	1,769	2,026	137
33	Butadiene	1,551	1,400	1,544	1,713	10
34	Propylene oxide	590	884	1,483	1,888	220
36	Acrylonitrile	520	915	1,338	1,543	197
37	Vinyl acetate	402	961	1,330	1,509	275
47	Aniline	199	330	495	632	218

Table 1: Volume of production for top 12 Extremely Hazardous Substances, 1970–1994.

It is important to note the variation in the magnitude of production increases from one chemical to another because this implies that increases can vary from one industry to another. Moreover, the volume of hazmat produced, stored, or transported can vary significantly from one geographical region to another. As noted earlier, McCarthy (1985) reported that the Los Angeles Standard Metropolitan Statistical Area (SMSA) has the second-highest number of chemical facilities in the United States, behind only the New York-New Jersey area. Within the Los Angeles SMSA, hazmat facilities are most heavily concentrated between the Port of Los Angeles/Long Beach and downtown Los Angeles. However, crude oil production, transportation, and refining in the Los Angeles Basin has decreased in recent years.

The increase in risk due to increasing total production at fixed-site facilities is compounded by the increasing scale of production and transportation. To obtain economies of scale, many chemical facilities have increased substantially in size over recent decades. Moreover, increased production throughout the United States necessarily results in an increase in transportation by pipelines, trains, trucks, ships, and barges. Finally, chemical facilities are often located in close proximity to one another so that producers of intermediate or consumer products can readily obtain their feedstocks from nearby producers of primary chemicals. The fact that major chemical facilities are clustered, rather than uniformly distributed within seismic zones has a number of consequences. First, geographical clustering of major chemical facilities decreases the likelihood that any particular earthquake would strike major chemical facilities. This could account for the rarity of EIHRs producing acute public health threats. However, geographical clustering would substantially increase the magnitude of the consequences that occur when an earthquake does strike the chemical facility cluster. Thus, even though clustering decreases the probability of any major EIHRs (compared to a uniform distribution of major chemical facilities), it increases the magnitude of the consequences (especially the casualties resulting from uncontrolled releases) that would be expected when an earthquake does strike. Finally, the catastrophe potential resulting from chemical facility clustering would be expected to be especially high in areas where chemical facility clusters were located in close proximity to high densities of residential and commercial population, or special facilities such as schools, nursing homes, hospitals, and jails.

In summary, there are compelling statistical reasons for believing that the absence of a historical record of major earthquake-initiated hazmat releases does not imply that there is either a low probability or negligible consequences of such events. The fact that the cumulative frequency of catastrophic EIHRs (i.e., those producing acute public health threats) observed to date is essentially zero definitely does not mean that the corresponding probability of such an event is zero. The underlying geology of Southern California, for example, is such that a major earthquake affecting the chemical facility cluster located between the cities of Los Angeles and Long Beach can be expected in the lifetimes of those now living (Toppozada, Bennett, Borchardt, Saul & Davis, 1988). Such an event is likely to be the first event to test the seismic vulnerability of such a cluster of modern chemical facilities.

Previous analyses of the EIHR threat

Given the potentially severe consequences of EIHRs, one might expect that previous accounts of earthquake impacts or planning studies addressing earthquake hazard mitigation actions have examined the issue thoroughly. That is, an analogy would be expected with the commercial nuclear power industry, whose potential for catastrophic consequences from a release of radioactive materials has generated an extensive series of safety analyses, voluminous regulations, substantial investments in safety systems, and extensive emergency planning.

However, EIHRs have not received the attention from planners and analysts that is commensurate with the magnitude of their potential consequences. Only recently have studies been conducted to provide the types of empirical data and systematic analyses needed to assess the hazards, and identify and evaluate alternative hazard mitigation and emergency preparedness actions. Perkins and Wyatt (1990) provided a useful summary of hazmat incidents in recent U.S. earthquakes in which they reported that the 1971 San Fernando (M 6.6) initiated many natural gas leaks, 100 of which were responded to by fire departments, and one-third of which caused fires. The earthquake also caused 18 hazmat releases (one-third of which caused fires). The fact that the releases occurred in facilities with minor structural damage indicates that the containment systems were more susceptible to damage than were the buildings themselves. The proportion of hazmat facilities experiencing releases cannot be determined because no figures are available for the number and location of structures housing hazmat. However, the number probably was small because the high intensity zone (MMI VIII to X) was in residential or uninhabited areas.

The 1983 Coalinga earthquake (M 6.7) also produced many natural gas line breaks but no dangerous releases occurred because the gas supply line to the town was closed immediately after the earthquake struck. Several tank and pipeline failures occurred at oil drilling and processing facilities; most were due to pipe connection failures, but were confined. Chlorine tanks at the local treatment plant slid up to ten inches, but slack in the attached piping was sufficient to handle the displacement. There were nine hazmat releases, one of which caused a fire, and three of which were in facilities with major structural damage. As was the case in the San Fernando event, the proportion of hazmat facilities experiencing releases cannot be calculated because figures are lacking for the total number and location of structures housing hazmat at the time of the earthquake. Once again, the number probably was small because the high intensity zone (MMI VIII to X) was sparsely inhabited or in a small town.

The 1987 Whittier Narrows (M 6.1) earthquake resulted in a total of 1411 natural gas line leaks, three of which caused fires (there were only five fires initiated by the earthquake). There were 30 hazmat releases, the most significant of which involved the release of half of the contents of a 1-ton chlorine cylinder. In this earthquake, as well, the proportion of hazmat facilities experiencing releases cannot be calculated because of the lack of data on the number of structures housing hazmat at the time of the earthquake. The density of hazmat facilities in the high intensity zone (MMI VIII to X) probably was larger than for the San Fernando and Coalinga earthquakes because the high intensity zone was in an urban, moderately industrialized area, but the total number of hazmat facilities affected might not have been larger because the smaller magnitude of the earthquake produced a smaller sized (in square miles) area of high intensity shaking.

The 1989 Loma Prieta (M 7.1) earthquake initiated a total of 3–4 leaks in high pressure natural gas lines, 300–400 in low pressure lines, and innumerable leaks in distribution lines (no final count could be made because entire sections of pipe were replaced without being tested for leaks in such heavily damaged areas as the Marina District). There were over 300 hazmat releases, 50 of them involving hazardous gases other than natural gas. In one of these incidents, a food processing plant experienced failure of restraints on a ceiling-mounted evaporator, rupturing a 2 inch pipe carrying anhydrous ammonia. Between 5,000 and 20,000 pounds of ammonia was released, but the plant was safely evacuated and the plume dissipated. Once again, lacking data on the number and location of hazmat facilities in the high intensity zones, it is not possible to calculate the proportion of these facilities that experienced a release.

One of the most impressive characteristics of the hazmat incidents that occurred in previous earthquakes is their variety and seeming improbability. Some incidents have involved the conjunction of seemingly fantastic sequences of events. For example, the 1964 Alaska earthquake generated tsunamis (seismic sea waves) that toppled the Standard Oil Company's storage tanks, causing them to rupture and spill their contents. The first tsunami also caused a break in the hose connections to an oil tanker loading diesel fuel, releasing fuel that ignited. The burning fuel was carried inland by the next wave and, in turn, ignited one end of a train, 40 of whose railcars carried oil. The cars exploded in a chain reaction ending with the ignition of the Texaco bulk storage yard eight blocks away.

In another case, an extremely small quantity of hazmat caused a substantial amount of damage. The Whittier earthquake of 1989 tipped over a one gallon container storing sodium metal under kerosene in a California State University, Los Angeles science laboratory. A water leak from a safety shower, ruptured when the shaking broke a threaded connection, reacted with the sodium to produce hydrogen gas, which ignited. Because the earthquake had failed the sprinkler system, the fire spread throughout the laboratory vaporizing mercury and exposing asbestos. The cleanup cost exceeded $237,000.

In summary, recent empirical data suggest that EIHR threat is a problem that warrants significantly more attention than it has received to date. Specifically, the magnitude of the problem increases with the magnitude of the earthquake and the proximity to the epicenter of facilities storing, processing, or transporting hazmat. The available data are severely limited because only one previous study (Perkins & Wyatt, 1990) has attempted to conduct a search thorough enough to ensure that a large proportion of the EIHRs that did occur were entered into their database. Even this study is limited by the fact that EIHRs were not categorized by type, although the investigators' dissemination of their database made it possible to perform a post-hoc categorization. Most significantly, no data are available on the locations of the releases (in terms of MMI shaking intensities) or the number of hazmat facilities in those areas. Thus, it is impossible to estimate the proportions of facilities experiencing a release. As will be discussed below, such data are essential to the development of empirical earthquake damage ("fragility") curves that can be used in analytic models of earthquake loss estimation (e.g., Tierney, et al., 1990).

The lack of satisfactory empirical data on EIHRs has created significant problems for those conducting loss estimation studies to project the casualties and damages that could be expected from earthquakes of different magnitudes occurring throughout the United States. Unfortunately, initial analyses of this problem were extremely limited in scope, thus necessarily underestimating the risk of EIHRs. Further, such studies made assumptions about accident consequences that not only cannot be defended on analytic grounds, but are substantially at variance with the available empirical data. One example of the way in which the EIHR problem has been addressed in earthquake loss estimation studies can be found in Federal Emergency Management Agency (1985), known as the "Six City" study because it examined damage and casualty assessment in six cities following either a magnitude 7.6 or 8.6 earthquake in the New Madrid Seismic Zone (NMSZ). The study's stated purpose was to estimate the damage and casualties that would result from structural collapse due to ground shaking and soil liquefaction. The study also briefly addressed flooding due to dam or levee collapse, and fire resulting from gas leaks, flammable liquid spills, and electrical shorts unchecked due to loss of fire suppression capabilities.

The study's discussion of natural gas pipelines asserted only that this product is lighter than air and, thus, any leak from a pipeline rupture would harmlessly diffuse into the air. As will be demonstrated in the later discussion of actual experience with EIHRs, this assessment is incorrect and, indeed, could be accurate only if the leaks were few, and isolated from ignition sources as well as combustible structures (none of which conditions are true in urban earthquakes). Effects of spills from the many major petroleum pipelines that pass through the NMSZ were not addressed at all. Further, the authors of the Six City study contended that conflagrations would be unlikely to occur because they assumed that any fires that did occur would be widely dispersed and unlikely to cause a significant number of casualties. No clear justification was offered for the assertion about the incidence of earthquake-initiated fires and no specific estimates of casualties were made for this consequence.

The study also examined the loss of hospital facility function due to the direct impacts of structural collapse and casualties among medical personnel, but neglected the effects of hazmat contamination from medical laboratory facilities on such functional losses. Finally, the study's discussion of port facilities did note that two categories of hazardous materials (petroleum and petroleum products, and chemicals) are among those ports' five principal commodities, but did not address the effects of an earthquake on the port facilities handling or storaging these materials. This omission is especially significant because the report notes in a different context that soils in floodplains are particularly susceptible to liquefaction. With regard to fixed site chemical facilities, the study ignored the direct effects of ground motion or soil failure (surface fault rupture, liquefaction, or landsliding) on storage tanks, pipes and valves, or the indirect effects on these components of structural collapse by the buildings in which they are housed. Nor did it address the potential effects of loss of offsite utilities (electric, gas, water, and communications) on plant operability. All of these omissions are significant because of the potential for damage to bulk containers of hazardous materials to have casualty effects that are non-linearly related to the magnitude of the physical damage to the facility. That is, the rupture of a single three inch pipeline might represent a perhaps a few hundred dollars worth of damage, but if carrying an extremely toxic gas could lead to thousands of casualties and billions of dollars in liability.

The greatest shortcomings of investigations like the Six City study are the failure to address the problem of EIHRs in ways that would guide further hazard assessment, hazard mitigation, and emergency preparedness actions. Thus, it is necessary to produce reasonable estimates of the potential sources (natural gas pipelines, oil pipelines, oil refineries, chemical production and storage facilities) and locations vulnerable to hazmat releases. It also is important to estimate the proportion of fixed-site facilities and transportation routes in high damage areas (MMI categories

VIII–X) likely to experience releases, the magnitude of those releases (and, thus, the size of the areas affected by those releases) and the potential for tertiary effects such as fires. Finally, such studies should estimate the potential casualties, social disruption, and economic losses resulting from these releases.

More recent studies have provided empirical data and analyses that rectify some of the deficiencies of earlier studies. Some of the limitations of previous analyses have led a number of investigators to combine engineering analyses with expert judgment to assess EIHR risks. Nyman, Prosser, Moriwaki and O'Rourke (1993) investigated the vulnerability of petroleum pipelines to landslides and liquefaction, especially at river crossings or on vulnerable slopes where large soil displacements could produce pipeline rupture. Their study, which examined the effects of ground shaking on pump station structures (buildings and storage tanks), operating systems (mechanical, electrical, instrumentation and control, communications), and other contents (storage racks and cabinets), indicated that pipeline rupture was not likely. The authors concluded that improved anchorage for new construction was advisable, but expensive mitigation measures for existing lines were not justified by the marginal reduction in seismic vulnerability. Instead, they recommended that emergency response plans for earthquake-initiated oil pipeline spills identify the most likely locations for liquefaction and landsliding, anticipate the types and distribution of damage, provide for an adequate inventory of replacement pipe and spare parts, and establish seismically secure emergency maintenance centers. They also advocated that the spill response plans recognize the potential for multiple concurrent incidents, and response impediments due to infrastructure damage (loss of roads, bridges, electric power, and communications). However, they did not provide any estimates of the magnitude of a potential spill, the speed and effectiveness of oil recovery, or the costs of pipeline retrofits or a major cleanup. All of these factors are quite uncertain, making decisions about the implementation of mitigation actions quite likely to be significantly influenced by the assumptions made by the analysts.

Nyman and his colleagues' (1993) recommendations for the development of comprehensive emergency response plans are certainly appropriate, but deserve careful study in light of Schiff and

Tang's (1993) examination of likely earthquake-initiated damage to the electric power and communication systems needed to support emergency responders. These authors noted that extrapolation from reports of past damage must be done cautiously because so few large or great earthquakes have occurred in major metropolitan areas since the introduction of modern power and communication systems. They reported that commercial electric power still was unavailable in the most severely damaged areas 24 hours after the earthquake following San Fernando and Loma Prieta and that telephone systems are affected more by overload (up to 20 times normal traffic) than by physical damage. They contended that the introduction of optical fiber and digital switches has impaired system diversity and redundancy by reducing the dispersion of transmission lines (multiple trunks on the same path) and increased the size and importance of nodes. Increased use of optical fiber also was thought to increase dependency on commercial electrical power.

A related problem is a growing trend toward collocation of pipelines, electric power lines, and transportation corridors. Collocation increases vulnerability to a common cause failure (e.g., permanent ground deformation) disrupting all systems simultaneously. It also increases vulnerability to reciprocal failures (one system failing another) and synergistic effects (two damaged systems producing far more severe consequences than would be expected from an additive combination, such as oil floating on water being ignited by short circuits on downed electrical lines). Each of these types of effects can increase the scope and magnitude of the damage. They also can increase the difficulty of repair following the earthquake through problems of system interdependency, such as the need for electric power to pump water (Ballantyne, 1993).

These studies of EIHRs and infrastructure damage have provided valuable perspectives but have not yet developed a comprehensive view of EIHR damage and casualties. This point was underscored by a recent comprehensive assessment of state-of-the-art earthquake loss estimation methodologies (Federal Emergency Management Agency, 1994) that could find only one study that attempted to provide systematic quantitative estimates of EIHR damage and casualties. This study, conducted by Tierney, Seligson, and Eguchi (1990), involved a multistage analysis of EIHR risk for 22 large ammonia and chlorine facilities using a deterministic distance-magnitude relationship to calculate peak ground accelerations (PGAs) for each facility. PGAs were then converted to MMI values, and modified to adjust for the effects of site soil characteristics. The estimated seismic inputs were then applied to "generic" facility designs consisting of the components typically found in two types of plants. One generic design was for a chemical processing system, which consisted of a pressurized storage vessel, an exothermic reactor, piping, and a separator/regenerator. The other generic design was a storage and transfer model, which consisted only of a storage vessel and associated piping. The investigators used available empirical data and expert judgments to construct generic earthquake damage ("fragility") curves for critical processing (storage vessels and reactors) and control (temperature and feedstock) systems.

The authors noted a number of limitations in the scope of their study, including the small number of sources (22), a small number of chemicals (ammonia and chlorine), and consideration only of ground shaking (not ground deformations such as surface faulting and liquefaction, or secondary hazards such as building collapse and fire). The use of generic facilities also necessarily assumed the facilities were in good condition (i.e., ignoring the age of the building and equipment, and the quality of original construction and subsequent maintenance), and the use of generic atmospheric conditions and aggregated population data. All of these factors would be expected to influence the study's results.

Despite these limitations, the investigators obtained some useful results in their analyses of facility performance in three postulated earthquakes. They found that for a simulated Newport-Inglewood fault event (M 7.0), 15 of the facilities would be in MMI Zone VIII and another 5 in Zone IX. The latter area would be expected to have significant levels of damage from shaking. Approximately 133,000 people would be exposed to levels of hazardous materials in excess of Emergency Response Planning Guidelines Level 3 (the maximum for one hour exposure without risk of life-threatening health effects; 20 ppm for chlorine and 100 ppm for ammonia) in such an event.

Somewhat surprisingly, less damage would be expected from the greater magnitude Southern San Andreas fault event (M 8.3), a result attributable to the distance of the facilities from the epicenter. Only four of the facilities would be in MMI Zone VIII and none would be in the highest damage zone (MMI Zone IX). Approximately 21,000 people would be exposed to levels of hazardous materials in excess of ERPG–3.

The small magnitude Whittier Narrows event (M 5.9) yielded the lowest levels of predicted hazard. Only one of the facilities was in MMI Zone VIII and none were in the high damage Zone IX. Only about 7,000 people would be exposed to levels of hazardous materials in excess of ERPG–3. On the basis of their analyses, the authors concluded that chlorine is the more serious threat of the two chemicals, and that the most likely failure mode in these facilities is the piping, not the storage and reactor vessels.

Assessment of previous research

The small amount of work on EIHRs that does exist is valuable, but limited in scope. Specifically, there are mostly anecdotal—rather than systematic—studies of the EIHRs that have occurred, emergency response actions to those releases, and loss of support infrastructure. The fundamental problem is that most studies provide rich verbal descriptions of individual events rather than data on the statistical incidence of event types that would enhance subsequent hazard assessments (Andrews, 1988; Association of Bay Area Governments, 1990a; Tierney, 1988). Moreover, previous studies (Association of Bay Area Governments, 1990a, 1990b; Tierney & Anderson, 1992; Tierney, Seligson & Eguchi, 1990) have identified useful mitigation and preparedness measures, but have failed to provide data that can be used to evaluate the relative efficacy of alternative emergency preparedness and hazard mitigation actions. In addition, analytic studies have been narrowly focussed upon specific types of releases (e.g., oil spills or toxic chemical releases) rather than examining a broad range of EIHR threats, while reviews of seismic hazard mitigation measures (O'Rourke & Shinozuka, 1993; Schiff & Tang, 1993; Werner, 1993) either mention this problem of EIHRs only in passing, or not at all. Finally, knowledge of the factors affecting adoption of earthquake-initiated hazmat mitigation and preparedness measures also is largely anecdotal (Barlow, 1993; Seigel, 1989).

In summary, much of the existing research on EIHRs is incomplete and, in many of the cases where different investigators have addressed the same topic, significantly different conclusions have been drawn. Recall that the Six City study concluded that fires (most of which are initiated by flammable liquids and gases) would make a negligible contribution to the seismic damage. By contrast, Fligg (1993) reported that the All-Industry Research Advisory Council report concluded that an M 6.5 earthquake on the Newport-Inglewood fault would cause between $5 and 17 billion in fire damage alone.

Systematic examination of previous research indicates that there is a need for careful study of the likelihood and consequences of EIHRs. Specifically, further data are needed on the direct effects of different earthquake impact modes (ground shaking, surface fault rupture, soil liquefaction) on hazmat containment systems and also the indirect effects of these impact modes through structural collapse. These impacts need to be examined separately for each of the different types of hazmat containment systems used in transportation (e.g., oil pipeline, natural gas pipeline, railroad tank car, tank truck), and at fixed-site facilities for hazmat storage and processing. The analysis of transportation modes is somewhat easier than the analysis of fixed-site facilities because of the substantially greater variety in the design of the latter types of facilities (cf. Tierney, et al., 1990). A thorough examination would look at the potential for releases in each of the four principal categories (household, occupational, chronic environmental, and acute public health), along with the potential for casualties, social disruption, and economic loss. The Six City study's examination of the loss of medical personnel due to death or injury suggests that staffing issues be examined across a wide range of emergency response organizations, public and private. Moreover, the foreseeable problems of impeded transportation suggests that there also should be an examination of lack of physical/administrative access to hazmat release sites.

Economic losses can be categorized further as consisting of property and capital equipment damage, loss of irreplaceable data, lost revenue, market share, customer loyalty waiting for site inspection and repairs, and legal liability for workers compensation and other claims (Fligg, 1993). Assessment of these impacts, especially property and capital equipment damage, should recognize the effects of earthquake intensity and existing seismic resistance on the magnitude of impacts that are sustained. The effects of earthquake intensity can be accounted for by correlating the incidence of EIHRs with the level of earthquake intensity in each of the impact zones. Finally, alternatives for hazard assessment, hazard mitigation, and emergency preparedness should be examined as mechanisms for EIHR hazard management in terms of their effectiveness in reducing seismic impacts, as well as their costs, time requirements, and barriers to implementation.

Some of the deficiencies of previous research can be overcome by conducting a further examination of the significance of EIHR incidents that occurred during the Northridge earthquake and examination of their impacts on hazmat handlers. Providing a comprehensive assessment of the problems that occurred there requires an examination of accounts of the releases that were reported in the popular newsmedia, the scientific and professional literature, and agency reports. However, retrieval of data on the extent to which the Northridge earthquake initiated hazmat incidents in transportation and fixed-site facilities will make only a limited contribution to our understanding of EIHRs. It also is important to examine local emergency organization's preparedness for responding to the demands of EIHRs and the degree to which emergency responders were impeded by other impacts, especially infrastructure disruption (e.g., commercial electric power, water, and communications). The ultimate objective of this effort is to elaborate the implications of the Northridge earthquake for future earthquakes of greater magnitudes (and, thus, greater destruction and more severe and numerous releases) and in other locations. Thus, we are interested in generalizing from the hazmat releases that did occur at Northridge to what could happen in other California locations (especially those like the Los Angeles-Long Beach chemical facility cluster) as a result of an earthquake of equal or greater magnitude. In addition, we want to examine what could happen in an earthquake of similar or greater magnitude occurring in the Central or Eastern United States where there are less stringent requirements for seismic design and chemical safety mitigation measures, and lower levels of emergency response capability.

This concern with generalization to other earthquake magnitudes and other locations makes it essential to examine the physical and social context in which the Northridge releases occurred.

Recognizing that hazard vulnerability is a joint function of the characteristics of the natural event system and the human use system (cf. Burton, Kates and White, 1978), we need to examine the observed damage in terms of the hazard assessment, hazard mitigation, and emergency preparedness activities undertaken by hazmat handlers to reduce EIHR risks. In turn, the hazmat handlers' actions have been influenced by a network of market forces, industry-wide initiatives, and governmental regulatory requirements.

Actual releases in the Northridge earthquake

The Northridge earthquake, which struck at 4:31 AM on January 17, 1994, caused 57 fatalities (one of which was an emergency responder), 9,158 serious injuries, and either moderately or severely damaged approximately 12,500 structures at a cost of over $20 billion (California Governor's Office of Emergency Services, 1994). The event has been classified as a moderate earthquake (M6.8), but had unexpectedly large effects because of its unprecedented horizontal and vertical accelerations. The earthquake impacts receiving the most extensive newsmedia coverage were the apartment and freeway collapses. Only a few hazmat incidents received much attention from the national newsmedia or in early agency assessments (Jonientz-Trisler, 1994), but many more were identified and responded to by state and local agencies.

Hazmat specialists in affected jurisdictions were concerned about hazmat releases that probably had occurred, but would not come to the attention of government agencies if they were small and, thus, did not require emergency response assistance by offsite agencies, and would not be subject to legal reporting requirements. Consequently, the Los Angeles County Fire Department Health Hazardous Materials Division (HHMD) directed a thorough postincident assessment of earthquake-initiated hazmat releases from command posts in Santa Clarita and Van Nuys (Los Angeles County Fire Department, 1994). Staff at the Santa Clarita command post were teamed with city and county building inspectors to examine the condition of all structures in that area, which included mostly MMI categories VIII and IX. The magnitude of postincident building inspection program can be seen in the fact that it involved over 85,664 buildings in the City of Los

Angeles alone and required supplementing the normal professional staff with over 1440 volunteers (City of Los Angeles Department of Building and Safety, 1994). As shown in Table 2, the Santa Clarita HHMD team participated in 598 hazmat assessments, 151 of them at industrial sites and 376 at commercial sites. They identified 52 sites (8.7% of the total number of structures inspected) with hazmat concerns. Of these, 28 were industrial and 16 were commercial sites. Thus, 18.5% of the industrial, and 4.3% of commercial sites in this area had hazmat release problems. Most of the sites were cleaned up by their owners or tenants, but 19 (36.5%) required cleanup and waste removal by HHMD's hazardous waste cleanup contractor.

	Type of facility			
Site	Industrial	Commercial	Other	Total
Santa Clarita	28/151 (18.5%)	16/376 (4.3%)	8/71 (11.0%)	52/598 (8.7%)
Van Nuys	11/226 (4.9%)	27/561 (4.8%)	44/902 (4.9%)	82/1689 (4.9%)
Total	39/377 (10.3%)	43/937 (4.6%)	52/973 (5.3%)	134/2287 (5.9%)

Table 2: Earthquake-initiated hazmat releases (EIHRs) at fixed site facilities.

The Van Nuys command post's assessment encompassed a much broader area, including the entire San Fernando Valley (MMI categories VIII–IX), together with Glendale (MMI VI–VII), Santa Monica (MMI VII–VIII), West Los Angeles (MMI VIII–IX), Culver City (MMI VII), Hollywood (MMI VII–VIII), and selected facilities north of Jefferson Avenue and west of the Harbor Freeway (MMI VIII). A list of sites that might have had hazmat releases was constructed from sources including *a)* the list of facilities inspected annually by HHMD because of their high volumes of acutely hazardous materials (AHMs); *b)* lists of AHM handlers provided by the cities of Burbank, Glendale, Santa Monica, Culver City, and Los Angeles; *c)* businesses listed in the telephone directory yellow pages in the categories of nurseries, pool supply stores, and paint supply stores; *d)* commercial/industrial facilities reported by the Los Angeles City Building and Safety damage assessment database to have suffered extensive structural damage; *e)* schools, colleges and universities; and *f)* medical facilities and laboratories. Of the 1689 hazmat assessments conducted by the Van Nuys command post (226 at industrial sites and 561 at commercial sites), the inspection team found 82 sites with hazmat concerns (4.9% of the total number of structures inspected). Of these, 11 were industrial and 27 were commercial sites. Thus, 4.9% of the industrial, and 4.8% of commercial sites in this area had hazmat release problems. It is noteworthy that only two of the industrial facilities (both of them plating operations) and none of the commercial facilities with hazmat release problems sustained structural damage.

Most of the sites were cleaned up by their owners or tenants, but 2 (2.4% of the total) required cleanup and waste removal by HHMD's hazardous waste cleanup contractor. The agency reported that the greatest potential for acute health hazards was found at plating facilities or manufacturing facilities having large open top tanks of plating solutions; retail pool supply stores; laboratory facilities in schools, universities, hospitals; and independent medical laboratories (Los Angeles County Fire Department, 1994). Indeed, 22 of the 226 industrial cleanups (9.7%) were at plating facilities.

As Table 2 indicates, there were distinct differences between the Santa Clarita and Van Nuys command posts in terms of the proportion of industrial facilities experiencing EIHRs, 18.5% and 4.9%, respectively. The differences are attributable to the fact that both the commercial and industrial facilities in the Santa Clarita area are older and more tightly clustered in an area of high seismic intensity (MMI VIII and IX). By contrast, the industrial and commercial facilities in the Van Nuys area tend to be newer and more geographically separated. Most of the commercial facilities are located in the western portion of the impact area where seismic intensities were higher (MMI VIII), while the industrial facilities are located in the eastern portion of the impact area where seismic intensities were lower (MMI VII).

In total, HHMD documented 134 locations with hazmat problems and 60 emergency hazmat incidents, of which 21 were at businesses, 17 at residences, and 9 at schools. There also were 5 at hospitals or medical facilities, 5 on public property, and 3 in other locations. Only 10 of the emergency incidents were classified by HHMD as major (Los Angeles County Fire Department, 1994).

There were no acute public health threats involving explosives, etiologic agents, radiological materials, or large quantities of toxic gases, although there was a significant incidence of asbestos abatement problems, which ultimately could present a chronic health hazard. There was only one acute public health threat involving a significant release of corrosive liquid, but there were many releases of flammable liquids or gases. The remaining incidents of major significance can be classified as involving chronic environmental and occupational threats. The following discussion will address the most significant of these in some detail. Discussion of these specific incidents will illustrate some the problems that can arise in responding to earthquake-initiated hazmat releases and suggest some ways in which such responses can be made more effective. The discussion also will explore the implications of the sheer number of incidents and the likely implications of this problem for preincident planning and response prioritization during a future disaster.

Train derailment

The California Public Utilities Commission (1994) reported that the earthquake caused a section of railroad track within 2 city blocks of the epicenter to move approximately 4 inches off center. When a westbound freight passed over the deformed section of track at approximately 30 mph, the lead locomotive and 29 cars derailed. One of 13 tankcars spilled an estimated 2000 gallons of sulfuric acid (out of a total capacity of approximately 13,350 gallons for that car, and 173,550 capacity for the entire group of tank cars), while an additional 1000 gallons of diesel fuel spilled from the locomotive. The Southern Pacific (SP) dispatcher in Roseville was notified of the earthquake at 4:45 AM by personnel at SP yards in the vicinity and, following SP Standard Operating Procedure for earthquakes exceeding magnitude 6.0, all trains within 100 miles of the epicenter were stopped until tracks could be inspected.

Petroleum pipeline spills

Following standard operating procedures for hazmat liquid pipelines, all petroleum pipeline pumping stations shut down within about one minute after the earthquake was detected. The resulting reduction in pipeline pressure limited, but could not eliminate, releases from the 9 petroleum pipeline ruptures that were reported by the California State Fire Marshal (1994). One of these releases involved the UNOCAL Torrey Line, while the other eight occurred on the ARCO/Four Corners line. A subsequent spill, tangentially related to the earthquake, occurred at Grasshopper Canyon/Castaic Lake on 22 January when ARCO was pressure testing another pipeline for reopening after it had been shutdown during the earthquake. The Grasshopper Canyon spill diverted some emergency response resources, but ARCO sources indicate that it did not impede response to the other spills.

The 63 mile long UNOCAL Torrey Line, originally built in 1955, runs from Piru in Ventura County to the UNOCAL refinery in Torrance (Los Angeles County). Although the pipeline has a normal throughput of 19,200 barrels (806,400 gallons) per day (1,393,200 gal. per day maximum), the pipe failure (a 2 inch crack in the top of the pipe) released only about 100 gallons of crude oil into the soil in a remote area. No injuries occurred as a result of the release, and all contaminated soil was recovered (California State Fire Marshal, 1994).

The ARCO/Four Corners Line #1 is a 10-inch pipeline carrying third party crude oil from Kern County into Los Angeles County for processing at various refineries (ARCO Pipeline Company, 1995). The 130 mile pipeline, which originally was built in 1925 and relocated when Interstate 5 was constructed in 1959, has approximately 55 miles of girth acetylene butt-welded pipe (from the 1925-era), 67 miles of arc-welded pipe, and 8 miles with unidentified types of welds. Even though the line was not in operation on the day of the earthquake, the California Fire Marshal's Office estimated that the resulting spills totalled over 230,000 gallons. Early reports indicate that about 71,000 gal. of product was recovered (approximately one-third of the amount spilled) although ARCO Pipeline more recently estimated that over 145,000 gallons were recovered (nearly two-thirds of the spill). Emergency response and cleanup costs through the first two months after the spills exceeded $15 million.

Most of the spills occurred on sections of the pipeline that were under low pressure, thus resulting in small quantities of product released into sparsely populated areas where the spilled product remained in close proximity to the release point. A spill at Posey Canyon/Pyramid Lake was, nonetheless, of concern because it was a potential threat to drinking water sources for Los Angeles County.

Two of the three most significant spills occurred in urbanized areas where the crude oil leaked into roadways, combined with releases from ruptured water mains and entered storm drains. The high mobility of the product (due to mixture with water and travel over impermeable surfaces such as pavement and concrete drains), created a significantly more hazardous situation. In one of these incidents, the leaking crude oil was ignited and caused one injury (a burned motorist) and some property damage (5 houses and 20 automobiles).

The release with the greatest environmental impact was a 173,000 gallon spill of light crude oil from the Newhall Booster Pump Station in Santa Clarita. The release began with a pipeline rupture just downstream of the pump station. An estimated 67,500 gal. drained from the pipeline itself and another 105,500 gal. drained from a storage tank (approximately 6.7% of the tank's 1.6 million gal. capacity) through the pipe rupture (ARCO Pipeline Company, 1995). Here, as with other spills in urban areas, crude oil combined with releases from ruptured water lines and flowed down a street. After entering a storm drain, the oil combined with wastewater from damaged sewage treatment plants, and contaminated about 12 miles of river. At its peak, this spill required 17 responders from the federal government (including the U.S. Fish and Wildlife Service, Environmental Protection Agency, and Coast Guard), and 34 from the state government (including the California Department of Fish and Game, which was designated as the lead response agency). In addition, there was a 100 person cleanup crew from the state, as well as 489 persons from private industry, environmental groups, and property owners. Within 24 hours of the earthquake, underflow dams had been constructed and floating oil was being removed from the river by vacuum trucks (Shane, 1994). An oil spill action plan was devised in which the spill corridor was divided into 8 river segments, based principally on the availability of access roads and suitable oil collection sites. For most riverine segments, backwater areas were selected or created by means of booms to place oil skimmers. In the remainder, filter fences or sorbent pads were used.

Problems of misplaced response priorities initially arose when most of the response personnel were assigned to vacuum streets and drains near the source of the spill (a cleanup function) before the incident had been stabilized by removing all the floating oil from the river (an emergency response function). This misallocation of resources was particularly significant because there was a forecast of rain showers within a few days. Rainfall would increase river flow, hamper the emergency response operations, further spread the unrecovered oil, and thus, significantly enlarge the contaminated area. The premature allocation of resources to cleanup operations was compounded by the limited effectiveness of product recovery operations in some segments of the river. A solution was achieved by using the Incident Command System to create an organizational structure by which the number of contractor personnel was doubled, and the bulk of the responders were shifted from upstream segments (where cleanup was supervised by the California Department of Fish and Game) to the downstream segments (where free oil recovery was supervised by the US Coast Guard's Pacific Strike Team). In addition, each river segment was assigned an ARCO Pipe Line (APL) supervisor having authority to expend company resources, and support was requested from the National Oceanic and Atmospheric Administration for scientific assessments of local meteorological and hydrological conditions.

Over the course of the next three days, oil diversion and recovery operations intensified in the downriver segments, but were impeded by difficulties in removing oiled vegetation from the river. Six days after the earthquake, responders began to fortify downstream berms in anticipation of a 3 inch rain forecast within 24 hours. Fortunately, the rain was only a half-inch and it arrived more than 24 hours later than was forecast. The slight increase in river level and rate of flow caused minor damage to dams and booms, which was quickly repaired. By the eighth day of the response, removal of oiled vegetation was elevated to the top priority, although some free oil continued to be removed. Removal of oiled vegetation and flushing of contaminated soils and sediments in the floodplain continued and by the twentieth day of the response, damage to fish and wildlife apparently had been terminated. On March 2, over six weeks after the earthquake, the last river segment was approved for final cleanup and the last removal action completed. Contaminated soil was taken to APL's Lake Pump Station for use in constructing berms and making road bases for access to pump stations, while contaminated vegetation and other debris was compacted and taken to an approved disposal site. The pipeline operator's final cost for the cleanup was approximately $12 million (Shane, 1994).

The Federal Onscene Coordinator observed that the earthquake's damage to infrastructure (roads, telephone lines, electric power, and potable water) substantially impeded response to the incident. Moreover, lodging for response personnel was in short supply because the large contingent of contractors and local residents whose homes were uninhabitable booked up all the local motels. The normal hazards of working on the river were compounded by concerns about the stability of upstream dams, and the possibility of flooding following rainstorms. Other hazards included congested vehicle and pedestrian traffic in the limited access routes to the river, and the heavy air traffic of newsmedia and spectators flying over the river (a problem that was mitigated by asking the FAA to restrict the airspace). The usual problems of emergency communications also were in evidence, with teams typically being able to establish radio contact only with responders from their own organizations.

Organizational problems included the responsible party's (ARCO/Four Corners) inaccurate initial notification (the initial report was of an unknown quantity of oil spilled, no waterways affected, and a hazmat team on the scene), and limited expertise in supervising a major inland oil spill. Contractor personnel were similarly unprepared, attempting to use open-sea booms having 12 inch skirts that were unsuitable for the shallow waters and rapid currents of the river. Their lack of training required close oversight by more highly trained members of the California Office of Oil Spill Prevention and Response and the US Coast Guard Pacific Strike Team (PST) to provide technical guidance. Even this close supervision could not eliminate all problems because the PST members did not have the authority to give direct orders to contractors. Another problem arose from the conflicting goals of speedy oil removal and minimization of damage to wildlife habitat, with the federal resource trustee (U.S. Fish and Wildlife Service) strongly emphasizing the latter and the state agency (California Fish and Game) being more willing to accept some degree of habitat damage to expedite the removal of oil (and thus limit the risk of substantial damage in the event of flooding).

Natural gas releases

Southern California Gas (1994) reported 35 breaks in its natural gas transmission lines and 717 in its distribution lines, and found that about 74% of the 752 leaks involving company pipelines were corrosion related. As was the case with the crude oil pipelines, most (27 out of 35) noncorrosion-related failures in the natural gas transmission system were cracked or ruptured oxyacetylene girth welds in pipelines predating 1932 (O'Rourke & Palmer, 1994).

One pipeline related fire occurred near Fillmore, where gas escaping from a ruptured transmission line was ignited by a downed power line and burned a mobile home in an adjacent trailer park. A larger incident occurred when a 22 inch transmission pipe (Line 120) was severed near Balboa Boulevard in Granada Hills and the release was ignited by a passing motorist. Response to the resulting fire was impeded by the simultaneous rupture of a nearby water main, but damage was limited to the destruction of 5 houses because the responding fire companies were able to draft water from swimming pools. Unlike most other failures, the Balboa Boulevard pipeline rupture involved an electric arc girth weld, but it too was constructed in the early 1930s. Line 120 had been scheduled for replacement and was paralleled by a new 24 inch electric arc girth welded X-60 steel line which survived the quake with no damage (O'Rourke & Palmer, 1994).

There were 15,021 natural gas leaks at customer facilities. Many of the latter were very small in volume, and were detected with sensitive gas detection instruments at the time service was restored (122,886 gas meters were closed by the customer or emergency personnel in the immediate aftermath of the earthquake, and service could be restored only by a utility technician). Natural gas leaks in the Southern California Gas (SoCal Gas) service area resulted in 3 street fires, 51 structural fires (23 of them totally destroyed), and 172 mobile homes totally destroyed by fires (Southern California Gas, 1994). The greater incidence of mobile home fires than structural fires is particularly noteworthy because there are far fewer mobile homes (350,000) than other structures (4,500,000) in the SoCal Gas service area. The rate of natural gas-related mobile home fires (49.1 per 100,000) is over forty times the rate of natural gas-related structural fires (1.1 per 100,000). A significant number of the mobile home fires resulted because inadequate bracing allowed them to fall off their foundations, severing gas lines and igniting fires. In most cases, residents of the affected structures could readily detect the danger (see or hear fire, smell a gas leak or smoke) and protect themselves by evacuating. It is likely that this is the reason why there were no reported casualties attributed to this cause.

University science laboratory hazmat releases and fires

The earthquake produced extensive hazardous materials spills and fire in all 3 buildings of the California State University, Northridge (CSUN) science laboratory complex. Two of these buildings showed smoke on their third floors when firefighters arrived at 7:55 AM (Burmeister, 1994). The initial response was hindered by lack of water at the fire hydrants and, later, by 30–40 chemical explosions within the first half-hour after responders arrived. The smaller of the fires was extinguished within a hour of arrival, but the larger fire required drafting from swimming pools elsewhere on campus and from hydrants 800 feet from the building. In the course of attacking the second fire, a third (small) fire was found and rapidly extinguished. The large fire was knocked down approximately 2 hours after arrival, permitting attack on interior fires in the immediate vicinity of the chemical storage areas. Amounts and locations of all type of hazardous materials were identified through consultation with laboratory staff and campus technicians, together with review of documents. Firefighters wearing self contained breathing apparatus and using blowers to ventilate the area ahead of themselves successfully extinguished the remaining fires and secured the scene pending the arrival of personnel from the County Health Department to supervise the cleanup. No casualties occurred during this incident, an outcome that is attributable in part to the fact that the earthquake occurred during the early morning hours (thus avoiding casualties among commercial building occupants). Moreover, the fire fighters avoided chemical exposure casualties by exercising caution in their response—due to their recognition that the fire was not a threat to other structures and that the chemicals were no threat to offsite populations.

Aerospace industrial facility hazmat releases

Rockwell's Rocketdyne Division, which designs, manufactures, and tests rocket engines and related systems for military and scientific space missions, has three facilities in the San Fernando Valley area—all within 4 miles of the earthquake epicenter. At the time of the earthquake, the company had allocated substantial resources for seismic safety, including significant capital and annual operating expenditures for seismic hazard assessment, structural mitigation. and emergency preparedness (Sherer & Rodman, 1994). A hazard analysis was completed in 1989 and recommended remediations were incorporated into 5-year and 10-year Seismic Upgrade Plans funded by subsequent budgets. Further hazard analyses were conducted on soils (liquefaction), structures, and fire protection equipment. Upgrades included structural retrofits to critical facilities and anchoring of equipment such as boilers, substations, electric generators, hazardous liquid tanks, and compressed gas cylinders.

All three facilities suffered significant damage from the quake. One facility experienced a partial roof collapse, necessitating closure of the building and transfer of the 400 employees to another site. Assistance from a licensed contractor was required because entry needed to be made to retrieve critical equipment from the "red tagged" building. Another facility experienced numerous structural failures (concrete block and precast concrete walls, tilt-up concrete panel, roof supports, structural connectors, equipment mezzanine), and substantial damage to equipment (bridgecrane, suspended ceilings, and light fixtures). Rupture of chilled and potable water, and fire protection systems resulted in substantial water damage to building contents. The main facility experienced similar types of damage and, in addition, suffered the rupture of a 20,000 gallon fiberglass water tank. The facility also experienced significant problems due to numerous, small hazardous materials spills confined within the buildings. Acid tanks in the plating department lost part of their contents due to "sloshing" but the overflow was confined by curbs and channeled through gutters into holding tanks. Other tanks and containers spilled hazardous chemicals onto laboratory floors.

The seismic safety natural gas shutoff valves activated as designed, probably preventing fires or explosions that would have resulted from the natural gas line breaks that did occur inside the facilities. The effective performance of seismic shutoff valves was particularly important because failed water pipes caused a loss of fire protection water from the onsite storage tanks (all 180,000 gal. at one facility and 80% of a 250,000 gal. tank at another facility), while damage to city water mains caused a near total loss of offsite water supply. Although flexible couplings installed between the water tanks and fire pumps performed as designed, the low water level alarm and sight gauge on the water tanks erroneously indicated water supplies were adequate. The loss of fire protection water, together with the loss of electrical power for nearly 60 hours, compounded the difficulty of welding and cutting operations involved in mitigating structural damage. Moreover, the time of day when the earthquake impact occurred (4:31 AM) meant that staffing was minimal and emergency crews had to be recalled to the site. Unfortunately, many members of the emergency crews routinely commuted long distances to the plant because they could not afford the high price of real estate in the immediate vicinity of the plant. Thus, the emergency recall and the subsequent recovery operation were significantly impeded by the damage to the public transportation system. Failure of the fire alarm system placed an additional demand on emergency personnel, who had to be diverted from other activities to fire patrol duty. Finally, the sheer extent of the damage, together with the other problems, delayed completion of the damage assessment and assurance of incident stabilization. As a result, damage to some equipment was not detected before the occurrence of aftershocks that could have produced a subsequent failure. Other problems included failure of the emergency generator for the Security Control Center at one facility leading to a loss of lighting and fire alarm documentation, an insufficient number of combustible gas indicators and other equipment for emergency responders.

Despite the obstacles, 750 contractors were soon at work around the clock to restore manufacturing operations. Cleanup of liquid spills was performed readily by qualified personnel in accordance with OSHA requirements, though some creative solutions were needed to provide decontamination of cleanup crews. Asbestos abatement turned out to be more extensive than expected because the water damage caused floor tiles to buckle, causing the asbestos contained in them to become friable. Casualties were limited to 3 minor injuries, while total costs for structural repairs and cleanup (including both hazardous and nonhazardous materials) exceeded 50 million dollars. These costs do not include the lost wages for employees or lost business experienced by the company.

Water filtration plant

The Joseph Jensen Filtration Plant, operated by The Metropolitan Water District of Southern California, is located approximately 20 miles west northwest of the city of Los Angeles and 6 miles northeast of the earthquake epicenter. As a part of its treatment process, the plant chemically purifies drinking water that is pumped in through an 84 inch influent line that receives water from the California Aqueduct via Castaic Lake. The facility has 10 chemical tanks and a chemical unloading facility, which houses a railroad tankcar of chlorine. The plant experienced little damage to its chemical handling facilities. Only one of the chemical tanks (containing 37,279 gal. of caustic soda) moved on its base during the earthquake, even though none of them were anchored to the foundations. No releases occurred, and the tank was later emptied, repositioned, and anchored without further incident. A report of chlorine odor near the main control building led to the excavation of a 6 inch PVC chlorine solution line, which was found to have a small crack. The damaged section subsequently was replaced, encased in concrete, and backfilled. Within the chemical unloading facility, the earthquake moved the chlorine railcar approximately 18 inches but did not topple it. The movement of the railcar against the unloading facility's access platform failed the bridge and damaged the railcar's handrails but did not puncture the tank shell or cause any releases. The damaged components were replaced and the access ramps to the railcars are now left in the upright position to avoid future seismic damage.

The most significant source of damage to the facility was a break in the 84 inch influent pipe, which engineering analyses concluded was due to a faulty weld. The incomplete fusion of the weld with the bell base material led to low-cycle fatigue and final rupture from seismic forces.

Metropolitan's (1994) after-action report was notable for its thoughtful critique of the organization's emergency response. Among other findings, the authors of the report noted that half of the members of the Engineering Division's Damage Assessment Teams reported to their assigned sites, while another 14% called in for instructions, but were not activated for emergency duty. Of those not reporting for duty, 40% had problems at home or encountered obstacles in transit to their assigned sites, another 40% were unexcused, and the unresponsiveness of the remainder was classified as "questionable." As was the case at Rockwell, these data raise questions about hazmat facilities' ability to recall adequate numbers of offsite presonnel to successfully combat emergency conditions in the aftermath of a moderate to major earthquake.

Impacts on lifelines

As noted earlier, damage to transportation routes, water, electric, and communications systems which also presented significant problems following the earthquake, deserve attention because of their significance to EIHRs. Overall, damage to transportation routes was classified by the state as "minimal or easily repairable" (California Governor's Office of Emergency Services, 1994) and limited mostly to overpasses in areas of extremely high ground motion, soft soils, and inadequate structural reinforcement. Many traffic signals (4000 in the City of Los Angeles alone) were out of service because of seismic damage. Severe traffic disruption was experienced in the immediate aftermath of the earthquake, but none of the data provided by the City of Los Angeles Department of Transportation (1994) indicates that any areas were unevacuable because of impassable streets. Indeed, many of the department's traffic engineers lived in areas where telephone service was disrupted, but spontaneously reported to freeway collapse locations that were identified in commercial radio news broadcasts.

Not unexpectedly, the Northridge earthquake caused severe outages of electrical power. What was unanticipated, however, was that service was lost throughout most of the Los Angeles area. Moreover, only half of the two million customers who lost power had service restored by nightfall. Consistent with previous analyses (Burbenn, Hawkins, Ostrom & Richau, 1992), Southern California Edison (1995) found virtually no damage to generating facilities, but significant damage to substations in the area of strong shaking. In many cases, the damage could be traced to specific types of components (e.g., porcelain breakage in disconnect switches), while in other cases it was limited to components from specific vendors (GE ATB circuit breakers).

About 150 square miles of the Valley were without water immediately after the earthquake. Reasons for the outages included well site damage, reservoir failure, loss of electric power for pumping, and pipe failure (California Public Utilities Commission, 1994). Water treatment plant damage was repaired quickly, but pipeline breaks took 2–10 days to repair. The California Governor's Office of Emergency Services (1994) initially estimated at least 1200 leaks in the San Fernando Valley and 300 in the Santa Clarita Valley, but Manning (1994) later reported over 3000. Whatever the exact total, repairs to the distribution system took until early February to be completed, which necessitated the dispatch of 29 mutual-aid water tenders by LAFD to maintain fire and hazmat response capability. Water service to a broader area also was affected because all four pipelines from Northern California pass through the San Fernando Valley to deliver water to the Los Angeles metropolitan area.

There was widespread disruption of telephone communications, but more of this was caused by telephone congestion than by damage to phone lines or switching equipment. Pacific Bell (1995) reported completing 154 million calls on the day of the earthquake, more than twice its normal load of about 73 million calls. At one central office, call attempts increased from an average of 2,000 per hour to 250,000 per hour. Pacific Bell also experienced disruption to 30,000 telephone lines in areas where homes and businesses suffered structural damage, while GTE reported the temporary loss of one central office switching facility whose service was restored within 12 hours.

Impacts on critical emergency response facilities

There were extensive impacts on medical facilities in the areas of greatest shaking. Although these facilities did not experience structural collapse, nonstructural damage caused six hospitals in the San Fernando Valley to declare an "Internal Disaster" which removed them from operational status (Cowen, 1994). In some cases, the problem was loss of power or water (Anthony, 1994, reports that all 14 hospitals in LAFD Division 3 were forced to rely on emergency generator power and water supply), while in other cases, releases of hazardous materials occurred within the facilities (e.g., laboratories) themselves. Altogether, 18 hospitals in the impact area were rendered temporarily nonfunctional, with 8 hospitals requiring the evacuation of a total of 928 patients. Although these facilities represent only a small fraction of the total number of hospitals in Los Angeles County (112), or in the five county area of Los Angeles, Orange, Riverside, Santa Barbara, and Ventura counties (268), the net loss of 2,500 beds throughout Los Angeles County left only 136 critical (669 noncritical) beds remaining available at the height of the emergency (Cowen, 1994). The loss of these facilities was compounded by the loss of direct voice communication between paramedic units and base hospitals. This condition required the implementation of Communication Failure Protocols, which permit paramedics to initiate treatment if they believe that a delay would jeopardize a patient's safety. On-line medical control was re-established through the use of amateur radio operators to link the hospitals to the Fire Department's Valley Medical Branch which, in turn, was able to communicate with the available 52 paramedic and 13 EMT rescue ambulances. However, the use of the Failure Protocols was not discontinued until just over 7 days after the initial seismic shock.

One obvious consequence of the loss of medical treatment facilities in the impact zone is that those suffering from exposures to toxic chemicals, burns from flammable materials, or traumatic injuries from explosions would have to travel farther to receive definitive care. In addition, however, the need to evacuate the patients already in these facilities would exacerbate the demand on the limited supply of ambulances and other transportation vehicles. Disaster Medical Assistance Teams were provided by FEMA, but did not arrive until several days after the earthquake.

Regional incident command

Most hazmat incidents are restricted to a single site. As a result, emergency response operations can be directed by a single onscene Incident Commander (National Emergency Training Center, 1989). By contrast, earthquakes can be expected to generate multiple incidents that may or may not be able to be handled independently of each other, but which inevitably compete for scarce community resources of personnel and equipment. The preceding description of hazmat incidents in the Northridge earthquake shows that this event was no exception.

Local emergency operations centers were activated almost immediately, the Los Angeles City EOC being activated only 4 minutes after the shocks began (Manning, 1994). Fire suppression and emergency medical services (EMS) personnel responded to safe areas and conducted a departmental status check which was followed by an emergency assessment in which each field unit conducted an inspection of its geographical area of responsibility. Fire department helicopters provided a simultaneous assessment of predesignated critical facilities such as freeway overpasses, hospitals, and dams. Within 3 hours, more than 100 separate incidents were being handled by LAFD units.

The LAFD Emergency Earthquake Operational Plan (EEOP) is a substantially decentralized plan in which the Battalion Commander is the focal point of command and control within a specific geographic area. Following earthquake impact, each battalion is responsible for immediately protecting the safety of its personnel and equipment, conducting a status check of its units, conducting reconnaissance of their geographical districts, and reporting the status of the situation and departmental resources (Mittendorf, 1994). Battalion commanders establish command posts and staging areas to manage incident notification, dispatching, reconnaissance, and interdepartmental/interagency coordination. Reconnaissance is conducted along predesignated routes using maps that identify special hazards and critical facilities within their districts.

Procedures call for response situations, such as fires and collapsed buildings, to be bypassed until the reconnaissance and subsequent situation status report are concluded. These reconnaissance operations at the battalion level are supplemented by helicopter flights at the divisional level.

Battalion operations are then conducted according to the first priority of immediate lifesaving and the second priority of fighting fires with conflagration or loss-of-life potential. Procedures call for care in search and rescue operations because of the high level of hazard to rescue personnel, and the significant time and resources expenditures involved in extricating trapped victims from multioccupancy structures such as highrise apartment and office buildings. Recognizing the likelihood of loss of water supply, procedures call for personnel to notify the Department of Water and Power of any identified breaks, to attempt intersystem pumping, to consider alternate water sources (swimming pools, water tank trucks), and to conserve water by selective extinguishment and perimeter control operations. To the extent practicable, documentation is maintained for operational critiques, after-action reports, and legal support.

As Anthony (1994) noted, a systematic strategy was needed for identifying and isolating leaks and breaks in water lines. An effective, but time-, labor-, and equipment-intensive solution was developed by which fire hydrants in inoperable water service zones were connected to those in operable service zones by means of pumps on fire apparatus. Optimal pumping locations were determined in consultation with the Department of Water and Power, and the inoperable grid filled through hydrants on its perimeter. Fire department personnel traversed the inoperable grid from its lowest elevation to its highest elevation searching for leaks. Minor leaks were mapped for later repair, while major leaks were mitigated by closing the nearest gates that would isolate the leak. Patterns of gate closure were selected to minimize the size of the area remaining without water service.

The Los Angeles city EOC provided a location from which key organizations could coordinate actions with LAFD. These included the L.A. Police Department for security and evacuation support; Building and Safety for structural assessments; Public Works for debris removal; General Services for logistical support; the Department of Water and Power and Southern California Gas for utility control; and Recreation and Parks, L.A. Unified School District, and the American Red Cross for sheltering the homeless (Borden, 1994).

Operations at LAFD headquarters did not proceed without impediments. As Cready (1994) reported, the earthquake interrupted power to the LAFD dispatch center which, in turn, triggered the emergency generators. The generators supplying power for lighting, radio, and a portion of the electrical outlets functioned as needed. However, one of the generators supplying power to the dispatch computer failed about two hours into the incident when a radiator hose break caused a loss of coolant. In turn, the generator overheated (causing a sprinkler head to fuse and flood the cable spaces under the computer) and the engine seized. The protective circuit sensed an overload and shut down the second generator, forcing the electrical system to draw down the 15 minute battery backup until it was exhausted. Power was restored about one hour later, but the computer remained shut down for another 4 hours until the water was pumped out of the cable raceway. In the meantime, dispatch was conducted in manual mode.

After-action reports identified a number of problems hat have plagued emergency responders in previous disasters. Los Angeles County Emergency Operations Center Staff (1994) noted a number of command/control and management issues. These included problems in the roles of key Emergency Management executives and the Emergency Management Council, as well as lack of 24 hour coverage and designation of duty officers for each department. This report also identified problems with insufficient financial guidance for emeregency expenditures, poor internal coordination of outside (e.g., state and federal) offers of assistance, liaison problems with the state Office of Emergency Services, and insufficient EOC communications equipment. Also reported were problems in collecting and integrating damage assessment information, timely assessment of the structural safety of governmental buildings following the earthquake, and coordinating the timely and accurate dissemination of public information with other departments and jurisdictions.

Comparison of Northridge events with previous incidents and analyses

The 134 locations with hazmat problems and 60 emergency hazmat incidents officially reported in the M 6.8 Northridge earthquake are clearly more numerous than those reported in any previous earthquake. Recall that Perkins and Wyatt (1990) cited 18 EIHRs in the M 6.6. San Fernando quake, 9 EIHRs in the M 6.7 Coalinga quake, 30 EIHRs in M 6.1 Whittier Narrows quake, and 50 EIHRs in the M 7.1 Loma Prieta quake. Although the numbers of hazmat incidents appear to vary from one earthquake to another, there is no apparent correlation between earthquake magnitude and the number of EIHRs reported. Indeed, it would be quite surprising if a strong correlation were found because, as noted earlier, the number of EIHRs would be expected to be a function of many other variables in addition to the magnitude of the earthquake. One of these factors is the nature of the soils—more damage and releases would be expected in areas underlain by loosely consolidated soils than by bedrock. Two other factors are the number and structural characteristics of the region's hazmat facilities—more damage, releases, casualties, and losses would be expected in areas having more numerous and brittle structures housing hazmat storage and processing facilities. The fourth and fifth variables have to do with building contents. More damage, releases, casualties, and losses would be expected from facilities having less seismic resistance in their chemical containment and control systems, and in other building contents (e.g., bridgecranes, shelving, lighting fixtures) whose collapse might cause the chemical containment systems to fail.

Three final variables are related to the completeness of incident reporting. The sixth variable concerns the characteristics of the hazmat—more complete reporting would be expected for hazardous substances that are more noticeable (i.e., are closer to inhabited areas; have distinctive sights, sounds, or odors; or produce immediate, persistent, severe, and distinctive physical symptoms). The seventh variable concerns legal reporting requirements—reports would be expected to be more complete in jurisdictions that have more stringent reporting requirements and are willing to enforce those requirements. Finally, completeness of reports would be expected to be affected by the diligence of local officials in seeking to identify EIHRs from facilities in which hazmat releases were not otherwise required to be reported.

Until a satisfactory data base can be developed with accurate data on all of these relevant variables, it will not be possible to draw any firm conclusions about the relative importance of relevant risk factors, or on the causal impact of altering some of the variables through hazard mitigation and emergency preparedness actions. For example, one cannot determine if increasingly stringent seismic structural codes are having any appreciable impact on hazmat risk reduction because the multitude of relevant variables in comparison to the number of earthquakes makes it difficult to identify any broad empirical patterns in vulnerability. However, there are a number of observations that can be made regarding each of the specific sources of hazmat threats discussed in previous sections. Each of these is discussed in turn below.

Pipelines and pumping facilities

As in previous earthquakes, natural gas leaks were common, and account for many of the fires that took place during the earthquake. These data tend to support the conclusions of studies projecting high levels of fire losses in more severe earthquakes, and are substantially at variance with studies (e.g., the Six City study) projecting no significant losses from this source.

The ARCO/Four Corners spills point to the importance of oil spills in urban and environmentally sensitive areas. The spill into the river was substantially more serious than the experience at Coalinga where the spills were contained, but less catastrophic than the spills and fires that occurred in the 1964 Alaska earthquake. Oil pipeline releases were far more common at Northridge than in recent earthquakes, but most of the damage that did occur was caused by old acetylene joint welds (recall that this also was a problem at the water filtration plant and natural gas pipelines) rather than the failure mechanisms identified by previous investigators. Previous studies identified concerns about pipeline sections that are corroded or have long spans anchored at two locations experiencing large relative displacement (Nyman et al., 1993). Consequently, the failure mode occurring in this earthquake appear to be an additional source of concern not previously emphasized by earthquake researchers.

The magnitude of the Santa Clarita release is noteworthy because the pipeline was at low pressure at the time of the earthquake; normal operating pressures would have released greater quantities. More significant is the uncertainty about the amount of spilled oil recovered, with the lower (33%) and upper (62%) estimates differing substantially from the 50% estimate used by Nyman and his colleagues in their study of oil spill mitigation measures from pipelines in the NMSZ. The slow pace of the Santa Clarita recovery operations (six weeks) together with vulnerability to disruption by rain (a far more likely impediment in central or eastern earthquakes), also underscore a major need for careful hazard assessments of this source of EIHRs.

Rail lines and yards

There was only one railroad tankcar release, but this represents a category not reported in recent earthquakes. The fact that only one of the 14 tankcars released its cargo suggests that existing industry design and construction practices provide a significant degree of protection. This makes sense because railroad tankcars are designed to protect against the hazards of routine operation, and derailment is one of those routine hazards. Moreover, major railroads have instituted procedures to minimize the risk of derailment following a earthquake (California Public Utilities Commission, 1994). For example, the Union Pacific Railroad (1993, 1994) subscribes to a seismic warning service and has procedures that permit rapid notification of train crews in the vicinity of the earthquake epicenter. This procedure eliminates all but a few minutes of vulnerability to derailment. However, questions remain about potential problems at railyards because seismic forces are strong enough to topple a standing railcar (recall that the railcar at the water filtration plant was moved 18 inches). Thus, further research is needed to assess the expected number of releases from hazmat railcars in transit or in railyards, given the number of tankcars in an area and the likelihood of failure for a tankcar in each of the two modes of operation (stationary or in transit). Such an assessment is likely to show a low level of risk because the

Association of American Railroads (1991) reported that only 10.6% of the train derailments that occurred in 1990 resulted in hazmat releases. Moreover, only about one-fifth of all hazmat railcar releases involved gases, which is the category most likely to produce an acute public health hazard. Nonetheless, a thorough assessment of EIHR risks from rail transportation would provide emergency responders with a basis for developing plans and prepositioning the appropriate resources.

Highways and warehouses

As has been the case for previous earthquakes, no releases were reported from tank trucks carrying hazmat. The apparent implication of this empirical data is that the risk of EIHRs from this source is negligible. This assessment of negligible risk can be supported by the logical arguments, as well. First, hazmat tank trucks are ubiquitous in urban areas—making exposure to seismic forces nearly uniform geographically and quite significant in any given earthquake. As is the case with railroad tankcars, hazmat tank trucks are designed to resist the shocks of routine accidents. Thus, the tanks themselves are relatively resilient. Moreover, the vehicles themselves are quite similar to those used for the shipment of other types of goods. Thus, the experience of all trucks in earthquakes is relevant for assessing the vulnerability of hazmat tank trucks. Previous experience in earthquakes indicates that the principal initiating event for earthquake initiated accidents involving motor vehicles is the collapse of freeway bridges and viaducts. Thus, the probability of an EIHR originating from a hazmat tank truck appears to be equal to the probability that a tank truck will be located at one of these vulnerable structures when it collapses. Of course, it is noteworthy that the State of California is implementing a major program of seismic retrofitting for such structures, an effort that will further reduce the risk of EIHRs from this source. Needless to say, the same cannot be said for other regions of the country.

Although shipments of hazmat, particularly by tank truck, appear to have relatively low risk, the same cannot be for the terminal facilities (storage tanks and warehouses). Bulk quantities are stored in tanks which have the problems identified by Perkins and her associates (Perkins &

Wyatt, 1990; Perkins, Wyatt & Selvaduray, 1991). A number of types of hazmat, particularly those packaged for sale to sale to consumers, are shipped in glass containers held in cardboard boxes–neither of which can be regarded as highly resistant to stress. The situation is aggravated by the fact that the boxes are commonly stored in tall piles or on high shelves in warehouses containing a wide assortment of hazmat. The variety of hazmat in warehouses creates the potential for chemical reactions among incompatible spilled products and fires that could produce lethal combustion products if ignited. Further research is needed to assess the hazards of EIHRs associated with warehouses.

Ships, barges, and port facilities

There are no navigable waterways and no port facilities in the high intensity zones for the Northridge earthquake. The nearest commercial port facilities of any significance are in the Long Beach area where the intensities experienced (MMI V–VI) in the port area were so low that no specific inferences can be drawn about the performance of such facilities in future earthquakes. However, as with other types of facilities, reasoned inferences can be drawn from analyses of the types of containment systems present in these facilities, together with an assessment of the physical and administrative systems installed to ensure the integrity of the primary containment systems.

Fixed-site facilities

As noted earlier, hazmat releases occurred at approximately 20% of the industrial facilities and 5% of the commercial facilities inspected by HHMD. Such data are more useful than the raw counts of releases reported in previous studies because, as noted earlier, a defensible risk assessment requires estimates of the *incidence* of hazmat releases (i.e., the number of hazmat facilities experiencing a release divided by the number of hazmat facilities in the area). Previous researchers' lack of access to denominator data (i.e., the number of hazmat facilities in the impacted area) has been a major impediment to the development of such estimates. However, recent legislation in the state of California has overcome the major obstacle. California Health and

Safety Code 6.95 requires each facility with more than 500 pounds of solid, 55 gallons of liquid, or 500 cubic feet of gas (at standard temperature and pressure) to identify itself to its local Administering Agency (typically a fire department). The availability of data of hazmat quantities and the addresses (including ZIP Codes) at last makes it possible to determine the number of hazmat facilities in any given area and, in turn, project the incidence of hazmat releases in future earthquakes.

Assessing the incidence of hazmat releases over a wide range of intensity zones would be valuable because there remain uncertainties about the ability of mechanical and electrical systems components to survive moderate earthquakes (M 4–6) that would not fail the building structures. Lama (1993) has contended that equipment anchorages are more likely to fail than are modern structures themselves, and strongly emphasizes the importance of seismic anchoring of equipment and the assurance of this anchoring by frequent maintenance of prescribed torquing. The need for frequent maintenance is significant because companies in economic difficulty tend to cut back first on such expenditures as maintenance and safety staff.

Fixed-site facilities, like pipelines, differ significantly from rail and truck in terms of their seismic resilience. The differences in vulnerability arise from the materials and design of the different types of containment systems involved. Most containment systems are cylinders, but they differ in their length (relative to their radius), the thickness of the cylinder walls, and their orientation in relation to gravitational and seismic forces. Thus, pipes are by their very nature long horizontal cylinders that contain large amounts of material, and are not designed for significant amounts of axial or lateral movement. Tank trucks and railroad tankcars are relatively short horizontal cylinders containing large amounts of material, but designed for significant amounts of movement). Pressurized gas cylinders are relatively long vertical cylinders containing small amounts of material, and designed for significant amounts of movement (it is the valve that is the weakpoint), while large storage tanks are generally tall, thin-walled vertical cylinders containing large amounts of material, and not designed for significant amounts of movement. The vulnerability of individual components of containment systems has been summarized in a series of reports from the Association of Bay Area Governments, but further research along the lines of the investigation by Tierney, et al. (1990) is needed to assess the overall vulnerability of containment systems in different types of facilities. Hazard assessment for different facility types, in turn, would provide a basis for identifying generic hazard mitigation and emergency preparedness actions that would reduce EIHR hazards from the most dangerous facilities.

Emergency response infrastructure

Perhaps even more than in previous California earthquakes, the extensive damage to electric power, water, and communications systems created significant problems for emergency response. Moreover, the loss of these critical utilities could be upwards of days. Under such circumstances battery backup to commercial electric power is almost certain to be inadequate. Compared to previous earthquakes, it appears that many more locations were without electric power, water, and natural gas for periods of 12–24 hours after the earthquake.

As noted earlier, the physical damage to telephone communications was small compared to the loss of service due to overload because demand rose at one point to 125 times normal usage. This underscores the need for means of communication other than normal commercial telephone service. Radios certainly seems to be an important means of backup communication. However, the effectiveness of cellular telephone service seems to be somewhat controversial. Many organizations reported this form of communication significantly enhanced their effectiveness, which certainly seems to indicate they were able to get access to telephone lines in spite of the high levels of telephone traffic. Moreover, Schiff and Tang's contention that fiber-optic circuits have a higher degree of vulnerability conflicts with GTE California's (1994) contention that new fibre-optic rings and retrofitting of central office switching facilities will reduce seismic vulnerability.

It is noteworthy that there was some damage to emergency response facilities (leaking natural gas and sprinkler lines). The EOC damage that occurred during the Northridge earthquake was relatively small. The most significant EOC damage was experienced in the high intensity area of Santa Clarita, where building inspectors red-tagged and evacuated the City Hall/Emergency

Operations Center two days after the earthquake. As in many previous earthquakes, problems of lack of emergency responder communications also arose because of vulnerability of radio systems to loss of commercial electricity to power the transmitters; however, there were reports here of structural failure of antennas in mountainous areas subject to landsliding.

Casualties, disruption, and damage

Overall, the data from Northridge show no documented evidence of any deaths or injuries attributed to hazmat (out of a total of 57 fatalities and 9158 serious injuries experienced during the 1994 earthquake). The absence of a significant number of hazmat exposure victims was quite fortunate, given the significant loss of hospital capacity. Some of the loss of medical facilities was due to hazmat incidents within the hospitals, but this clearly was less important than the loss due to problems with electric power, water supplies, and communications. The low level of hazmat casualties is consistent with the nature of the threats involved (chronic environmental, occupational, and household threats rather than acute public health threats), and the absence of any hazmat casualties reported in recent California earthquakes.

The damages attributable to the hazmat releases are uncertain because facilities with hazmat releases often suffered other damage to structures and contents. The fraction of the cost of recovery from the earthquake that was attributable to the hazmat release was not separately recorded by organizations experiencing damage. The few cases where damage data are available (e.g., the Santa Clarita oil spill), indicate that hazmat cleanup is an extremely slow and expensive process. One major environmental cleanup contractor, which performed most of the county's cleanups in the Newhall/Santa Clarita area, reported that they were working at full capacity by the end of January and that their January/February business volume represented a 100% increase over the dollar volume of their contracts for the same two month period of the previous year. By February, all local cleanup firms were fully booked and outside firms were coming in to meet the excess demand.

The context of Southern California EIHR vulnerability

As noted earlier, the purpose of this study extends beyond documentation of the impacts of the Northridge earthquake to learning lessons that can be applied to hazmat releases initiated by earthquakes elsewhere in California and in the Central and Eastern regions of the United States. One critical implication of the principle that severity of hazard impacts depend upon the interaction of the physical and social systems is that the appropriate lessons to be learned from the Northridge earthquake can be understood only in terms of the region's hazard vulnerability at the time of the earthquake. In turn, this requires an examination of the hazard assessment, hazard mitigation, and emergency preparedness actions taken *before* the earthquake struck. These actions have been determined by a complex matrix of market forces and governmental regulations.

A typology of EIHR hazard management actions

The wide variety of hazard management measures that can be taken poses a problem in assessing the adjustments of hazmat handlers to the possibility of internally- or externally-initiated hazardous materials releases. As noted earlier, internally-initiated hazardous materials releases have long been of concern (Mascone, Gordon & Vagl, 1988; Prugh & Johnson, 1988). Externally-initiated hazardous materials releases have received less attention, but appear to be increasing in frequency and magnitude in recent years (Showalter & Myers, 1994).

Typologies of hazard management measures have been addressed by a number of sources. One of these is the list of topics addressed in Prugh and Johnson's (1988) classification of techniques for mitigating toxic vapor releases, which emphasizes methods for lowering the probability of a release, as well as techniques for detection and corrective response to a release in progress. Another typology is derived from Perkins and Wyatt's (1990) report for the Association of Bay Area Governments on methods for mitigating hazardous materials releases in earthquakes, who developed a list of private business and local government actions to mitigate EIHRs.

A third source is Lindell and Perry's (1992) typology of emergency management functions, which emphasizes post-release response actions. Their classification scheme is similar to a typology of emergency response functions that form the framework for the Incident Command System (National Emergency Training Center, 1989).

These lists have been organized in terms of many categorization schemes, including primary versus secondary prevention (Ashford, Gobbell, Lachman, Matthiesen, Minzner & Stone, 1993; Perkins, Selvaduray & Wyatt, 1991; Perkins & Wyatt, 1990); and preventive, corrective, and protective safety actions (Lindell, 1994). Other sources include a list of actions contained in a survey of chemical facilities reported by Mascone, Gordon, and Vagl (1988) and the OSHA Process Safety Management Rules (Code of Federal Regulations, 29 CFR 1910.119).

A typology was constructed using the principal features of each of the preceding classification systems (see Appendix A). The composite list consists of 13 broad categories comprised of two types of hazard assessment, eight types of hazard mitigation, and three types of emergency preparedness actions. A preliminary test of its completeness has been conducted by examining its consistency with a small sample of Risk Management and Prevention Plans submitted to the Los Angeles County Fire Department Health Hazardous Materials Division.

For hazmat handlers, hazard assessment actions include environmental hazard assessment and chemical hazard assessment. Environmental hazard assessments provide information about geological, hydrological, and meteorological hazards, building structures, non-structural elements, and building contents. Chemical hazard assessment includes chemical inventory audits, hazard and operability studies (HAZOPs), and offsite consequence analyses.

Hazard mitigation actions included the substitution of less hazardous materials (such as sodium hypoclorite for chlorine gas in water purification), chemical inventory reduction (by reducing onsite amounts or eliminating hazardous chemical use altogether), plant site options (plant relocation, restriction of hazmat locations onsite, or control of surrounding land uses), and plant design options (such as soil/foundation engineering, structural strengthening). Other hazard mitigation measures include process equipment modifications (materials handling, improvements, chemical tank/reactor modifications, pipe modifications, process alarm/control systems, system component redundancy), external hazard protection (process equipment seismic protection, fire suppression enhancements), ergonomic design (equipment/storage area identification, enhanced equipment displays/controls/layouts), and administrative controls (security programs, management safety oversight, process operation modifications to less hazardous conditions, and written Standard Operating Procedures for plant operators, maintenance personnel, and contractors).

Emergency preparedness actions are addressed through provisions for incident command (incident assessment, onsite direction and control, offsite liaison, public information, administrative and logistical support). Other important components are provisions for preventive/corrective actions (engineered safety features, manual emergency response capabilities) and protective actions (warning, personnel, accountability, exposure control, site evacuation, medical treatment, and access control/security).

Although the need has been stressed repeatedly for hazmat facility owner/operators to adopt these risk reduction actions, there is little research on factors influencing their adoption. Reports by the U.S. Environmental Protection Agency (1988) and Ashford, et al. (1993) examined the effects of company size and industry on adoption of risk reduction actions, but these studies had limited sample sizes and did not examine the relevance of their data to EIHRs. However, the data from these studies indicate that large companies tend to be more actively involved in risk reduction actions, while primary producers (defined as companies in SIC codes 28 and 29) are more likely to have adopted chemical risk reduction innovations than secondary producers (defined as companies in the other manufacturing SIC codes, 20–27 and 30–39). The effect of product (i.e., primary versus secondary producer) appears to be more important than size in determining the degree of risk reduction innovation.

EIHR hazard management in a market context

Existing research is extremely limited in its understanding of the process by which the hazmat facility owner/operators adjust to the threat of EIHRs. Some of the most relevant research has examined local government agencies' adoption of effective disaster planning practices (Kartez & Lindell, 1987, 1990; Berke, Beatley & Wilhite, 1989; Lindell & Meier, 1994; Lindell & Whitney, in press). This research demonstrates that adoption of such practices depends upon an organization's internal/structural and external/contextual factors. The external/contextual factors include hazard vulnerability resulting from direct experience with disasters and vicarious experience received through the news media and personal communication (Kartez & Lindell, 1987, 1990), as well as community support and emergency planning resources (Lindell & Meier, 1994; Lindell & Whitney, in press) Internal/structural factors include an organization's staffing and structure, its organizational climate, and the personal commitment of its members (Lindell & Whitney, in press; Whitney & Lindell, 1995). When these factors promote a shared schema of disaster demands and agreement that mitigation and preparedness measures will achieve hazard management, a consensus about organizational capacity and commitment leads to the adoption of effective disaster planning practices.

The decision to implement these hazard management actions requires decision makers to engage in tradeoffs between the cost of the actions and an uncertain threat. A useful perspective on this decision making process can be found in the protective action decision model (Lindell and Perry (1989, 1992). This model, which integrates findings from research on a wide variety of natural and technological hazards (e.g., Kunreuther, et al., 1978, Kunreuther, 1993; Janis & Mann, 1978; Slovic, Kunreuther & White, 1974) recognizes that individual decision makers depart significantly from the assumptions of economic rationality (see Feldman & Lindell, 1990; Slovic, Lichtenstein & Fischhoff, 1988). According to this model, decision makers choose whether to continue normal activities, seek additional information, or take protective action based upon their assessment of the hazard and available protective actions. Decision makers' assessment of a threat in terms of its certainty, severity, immediacy, and duration influence their motivation to take action. A high level of threat promotes a search for an active response. An action is chosen from among the available alternatives on the basis of its perceived efficacy, cost, time requirements, and implementation barriers.

In the context of EIHR threat, hazmat handlers must determine an optimal allocation of resources to protect themselves. In order to make economically optimal allocations of resources, the asset manager must have adequate information available, accurately perceive the relevance of that information, and rationally evaluate it (Feldman & Lindell, 1990; Slovic, Lichtenstein & Fischhoff, 1989). The latter condition means that asset managers must have a realistic time perspective (short- vs. long term) in deciding whether to bear the loss, mitigate the hazard, engage in emergency preparedness, or purchase insurance (Burton, Kates & White, 1978). In addition, when there are market failures such as externalities, asset managers must be held accountable for the consequences that their actions have on others who did not participate in the decision. Beavers, Hall & Nyman (1993), for example, questioned the financial incentives of facility owners/operators to engage in hazard management efforts. They noted that the safety of employees, nearby residents, and concerns about liability might motivate such actions, but that such motivations would not assure uniform levels of protection. The level of hazard management actions is likely to differ among hazmat facility owners/operators (and, indeed, might be systematically low) if there is inadequate information about damage assessment and an opportunity to externalize the impacts of EIHRs. In a similar vein, Jirsa (1993) noted that provision of adequate (accurate and complete) hazard information to owners/occupants of buildings is necessary (but not sufficient) for them to make realistic decisions about hazard management actions.

At present, little is known about the processes by which hazmat facility owner/operators make decisions about the adoption of risk reduction actions. Specifically, little is known about their awareness and evaluation of the EIHR threat and about their awareness and evaluation of alternative risk reduction actions. The only available study on the topic was conducted by Tierney and Anderson (1992) who assessed the salience of EIHRs through interviews with 26 key individuals in Southern California responsible for emergency preparedness and response in government agencies, as well as major chemical manufacturing and processing facilities. The investigators reported that the key actors' perceptions of the likelihood of three different types of emergencies in Los Angeles between the year 1988 (the year the study was conducted) and the year 2000. When asked about the likelihood of a serious hazmat release producing multiple fatalities, responses ranged from 0–100%, with a mean of 63%. When asked about the likelihood of a major earthquake (M 6.0), responses ranged from 10–100%, with a mean of 60%. When asked about the likelihood of a major EIHR, responses ranged from 5–100%, with a mean of 62%. Most of the respondents expected the EIHR to involve transportation, not a fixed site facility, and to affect the community as well as the facility itself. No one expected EIHRs from an earthquake of M 5.0 or less, while one-half expected a release at a minimum magnitude of 5.0–6.5, and the other half thought a larger event (M 6.5–8.0) would be required to initiate hazmat releases. Most of the interviewees believed that the occurrence of an earthquake would present unusual obstacles to the hazmat emergency response but, surprisingly, 10% of the sample expected no difficulties other than the normal problems of emergency response.

It is noteworthy that this study was conducted prior to a number of important events that might have escalated perceptions of the hazard. Specifically, the Loma Prieta and Northridge earthquakes have taken place since the interviews, and significant legislation that had been passed at about the same time as the study (the federal requirement for Local Emergency Planning Committees under SARA Title III, and the state requirement for Risk Management and Prevention Plans) had not yet had an opportunity to exert an impact on risk perceptions.

Federal and state EIHR risk reduction activities

An important nonregulatory contribution to seismic safety has been made by the National Earthquake Hazard Reduction Program (NEHRP), led by the Federal Emergency Management Agency, National Science Foundation, and U.S. Geological Survey. This program has supported extensive research and planning on seismic safety. In addition, there are state seismic safety programs, all originating in California, which include the Alquist-Priolo Special Studies Zones Act, a requirement for a Seismic Safety Element in local land use planning and zoning, a requirement for notifying Unreinforced Masonry Building owners, provisions for gas shutoff valves, school related acts, and the Hospital Facilities Seismic Safety Act.

One of the national programs most relevant to EIHR risk reduction is Title III of the Superfund Amendments and Reauthorization Act (SARA Title III, also known as the Emergency

Planning and Community Right to Know Act of 1986) has led to enhanced community emergency planning for toxic chemical releases. This law requires public disclosure by facilities handling more than Threshold Planning Quantities of Extremely Hazardous Substances (EHSs), which are chemicals designated by the Environmental Protection Agency (1993) because of their high levels of toxicity and volatility. However, this legislation does not explicitly address seismic issues. Moreover, California LEPCs correspond to the multi-county state Office of Emergency Services districts which, in Southern California, includes Santa Barbara, Ventura, Los Angeles, and Orange counties. The fact that this area includes well over a thousand EHS facilities necessarily makes the SARA Title III rather different here than in other parts of the country where LEPCs correspond to single counties having a few dozen such facilities.

In addition, SARA Title I has led to the Occupational Safety and Health Administration's (OSHA's) improved emergency responder training. Other OSHA regulations include the Process Safety Management rule (29 CFR 1910.119). This regulation, which requires minimization or prevention of the consequences of catastrophic releases of toxic, reactive, flammable, or explosive substances by means of a process hazard analysis (PHA), provides indirect guidance for hazmat facility design according to Beavers, Hall and Nyman (1993). They also noted that a PHA should examine the potential for offsite (public and environmental) and onsite (employees and environmental) consequences, but indicated that most facilities have substantial difficulties in conducting these analyses because of their complexity and requirements for knowledge and skills not normally found onsite.

The requirements for first responder training supplement OSHA's existing Emergency Action Plan requirements, which are oriented toward employee protective actions, by upgrading the effectiveness and safety of those who would be called upon to implement preventive and corrective actions in an emergency. The Process Safety Management (PSM) rule extends this process by requiring the implementation of hazmat facility risk reduction actions, especially those in the areas of preventive and corrective actions that would reduce risks to the community as well.

There also are relevant state hazmat regulations, including the California Health and Safety Code Chapter 6.95 requirements for Area Plans to guide emergency response by local jurisdictions, Business Plans disclosing fixed-site facilities quantities and locations of hazmat and describing their emergency response planning and training, Risk Management and Prevention Plans assessing Acutely Hazardous Materials handlers' risk management activities, and regional Air Toxics Emission Asssessments and Plans. These requirements appear to have had a number of positive effects on EIHR risk mitigation. First, most Southern California Administering Agencies have reported that a significant number of AHM handlers notified that their quantity of AHMs would subject them to the requirement for an RMPP, elected instead to substitute less hazardous chemicals or decrease their chemical inventories. Second, the facilities that did prepare an RMPP were subjected to a seismic safety element in addition to the normal requirements of chemical process safety management. The seismic safety assessment examined the local seismic hazards that would be generated by proximity to local faults and the stability of local soils. In addition, the assessment examined the resistance of structures and contents, especially containment systems, to seismic forces.

There also are a number of issues associated with the implementation of these pieces of legislation, primary among which are staffing issues. Staffing issues arise because overseeing the risk management process requires specialized knowledge and skills. Preliminary interviews with Administering Agency personnel in California (see also U.S. Environmental Protection Agency, 1991) indicate that many jurisdictions took on responsibility for RMPPs to improve their access to hazmat information they considered important to the protection of firefighters responding to incidents at these facilities. There also are reports that some departments saw oversight responsibility for RMPPs as a way to increase the promotion opportunities for senior fire service officers by assigning them to supervise RMPP units. Regardless of the original motivation for taking on this regulatory burden, the knowledge and skills required for competent oversight of hazard identification, probability and consequence analysis, and combining these steps into the overall risk analysis exceeded that of the available personnel in these jurisdictions. Thus, most

Administering Agencies attempted to hire new staff with at least a bachelor's degree in chemical or environmental science or engineering. However, even with these qualifications, specialized training is required beyond initial hire. This startup time has created delays for hazmat handlers and incurs training costs that somebody must pay. In many jurisdictions, a significant number of hazmat handlers dropped out of the program by switching to inherently safer designs (especially quantity reduction and chemical substitution). This has meant that either fees go up or RMPP unit staffing goes down. Similar outcomes have been observed in the two other states, New Jersey and Delaware, having similar legislation. For example, New Jersey has experienced a decline from 600 to 125 hazmat handlers, although this is partly due to a change in the threshold planning quantity. The cost of program administration has been spread over the declining base of hazmat handlers in the program, thus dramatically escalating the costs per handler remaining in the program. Delaware has experienced a similar decline from 150 to 50 hazmat handlers.

Other staffing issues include problematic interactions between hazmat analysts/planners and their Fire Department command structure due to differences in educational level and mobility. Senior fire service personnel are relatively immobile because they lose seniority if they move to another department. This is not true for analysts who can move to other public or private sector organizations with no loss in pay or benefits. The problem may be even more significant in small jurisdictions than in large ones.

Organizational issues also include factors affecting relations with hazmat handlers. In most sectors of private industry, resistance has been limited to individual companies. However, other sectors have been generally combative and fought RMPP implementation through their trade associations. Ambiguities in the law's coverage of municipal agencies has created problems because water districts have a significant hazard (chlorine for water purification), but a lot of power to resist inclusion in the program. Administering Agency personnel sometimes must be persistent and cooperative with businesses in the face of resistance, not creating confrontations by needlessly appealing up their own chain of command for senior officials to take a hard line. On other occasions, confrontation has been necessary. For example, one hazmat handler refused to include a city hazmat specialist during the plant's Hazard and Operability Study. The company's legal counsel capitulated when the Fire Department Captain in charge of the RMPP unit threatened to make the handler resubmit the RMPP repeatedly until it was "done right." This underscores the need for analysts to understand the power they have, but also to have management support for their demands. To some extent management (and elected official) support will be a function of economic power. A large corporation may be able to coerce a small jurisdiction. However, it also is important to recognize that a large jurisdiction can coerce a small corporation. Political as well as economic power make a difference. Strong community support for safety can offset the threat of loss of jobs and tax revenue, assuming that a business that threatens to leave will do so. Such a threat is not likely to be acted upon if other factors such as land, labor, infrastructure, and capital costs of relocation offset the additional costs of increased safety. Even if the company does leave, it is possible that the departing business can be replaced.

Despite the number of these programs and the level of effort that has gone into them, the lack of any systematic effort to assess their impact on the risk of EIHRs makes it impossible to say with any degree of confidence that the likelihood of EIHRs falls within the realm of societally acceptable risks, or that adequate hazard mitigation and emergency preparedness actions have been taken to reduce those risks.

The state seismic safety legislation generally is deficient in failing to address any issues specific to hazardous materials and the facilities in which they are stored or processed. The state hazardous materials legislation is somewhat more comprehensive in that some programs provide local agencies with the authority to require facility owners/operators to address the impact of seismic events. This is true both for the Business and Area Plan Program (which applies to all businesses handling hazmat in quantities greater than or equal to 500 pounds, 55 gallons, or 200 cubic feet at standard temperature and pressure) and the RMPP program (which applies to all businesses handling EHSs in quantities greater than or equal to the Threshold Planning Quantities defined in §302 of SARA Title III) This is not true, however, for the Air Toxic Emission Assessments and Plans.

Local codes and standards

Perkins, Selvaduray & Wyatt (1991) identified a number of codes, standards, and programs affecting seismic safety and hazardous materials. National codes and standards include the Uniform Building Code (UBC), Uniform Building Code Standards, Uniform Plumbing Code (UPC), Uniform Fire Code (UFC), National Fire Protection Association (NFPA) Standards, and American National Standards Institute (ANSI) Standards. There also are some important local Toxic Gas Ordinances that were originated by communities in the Silicon Valley area. These ordinances are designed to be adopted as an appendix to the local fire code and, because they were originated in California, do include a number of explicit seismic provisions.

Because the Toxic Gas Ordinance is a phenomenon that presently is limited to California, it is safe to say that there are currently no nationally recognized guidelines for the design and evaluation or retrofit of hazmat facilities (Beavers, Hall & Nyman, 1993). The codes that do exist are intended to protect the life safety of building occupants from structural collapse, not necessarily to prevent damage to building contents such as hazmat containment, process operations, communications, and emergency response systems. Moreover, it is important to recognize that the organizations responsible for developing model building codes are nongovernmental organizations, and that the consensus approach they follow means that the process is slow, careful, and influenced as much by political and economic factors as by engineering analyses (National Earthquake Hazard Reduction Program, 1987). Local codes, in turn, are modifications of model codes, but the modifications themselves are as likely to accommodate political or economic constraints as local construction conditions and materials (Jirsa, 1993). In summary, model building codes are guidance documents that do not become legal requirements until they are adopted by local jurisdictions (Nordenson, 1993).

Perkins, Selvaduray & Wyatt (1991) reported that this process is expedited in California where the state adopts the codes as regulations and requires local jurisdictions to adopt them within 18 months, subject to modifications for local building materials and conditions. The UBC has the strongest seismic requirements of all the national codes, and also has some desirable conditions for hazardous facilities. However, the UBC is not retroactive, and thus has no requirement to upgrade buildings containing extremely hazardous materials (EHSs as defined by SARA Title III), even if located in a structure prone to collapse in an earthquake. UBC Standards for Automatic Fire Sprinklers and the important sections of the UFC also fail to address important issues relevant to the seismic performance of hazmat facilities in earthquakes.

Code enforcement is essential; there are numerous examples of building failure caused by inadequate design, construction materials, and construction practices. Thus, changes to model codes are only as good as local adopting agencies are willing to accept and enforce (Martin, 1993). The extent to which building officials enforce codes by checking plans and inspecting construction depends upon local laws and the availability of budget support (Nordenson, 1993).

Code changes are in a continuous state of reconsideration, but are typically adopted after an earthquake (Martin, 1993). For example, the 1971 San Fernando, 1985 Mexico City, and 1989 Loma Prieta earthquakes all led to major modifications to seismic codes, particularly in earthquake prone areas (Nordenson, 1993). Thus, building age is important because older structures were built under outdated codes. Moreover, the building inventory in the Eastern and Central United States is different from that of the West; with the former regions having many more unreinforced masonry structures (Jirsa, 1993).

There are virtually no code requirements specific to hazmat facilities, although the Uniform Building Code (UBC) does give some limited attention to them by requiring higher resistance to lateral forces in such structures. Existing guidance for the construction of hazmat facilities is limited to specific guidelines (Manrod, Hall & Beavers, 1981). Some design criteria and evaluation guidelines have been developed for the TransAlaska pipeline by Newmark (1975), for uranium enrichment facilities by Beavers (1980) and the Department of Energy (1980), and for liquid natural gas facilities by the National Fire Protection Association (1990), American Petroleum Institute (1990), and Department of Transportation (1991).

Industry initiatives

Industry initiatives such as the Chemical Manufacturers Association's Community Awareness and Emergency Response (CAER) and Responsible Care programs also are likely to have played a role in enhancing EIHR risk reduction. The CAER program requires participating facilities to develop comprehensive emergency plans that can be used in response to any hazmat release, whether it is initiated by an internal (e.g., process upset) or external (e.g., earthquake) event. The Responsible Care program requires participating companies to implement a set of principles that promote effective process safety management. The program consists of a number of standards on which each facility rates its performance. Many participating companies set performance goals for their facilities, and plant managers' annual performance appraisals (and thus their salary increases and promotion opportunities) address this aspect of their facility's operations.

Recommendations for future research

The research needs emerging from the experience in the Northridge earthquake are consistent with those identified in previous seismic research agendas (e.g., Central United States Earthquake Consortium, 1993; National Earthquake Hazards Reduction Program, 1987; National Science Foundation, 1993a, 1993b; Utah Seismic Safety Commission, 1995), but clearly indicate a need for EIHR assessment that has been missing from previous recommendations. Recommendations for future research can be divided into six categories, the first two of which are related to the development of new knowledge about EIHRs. These are the further development of techniques for loss estimation, and the identification and evaluation of alternative EIHR risk reduction actions. The other four categories of research recommendations are directed toward the more effective utilization of existing knowledge. These include an examination of the processes by which the technologies of hazard assessment, hazard mitigation and emergency preparedness can transferred to the local level; development of hazard awareness programs for local policy makers; development of analytic tools and training for local emergency planners; and development of job performance aids and training for local emergency responders.

Further development of techniques for loss estimation

There is an urgent need for comprehensive loss estimation studies to assess the impacts of EIHRs in different seismic zones throughout the country. The most immediate need is for regional assessments of EIHR threats that postulate reference earthquakes on faults near clusters of hazmat facilities. For example, the large number of chemical facilities in the Los Angeles metropolitan area (McCarthy, 1985), together with the potential for a significant earthquake on the Newport-Inglewood fault (Toppozada, et al., 1988) indicates that this is a highly vulnerable area for EIHRs. These factors, together with the results of the preliminary study by Tierney and her colleagues (1990), suggest that further investigations should be conducted that map hazmat facilities onto MMI seismic intensities for the Newport-Inglewood fault, link shaking intensities at facilities to expected containment systems damage, calculate the expected number of releases (together with their release rates and durations), and project the offsite exposures that would result. The resulting estimates of casualties should be based upon realistic data concerning the integrity of the emergency response system following a major earthquake and, thus, its ability to respond in a timely and effective manner. Such analyses would need to assess the survivability of warning systems, accessibility of evacuation routes, and integrity of residential structures for sheltering in-place. Such an assessment of the integrity of the hazmat emergency response system following a major earthquake would likely be the first of its kind and itself require a major analytic effort.

Such studies would provide a number of benefits. First, they would establish a foundation for estimating the benefits of hazard management activities—a common problem in environmental hazard management. Specifically, the problem is that the costs of hazard assessment, hazard mitigation, and emergency preparedness measures mandated by codes and regulations are borne immediately. Unfortunately, the benefits of those actions typically occur many years later and when they do occur, they are not likely to be recognized. The consequence of effective hazard mitigation, in particular, is property *not* contaminated or destroyed, and lives *not* lost due to hazmat exposure. Because these benefits of risk reduction are delayed and, worse yet, invisible when they do occur, promoting the adoption of hazard management actions is a difficult business.

Ideally, regional hazard assessments would determine each regions' vulnerabilities to EIHRs by means of a multi-step process (Federal Emergency Management Agency, no date; National Response Team, 1987; U.S. Environmental Protection Agency, 1987). First, analysts should focus on those areas of seismic zones in which large clusters of hazmat facilities are located close to faults with the potential for large magnitude earthquakes, and are constructed where they are vulnerable to seismic stresses such as intense ground shaking or ground failure. Second, the analysts should examine the categories of hazmat having the greatest likelihood of producing severe and irreversible impacts. Toxic gases and highly volatile liquids are a high priority for analysis because they can affect target populations rapidly through inhalation exposure. Hazardous liquids with low volatility also would be of great concern if they are present in large quantities, lack secondary confinement, and are likely to flow into waterways in the event of containment systems rupture. Thus, the categories of hazmat most deserving of attention are likely to be EHSs listed under SARA Title III (see U.S. Environmental Protection Agency, 1993), and petroleum products.

Third, potential release sites should be identified by locating fixed-site facilities handling hazardous materials and the transportation routes that serve these facilities. Data from fixed-site facilities should include the identity and quantity of hazardous materials onsite, seismic hazard (due to ground shaking or failure), vulnerability of structures and equipment to seismic damage, and the feasibility of protecting the local population from exposure.

As noted earlier, types of hazmat facilities differ substantially in their seismic vulnerability. Tank trucks and railcars appear to be much less fragile than other containment systems. However, hazmat facilities also differ in terms of the variability of fragility within types. Specifically, there is relatively little within-mode variation in the design (and thus, the seismic vulnerability) of pipelines, railroad tank cars, and highway tank trucks, but this is not true of fixed-site facilities. Chemical storage and processing facilities do vary significantly both in their designs and their seismic vulnerability. Consequently, analyses of the type conducted by Tierney, et al. (1990) must be extended to the types of hazmat storage and processing facilities located in a given region. Industry-specific generic designs could be developed for limited groups of Standard Industrial Classification (SIC) codes that handle the most highly hazardous substances and are most similar in terms of their types and quantities of hazmat releases. An additional need to group facilities on the basis of their likely failure modes makes it important to develop accurate data on containment system fragility.

Analysis of transportation routes (in this case, truck, rail, and pipeline) should focus on those points where there is most likely to be a containment system failure. As with fixed-site facilities, such failures would be determined by proximity to known faults (e.g., subject to high intensity ground shaking) and the nature of the soils (e.g., subject to landsliding) in the vicinity of the transportation route. The potential for containment system failures also would examine the structural vulnerability of transportation network infrastructure. Thus, analysis of truck and rail transportation would examine the potential for structural collapse of viaducts, overpasses, underpasses, or tunnels; analysis of pipelines might focus on areas in which the pipeline was the oldest and most subject to corrosion or weld failure.

These high probability release points for fixed-site and transportation facilities should be screened further to identify the subset located in geographical areas where a release could be rapidly dispersed (e.g., airborne vapors, or waterborne liquids) into areas with a high potential for casualties or damage. This subset would give greatest priority to areas that are ecologically sensitive (e.g., inland or marine waters), densely populated, or have relatively immobile populations such as schools, hospitals, nursing homes, and jails.

Once the most significant release points have been identified, there should be an assessment of vulnerable zones and emergency response capability, as well as actions that could be undertaken to mitigate the hazard. It will be necessary to estimate the capability for hazmat handlers to control those releases immediately following an earthquake so that the completed loss estimation model will have the capability for examining the sensitivity of loss estimates to varying degrees of timeliness and effectiveness in the emergency response. To the extent that this modelling capability can produce estimates of casualties, it will be responsive to the recommendations of CUSEC's (1993) Health and Medical panel, who also urged that the consequences of mass exposures to toxic chemicals be addressed in casualty models. Such casualty estimates for airborne toxics, together with environmental damage estimates for oil spills, will yield more accurate data on the benefits of risk reduction actions by fixed-site facilities, hazmat carriers, and local jurisdictions.

Moreover, it will be important to examine constraints on local hazmat emergency response capability, specifically in regard to the number of concurrent incidents that a given region could manage, and the implications of this limit on the requirements for hazard mitigation, onsite emergency response capability, and medical capability for treating hazmat exposures. There is a strong need for assessing the expected timeliness and effectiveness for emergency response to EIHRs, especially oil spills where a prompt and effective response could significantly reduce environmental damage, not to mention the cost of cleanup. The research should construct a planning scenario by identifying a plausible seismic event and determining the number and severity of oil spills that would be caused by that event. In addition, the study should examine the emergency response resources available in the region, together with the response constraints (impeded transportation; loss of commercial electric power, water, and communications capability; concurrent environmental events such as rain) that can be foreseen. The study should estimate the times required for teams to reach the spill sites, and the rate of spilled oil recovery over time. Such data, much of which might be acquired from records of nonseismic spills, would provide a basis for estimating the public and private sector costs of cleanup, and the environmental impact of the unrecovered oil.

It is important to recognize that EIHR loss estimation models would have important functions in addition to a projection of damage and casualties. Such models would provide a basis for assessing overall regional vulnerability and identifying the specific geographical areas and types of facilities that are the most vulnerable. Moreover, such studies are capable of guiding the development of mitigation, preparedness, response, and recovery programs for hazmat handlers, especially those having the highest risk facilities in each region. Not only should a comprehensive loss estimation provide a basis for determining whether more risk reduction measures are needed, it also should allow policy makers to decide what mix of mitigation, preparedness, response, and recovery programs are advisable, and what is the point at which the costs of mitigation measures have begun to outweigh their benefits (i.e., the magnitude of the risk reduction associated with those mitigation measures). Coordination of loss estimates from EIHRs with those from structural collapse also will be important; the principle of "competing risks" clarifies the wastefulness of trying to eliminate one source of hazard when another is much more likely to kill people. The Northridge earthquake, like previous experiences, clearly indicates that structural collapse is *usually* a greater hazard than EIHRs, but only further study will show what is the relative return on risk reduction investments in each of these two areas. As indicated earlier, the relative returns on such risk reduction investments are likely to differ significantly from one geographical area to another.

Finally, a comprehensive loss estimation study also would serve as an excellent basis for the CUSEC Hazardous Materials Panel's (1993) recommended program for developing hazard awareness by affected organizations in the private and public sectors. Such loss estimation studies are most likely to be successful if they are carefully linked to the planning tools used by existing organizations such as the Local Emergency Planning Committees instituted under SARA Title III. Thus, efforts should be directed toward making EIHR loss estimation programs compatible with computer systems routinely used by emergency planners for nonseismic toxic chemical emergency planning.

Identification and evaluation of alternative EIHR risk reduction actions

Once these loss estimation models have been developed, subsequent research should be directed toward refining them for use in evaluating the effectiveness of alternative hazard mitigation and emergency preparedness measures in reducing EIHR threats to health, safety, and the environment. Research to date (e.g., Perkins, Selvaduray & Wyatt, 1991) has identified general conditions under which containment failure is likely to occur, and the measures that can be taken to prevent this occurrence. Tank failure typically is a function of large size, elongated shape (tall cylindrical containers tend to experience "elephant's foot" buckling that deforms the walls and can fail the container), high elevation (which is prone to toppling), inadequate foundation (settling into gravel pads), and inadequate anchoring (tanks sliding and toppling). Other causes of hazmat releases are open tops (sloshing can lead to mixing and reaction of incompatible chemicals), corrosion (which weakens containment systems' seismic resistance), poor detailing (inadequate connections with external pipes, valves, and ladders), lack of internal baffles (allowing sloshing of liquids), and improperly installed floating roofs (fire ignition resulting from friction between roof and walls).

Industrial process piping is likely to fail when sliding and overturning industrial equipment shears connections, when threaded pipe separates, or when flange gaskets fail. Valve problems have included valves shaking open (producing a liquid release), and experiencing packing failure (causing a gas release). Other examples have included the jamming of float valves (leading to liquid overfill), and failure of pressure relief valves (initiating gas releases).

Moreover, previous research also has identified a wide range of risk reduction actions (see U.S. Environmental Protection Agency, 1988, for a review). Siting options are available to avoid new hazmat facility construction in high seismic hazard areas (i.e., due to proximity to faults, unstable soils, hillside areas) and creation of buffer zones between hazmat facilities and other land uses. Construction options include design to the requirements of the current UBC, removing hazmat from seismically vulnerable structures, strengthening vulnerable structures (including building out irregular plans), accommodating building/contents interactions, and using base isolation. Containment systems measures include increasing thickness of tank walls at their base, anchoring tanks to foundations, and improving the connections between storage tanks and the associated pipes, valves, and ladders. Other containment system enhancements include elevated tank support retrofit/replacement/relocation, corrosion inspection and maintenance, small diameter (1/2 to 4 inch) pipe bracing and flexible hose connection, large diameter (4 to 12 inch) pipe flexibility, arc-welding (rather than threading) connections between tanks and pipes, and fire sprinkler bracing. Hazmat inventory controls include minimizing hazmat use, minimizing supplies onsite, reducing the size of individual containers, segregating chemicals, and minimizing hazardous waste. There are also options for secondary containment/confinement, automatic shutoff device installation and protection through the use of seismometers, excess flow detectors, gas detectors, and loss of power or pressure detectors. Emergency response options include the development of emergency plans and procedures, and emergency responder training. They also include the acquisition of equipment and materials that are less vulnerable to seismic impacts (durability), backup systems to replace resources that are damaged (redundancy), or alternate methods of performing essential emergency response functions (diversity).

The identification of containment systems failure modes and recommendations for superior facility siting, facility design and layout, and operating techniques are major contributions to the practice of EIHR risk reduction. These techniques, especially release prevention measures, have been advocated by the U.S. Environmental Protection Agency (1988), and others. As such information becomes accessible to chemical and structural engineers responsible for designing hazmat facilities, one can expect reductions in the risks of EIHRs (and for that matter, all hazmat releases whether or not initiated by earthquakes) in new construction. However, guidance on containment system failure modes and seismic resistant engineering methods for *new* construction does not sufficiently address the concerns of those who must decide whether an *existing* installation is too hazardous and must be decommissioined. Interested parties to such decisions—including plant owner/operators, insurance raters, and local, state, and federal regulators—need information on the likely costs and benefits of retrofit. The expected benefits of retrofit are measured by a reduction in the incidence and severity of containment system failure but, as noted earlier, such data are sorely lacking and will require further analyses of generic containment systems to fill this information need.

Thus, the development of loss estimation models will play a key role in the evaluation of alternative hazard mitigation and emergency preparedness actions. The need for better models to project hazmat facility damage, releases, and casualties is consistent with the CUSEC (1993)

Disaster Intelligence panel's recommendation for improved methods of earthquake loss estimation. They proposed that such models be used to assess earthquake risk, identify hazard management programs and guide post-impact casualty and damage assessments. The panel called for predictive models capable of estimating structural damage based upon input parameters such as the earthquake magnitude, epicenter, and time of day. For most residential and commercial structures, seismic casualty estimates follow directly from the estimates of structural damage. However, casualty estimates for hazmat exposures would require intervening computations to estimate physical damage to containment systems at hazmat facilities (cf. Tierney, et al., 1990). Estimated releases of gases and volatile liquids then could be linked through conventional computer programs for hazmat exposure assessment (e.g., the CAMEO system) to estimate casualties from airborne toxics, although recognition of the extraordinary effects of seismic conditions is essential. Thus, adjustments must be made for the potential for window breakage in reducing the efficacy of sheltering in-place and road damage in increasing evacuation impediments. Such a strategy also would fit in with the CUSEC (1993) Hazardous Materials panel's recommendation for a survey to identify software being used by LEPCs for monitoring local vulnerability to hazmat hazards.

Examination of technology transfer processes for EIHR risk reduction

Further research also is needed to assess the degree to which hazmat handlers are reducing the risk of EIHRs by engaging in hazard assessment, hazard mitigation, and emergency preparedness actions. Given the wide array of EIHR risk reduction actions, a major question concerns the factors that govern the process by which alternatives come to the attention of, and are evaluated and adopted by, decision makers in the companies handling hazmat. As Ward (1987) has observed, accessibility and application of existing scientific knowledge is as much or more of a limiting factor in EIHR hazard management than is the adequacy of the scientific knowledge base itself. Tierney and Anderson's (1992) study highlights a significant need to examine hazmat handlers' perceptions of the risks of EIHRs from their facilities, the alternative hazard management actions they can take, the characteristics of those actions (e.g., efficacy, cost, time requirements, and implementation barriers), and the relative influence of these factors on their willingness to allocate resources to this problem. Following the pattern set by other risk perception studies (e.g., Slovic, Fischhoff & Lichtenstein, 1980), such studies could examine the degree to which hazmat handlers' risk perceptions are influenced by scenarios derived from federal and state agencies' EIHR hazard assessments. These studies should collect data in California and in the rest of the country to produce comparisons between regions having a long recognized seismic threat and those having lesser awareness of such hazards. It will be important to complement microanalytic studies of individual risk perception and evaluation with macroanalytic studies relying on the organization as the unit of analysis. These macroanalytic studies should draw on the literatures on diffusion of innovations, technology transfer, policy implementation, and organizational control systems. Such perspectives provide an ability to examine the social, economic, legal, and political factors that influence individual decision makers' awareness, adoption, implementation and evaluation of alternative risk reduction strategies.

The policy implementation approach, in particular, calls attention to societal mechanisms—ranging from pure market strategies to purely regulatory strategies—for promoting hazmat handler adoption of risk reduction actions. The pure market strategy is likely to produce suboptimal protection because of the failure of decision makers to conform to the assumptions of economic rationality. To the extent that suboptimality results from lack of information, hazard awareness programs may be successful; to the extent that suboptimality results from market externalities, regulatory approaches may be required.

Recent legislation appears to be taking a middle road by mandating hazard mitigation actions based upon *site-specific* hazard analyses rather than imposing uniform requirements for all hazmat handlers. As noted earlier, such legislation includes California's Health and Safety Code Chapter 6.95 requiring facilities handling Acutely Hazardous Materials (AHMs, which are identical to Extremely Hazardous Substances listed under SARA Title III) to develop Risk Management and Prevention Programs (RMPPs). Federal legislation in the Clean Air Act Amendments Section 112 (r) will extend similar requirements nationwide, but does not explicitly include a seismic provision.

These explicit legal mandates appear to be a key support for success of the hazmat facility risk reduction process because both the hazmat facility owner/operators and local politicians are bound by their requirements. These laws have created a process by which local politicians, who generally are not scientists or engineers, are given an explicit role in protecting the public health and safety from EIHR risks. Even if they don't understand the technical hazard analyses, they do understand a legal requirement.

It is important to recognize the demands that direct oversight of hazmat handlers puts onto local government. The need for local government agencies to acquire competence in seismic and hazardous materials risk assessment raises important issues regarding technology transfer to both Administering Agencies and hazmat handlers. These include access to specialized data, acquisition of new analytic skills, and organizational issues. In sum, there is some evidence of success for these federal and state laws that provide local oversight of hazmat facilities.

Future research efforts should follow the lead of previous studies of hazards mitigation policy evaluations (e.g., May & Williams, 1986) in conducting a systematic evaluation of this legislation and its implementation. This research also should examine the degree to which this legislation has led to EIHR risk reduction, both through unilateral actions by hazmat handlers (e.g., chemical substitution and source reduction), and through coordinated planning by industry, environmental groups, and local governmental agencies. Such research also should examine factors influencing the degree to which EIHR planning has promoted integration among emergency management, community planning, and medical services. Such factors might include the development of programs that focus on community response to disaster demands rather than upon the demands of specific regulations or on the routine missions and capabilities of different agencies.

Development of hazard awareness materials for local policy makers

One of the most reliably established findings in research on natural hazards is the low priority of natural hazards in the minds of policy makers and the public (Mileti, 1980; Rossi, Wright, Weber-Burdin, Pietras & Diggins, 1982; Wyner, 1984). The applicability of this finding to recently confirmed by Showalter and Myers (1994), who reported that representatives of state emergency management agencies found it difficult to generate interest in mitigating natural hazard initiated hazmat releases in the absence of local experience with such events. Ward (1987) identified five possible explanations for the problem of public apathy toward seismic risk. The first explanation is that the risks of earthquakes are not sufficiently great to justify increased activity. The second explanation is that decisionmakers believe earthquake risks are significant, but the cost of protection outweighs the risks. Third, decisionmakers believe that earthquakes are a problem, but only for someone else. Fourth, decisionmakers believe that earthquakes are a potential problem for them, but that someone else (e.g., the federal government) will pay for the reconstruction. The last explanation is that the decisionmakers simply do not know enough to pay attention or to be concerned. CUSEC's (1993) Hazardous Materials panel's recommendation for a hazmat mitigation course to be provided to senior officials in the chemical industry is a valuable suggestion to overcome the problem of low priority, but also needs to include training materials designed for senior elected and appointed officials in local and state government.

Development of analytic tools and training for local emergency planners

Efforts should be undertaken to identify ways in which the output from EIHR loss estimation programs can be used to supplement other resources (e.g., emergency planning workbooks) used by local emergency planners as tools for designing and testing alternative community hazard management programs. This may require the development of specialized training materials, such as planning guidelines and model plans that can be readily transferred to, and adapted by, community agencies. Such materials must be designed to accommodate the limited capability for hazmat emergency planning that is found in most communities, and evaluated to assure that they have achieved their intended objectives. Effective training program design requires a thorough assessment of training needs, while evaluation of effectiveness should address trainee reactions, learning, behavioral changes, and organizational outcomes (Goldstein, 1993). The training programs also should establish a clear linkage between purely seismic (without hazmat) and purely hazmat (without seismic) planning. This design philosophy that obviously is consistent with FEMA's promotion of Comprehensive Emergency Management (see Drabek & Hoetmer, 1991).

Development of training and job aids for local emergency responders

The experience in the Santa Clarita oil spill confirms the CUSEC (1993) Disaster Intelligence panel's emphasis on the need for disaster intelligence that can be translated into response priorities and the management of disaster operations based upon those priorities. Thus, personnel in state and local EOCs must have reliable computer systems that enable them to rapidly input data on situation status, query existing data bases, and project consequences in real-time.

The development of training materials to promote effective hazard mitigation measures *before* an earthquake should be complemented by similar materials for promoting effective emergency response to hazmat releases *during* an earthquake. In addition, the experience in Northridge and other earthquakes indicates that there is a high likelihood for disruption of communications. This means that provisions must be made for decentralized response to rapid onset airborne hazmat releases because local emergency responders facing multiple concurrent EIHRs may not be able to count on specialized technical assistance from their own EOCs, let alone from state or federal experts on toxic chemicals. First responders in areas near the highest risk facilities or chemical facility clusters must have adequate levels of training and must be provided with specialized site-specific procedures to supplement the information in the Department of Transportation Emergency Response Guidebook (1993).

Recommended hazard management actions

In addition to recommendations for future research, this study also has documented a need for immediate implementation of many hazard assessment, hazard mitigation, and emergency preparedness actions, both in California and elsewhere. It is crucial to recognize that there are relevant controls, practices, and institutions that are already a part of every community's governance mechanisms that can be adapted to the management of seismic threats in general, and EIHRs in particular (Ward, 1987). Indeed, it is only through these existing institutions and processes that seismic hazard management is likely to be achieved. Thus, the failure of existing organizations such as emergency management, community development, and public health to recognize seismic issues and develop comprehensive approaches to their resolution requires increased coordination and improved mechanisms for linking these organizations, not new organizations designed specifically for this purpose. Each of these areas of EIHR hazard management is addressed below.

One of the most significant recommendations would be to foster implementation of current knowledge. This can be achieved by increased dissemination to private and public sector decision makers of information about EIHR threats and about the available hazard mitigation and emergency preparedness that can be used to manage vulnerability to those threats. Such a recommendation necessarily oversimplifies the magnitude of this task because previous research variously labelled as technology transfer, policy implementation, and diffusion of innovations has found that moving scientific knowledge into practice must overcome some formidable obstacles. The National Earthquake Hazard Reduction Program (1987) correctly observed that mechanisms for research information transfer barely exist. What is transferred is largely determined by the entrepreneurial orientation and communication skills of the individual researcher rather than formal mechanisms for screening information for relevance to practitioners' needs. Pending completion of the research studies advocated in previous sections, there are ways to enhance attainment of this objective including establishment of concurrence on system performance goals through the establishment of standards and guidelines, "piggybacking" seismic upgrades onto nonseismic projects, and provision of fiscal incentives such as insurance premium reduction and federal earthquake insurance (Ballantyne, 1993). Requirements should be targeted toward the most cost-effective actions in the most seismically vulnerable areas.

Mobilizing support for EIHR risk reduction

Rubin (1987) contends that states are involved in earthquake hazard reduction through direct action such as legislation and technical assistance to lower levels of government. She advocates brief, carefully focussed meetings of public and private sector policy makers to attract immediate attention and elicit long term support for seismic safety. It is especially important to recognize that local elected officials are non-scientists who have a limited term of office. Local administrative officers have somewhat longer terms of office and, even when they leave office, take their newly acquired knowledge to similar positions in other jurisdictions. Mitigation and preparedness actions result mostly from external pressures or local earthquake experience. Neither FEMA nor any other federal agency has a centralized repository of information on seismic safety and, though there are specialized academic centers, their effectiveness in disseminating relevant information to local decisionmakers is unknown.

Kinsman (1987) also advocates distinguishing among different groups—elected officials, government agency heads and employees, the health and medical community, schools, business and industry, community organizations, and the general public. He recommends capitalizing on routinely scheduled meetings or, if that is not possible, keeping special meetings short and focussed. On occasion, a special workshop that includes members of many organizations can be scheduled to identify the common problems faced by individual organizations and to develop a shared agenda for resolving them. If there is continuing interest in the problem and its solution, a special purpose hazard management organization might serve as an appropriate mechanism. Such organizations will be successful only to the degree that they maintain member interest and activity through variety in the material presented and a sense of achievement toward members' goals (Whitney & Lindell, 1995).

In most cases, meetings should describe the hazard, how the individual is vulnerable to it, and what the individual can do about it (Lindell & Perry, 1992; Mileti & Fitzpatrick, 1993; Sorensen & Mileti, 1987). In both respects, the emergency manager should make it clear to the listeners by means of vivid examples that the hazard would affect them personally, identify actions that they are capable of implementing, and address the specific concerns that they have about potential implementation of those actions (Nilson, 1984). Specific concerns about the recommended action's lack of effectiveness, excessive cost or time requirements, or other implementation barriers such as lack of specific knowledge or equipment can be addressed by incorporating members of the target population in the planning process. This requires emergency managers to do their homework on their audiences.

Kinsman (1987) also recommends linking seismic safety to the individual's everyday job duties. For senior policy makers and agency heads, this might take the form of linking seismic safety to their responsibility for protecting the public. For lower level managers, the emphasis might be on their employees' health and safety. This strategy also has been advocated by Nilson (1984), who calls attention to the importance of political liability—the awareness that the potential tragedy of loss of life in an earthquake is not an "act of God," but is humanly preventable. In many cases, advocates should present seismic safety as but one aspect of an integrated approach to the overall protection of employee safety (Kinsman, 1987; Nilson, 1984). Thus, earthquake drills should be linked to fire drills; seismic safety advocates should seek coalitions with neighborhood associations seeking to improve other aspects of the quality of life.

Moreover, programs should be devised that rely on incentives for future actions (e.g., rewarding seismic designs for new structures) rather than penalties for past actions (e.g., requiring retrofits to old construction). Seismic safety advocates also should accept modest initial goals if more ambitious goals encounter resistance because small gains cumulate over time and a successful program might later be expanded (Nilson, 1984).

Finally, hazard awareness should be built around a core of public and private sector professionals with a continuing occupational interest in seismic safety. Such advocates can build hazard awareness among others by using a variety of media, ranging from coverage in the mass media (newspapers, radio, and television) to the inclusion hazard information about emergency resources and responsibilities in a special section of organizations' telephone directories.

Hazard assessment actions

Preimpact actions. There is a significant lack of two types of information about EIHRs. The first of these is information for local emergency planners and responders regarding inventories of hazmat (types, quantities, locations and methods of storage) in facilities throughout their jurisdictions. A major advance in recent years is the development of inventories of toxic chemical facilities, as mandated by SARA Title III. However, data on pipelines remains incomplete; the California Office of Oil Spill Prevention and Response (1994) concluded that state agencies have little information about the location and condition of pipelines. Moreover, while they have adequate paper records about fixed site facilities (oil wells and tank farms), this information is spread out over 6 different state agencies and is not accessible in real time by emergency managers. Similar uncertainties exist about the location, timing and quantities of rail, highway, and marine shipments. Lack of information about fixed-site facilities has been a serious problem in the past, but is in the process of being rectified by state and federal Right-to-Know legislation requiring disclosure of such information by facilities. However, there remain substantial difficulties in using this information to develop site-specific emergency plans for individual facilities—let alone the daunting prospects for integrating such data into regional plans for concurrent EIHRs.

The second type of information that is lacking concerns plausible estimates of EIHR consequences. A major problem here is that local emergency planners lack the skills and funds to perform comprehensive hazard assessments that could be used as a planning basis for developing emergency response plans. As noted earlier, recent state and federal legislation provide some assistance, but much remains to be done before it can be said that comprehensive hazard assessments for EIHRs have been developed. The California Health and Safety Code (6.95) requirement for Risk Management and Prevention Plans is similar to the Clean Air Act Amendments' 112(r) requirement for Risk Management Plans which recessitate the submission of hazard assessments by facilities handling the largest quantities of the most dangerous hazmat. However, there are no explicit seismic requirements for the federal legislation. In view of the deficiencies of previous EIHR hazard assessments, these regional hazard assessments should consider the full range of seismic effects, including ground shaking, surface fault rupture, soil liquefaction, landslides, and tsunamis and seiches.

Like the problems noted earlier for competition among incidents for scarce emergency response capacity, the level of environmental response/cleanup contractor capacity is limited and competition for these scarce resources will overload and probably backlog the regional capacity. Under such circumstances, allocation of resources to cleanup sites will be dictated by market forces unless preincident plans are formulated. In addition, hazmat contamination complicates and delays business restoration or building demolition (e.g., due to asbestos). In such cases, the limited capacity for hazmat cleanup could significantly jeopardize business recovery.

Postimpact actions. As noted earlier, the Los Angeles County Fire Department Health Hazardous Materials Division's comprehensive assessment of EIHRs during the Northridge earthquake was a major advance in disaster damage assessment. HHMD's efforts were essential to the prompt and complete mitigation of hazmat exposures, and provided critical data for subsequent hazard assessments. Local governments in future earthquakes should be strongly encouraged to follow this example by establishing hazmat damage assessment as an element of their earthquake emergency operations plans. The data collected from such assessments should be recorded in a way that permits later conversion from raw frequencies to proportions. This practice would permit subsequent analyses to examine the correlations between EIHR incidence and other variables such as MMI intensity and facility type. This suggestion is consistent with the recommendation of the CUSEC Health and Medical Panel (1993), who called for standardized disaster field assessment questionnaires. One way the Health and Medical Panel's recommendation for broader cooperation between public health and emergency management personnel can be achieved is through increased collaboration in planning for hazmat exposures initiated by nonseismic sources. The active cooperation of public health and emergency management personnel on issues arising from the implementation of SARA Title III would provide a continuing impetus for EIHR planning.

Hazard mitigation actions

Transportation by truck and rail. The absence of any EIHRs associated with these facilities does not, in itself, provide an adequate justification for assuming that they do not pose a significant threat for the future. However, two factors noted earlier, suggest that mitigation actions for these sources of EIHRs are likely to be of lower priority. The first of these is the fact that truck and rail containment vessels are designed for the more stressful transportation environment, while the second is that the major railroads appear to have adequate systems for reducing the likelihood of derailments by means of train stoppage following earthquake warnings. While such warning systems are likely to be highly effective in preventing trains from entering seismic impact areas, the present systems appear to be unable to prevent derailments of trains already in the impact area. One mitigation measure that might be effective in further reducing the risk of train derailment would be a more rapid seismic detection and response system.

Pipelines. There should be an expedited schedule for replacement of hazmat pipelines susceptible to failure in earthquakes. The highest priority should be given to oil pipelines in urban areas because of the threat of rapid spread (through mixing with water from ruptured water mains and flooding through streets) and ignition (by automobiles and downed electric wires). High priority also should be given to pipelines passing through valleys where releases could readily enter surface waters, such as lakes, rivers or streams. Indeed, such devices also would be appropriate for preventing natural gas releases from residential structures especially if installation included connection with "earthquake switches" for electrical panels that would reduce potential ignition sources, and upgrading of underground hazmat pipelines (Anthony, 1994).

A number of authors have emphasized the importance of seismic detection and shutoff devices for gas, high temperature energy, and electrical supply processes. These can prevent releases of hazmat and reduce damages (e.g., Fligg, 1993). In some cases, facility owners/operators will install these devices based upon an informed analysis of the substantial benefit/cost ratio of such installations. Other owners/operators will fail to install these devices because of lack of awareness of their availability, or because of misperceptions of benefits and costs. Thus, uniformity of adoption may need to be encouraged through nonmarket methods such as codes and regulations.

Fixed-site facilities. The extreme degree of variation in these facilities precludes any general recommendations regarding a single best, or even a few most suitable mitigation measures. As outlined in Appendix A, risk reduction actions can include inventory reduction, as well as site, design, and operations actions. The solution to the risk of EIHRs is to ensure that fixed-site facility owner/operators are aware of the EIHR hazard, examine a wide range of mitigation actions, and invest enough resources in mitigation actions to provide reasonable assurance that the public health and safety will be protected. The awareness of EIHR hazard should be guided by the loss estimation studies identified in the research recommendations, while the awareness of mitigation actions should be influenced by the evaluations of EIHR risk reduction strategies also discussed in that section. The specific mechanisms by which facility owner/operators are encouraged to make adequate resources investments in risk reduction actions will be discussed in the section below on government regulations.

Emergency response infrastructure. Regulations requiring increased hazard mitigation and emergency preparedness are a potential solution to the underemphasis on seismic resilience, but there could be problems in the escalation of seismic design requirements due to the large capital expenditures that would be involved. Because only a small portion of the capital investment can be upgraded in any one year, an earthquake occurring early in the program could expose the utilities to liability for noncompliance. Schiff and Tang (1993) contended that this makes extended or flexible implementation schedules essential. This recommendation seems reasonable and deserves serious consideration by policy makers, although the problem is complicated somewhat by the fact that an extended schedule creates an incentive for utilities to delay implementation, hoping for lax enforcement and/or recission of the regulations.

Another problem arises from an apparent trend toward increased seismic vulnerability aggravated by the competitiveness of investor-owned utilities, which pits short-term efficiency and profitability against seismic resilience gained through redundancy (i.e., deliberate slack resources).

Schiff and Tang (1993) observed that electric power utilities use standardized components throughout their systems, thus providing a stock of readily accessible replacement parts, but this is offset to some degree by the fact that few have emergency preparedness programs (plans and exercises) for a major seismic event. Initiatives may be required to spur these utilities to initiate such actions.

Contingent mitigation actions. One method of overcoming the frequently expressed objections to expending financial resources for a low probability threat would be to establish provisions for requiring hazmat facilities to implement the most expensive measures for hazard mitigation and emergency preparedness only after the publication of a specific prediction of a major earthquake. Such provisions would, of course, be least objectionable to hazmat handlers if the prediction were highly accurate with respect to the time and place of the seismic event. Unfortunately, present prediction technology cannot be said to have achieved highly accurate predictions, making prediction errors inevitable. However, mitigation contingent on predictions would provide a basis for more carefully focussing scarce governmental resources on the most highly vulnerable facilities and avoid expending private industry resources at times and in geographical areas in which the needs were not as great. This strategy would be most effective if a system for making earthquake predictions (whether short-, medium-, or long-term) were linked to a system for classifying hazmat facilities in terms of a risk index based upon the quantity, toxicity, and volatility of the chemicals onsite. Other prioritization factors might include the proximity to the fault, the seismic stability of the soils under the facility, and the vulnerability of its structures and containment systems. Such rating factors could be adapted directly from a comprehensive hazmat facility loss estimation model. Such efforts should be linked to more general investigations of policymaking and planning in response to an earthquake prediction.

Emergency preparedness actions

Pipelines. The events of the Santa Clarita spill show once again that there is significant room for improving the level of emergency preparedness for pipeline spills. Oil pipeline operators must develop systematic emergency preparedness programs that prepare emergency response plans and assess the effectiveness of these plans through drills and exercises. This would be especially important for those operating pipelines in the New Madrid Seismic Zone (NMSZ) because the potential for a very large number of concurrent spills affecting multiple local and state jurisdictions could substantially complicate emergency response. State and federal regulatory agencies must assure themselves that all operators with pipelines at risk have adequate emergency classification systems that can provide timely and accurate estimates of released quantities to regulatory agencies and affected jurisdictions. At minimum, an emergency classification system must have a small number (usually three or four) emergency classes that are defined by objectively measurable emergency action levels. In turn, each emergency class should identify the immediate incident command, preventive/corrective, and protective actions that must be taken by each of the responding organizations (see Lindell & Perry, 1992, for further details).

In addition, it is essential to ensure that all pipeline operators are not planning to call upon exactly the same contractors. If this is the case, contingency plans must be developed to identify alternate sources of emergency response assistance. Timely response to spills into waterways will be especially important given the number of cities in the NMSZ that draw from surface rather than ground water. Pipeline operators need to be able to verify that their intended contractors have adequate training and equipment for responding to inland oil spills.

Fixed-site facilities. Analyses are needed of the likely demand and potential resources available for hazmat cleanup following EIHRs. Such analyses for hazmat handlers could be incorporated into broader analyses of business recovery to support the development of community-wide economic recovery plans.

Residential neighborhoods. The LAFD recommended a study of the feasibility of enhancing its capability to draw water for firefighting from residential swimming pools (Anthony, 1994). This is consistent with the conceptualization of an earthquake as requiring a response from the community as a whole, not just professional emergency responders. Other ways of making use of the human and material resources available throughout the community also should be explored.

Emergency response infrastructure. Schiff and Tang (1993) also examined the potential for problems in developing procedures that assure communications capability for emergency responders and hazardous facilities. In particular, they warned that priority for service restoration cannot help if telephone damage assessment cannot be conducted because users' telephones are out of service. Similarly, they cautioned emergency preparedness analysts not to overestimate the success of special procedures to assure dial tone access and trunk access. They also noted that cellular phones will not overcome phone system overload if there is congestion within the same cell, if there is congestion on the Public Switched Network (land lines), or if there is a loss of commercial power and the cell has inadequate backup. Furthermore, there are numerous examples of battery and backup generator failure following seismic events. Many of these problems can be overcome if analysts correctly anticipate the nature of the damage that will occur. Schiff and Tang also noted that some California telephone companies have mobile switching units and mobile engine generators that can provide service in areas with damaged switching equipment.

Weber (1987) contends that communications systems must function effectively even if there is failure of commercial electric power, telephone systems, and even the dispatching facility. Every district has established safe areas for protection of apparatus, personnel, and essential equipment, as well as predetermined locations for command posts and staging areas. The fire department already has identified geographical areas subject to some earthquake-initiated hazards such as floods resulting from dam failure, oil releases and fires from ruptured pipelines. They also have addressed potential locations of roadway blockage due to building debris, bridge failure, and landslides that would impede fire unit access. Relevant materials, such as inundation maps, are located in every command vehicle show potential floodwater flows in the event of dam failures. These procedures should be extended to address vulnerable zone for hazmat facilities. Maps should designate the locations of hazmat facilities and their vulnerable zones. Command posts and staging areas should be located in areas that are outside identified vulnerable zones.

Government regulations and programs.

Mitigtion actions by hazmat handlers. The California Office of Oil Spill Prevention and Response (1994) concluded that problems of earthquake-initiated oil spills originated in an inconsistent pattern of enforcement of regulations covering routine spills. Lack of consistent prosecution, variation in the venues chosen for prosecution, and an erratic of penalties for those found guilty all are believed to contribute to a perception by responsible parties that the penalty for pollution is slight. The report proposes that cost recovery and penalties be standardized, and that such funds be returned to the budgets of the cognizant agencies. These seem to be reasonable conclusions, but the degree to which they can be supported by empirical research remains to be determined.

Another approach, which does not preclude enhanced enforcement of routine spills, involves the administration of requirements for risk management plans. In the state of California, which already has such a requirement, this would involve the completion of current RMPP activities (many Administering Agencies remain backlogged in their requests for and approval of RMPPs). Other states with seismic hazards, but lacking requirements for risk management plans, will be subject to a proposed EPA rule arising from the Clean Air Act Amendments of 1990. State and local jurisdictions' costs for processing risk management plans (RMPs) can be supported by fees which, together with the cost of developing the RMPs, would provide an incentive for facilities to reduce risks. State legislatures should consider devising fee structures that charge owner/operators for the risks their facilities' pose to the surrounding community and thus provide incentives for mitigation actions (Showalter & Myers, 1994). This fee-based incentive for mitigation could be reinforced through regulations administered by the state insurance commission requiring insurance companies to charge facilities according to their risk.

It is noteworthy that Executive Order 12699 ("Seismic safety of federal and federally assisted or regulated new building construction", January 5, 1990) recently mandated seismic safety of federal buildings constructed or leased by the federal government, or financed with federal assistance (i.e., with VA or FHA guarantees). Similar Executive Orders could be used to mandate systematic upgrades for seismic and hazmat safety for federal or state contractors.

Mitigtion actions by government. California's active program of seismic retrofit for vulnerable highway structures is likely to further reduce the likelihood of hazmat releases resulting from tank trucks involved in structural collapses, or the extent to which emergency response operations would be impeded by such collapses. Similar efforts are warranted in other seismically vulnerable states, as are efforts to mitigate or prepare for loss of telephones, electric power, water, and hospitals. In a number of cases, expenditures would have to be approved by state Public Utility Commissions.

Acknowledgements

This report benefitted from the contributions of many organizations that provided reports, described events, and shared data with us. We would like to thank the following agencies of the state of California: Emergency Services (David Kehrlein, David Zocchetti, Pradip Desai, Fred LerCari, Paula Schultz, Jim Hunt, Mary Ann Johnson), Environmental Protection (Scott Simpson), Fire Marshal–Pipeline Safety (Nancy Wolfe, Chuck Samo, Glenn Takeoka), Fish & Game–Oil Spill Prevention & Response (Adam Sutkis, Bob Sands, Mark Garcia, Fred Cole), Mines and Geology (Rick Wilson), State University–Northridge (Ron Norton, Office of Envirnomental Health and Safety, Bill Chatham, Facilities Manager), Occupational Health and Safety (Robert Hayes, Ginger Henry), Public Utilities (Harry Strahl, Fred Curry), Toxic Substance Control (Florence Pearson), Transportation (James F. Roberts), and Water Quality Control (Jim McCance, J.T. Liu)

We would like to thank the following county departments: Los Angeles District Attorney (Jack Douglas), Los Angeles Emergency Management (Robert Garrott, Amy Jaffke), Los Angeles Department of Public Works (Don Wolfe), Riverside Environmental Health Services Division (Martha Bahia), and San Bernadino Environmental Health (Holly Clark, Jennifer Campbell).

We also would like to thank the following departments of the city of Los Angeles: Attorney (Don Kass, Greg Parham), Building & Safety (Robert Ayers, Bob Steinbach, Nick Deliquadri, Dave Keim), Emergency Management (Robert Canfield), Fire (Anthony Markham, John Scherri, David Meyers), Hazardous and Toxic Materials (Mark Nakata), Sanitation (Tara Lusk), and Transportation (Jim Sherman).

Cooperating fire departments included Alhambra (Tom Phelps), Avalon (Terry Beadle), Beverly Hills (Mark Embrey), Burbank (Devin Burns), Covina (Al Lecou), Culver City (Kevin Smith), Downey (Robert Rowe), El Monte (Faith Collari, Dennis McDonald), El Segundo (Steve Tsumura), Gardena (Robert Nolan), Glendale (Jeffrey Halpert, Vasken Demmirjian), Hawthorne (Adam Cottle), Hermosa Beach (Mark Williams), Inglewood (Lorenzo Gartmon), La Verne (Ron Sillo), Long Beach (Rick DuRee), Los Angeles County (Barbara Yu, Jojo Comandante, Walter Uroff, William Jones, Ann Tsuda), Lynwood (Gerald Wallace, Jim Stewart), Manhattan Beach (Ken Shuck, Steve Age), Monrovia (Derek Young), Montebello (William Catron), Monterey Park (Jerry Wombacher), Orange County (Christine Boyd, Karen Peters), Pasadena (Jim Weckerle), Redondo Beach (Joel Coster), Santa Fe Springs (David Klunk), Santa Monica (Brian Johnson, Kent Coble), Torrance (Ken Hall, David Kulluk), Ventura County (Gary Girod, Brian Clark, Russell Cole), Vernon (Dave Telford), and West Covina (Bob Nagel).

Regional agencies that contributed to this report include: Association of Bay Area Governments (Jeannie Perkins), Metropolitan Water District of Southern California (Kevin McLaughlin), South Coast Air Quality Management District (James Lents, William Kelly), Southern California Association of Governments (Dudley Onderdant), and Western States Seismic Policy Council (Doug Bausch).

We also would like to thank the following federal agencies: Environmental Protection Agency Region X (Michael Ardito, Al Fisher), Federal Emergency Management Agency–Headquarters (James Lee Witt), and FEMA Region X (Chris Jonientz-Trisler).

Finally, we would like to thank the following organizations: American Association of Railroads (Chris Barkin), ARCO Pipeline (Albert Greenstein, Dan Reyneveld, Bryan Suszek, John Tsouvalas, Joanne Snapper), Arizona Division of Emergency Management (Michael Austin, Reggie Yates, Dan Roe), Burbank Unified School District (David Gott), Burlington Northern Railroad (Sharon Bailey), California Association of Hospitals (Neil Hardin, Alexander Redding), California Chamber of Commerce (Beth Felton), California Real Estate Association (Jeffrey

Lunndt), Dames and Moore (John Masuk), Dow Environmental (George Malouf), EQE Engineering (Jan Decker, Neil Blais, Steve Maher, Jim Goltz), GTE California (Mike Murray, Daniel Smith, Kevin Peterson), Kaiser Permanente—Santa Clara (Ray Graves), Materials Safety Data Systems—Bakersfield (Eric Hutchins), Pacific Bell (David Dickstein, L.A. Media Relations), Pacific Gas and Electric (Orville Plum, Dave Bradley, Edmund Sutter, Woody Savage), Rockwell Rocketdyne Division (Larry Rodman, Ronald Sherer, Paul Costa, Bob Melville), St. Joseph's Medical Center—Burbank (David Doughman), Santa Fe Railroad (Ed Chapman), Southern California Center for Health Resources—Los Angeles (Heidi Members), Southern California Edison (Gary O'Neil, Frank Haroldson, John Klopfer, Dennis Ostrom), Southern California Gas (Glenn LaFevers, Dan Rendler, Don Dockray), Southern Pacific Railroad (Mike Furtney), Union Pacific Rail Road (Leo Tierney), UNOCAL (Miles Kajioka, Bill Schramm, Pete Walters), Ventura County Department of Environmental Health (Greg Smith, Steve Kephart), and Vernon Dept of Environmental Health (Joan Francone, Lou Possebon).

References

Andrews, R. (1988). The Whittier Narrows, California earthquake of October 1, 1987—Emergency response. *Earthquake Spectra*, **4**, 25-30.

Anthony, D.F. (1994). Managing the disaster. *Fire Engineering*, **147** (8), 22-40.

Arnold, R.L. (1995). The Kobe Quake. *Disaster Recovery Journal*, **8**, 1-4.

Ashford, N.A., Gobbell, J.V., Lachman, J., Matthiesen, M., Minzner, A. & Stone, R. (1993). *The encouragement of technological change for preventing chemical accidents: Moving firms from secondary prevention and mitigation to primary prevention.* Cambridge MA: Massachusetts Institute of Technology Center for Technology, Policy and Industrial Development.

Association of American Railroads. (1991). *Tank car specialist course manual.* Pueblo CO: Association of American Railroads Hazardous Materials Training Center.

Association of Bay Area Governments. (1990a). *Hazardous materials problems in earthquakes: A guide to their cause and mitigation.* Oakland, CA: Author.

Association of Bay Area Governments. (1990b). *Hazardous materials problems in earthquakes: Background materials.* Oakland, CA: Author.

Ballantyne, D.B. (1993). Water and sewage systems. In *Monograph 2: Mitigation of damage to the built environment.* (pp. 183-198). Memphis TN: Central United States Earthquake Consortium.

Barlow, H.D. (1993). Safety officer accounts of earthquake preparedness at riverside industrial sites. *International Journal of Mass Emergencies and Disasters*, **11**, 421-435.

Bates, F.L. & Peacock, W.G. (1992). Measuring disaster impact on household living conditions. *International Journal of Mass Emergencies and Disasters*, **10**, 133-160.

Bates, F.L. & Peacock, W.G. (1993). *Living conditions, disasters and development.* Athens GA: University of Georgia Press.

Beavers, J.E. (1987). Current practices in earthquake preparedness and mitigation for critical facilities. In D.G. Barbee (ed.) *Earthquake training and education: A collection of issue papers.* FEMA 124. (pp. 97-104) Emmitsburg, MD: National Emergency Training Center.

Beavers, J.E., Hall, W.J. & Nyman, D.J. (1993). Assessment of earthquake vulnerability of critical industrial facilities in the Central and Eastern United States. In Central United States Earthquake Consortium (ed.) *Proceedings: 1993 National earthquake conference.* (pp. 81-90) Memphis, TN: Author.

Berke, P., Beatley, T. & Wilhite, S. (1989). Influences on local adoption of planning measures for earthquake hazard mitigation. *International Journal of Mass Emergencies and Disasters*, **7**, 33-56.

Borden, F.W. (1994). Disaster planning and operations. *Fire Engineering*, **147** (8), 34.

Bowie, G.R. (1994). Sylmar mobile home park fires. *Fire Engineering*, **147** (8), 52-62.

Burbenn, T.A., Hawkis, H.G., Ostrom, D.K. & Richau, E.M. (1992). The earthquake vulnerability of a utility system. *Proceedings of the American Power Conference*, **54**, 224-227.

Burmeister, W.H. (1994). The Cal State Northridge fires. *Fire Engineering*, **147** (8), 50.

Burton, I., Kates, R.W. & White, G.F. (1978). *The environment as hazard.* New York: Cambridge University Press.

California Department of Conservation. (1994). *An investigation of pipeline regulatory juridsiction in the state of California.* Sacramento CA: Author.

California Fire Marshal. (1994). *Results of preliminary investigation: Hazardous liquid pipeline ruptures due to January 17, 1994 Northridge earthquake.* Sacramento CA: Author.

California Governor's Office of Emergency Services. (1982). *State of California Hazardous Materials Contingency Plan.* Sacramento CA: Author.

California Governor's Office of Emergency Services. (1994). *Northridge earthquake January 17, 1994 Interim report.* Sacramento CA: Author.

California Public Utilities Commission. (1994a). *Revenue impact of the San Fernando Valley earthquake.* San Francisco CA: California Public Utilities Commission Water Utilities Branch.

California Public Utilities Commission. (1994b). *Report on California railroads' preparedness and response for earthquakes.* Sacramento CA: Author.

California State University, Northridge. (1994). *Written notification as required under 40 CFR section 355.40.* Northridge CA: California State University, Northridge Office of Environmental Health and Safety.

Center for Chemical Process Safety. (1989a). *Guidelines for chemical process quantitative risk analysis.* New York: American Institute of Chemical Engineers.

Center for Chemical Process Safety. (1989b). *Plant guidelines for technical management of chemical process safety.* New York: American Institute of Chemical Engineers.

Center for Chemical Process Safety. (1989c). *Guidelines for technical management of chemical process safety.* New York: American Institute of Chemical Engineers.

Central United States Earthquake Consortium. (1993). *A framework for action: Findings and recommendations.* Memphis TN: Author.

Chemical Manufacturers Association. (no date). *Responsible care: A public commitment.* Washington DC: Author.

Cheu, D.H. (1987). Planning concepts for a catastrophic earthquake in California: The medical response. In D.G. Barbee (ed.) *Earthquake training and education: A collection of issue papers.* FEMA 124. (pp. 69-81) Emmitsburg, MD: National Emergency Training Center.

City of Los Angeles Department of Transportation. (1994). *Northridge earthquake transportation response after-action report.* Los Angeles CA: Author.

City of Los Angeles Department of Building and Safety. (1994). *1994 Northridge earthquake after-action report.* Los Angeles CA: Author.

Committee on Preparedness, Awareness, and Public Education. (1993). *Monograph 3: Preparedness, awareness, and public education.* Memphis TN: Central United States Earthquake Consortium.

Cooke, D. (1995). L.A. earthquake puts city disaster planning to test. *Disaster Recovery Journal,* **7**, 10-14.

Cowen, A.R. (1994). EMS Operations. *Fire Engineering,* **147** (8), 156-159.

Creasy, C.R. (1994). Emergency communications. *Fire Engineering,* **147** (8), 40-42.

Dillon, R.M. (1987). Development of seismic safety codes. In D.G. Barbee (ed.) *Earthquake training and education: A collection of issue papers.* FEMA 124. (pp. 82-89) Emmitsburg, MD: National Emergency Training Center.

Drabek, T. E. (1986). *Human system responses to disaster: An inventory of sociological findings.* New York: Springer-Verlag.

Drabek, T. E. & Hoetmer, G.J. (1991). *Emergency management: Principles and practice for local government.* Washington DC: International City Management Association.

Drabek, T. E., Mushkatel, A.H. & Kilijanek, T.S. (1983). *Earthquake mitigation policy: The experience of two states.* Boulder CO: University of Colorado Institute of Behavioral Science Monograph 37.

Durkin, M.E. & Theil, C.C., Jr. (1993). Toward a comprehensive regioual earthquake casualty modeling process. In Central United States Earthquake Consortium (ed.) *Proceedings: 1993 National earthquake conference.* (pp. 557-566) Memphis, TN: Author.

Eguchi, R.T. (1987). Current practice in earthquake hazard mitigation for utility lifeline systems. In D.G. Barbee (ed.) *Earthquake training and education: A collection of issue papers.* FEMA 124. (pp. 105-111) Emmitsburg, MD: National Emergency Training Center.

Federal Emergency Management Agency. (1985). *An assessment of damage and casualties for six cities in the Central United States resulting from earthquakes in the New Madrid Seismic Zone.* Washington, D.C.: Author.

Federal Emergency Management Agency. (1994). *Assessment of the state-of-the-art earthquake loss estimation methodologies, FEMA-249.* Washington, D.C.: Author.

Federal Emergency Management Agency, American Petroleum Institute, and International Association of Fire Chiefs. (1985). *Fire service emergency management handbook.* Washington, D.C.: Federal Emergency Management Agency.

Federal Emergency Management Agency, U.S. Department of Transportation, and U.S. Environmental Protection Agency. (no date). *Handbook of chemical hazard analysis procedures.* Washington, D.C.: Federal Emergency Management Agency.

Feldman, J. & Lindell, M.K. (1990). On rationality. In I. Horowitz (Ed.) *Recent economic thought: Organization and decision theory.* Boston: Kluwer Academic Publishers.

Finegold, A. F. & Solyst, J. (1994). *Emergency Planning and Community Right to Know Act: A status of state actions–1993.* Washington DC: National Governors' Association.

Fligg, A.Y. (1993). New developments in earthquake disaster prevention and non-structural hazard mitigation. In Central United States Earthquake Consortium (ed.) *Proceedings: 1993 National earthquake conference.* (pp. 307-316) Memphis, TN: Author.

Gillespie, D.F. & Colignon, R.A. (1993). Structural change in disaster preparedness networks. *International Journal of Mass Emergencies and Disasters,* **11**, 143-162.

Gillespie, D.F., Colignon, R.A., Banerjee, A.M., Murthy, S.A. & Rogge, M. (1993). *Partnerships for community preparedness.* Boulder CO: University of Colorado Institute of Behavioral Science Monograph 54..

Godschalk, D.R. (1991). Disaster mitigation and hazard management. In T.E. Drabek & G.J. Hoetmer (eds.) *Emergency management: Principles and practice for local government.* Washington DC: International City/County Management Association

Gldstein, I.L. (1993). *Training in organizations, 3rd. ed.* Pacific Grove CA: Brooks/Cole.

Grases, J. (1993). Seismic reliability improvement by retrofitting oil refinery equipment. In Central United States Earthquake Consortium (ed.) *Proceedings: 1993 National earthquake conference.* (pp. 317-326) Memphis, TN: Author.

Grieshop, J.I. & Stiles, M.C. (1989). Risk and home pesticide users. *Environment and behavior,* **21**, 699-716.

GTE California. (1994). *GTE California' announces customer relief measures for earthquake victims, updates network status.* Thousand Oaks CA: Author.

Holzer, T.L. (1994). Predicting earthquake effects: Learning from Northridge and Loma Prieta. *Science,* **265**, 1182-1183.

Jirsa, J.O. (1993). Buildings: General issues and characteristics. In *Monograph 2: Mitigation of damage to the built environment.* (pp. 3-18). Memphis TN: Central United States Earthquake Consortium.

Jonientz-Trisler, C. (1994). *Notes on the Seismic Safety Commission emergency meeting on the Northridge earthquake, 10-11 February 1994.* Bothell WA: Federal Emergency Management Agency.

Kartez, J. D. & Lindell, M. K. (1987). Planning for uncertainty: The case of local disaster planning. *American Planning Association Journal,* **53**, 487-498.

Kartez, J. D. & Lindell, M. K. (1990). Adaptive planning for community disaster response. In R. T. Sylves & W. L. Waugh, Jr. (eds..) *Cities and disaster: North American studies in emergency management.* Springfield, IL: Charles C. Thomas.

Kinsman, R.W. (1987). Earthquake awareness and education: A perspective from a local emergency services office. In D.G. Barbee (ed.) *Earthquake training and education: A collection of issue papers.* FEMA 124. (pp. 50-63) Emmitsburg, MD: National Emergency Training Center.

Kunreuther, H., R. Ginsberg, L. Miller, P. Sagi, P. Slovic, B. Borkan and N. Katz. (1978). *Disaster insurance protection: Public policy lessons*. New York: Wiley.

Lama, P.J. (1993). Seismic survivability of mechanical and electrical equipment. In Central United States Earthquake Consortium (ed.) *Proceedings: 1993 National earthquake conference*. (pp. 297-306) Memphis, TN: Author.

Lambright, W.H. (1985). The Southern California Earthquake Preparedness Project: Evolution of an "earthquake entrepreneur." *International Journal of Mass Emergencies and Disasters*, **3**, 75-94.

Lindell, M.K. (1994). Motivational and organizational factors affecting implementation of worker safety training. In M.J. Colligan (Ed.) *Occupational Medicine State of the Art Reviews: Occupational Safety and Health Training*. Philadelphia: Hanley & Belfus.

Lindell, M. K. (1995). Assessing emergency preparedness in support of hazardous facility risk analyses: An application at a U.S. hazardous waste incinerator. *Journal of Hazardous Materials*, **40**, 297-319.

Lindell, M.K. & Meier, M.J. (1994). Effectiveness of community planning for toxic chemical emergencies. *Journal of the American Planning Association*, **60**, 222-234.

Lindell, M. K. & Perry, R. W. (1992). *Behavioral foundations of community emergency planning*. Washington, DC: Hemisphere.

Lindell, M.K. & Whitney, D.J. (in press). Effects of organizational environment, internal structure and team climate on the effectiveness of Local Emergency Planning Committees. *Risk Analysis*.

Los Angeles County Emergency Operations Center Staff. (1994). *After-action review: The Northridge earthquake* . Los Angeles CA: Author.

Los Angeles County Fire Department. (1994). *Northridge earthquake report: Health hazardous materials division*. Los Angeles CA: Author.

Los Angeles County Fire Department. (1992). *Risk management and prevention program guidelines*. Los Angeles CA: Author.

Manning, D.O. (1994). Message from LAFD Chief Engineer and General Manager. *Fire Engineering*, **147** (8), 10.

Martin, H.W. (1993). Recent changes to seismic codes and standards: Are they coordinated or random events. In Central United States Earthquake Consortium (ed.) *Proceedings: 1993 National earthquake conference*. (pp. 367-376) Memphis, TN: Author.

Mascone, C.F., Gordon, H.S. & Vagl, D.L. (1988). CPI safety: High marks but...," *Chemical Engineering*. October 10, 74-86.

May, P.J. & Williams, W. (1986). *Disaster policy implementation: Managing programs under shared governance*. New York: Plenum Press.

May, P. (1988). Implementation research perspectives: Earthquake risk reduction policy. *International Journal of Mass Emergencies and Disasters*, **6**, 75-89.

McCarthy, J. (1985). Population living near chemical manufacturing plants. *Memo to the Senate Environmental and Public Works Committee, February 22.* Washington DC: Congressional Research Service

The Metropolitan Water District of Southern California. (1994). *Damage and repair report for Joseph Jensen Filtration Plant: Northridge earthquake January 17, 1994.* Los Angeles CA: Author.

Michigan State Police Emergency Management Division. (1994). *Warning, evacuation & in-place protection handbook, EMD PUB-301.* Lansing MI: Author.

Mileti, D.S. (1980). Human adjustment to the risk of environmenal extremes. *Sociology and Social Research,* **64**, 327-347.

Mileti, D.S. & Fitzpatrick, C. (1993). *The great earthquake experiment: Risk communication and public action.* Boulder CO: Westview Press.

Mittendorf, J.W. (1994). LAFD earthquake preplanning. *Fire Engineering,* **147** (8), 14-21.

National Earthquake Hazards Reduction Program. (1987). *Commentary and recommendations of the expert review committee.* Washington DC: Federal Emergency Management Agency.

National Emergency Training Center. (1989). *The Incident Command System: Student Manual.* NFA-ICS-SM. Emmitsburg MD: Author.

National Fire Academy. (no date). *Hazardous materials operating site practices.* Emmitsburg MD: Author.

National Fire Protection Association. (1988). *Professional competence of responders to hazardous materials incidents. Standard 472.* Boston MA: Author.

National Institute for Chemical Studies. (1988). *Protecting the public in a hazardous material emergency: Final project report and technical support appendices. Charleston WV: Author.*

National Institute for Occupational Safety and Health. (1990). *NIOSH pocket guide to chemical hazards.* Washington, D.C.: U.S. Government Printing Office.

National Institute of Standards and Technology. (1994). *1994 Northridge earthquake: performance of structures, lifelines and fire protection systems.* Special Publication 862. Gaithersburg MD: Author.

National Research Council. (1994). *Practical lessons from the Loma Prieta earthquake.* Washington, DC: National Academy Press.

National Response Team. (1987). *Hazardous materials emergency planning guide, NRT-1.* Washington DC: Author

National Science Foundation. (1993a). *Directions for research in the next decade: National Science Foundation programs in earthquake engineering and earthquake-related earth science—Report on a workshop.* Washington, DC: Author.

National Science Foundation. (1993b). *Directions for research in the next decade: National Science Foundation programs in earthquake engineering and earthquake-related earth science—Proceedings of a workshop.* Washington, DC: Author.

Nigg, J. (1982). Awareness and behavior: Public response to prediction awareness. In T.F. Saarinen (Ed.) *Perspectives on increasing hazard awareness* (pp. 71-96). Boulder, CO: University of Colorado Institute of Behavioral Science Program on Environment and Behavior Monograph 35.

Nilson, D.C. (1984). How to gain attention and commitment of political officials: An earthquake politics primer. In P.L. Gori (Ed.) *Primer on improving the state of earthquake hazards mitigation and preparedness* (pp. 48-54). Reston, VA: United States Department of the Interior Geological Survey Open File Report 84-772.

Noll, G.G., Hildebrand, M.S. & Yvorra, J.G. (1988). *Hazardous materials: Managing the incident*. Stillwater: OK: Oklahoma State University Fire Protection Publications.

Nordenson, G.J.P.. (1993). Seismic codes. In *Monograph 2: Mitigation of damage to the built environment*. (pp. 89-114). Memphis TN: Central United States Earthquake Consortium.

Nyman, D.J., Prosser, W.J., Moriwaki, Y. & O'Rourke, T.D. (1993). Earthquake vulnerability of a 40-inch crude oil pipeline in the Central United States. In Central United States Earthquake Consortium (ed.) *Proceedings: 1993 National earthquake conference*. (pp. 587-596) Memphis, TN: Author.

Occupational Safety and Health Administration. (1992). *Process safety management: Guidelines for compliance. OSHA-3133*. Washington DC: Author.

Olson, R.S. & Olson, R.A. (1993). "The rubble's standing up" in Oroville, California: The politics of building safety. *International Journal of Mass Emergencies and Disasters*, **11**, 163-188.

O'Rourke, M. & Shinozuka, M. (1993). Gas and liquid fuel systems. In *Monograph 2: Mitigation of damage to the built environment*. (pp. 171-182). Memphis TN: Central United States Earthquake Consortium.

O'Rourke, T.D. & Palmer, M.C.. (1994). Earthquake performance of gas transmission pipelines during the Northridge earthquake. *NCEER Bulletin*, **8**(2), 1-5.

Pacific Bell. (1995). *Pacific Bell prepares for California's next earthquake*. Los Angeles CA: Author.

Palm, R. (1987). Pre-disaster planning: The response of residential real estate developers to special studies zones. *International Journal of Mass Emergencies and Disasters*, **5**, 95-102.

Peacock, W.G., Killian, C.D. & Bates, F.L. (1987). The effects of disaster damage and housing aid on household recovery following the 1976 Guatemalan earthquake. *International Journal of Mass Emergencies and Disasters*, **5**, 63-88.

Perkins, J.B., Selvaduray, G. & Wyatt, G.E. (1991). *Toxic gas releases in earthquakes: Existing programs, sources, and mitigation strategies*. Oakland CA: Association of Bay Area Governments.

Perkins, J.B., Selvaduray, G. & Wyatt, G.E. (1991a). *Manual of techniques for preventing or controlling toxic gas releases in earthquakes*. Oakland CA: Association of Bay Area Governments.

Perkins, J.B., Selvaduray, G. & Wyatt, G.E. (1991b). *Review of emergency preparedness programs for preventing or controlling toxic gas releases in earthquakes.* Oakland CA: Association of Bay Area Governments.

Perkins, J.B. & Wyatt, G.E. (1990). *Hazardous materials problems in earthquakes: A guide to their cause and mitigation.* Oakland CA: Association of Bay Area Governments.

Perkins, J.B. & Wyatt, G.E. (1991). *Sources of toxic gas releases in earthquakes.* Oakland CA: Association of Bay Area Governments.

Perry, R.W. & Lindell, M.K. (1989). Communicating threat information for volcano hazards. In L. Walters, L. Wilkins and T. Walters (eds.) *Bad tidings: Communication and catastrophe.* Hillsdale, NJ: Lawrence Erlbaum.

Perry, R.W. & Lindell, M.K. (1990). *Living with Mt. St. Helens: Human adjustment to volcano hazards.* Pullman WA: Washington State University Press.

Prugh, R,W. and Johnson, R.W. (1989). *Guidelines for vapor release mitigation.* New York: American Institute of Chemical Engineers.

Rossi, P.H., Wright, J.D., Weber-Burdin, E., Pietras, M. & Diggins, W.F. (1982). *Natural hazards and public choice: The state and local politics of hazard mitigtation.* New York: Academic Press.

Rubin, C.B. (1987). Local public commitment to reduce earthquake hazards. In D.G. Barbee (ed.) *Earthquake training and education: A collection of issue papers.* FEMA 124. (pp. 41-49) Emmitsburg, MD: National Emergency Training Center.

Schiff, A.J. & Tang, A. (1993). Electric power and communication systems. In *Monograph 2: Mitigation of damage to the built environment.* (pp. 147-169). Memphis TN: Central United States Earthquake Consortium.

Schneider, L. (1994). Report from Battalion 15. *Fire Engineering,* **147** (8), 42-52.

Seigel, G.B. (1989). The state of seismic mitigation management in U.S. Pacific basin seaports and harbors. *International Journal of Mass Emergencies and Disasters,* **7**, 168-182.

Seligson, H.A., Eguchi, R.T. (1993). Application of a regional hazard assessment methodology using GIS for a midwestern natural gas pipeline system. In Central United States Earthquake Consortium (ed.) *Proceedings: 1993 National earthquake conference.* (pp. 153-162) Memphis, TN: Author.

Shane, D.M. (1994). *Federal On-scene Coordinator's report: ARCO's Four Corner pipeline spill, Santa Clara River, Los Angeles and Ventura Counties, January 17-March 2, 1994.* San Francisco CA: U.S. Environmental Protection Agency Region IX.

Sherer, R.S. and Rodman, L.E. (1994). *Lessons learned and impact on major aerospace company resulting from the Magnitude 6.7 Northridge earthquake.* Canoga Park CA: Rockwell Aerospace Rocketdyne Division.

Showalter, P. S. & Myers, M.F. (1994). Natural disasters in the United States as release agents of oil, chemicals, or radiological materials between 1980–1990: Analysis and recommendations. *Risk Analysis,* **14**, 169-182.

Slovic, P., Fischhoff, B. & Lichtenstein, S. (1980). Facts and fears: Understanding perceived risk. In R.C. Schwing & W.A. Albers, Jr. (eds) *Societal risk assessment: How safe is safe enough?* New York: Plenum Press.

Slovic, P., Lichtenstein, S. & Fischhoff, B. (1988). Decision making. In R.C. Atkinson, R.J. Herrnstein, G. Lindzey & R.D. Luce (eds) *Stevens' handbook of experimental psychology, 2nd edition, Volume 2.* New York: Wiley Interscience.

Southern California Edison. (1994). *Edison lessons learned report on the Northridge earthquake.* Rosemead CA: Author.

Southern California Gas Company. (1994). *Northridge earthquake gas delivery system integrity study.* Los Angeles CA: Author.

Sorensen, J.H. & Mileti, D.S. (1987). Programs that encourage the adoption of precautions aganist natural hazards: Review and evaluation. In N. Weinstein (ed.) *Taking Care: Why People Take Precautions* (pp. 208-230). New York: Cambridge University Press.

Stratton, J.W. (1989). Earthquakes. In M.B. Gregg (ed.) *The public health consequences of disasters.* Atlanta GA: Centers for Disease Control and Prevention.

Tierney, K.J. (1988). The Whittier Narrows, California earthquake of October 1, 1987—Social aspects. *Earthquake Spectra,* **4**, 11-23.

Tierney, K.J. & Anderson, R.C. (1992). Risk of hazardous materials releases following an earthquake. In *Proceedings of the Port of Los Angeles Seismic Workshop.* San Pedro, CA: Port of Los Angeles.

Tierney, K.J., Seligson, H.A. & Eguchi, R.T. (1990). *Chemical hazards, mitigation, and preparedness in areas of high seismic risk.* Los Angeles, CA: Dames & Moore.

Toppozada, T.R., Bennett, J.H., Borchardt, G., Saul, R. & Davis, J.F. (1988). *Planning scenario for a major earthquake on the Newport-Inglewood fault.* Special publication 99. Sacramento CA: California Department of Conservation, Division of Mines and Geology.

Turner, R.H. (1987). Waiting for disaster: Changing reactions to earthquake forecasts in Southern California. *International Journal of Mass Emergencies and Disasters,* **1**, 307-334.

Union Pacific Railroad Company. (1993). *Emergency response procedures for spills of hazardous materials, oil or other enviornmental pollutants: Harriman Dispatch Center.* Omaha NE: Author.

Union Pacific Railroad Company. (1994). *Emergency response procedures for spills of hazardous materials, oil or other enviornmental pollutants: Los Angeles Service Unit, Canyon Subdivision, Feather River Canyon.* Omaha NE: Author.

U.S. Department of Commerce and Department of Labor. (1994). *Chemical and allied product production in the U.S.; Summary statistics volume: Cumulative.* Washington D.C.: Government Printing Office.

U.S. Environmental Protection Agency. (1987). *Technical guidance for hazards analysis: Emergency planning for extremely hazardous substances.* Washington D.C.: Author.

U.S. Environmental Protection Agency. (1988). *Review of emergency systems: Report to Congress*. Washington D.C.: Author.

U.S. Environmental Protection Agency. (1993). *List of lists*. Washington D.C.: Author.

U.S. Department of Transportation. (1993). *Emergency response guidebook*. Washington D.C.: Author.

Urbanik, T. (1994). State of the art in evacuation time estimate studies for nuclear power plants. *International Journal of Mass Emergencies and Disasters*, **12**, 327-343.

Utah Seismic Safety Commission. (1995). *A strategic plan for earthquake safety in Utah*. Salt Lake City UT: Author.

Wagner, L.J. (1994). Personal communication dated 22 September, 1994.

Ward, D.B. (1987). Management of earthquake safety programs by state and local governments. In D.G. Barbee (ed.) *Earthquake training and education: A collection of issue papers*. FEMA 124. (pp. 32-39) Emmitsburg, MD: National Emergency Training Center.

Weber, J.S. (1987). Current fire service role in preparing for and responding to earthquakes. In D.G. Barbee (ed.) *Earthquake training and education: A collection of issue papers*. FEMA 124. (pp. 64-68) Emmitsburg, MD: National Emergency Training Center.

Werner, S.D. (1993). Ports and air transportation systems. In *Monograph 2: Mitigation of damage to the built environment*. (pp. 135-146). Memphis TN: Central United States Earthquake Consortium.

Wilson, A. (1993). The trouble with tremblers. *InfoMagazine*, 1993(4), 24-25.

Whitney, D.J. & Lindell, M.K. (1995). *Antecedents and outcomes of organizational commitment in voluntary organizations*. East Lansing MI: Department of Psychology.

Wyner, A. (1984). Earthquakes and public policy implementation in California. *International Journal of Mass Emergencies and Disasters*, **2**, 267-284.

Appendix A: Typology of EIHR risk reduction actions

I. Hazard Assessment Actions

Environmental hazard assessment

- Geologic hazard assessment
- Hydrological hazard assessment
- Meteorological hazard assessment
- Building structural assessment
- Non-structural elements assessment
- Building contents assessment

Chemical hazard assessment

- Chemical inventory audit
- Hazard analyses for process and material modifications
- Offsite consequence analyses

II. Hazard Mitigation Actions

Inventory reduction

- Substitution of non-AHM materials
- AHM inventory reduction
  - AHM use eliminated (plant shut down, product discontinued)
  - Onsite storage of AHM reduced below reportable quantity
  - Annual rate of AHM consumption reduced

Site/design/operation

- Plant site options
  - Plant relocation
  - AHM locations restricted
  - Control of surrounding land uses
- Plant design options
  - Soil/foundation engineering
  - Structural strengthening
- Process equipment modifications
  - Materials handling
    - Materials handling equipment (e.g., hoists)
    - Loading/unloading area surface improvements
  - Chemical tank/reactor modifications
    - Vessel strengthening
    - Vessel size reduction
    - Pressure relief devices
  - Pipe modifications
    - Strengthening
    - Check valves and other isolation devices
  - Process alarm/control systems
    - System technical specification deviations (pressure, temperature, level, flow)
    - External events detection (seismic activity, loss of power, fire)
    - Interlocks
  - System component redundancy
    - Backup tanks for vapor/liquid transfer
    - Process component (e.g., pump/agitator/cooling system) redundancy
    - Back-up utilities (electricity, gas, communications, water)
    - Control equipment/data base redundancy

- External hazard protection
  - Process equipment seismic protection
    - Base isolation
    - Tank/reactor vessel
      - Bracing/anchoring
      - Center of gravity reduction
      - Open vessel sloshing prevention
      - Cylinder valve protection
    - Pipe/pipe connection enhancements
      - Flexible hose connectors
      - Joint welding
  - Fire suppression systems (flame arrestor, water deluge, inert atmosphere)
- Ergonomic design
  - Equipment/storage area identification
  - Equipment displays, controls, and layout
- Administrative controls
  - Security programs
  - Management safety oversight
    - Periodic plant-safety audits
    - Incident investigations
    - Management of change
  - Process operation modifications to less hazardous conditions (temperature, pressure)
  - Operator/maintenance/contractor procedures
    - Job performance aids (e.g., written SOPs, EOPs)
    - Safety training content/frequency (e.g., process hazard communication)
    - Delivery/storage procedures
      - Chemical delivery procedures
      - Access controls
      - Chemical storage time limits
      - Chemical segregation
    - Work permits (e.g., hot work)
    - Work verification
    - Periodic system component inspections and tests (e.g., corrosion)

III. Emergency Preparedness Actions
Incident command

- Incident assessment
  - Release detection (loss of pressure/excess flow/leak detection)
  - Environmental monitoring (airborne concentration monitoring)
  - Physical damage assessment
  - Emergency classification
- Onsite direction and control
    - Emergency organization mobilization/demobilization
  - Emergency facilities & equipment mobilization/demobilization
  - Response planning
    - Technical analysis
    - Resource status assessment
- Offsite liaison (mutual aid plans, community emergency plans, ad hoc response)
- Public information

- Administrative and logistical support
  - Service (communications, medical, food)
  - Support (supply, facilities, ground support)
  - Finance (time, cost, procurement, claims/compensation)
  - Documentation

Preventive/corrective actions

- Engineered safety features (automated or passive)
  - Remote or automatic control valves
  - Vapor release countermeasures
    - Sprays/curtains (water , steam, air)
    - Ignition initiation/prevention devices
    - Ventilation systems (AHM dilution, critical facility isolation)
    - Scrubbers
    - Condensers
  - Liquid release countermeasures
    - Dilution
    - Neutralization
    - Covers (liquids, foams, solids)
    - Sorbents
    - Secondary chemical containment (cabinets, sealed buildings, block houses, dikes, berms, underground sumps)
- Emergency response capabilities (manual)
  - Emergency shutdown systems
  - Chemical process spare-parts and emergency response materials stocks
  - Emergency response training and procedures
  - Emergency lighting
  - Patching and plugging materials
  - Search and rescue equipment
  - Personal hazard monitors
  - Personal protective equipment (including respiratory protection)
  - Decontamination equipment

Protective actions (plant personnel)

- Evacuation/in-place protection decisionmaking procedures
- Emergency alert/warning systems (PA/siren) and procedures
- Safe havens for in-place protection
- Personnel accountability
- Emergency worker hazard exposure control
- Search and rescue teams and equipment
- Emergency medical treatment
- Plant access control and security