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Identifying and managing conjoint threats: Earthquake-induced hazardous materials releases in the US

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Abstract

Hazardous materials (hazmat), in many forms, are ubiquitous in modern society. Not only are they present in manufacturing and commercial establishments, but also in homes, medical facilities, laboratories and schools. Further, hazmat is transported by truck and rail and pipeline and stored in large tanks. Indeed, these materials are both integrated into communities in fixed facilities and circulate through neighborhoods in the transportation process. In areas that are vulnerable to earthquakes, the presence of hazmat poses special problems. This article examines the nature of earthquake-induced hazmat releases, their likelihood and their impact on emergency response systems. It is argued that hazmat incidents become an additional disaster agent that must be integrated into the management framework for earthquakes. Under specified conditions, an earthquake could initiate releases from many sources simultaneously, severely taxing the emergency management system. Further, earthquake-related obstacles to emergency response severely hamper the management of hazmat releases. These obstacles include loss of communication capacity, overload of the emergency medical system, loss of warning systems for the public, and impediments to incident access caused by road buckling, fires, rubble, structural collapse and flooding from damaged water mains. A case review of the hazmat problems that arose during the Northridge earthquake is reported to identify challenges posed for emergency managers. The article closes with a series of recommendations for mitigation, preparedness and emergency response.

Keywords: Hazardous Material; Earthquake; Disaster Management; Planning

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1. Introduction

Hazardous materials, in many forms, are ubiquitous in modern American Society. Indeed, they have become so commonplace that obvious chemical dangers are often not identified as such. Further, hazardous materials (hazmat) repositories are literally distributed through communities in the form of corner gasoline stations, drycleaning services, swimming pool shops, paint stores and home improvement centers as well as others. The identification of the dangers associated with hazardous materials in communities has lead governments to develop and formalize emergency management protocols.

The purpose of this article is to look at hazardous materials, not as a self-initiating danger, but as a secondary hazard associated with the earthquake threat. In recognizing the distribution of hazmat through communities, the principal theme here is to examine the impact of such incidents upon the capacity of the emergency response system, and derive suggestions for mitigation and preparedness that minimize potential negative consequences. In accomplishing this goal, we will first address the nature of the problems posed by earthquake-initiated hazardous materials releases. This includes a discussion of the plausibility of the threat and the patterns of reporting for hazardous materials incidents in recent earthquake events. The second section of the paper recounts actual releases that were documented in the Northridge earthquake of 1994. This material is presented as case data specifically addressing hazmat events, rather than looking at the larger scope of damages (for example to traditional lifelines – water, sewer, electricity – or buildings). The purpose is to document the extent of hazmat activity as a basis for identifying subsequent response-connected difficulties. Finally, the closing section is devoted to presenting a series of suggestions for adaptive changes in hazard management strategy. These suggestions include measures related to hazard assessment, hazard mitigation and emergency preparedness.

Although the case data presented here were accumulated in California, the management recommendations are meant to apply to virtually any area where the earthquake threat combines with the presence of hazardous materials. Certainly high risk of earthquake-initiated hazardous materials releases (EIHRs) prevails in California, particularly along the Newport-Inglewood fault region southwest of downtown Los Angeles. But the threat is also present along the remainder of the San Andreas fault zone (extending into Washington, Oregon, and southwest Arizona), the Wasach Range, and throughout a large part of the midwest surrounding the New Madrid fault zone.

2. The earthquake-induced hazmat problem

The presence of grouped, or even dispersed, hazardous materials in an area subject to earthquakes poses a variety of challenges. Perhaps the greatest concern here is with the potential for overloading the emergency response system and compromising its ability to minimize losses to persons and property. The mechanism of the overloading tends to stem from the potential to create, simultaneously with earthquake response demands, a range and multitude of hazardous materials related demands. This problem is compounded by the traditional separation of earthquake emergency planning and response activities from those associated with hazardous materials. Thus, very different actors, with different skills, training and agency affiliations tend to be involved in preparing for and responding to each type of incident. The overlap that does exist tends to be response-related, particularly in the area of citizen rescue by fire departments, and thereby exacerbates normal response personnel shortages.

In an earthquake threat environment, potential hazmat incidents can arise from myriad sources. Hazmat can be released from fixed site facilities through failure of storage tank foundations, valve rupture, or pipe connections. Such failures can stem from ground motion or ground failure (surface fault rupture, soil liquefaction or landsliding), or indirectly when buildings housing hazmat experience structural collapse [1]. Further, hazmat can be released in connection with the transportation process if seismic forces cause pipeline rupture, train derailment or tank truck accidents. In fact, just general structural damage or interruption to water systems, sewer systems, or electrical lines – common events in earthquakes – can result in shutdowns or system failures that produce hazmat releases by overstressing storage vessels, pipes and valves, or by failing mixing and cooling systems, or by failing back-up control systems. It should not be ignored that the form of the hazardous materials to be managed may range from semi-solid materials, through liquids, to gases, and include any combinations of these forms.

While the number of different ways hazmat releases can occur is large, a major danger stemming from earthquake-induced hazmat incidents is that many different releases can occur in a short time period in many different hazmat locations. Whether hazmat releases are precisely concurrent or take place sequentially over a few hours or days, or both, the impact on the emergency response system could be substantial. The environment becomes one characterized by many hazmat "disasters" that must be responded to in the context of an earthquake "disaster". This is particularly problematic because the planning process upon which hazmat response practice is based contains assumptions that are not consistent with the earthquake environment.

Three examples are worthy of mention here. First, hazmat response is usually based on the assumption that releases will occur singly, or at least sequentially at one site [2]. Under normal circumstances, this assumption is appropriate because releases from different facilities are infrequent and statistically independent events. An earthquake, however, forms a common "cause" for hazmat releases over a potentially large geographic area (so statistical independence is lost) and the probability of multiple concurrent releases is much greater. Further, earthquake aftershocks make hazmat releases more difficult to stabilize and increase the probability of sequential releases at the same site. Second, hazmat response practice assumes that access to the site of a release will not be a problem. A major consequence of earthquakes is damage to transportation systems – destroying or blocking roadways through a number of direct and indirect mechanisms. Even locating routes that are not blocked can be difficult because of communication system failures that routinely occur. Third, hazmat response practice tends to assume that appropriate equipment and adequate personnel will be either available as an existing team, or obtainable in reasonable time through existing mutual assistance agreements. This assumption becomes problematic in an earthquake environment because of the probability that multiple hazmat events could be perpetrated over a large area. Thus, getting appropriate or even enough equipment to cover jurisdictional events may be hindered by road access limitations, but thwarted by the presence of multi-jurisdictional response demands. In an earthquake setting adjacent jurisdictions may be plagued with high response demands of their own, reducing the sharing capability achieved through mutual aid pacts.

2.1. *Plausibility of the EIHR threat*

It is easy to construct abstract scenarios in which earthquake-initiated hazmat releases challenge emergency response systems. In spite of this, relatively little attention has been paid to the issue in the earthquake planning literature [3]. The research community, with a few notable exceptions, also has for the most part not focused on the question of EIHRs [4]. In part this may be a function of the fact that the level of reported hazardous materials releases during past earthquakes has been very low. Some emergency managers might therefore conclude that the past frequency of EIHRs is so low that in preparedness plans, the issue need not be addressed. Inattention to a problem solely based on historical frequency of occurrence is not, however, an acceptable approach to emergency management or any type of strategic planning [5]. Instead, vulnerability analyses should be technically based (on hazard characteristics and possible consequences) as well as empirical (statistical occurrence frequencies).

When one looks at historical data, it is clear that most earthquake casualties have been caused by structural collapse [6], but hazmat releases – with small human consequences – have taken place. Post-impact assessments of recent California events including Whittier Narrows [7,8] and Loma Prieta [9] do reveal that only a few significant hazmat releases could be traced to the earthquakes. There are two perspectives that must be considered when looking at historical examples of EIHRs. The first is the notion of what causes EIHRs to happen. For example, the presence of EIHRs is logically related to the magnitude of the earthquake event (in combination with other variables like the characteristics of soils); the state of mitigation measures (code requirements) in force both currently and when the building and hazmat systems were constructed; the type, quantity and degree of dispersion of hazmat facilities in the impact area; and the timing of the event relative to the operation of the facilities (at 3am on a Sunday, the systems may be shut down).

Beyond counting actual occurrences, the *reporting* of EIHRs to authorities (and their subsequent inclusion in afteraction reports) is impacted by additional variables. Indeed, "because of the massive overall destruction of an earthquake, the actual number of hazardous materials incidents may go unreported" [10] (p. 22). Hence the completeness of *reporting* of hazmat incidents would be affected by at least three factors. The first is the characteristics of the hazardous materials themselves: more complete reporting would be expected for releases that were noticeable to citizens and authorities – those accompanied by visible or sensory cues (distinctive sights, sounds or odors). Second, one must consider the wording of legal reporting requirements. More complete reporting would be expected in jurisdictions with stringent requirements and stringent enforcement. Finally, the completeness of reporting is affected by the diligence of local officials. Higher reporting levels would be expected where local officials have the time, manpower and motivation to identify and document EIHRs. Ultimately it is not the actual *occurrence* of EIHRs that is attended to in historical earthquakes; instead, *reported* EIHRs are what find their way onto the record.

Consequently, in trying to calculate the probability of EIHRs by counting incidents in historical earthquakes, one is relying on *reported* events and thereby risking serious underestimation of the magnitude of the problem. The underestimation occurs because reported frequency doesn't equal actual occurrences and because there is no reason to confine future predictions to the same characteristics (magnitude, hazmat distribution, soil conditions, mitigation measures implemented, etc.) of past events. Therefore, it is inappropriate to argue that the presence of few observed EIHRs in past earthquakes forms a reasonable basis for concluding that such events will continue to be rare in future earthquakes. When one considers the number of sites and large human populations near them that possess a vulnerability profile indicating that EIHRs are likely – presence of an earthquake threat, appropriate soil conditions, low levels of mitigation activity (through code or otherwise), and the presence of hazmat – then it is clear that EIHR planning should become a priority in mitigation, preparedness and response planning.

3. EIHRs in the northridge earthquake

The presentation of case data on EIHRs during the Northridge earthquake permits assessment of the types and nature of hazmat incidents in a moderate earthquake, explication of the types of response issues that arise, and an appreciation of the earthquake environment as a setting for management of hazmat events. It should be noted that the purpose of this review focuses upon EIHRs and is not intended to be a thorough review of the broader consequences of the Northridge earthquake. At 4:31 AM on January 17, 1994, coinciding with the California observance of Martin Luther King Day, an earthquake caused 57 deaths, 9,158 serious injuries, and moderately or severely damaged approximately 12,500 structures at a cost of more than $20 billion. Although the event was classified as a moderate earthquake (M6.8), the unexpectedly large consequences were a function of its unprecedented horizontal and vertical accelerations. Newsmedia coverage of the event focused on apartment building and freeway collapses (one of the latter cost the life of a highway patrol motorcycle officer). Only a few hazmat incidents were covered by the media or appeared in early damage assessments [11], but many more were identified and responded to by state, county and municipal agencies.

The overall hazmat picture after Northridge was characterized by a few large events, with a greater number of smaller events. Of course, here we are dealing with *reported* events. There was much concern by hazmat specialists in earthquake-impacted areas about releases that probably had occurred but might not come to the attention of responsible government agencies. In general, if releases are small and do not require emergency response assistance by offsite or outside agencies, they may not be subject to legal reporting requirements. Consequently, the Los Angeles County Fire Department Health and Hazardous Materials Division (HHMD) directed a thorough postincident assessment of EIHRs [12]. The assessment focused on two principal command posts, one in Santa Clarita and the other in Van Nuys. Staff at the Santa Clarita post teamed with city and county building inspectors to examine the condition of all structures in that area, which included primarily MMI intensities of VIII and IX. The magnitude of the building inspections was immense, involving more than 85,664 buildings in the City of Los Angeles alone, and required supplementing the normal professional staff with more than 1,440 volunteers [13].

The Santa Clarita HHMD team participated in 598 hazmat assessments, 151 of them at industrial sites and 376 at commercial sites. Fifty-two sites (8.7% of the total number of buildings inspected) were identified as having some level of hazmat concern. Of these 52 sites, 28 were industrial and 16 were commercial. Consequently, 18.5% of the industrial and 4.3% of the commercial sites inspected experienced an EIHR. the majority of these sites were cleaned up by owner-tenants, but 19 (36.5%) required cleanup and waste removal by HHMD's hazardous waste cleanup contractor.

The Van Nuys command post assessment area was geographically larger, including the entire San Fernando Valley (MMI 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). Authorities assembled a list of sites that might have EIHRs from several sources, including: (1) the list of facilities annually inspected by HHMD due to high volumes of acutely hazardous materials (AHMs); (2) lists of AHM handlers provided by the cities of Burbank, Glendale, Santa Monica, Culver City and Los Angeles; (3) businesses listed in the telephone directory under categories of nurseries, pool supply stores and paint supply stores; (4) businesses in the Los Angeles City Building and Safety Department database that suffered extensive structural damage; (5) lists of schools, colleges, and universities; and (6) medical facilities and laboratories. A total of 1,689 hazmat assessments were conducted based on this listing (226 at industrial sites and 561 at commercial sites). The inspections yielded 82 sites with hazmat concerns (4.9% of the total structures inspected); 11 (4.9%) were industrial and 27 (4.8%) were commercial.

It is noteworthy that in the Van Nuys command post area, only two of the industrial facilities (both plating operations) and *none* of the commercial facilities that experienced hazmat releases also experienced structural damage. For hazard management purposes, it is often assumed that hazmat releases will only be found where structural damage is also present. The experience at Van Nuys demonstrates that structural damage is not a necessary cause of EIHRs. Indeed, HHMD reported that the greatest potential for acute health hazards was found at: plating facilities or manufacturing facilities with large open top tanks containing chemical solutions; retail pool supply stores; and school, university, hospital and independent medical laboratories. Plating operations alone accounted for 9.7% of the industrial cleanups (22 out of 226). Overall, most of these sites were cleaned up by owner-tenants, but 2 (2.4% of the total) required cleanup and removal by an HHMD contractor.

Among all the hazmat events during Northridge, there were none involving explosives, etiologic agents, radiological materials, or large quantities of toxic gases, although there was a significant incidence of asbestos abatement problems. There was only one case of a significant release of a corrosive liquid, but there were many releases of flammable liquids and gases. Most of the major incidents involved the potential for chronic environmental or occupational (workplace) threats. The remainder of this discussion summarizes the circumstances associated with the larger EIHR incidents.

3.1. Train derailment

The California Public Utilities Commission [14] reported that the earthquake caused a section of railroad track within two city blocks of the epicenter to move approximately 4 inches off center. When a westbound freight train passed over the damaged track, the lead locomotive and 29 cars derailed. One of 13 tankcars spilled an estimated 2000 gallons of sulfuric acid (of a car capacity of 13,500 gallons), and 1000 gallons of diesel fuel spilled from the locomotive. The Southern Pacific dispatcher was notified at 4:45am, and following standard operating procedure for earthquakes exceeding M6.0, all trains within 100 miles were stopped until tracks could be inspected.

3.2. Petroleum pipeline spills

Following standard operating procedure for hazmat liquid pipelines, all petroleum pipeline pumping stations were shut down immediately after the earthquake was detected. The resulting reduction in pipeline pressure limited, but could not eliminate, releases from the nine pipeline ruptures that were reported by the California State Fire Marshal [15]. One of these releases involved the UNOCAL Torrey Line, while the other eight occurred on the ARCO/Four Corners line. A subsequent spill, only tangentially related to the earthquake, occurred at Grasshopper Canyon/Castaic Lake on January 22 when ARCO was pressure testing another pipeline for reopening after it had been shut down during the earthquake.

The UNOCAL Torrey Line, originally built in 1955, has a normal throughput of 806,400 gallons per day. The pipeline failure (a two 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 were associated with the release and all contaminated soil was recovered.

The multiple breaches of the ARCO Four Corners line – originally built in 1925 and relocated in 1959 – involved significantly greater consequences. Even though the pipeline was not in operation on the day of the earthquake, the California Fire Marshal's Office estimated that the total spills amounted to more than 230,000 gallons. Property damage (to five houses and 20 automobiles) and one injury to a motorist were reported in connection with one spill when leaking crude oil was ignited. Early estimates placed the amount of recovered material at one-third (71,000 gallons) of the spill, while recently ARCO Pipeline sources placed the amount recovered at nearly two-thirds. Most of the spills were on sections of the pipe under low pressure, so only small quantities of oil were released (compared with the capacity of the pipe) and the product remained at close proximity to the release point. However, emergency response and cleanup costs durimg the first two months after the spills exceeded $15 million.

The greatest environmental impact was associated with an ARCO Pipeline spill of 173,000 gallons of light crude oil from the Newhall Booster Pump Station in Santa

Clarita. An estimated 67,500 gallons drained from the pipeline itself, while another 105,500 gallons drained from an associated storage tank – about 6.7% of the tanks 1.6 million gallon capacity [16]. The crude oil combined with releases from broken waterlines and flowed down a street into a storm drain. In the drain, the oil and water combined with wastewater from damaged sewage treatment plants and contaminated approximately 12 miles of river. On March 2, more than six weeks after the earthquake, the last river segment was approved for final cleanup and the last removal action was completed. The pipeline operator's final cost for the cleanup was approximately $12 million.

3.3. Natural gas releases

Southern California Gas [17] reported 35 breaks in its natural gas transmission lines and 717 breaks in distribution lines. About 74% of the 752 leaks were corrosion related. As was the case with crude oil pipelines, most other leaks (27 out of a total of 35) were cracked or ruptured oxyacetylene girth welds in pipes assembled before 1932 [18]. Two of the larger incidents involved fires. One fire was located near the town of Fillmore where a ruptured transmission line was ignited by a downed power line and burned a mobile home. In the other incident a 22 inch transmission line was severed and the release was ignited by a passing motorist. Fire response was impeded by the simultaneous rupture of a nearby water main, and the fire destroyed five adjacent homes.

There were 15,021 natural gas leaks at customer facilities. Many of these were small leaks, detected and repaired at the time of service restoration (122,886 gas meters were closed by customers or emergency personnel in the aftermath of the earthquake). Natural gas leaks in the Southern California Gas service area resulted in three street fires, 51 structure fires (23 of them totally destroyed), and fire destruction of 172 mobile homes. There was a much greater incidence of mobile home fires (49.1 per thousand) than other structure fires (1.1 per thousand). Many of the mobile home fires erupted when inadequate bracing permitted them to fall from foundations, severing gas lines and igniting fires. There were no casualties reported in mobile home fires, probably because residents could readily detect the danger (see or hear fire, smell the gas leak or smoke) and protect themselves by evacuating.

3.4. University science laboratory

The earthquake produced extensive hazardous materials spills and fire in all three buildings of the California State University (Northridge) science laboratory complex [19]. The fires were not a threat to other buildings, but response was hampered by loss of water at hydrants. By drafting water from swimming pools and using hydrants about 800 feet from the buildings, firefighters managed to bring them under control within two hours. Locations and quantities of hazmat were identified through interviews with laboratory personnel and documents. Areas of hazmat spills were isolated and ventilated, and personnel from the County Health Department supervised cleanup. There were no casualties during this incident, probably owing to the early morning occurrence of the earthquake.

3.5. Aerospace industrial facility

Rockwell's Rocketdyne Division, which designs, manufactures and tests rocket engines and related systems, has three facilities in the San Fernando Valley area. All are located within four miles of the earthquake epicenter. At the time of the earthquake, the company had allocated substantial capital and operating expenses for seismic hazard assessment, structural mitigation and emergency preparedness [20]. While all the facilities experienced significant structural damage and water damage from ruptured pipes and containers, the level of hazmat incidents was not major. Acid tanks in one facility lost part of their contents due to "sloshing" but the overflow was confined by secondary containment measures. There were numerous spills from other tanks and containers onto laboratory floors, but none were extensive and all were cleaned up by qualified personnel following OSHA requirements. Asbestos abatement turned out to be more extensive than anticipated, largely due to water damage to floor tiles resulting in buckling which allowed the asbestos contained in the tiles to become friable. Casualties were limited to three minor injuries, though the cost of building repair was estimated to exceed $50 million. Clearly, the low level of hazmat incidents was a function of the extensive mitigation measures undertaken by the company.

3.6. Hazmat in earthquake aftermath

The 134 locations with hazmat problems and 60 emergency hazmat incidents officially reported in the M6.8 Northridge earthquake are clearly more numerous than those reported in previous California earthquakes. Perkins and Wyatt [21] cited 18 EIHRs in the M6.6 San Fernando earthquake, 9 EIHRs in the M6.7 Coalinga event, 30 EIHRs in the Whittier Narrows quake, and 50 EIHRs following Loma Prieta. Although the number of reported incidents varies from one earthquake to the next, their occurrence underscores the notion that the events do happen. As we have argued, some of the variation is probably due to differences in soil conditions and the state of mitigation measure effectiveness. The number of hazmat incidents does not seem to be dependent on the magnitude of the earthquake, and as the Northridge experience establishes, EIHRs can even occur when structural damage is minimal or absent. It is also plausible that the reported incidents represent an underestimate of the actual incidents (especially in historical events but also in Northridge in spite of official efforts to locate and document them). Finally, while none of the 57 fatalities in Northridge were attributable directly to hazmat, under the right conditions, the potential for deaths and injuries remains great. The major issue with hazmat in Northridge was the very high dollar cost of response and cleanup.

A key point relative to managing hazmat spills in the aftermath of an earthquake is that this environment is substantially different than the one in which hazmat response and cleanup normally takes place. When two hazards with potentially high negative consequences intersect, the challenges with managing each are greatly magnified. In effect, the hazmat emergencies become an additional threat that must be integrated into the response framework for the earthquake. The coincidence of hazmat and earthquake damages exacerbate normal incident management issues such as impacts on lifelines, loss of communication systems capacity, sources of threats to life and health, and limitations on the capacity of the area medical system and other critical response facilities. With respect to managing hazmat incidents themselves, earthquake-generated obstacles to emergency response were significant, including loss of communication capacity, personnel shortages due to multiple simultaneous events, loss of warning system capacity to the public, and impediments to incidents stemming from road buckling, fire, rubble, structural damage to buildings, and flooding from water mains. It is fortunate that in Northridge the principal consequences of reported hazmat incidents were either localized threats in the workplace (occupational threats) or releases that posed chronic threats to the contacted environment. The absence of acute public health threats like those associated with hazardous gases forming plumes meant that reliance on emergency systems used for warning, evacuating, sheltering and providing medical interventions was not necessary on a large scale.

4. Recommendations for managing EIHRs

The case information from Northridge, combined with knowledge of the nature of the EIHR threat, form the bases for a variety of possible hazard assessment, mitigation and emergency preparedness actions that could be undertaken in California and elsewhere. In a time of shrinking government budgets and "reinvention" of government, one must approach such policy actions cautiously. It is critical 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 [22]. Indeed, it is only through these processes that effective seismic hazard management is likely to be achieved. What is required is increased coordination and improved mechanisms for linking government agencies and organizations already concerned with emergency management, public health and community development. It is unlikely that the creation of new organizations to mitigate, prepare for and respond to EIHRs would represent an appropriate policy response to the problem.

One of the most important steps in managing the EIHR threat simply involves fostering the *implementation* of existing knowledge. Promoting this goal demands, for the most part, only increased information dissemination to private and public organizations. This permits decision-makers to become aware of the EIHR threat and the available mitigation and emergency preparedness actions to manage vulnerability. Certainly this recommendation oversimplifies the magnitude of the task of transferring technical knowledge to practitioners and into practice. The National Earthquake Hazard Reduction Program [23] correctly acknowledged that mechanisms for research information transfer barely exist. Pending the development of such mechanisms one can, however, approach the issue a variety of ways, including establishment of concurrence on system performance goals (through setting standards and guidelines), "piggybacking" seismic upgrades onto nonseismic projects, and providing fiscal incentives such as insurance premium reduction and federal earthquake insurance [24]. Requirements, of course, should be targeted toward the most cost-effective actions in the most seismically vulnerable areas.

Much is already known about strategies for enhancing awareness of seismic hazards and thereby mobilizing support for EIHR risk reduction [25,26]. Rubin [27] contends that states are involved in earthquake hazard reduction through direct actions such as legislation and technical assistance to lower jurisdictions. She advocates brief, carefully focussed meetings of private and public sector policy makers to attract immediate attention and elicit long term support for seismic safety. Similarly, Kinsman [28] advocates use of ''focus groups'' and meetings for information dissemination. The state of Arizona, through the Division of Emergency Management, has demonstrated that such strategies are particularly effective. The Arizona Council for Earthquake Safety (ACES), composed of statewide representatives of government and private sector actors, began as small, structured meetings with relevant decision makers and grew into a large group with a core of members (appointed by the Governor) and associate members. Over an approximately three year period, the level of awareness and activity relative to managing the seismic hazard increased substantially. The organization sponsors quarterly meetings, serves as a central accumulation and distribution point for seismic hazard information, and has conducted major research projects (including a statewide vulnerability analysis, mapping projects, and survey research on government preparedness). Meetings are advertised, open to the public, and the organization provides technically qualified speakers, as well as learning aids – including video tapes and maps and booklets – to organizations, schools and citizens. Such organizations tend to require intensive effort and will be successful only to the extent that they maintain member interest and activity through a sense of achievement of group goals [29]. Clearly the success of the Arizona operation hinged on strong managerial support and staff expertise and dedication, but the absolute level of dollar resources demanded yielded very high returns in mitigation and preparedness. This model would certainly function equally well in other states, and could also be adapted to county and even municipal jurisdictions.

Finally, the Arizona experience as well as the existing literature [5,30] permit the identification of pitfalls that can be avoided in attempts to build awareness. Perhaps the most important strategy is to create programs that emphasize the positive side of seismic safety. It has long been known that information campaigns based on creating fear or posing punishments have only mixed results in dealing with low probability-high consequence dangers. Thus, programs should rely on *incentives* for positive future actions (e.g., rewarding seismic designs for new structures) rather than penalties for past actions (e.g., requiring retrofits to old construction). Similarly, emphasizing the positive business consequences of seismic safety (insuring competitiveness, reduction of losses) is more likely to communicate with the private sector hazmat handlers. Seismic safety advocates should also accept modest initial programs if more ambitious goals encounter serious resistance. An initially successful small program is more likely to be expandable in the future [30]. Last, hazard awareness should be built around a core of public and private sector professionals with a continuing occupational interest in seismic safety. Although these professionals may circulate to other jobs and geographic locations over time, the climate for seismic safety that they build in organizations and professional societies is likely to endure.

4.1. Hazard assessment actions

Relative to preimpact assessments of seismic vulnerability, two types of information about EIHRs are conspicuously lacking. The first kind of information is data for local emergency planners and responders regarding inventories of hazmat (types, quantities, locations, and methods of storage) throughout their jurisdictions. The development of inventories of toxic chemical facilities, as mandated by SARA Title III, represents a major advance in this area. These requirements do not pertain to pipelines, however, and uncertainties still exist regarding the location, timing and quantities of hazmat transportation by rail, highway and marine carriers. Presumably state and federal Right-to-Know legislation requiring disclosure will begin to rectify the problems. An attendant difficulty arises in the response phase, when emergency responders need this type of information. Currently, the data are often in the form of paper records, kept in decentralized locations. A centralized, computerized databank – perhaps linked to a GIS system – would go far to provide timely access for responders.

The second type of information that is lacking deals with plausible estimates of EIHR consequences. The problem is that local emergency managers often lack access to technical expertise and funding needed to develop comprehensive assessments. As a result, local emergency managers can be in the position of not having effective vulnerability data upon which to base emergency response plans. Again, federal and state legislation provides some assistance, but much remains to be done to achieve comprehensive EIHR assessment. For example, the California Health and Safety Code (6.95) and the federal Clean Air Act Amendments 112(r) both require the development of risk management plans by some facility operators, but there are no explicit seismic requirements for the federal legislation.

Both types of information would enhance the ability of local emergency managers to create effective response plans. Furthermore, this information would also permit more effective planning in the immediate aftermath for cleanup and recovery. As noted earlier, the level of cleanup contractor capacity is limited, and competition for these resources will overload and probably backlog the regional capacity. This means that cleanup will become triaged, extending both the time of potential exposure to hazmat, and the time required to resume operations at affected organizations. Thus, business restoration and building demolition (e.g., due to asbestos) will be slowed and could jeopardize business recovery and/or resumption of government operations.

Finally, at least one postimpact hazard assessment activity should be institutionalized. That is the inclusion of hazmat damage assessments as an element of earthquake emergency operating plans. This practice provides not only important information for structuring response, but also permits subsequent analyses of relationships between EIHR incidence and other characteristics such as earthquake intensity, specific mitigation measures and facility type. The procedure adopted by the Los Angeles County Fire Department HHMD serves as a working example of such a system where prompt and complete mitigation of hazmat exposures was achieved.

4.2. Hazard mitigation actions

Hazard mitigation for earthquakes (and particularly EIHRs) is often criticized because it involves expending financial resources for a low probability event. One means of reducing this objection involves the notion of emphasizing and enforcing mitigation actions for hazmat facilities relative to their vulnerability to seismic hazards. In this way, scarce governmental resources could be focused on the most vulnerable facilities, and private industry resources would be expended at times and in geographic areas where the needs were greatest. Implementation of such a strategy requires coordination of hazmat and seismic risk assessment, resulting in a type of seismic zonation that includes hazmat characteristics. Of course the system would be most effective in the context of an accurate system to *predict* earthquakes (especially medium and long term predictions). With this type of technology, one could reserve the most costly mitigation measures for facilities located where an earthquake was predicted. In spite of the embryonic state of earthquake prediction, this type of approach could go far to reduce the resistance to earthquake mitigation measures.

Other hazard mitigation actions can be grouped in terms of the focus of the measure. Transportation of hazmat by truck and rail has historically involved few releases attributable to earthquakes. It is probably reasonable that mitigation measures in this arena be assigned a lower priority. In both cases, hazmat is transported in containment vessels specially designed for the rigors of movement, which affords a significant degree of protection against release in earthquakes as well.

In contrast, pipelines are considerably more vulnerable. A large measure of prevention could be achieved through the development of an expedited schedule for replacing vulnerable pipelines in seismically active areas. Such a program should focus on the replacement of old sections of pipe (which typically contain problem welds), and oil pipelines that run through or near urban areas. In the latter case, the hazmat threat is enhanced because of rapid spread (through mixing with water from ruptured mains) and the potential for ignition (by automobiles and downed electric wires). High priority should also be given to pipelines that pass through valleys where releases could easily enter surface waters such as lakes, streams or rivers.

Fixed-site facilities are so variable that it is difficult to define any general recommendations for mitigation measures that would be appropriate across the board. Risk reduction actions can include reducing the hazmat inventory on site, as well as changes in site layout, system design and system operation. Most specific mitigation measures would logically flow from a careful vulnerability (HAZOP) analysis like those conducted in California in keeping with section 6.95 of the Health and Safety Code. Such reviews can take advantage of the body of measures available that reduce EIHRs such as seismic detection and shutoff devices for gas, high temperature energy and electrical supplies that prevent hazmat releases and minimize damages [31]. Ultimately, the solution to EIHR risk in fixed facilities is to insure that owner/operators are aware of the danger, examine a range of mitigation options, and invest sufficient resources to insure protection. In some cases, owners will undertake mitigation based upon an informed analysis of the benefit/cost ratio of such measures. It is easy to argue that the cost of mitigation is much less than the cost of cleanup, repair, and business lost in connection with an EIHR. It is probable, however, that to achieve reasonable coverage of the EIHR threat nonmarket methods such as government codes and regulations will be necessary. Once codes are established, the resistance to the costs associated with compliance can be reduced by creating extended or flexible implementation schedules.

That is, local authorities can – based on vulnerability of structures and systems – permit the adoption of mitigation as a series of stages, perhaps extended over a period of years, wherein the operator would implement the most critical mitigation measures first and subsequently upgrade the level and extent of protection [31]. The feasibility of this recommendation does depend on the presence of diligent enforcement of the adoption of measures, since some operators may attempt to delay installation to cut costs in the hope that enforcement will be lax or that the codes will change over time.

4.3. Emergency preparedness actions

James Lee Witt, Director of FEMA, has argued that the agency's principal emphasis should be upon mitigation measures. We strongly agree that mitigation of EIHRs, in *both* the short and long run, will be much less expensive than continuing the present state of affairs. Even the best prevention plans can be overpowered by natural and threats, however, so it is important to also enhance preparedness for EIHRs. At the most generic level, there is a definite need for higher levels of coordination between planning for earthquake preparedness and preparedness for hazardous materials emergencies. An important specific aspect of this coordination involves developing a detailed picture of the earthquake impacts, and devising strategies for conducting hazmat emergency response in that environment. The experience in Northridge indicates that the response environment is likely to be characterized by:

- Difficulty with access to the site of the hazmat incident;
- Difficulty with access to the hazmat incident once on site;
- Shortages of equipment itself;
- Shortages of qualified response personnel;
- Presence of multiple incidents (involving multiple forms of hazmat) simultaneously;
- Scarce resources and personnel for cleanup;
- Possible loss of water and electricity, with reduced communications;
- Threats from aftershocks to responder personnel and equipment, also increased likelihood of new/renewed hazmat releases.

One can approach such a response environment by adopting a variety of classes of preparedness measures not normally part of hazmat planning, including:

- Emphasizing that hazmat operators should be able to conduct their own damage assessment and containment;
- Insuring that hazmat operators in a given area do not all plan to rely on the same cleanup contractors;
- Developing a volunteer cadre of minimally trained responders for emergency supplementation of staff;
- Developing cooperative protocols to obtain information on street and access conditions with other agencies (e.g., police, other fire units, paramedics, building inspectors);
- Training responder personnel in techniques for self-protection and equipment protection for earthquakes/aftershocks;
- Developing a protocol for triage of incident response when dealing with multiple incidents.

As the above suggestions indicate, the two most important notions to emphasize in enhancing emergency response to EIHRs are coordination and capacity. Coordination must take place at several levels. Foremost, there needs to be coordination between hazmat specialists and earthquake specialists for all phases of management. The results of this collaboration should be communicated to all types of responder organizations as a basis for regional incident management. Also, hazmat handlers, clean up contractors need to be acknowledged as partners in the incident management structure. Finally, response strategies should emphasize the flexibility to expand capacity where possible. This involves the use of triage protocols, volunteer cadre, and planning for self-protection by handlers.

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