INTRODUCTION

Most large earthquakes that pose a danger of strong ground motion in Mexico City occur along the subduction zone where the Cocos plate is moving beneath the North American plate, one of the most active subduction thrust faults in the Western Hemisphere (Esteva, 1988). The earthquakes of September 19 and 20, 1985, measuring 8.1 and 7.5, respectively, originated on a segment of this subduction zone known as the Michoacan gap. The first of these two events killed 10,000 people, left tens of thousands homeless, and caused the collapse of over 200 multi-story buildings and serious damage to 757 other buildings. This seismic zone has generated 42 earthquakes of magnitude 7 or greater this century, and there is concern that the next major earthquake to affect Mexico City will occur along the Guerrero Gap of the subduction zone, which lies approximately 320 kilometers from the capital. This section of the zone has been quiescent for more than 30 years and scientists believe that an earthquake, similar in size to the one in 1985, has a high probability of occurring before the year 2000 (Espinosa-Aranda et al., 1995).

The frequency of large earthquakes in the subduction zone, the distance over which damaging ground motion from these events must travel to reach Mexico City, and the vulnerability of the capital due to soil conditions and structural characteristics make the city an ideal laboratory for an earthquake early warning system. In the aftermath of the Great Michoacan earthquake, pressure to improve seismic safety intensified and the Mexican government embarked on a comprehensive program that included revised building codes, improved planning, public education and, in collaboration with scientific institutions, the world’s first publicly available earthquake early warning system (EWS). The purpose of the earthquake early warning system, called the Sistema de Alerta Sísmica (SAS), is to warn government officials, the operators of vital services, and the population that an earthquake has just occurred on the Guerrero section of the subduction zone and to provide as much as 50–70 seconds of advance warning before damaging ground motion generated by the earthquake reaches Mexico City.

SAS is a cooperative effort between the Federal District of Mexico and a private research institute, the Center for Seismic Instrumentation and Records (CIRES), with Mexico City’s Public Works department serving as lead agency. Development of the early warning system began in 1989 and was completed in August 1991 at a reported cost of $1.2 million. Mexico City’s SAS consists of a seismic detector system, a digital telecommunications system that operates between the state of Guerrero and Mexico City, and a central control system located within CIRES in Mexico City from which the signal that triggers the automated public alert receivers is broadcast.

The seismic detector system consists of 12 digital strong motion field stations located along a 300 km stretch of the Guerrero coast, arranged 25 kilometers apart. Each field station includes a computer that continually processes local seismic activity as transmitted by a three-accelerograph array serving the station. These instruments record seismic activity that occurs within a 100 km radial coverage area around each station. Programmed into each field station computer is an algorithm that can detect the occurrence of an M > 6 earthquake within 10 seconds of its initiation with an 89% confidence level. At least two stations must confirm the occurrence of the earthquake before the public alert signal is automatically sent from CIRES (Espinosa-Aranda et al., 1996).

The SAS communications system consists of a VHF central radio relay station, located near the Guerrero coast, and six UHF radio relay stations located between the Guerrero coast and Mexico City. Each station has a receiver and transmitter that operate continuously and are tested at regular intervals. The tests also serve to monitor the operational status of all field stations. Two seconds are required for information sent by one of the field stations on the Guerrero coast to reach Mexico City. The purpose of the control system is to continually receive information on the status of the entire SAS, including the operational status of the field and com-
munication relay stations, as well as the actual detection of an earthquake in progress. Information received from the stations is processed automatically to determine magnitude and is instrumental in the decision to issue a public alert (Jimenez et al., 1993). Warnings are disseminated via commercial radio stations and audio alerting mechanisms to residents of the city, 25 Mexico City public schools, government agencies with emergency response functions, the national electric power utility, and Mexico City's main public transportation system, the Metro.

The purpose of this study is to examine the Sistema de Alerta Sismica from a policy and behavioral response perspective. We will focus on several issues including the operation of the SAS on September 14, 1995 and perceptions of the utility of the system in the aftermath of this "exercise," the potential for further deployment of the system to additional communities and organizations in Mexico City and, most importantly, the identification of transferable lessons that could inform decisions regarding the deployment of an earthquake early warning system in the United States.

EARTHQUAKE EARLY WARNING, PUBLIC POLICY AND BEHAVIORAL RESPONSE: PREVIOUS STUDIES

In the most comprehensive study of the feasibility of an operational EWS, Holden and colleagues (1989) set out to (1) identify possible earthquake scenarios for seismic activity along the San Andreas fault north of the Los Angeles metropolitan area, (2) describe and evaluate an EWS, (3) assess the value of a warning, and, (4) describe the funding, management, reliability, and liability aspects of an EWS. The conclusion reached by these researchers, based on surveys of potential users and an expert review of industrial applications, was that construction of an EWS in California was not justifiable at that time.

They found that the preference of potential users for warning times of 30 seconds or greater limited the utility of an EWS to a large event on the southern San Andreas fault. Their cost-benefit analysis revealed that an EWS must produce savings at least 50 times the annual cost of the system (equipment and maintenance costs) and 10 to 50 times the cost of a false alarm to be justifiable. Finally, the preference of potential users for human intervention and decision making rather than trusting automatic warning systems reduced the length of available warning time.

A crucial, though somewhat neglected, finding of both the surveys and the expert evaluation was that "personnel safety" was a significant EWS benefit. In addition, the survey revealed that nearly half of the respondents who reported a dollar amount when asked to estimate the cost of a false alarm indicated false alarm costs of zero dollars. In a later report prepared by the National Research Council (1991), the results of the Holden study were critically reviewed, with the NRC expressing the view that a "market survey" was an unreliable method of assessing the utility of a new technology.

There is a rich and abundant social scientific literature on behavioral aspects of natural hazard warnings. One of the areas which has generated considerable interest is individual and collective perceptions and actions in response to a natural hazard warning. An extensive literature has yielded findings that suggest beliefs and response to warnings are complex and subject to a variety of influences. Contrary to popular myths that people faced with an imminent warning will panic, studies of collective behavior in disaster warning situations have consistently found that maladaptive behavior is rare (this literature summarized in Drabek, 1986).

The social science literature suggests that people who receive warnings may at first react with disbelief followed by information-seeking behaviors that confirm or refute the message content (Mileti and Fitzpatrick, 1993). Beliefs and actions in response to warnings are also affected by various message qualities including content, source, and the number of messages received. Warning messages that are specific, particularly in terms of the nature of the threat and the location of expected impact, are more likely to produce belief and action (Perry et al., 1981). Warnings issued by official sources, mainly emergency services organizations, and multiple messages also contribute to belief and action (Mileti, 1975).

In addition to warning message characteristics, response to warnings also varies with social and demographic aspects of the population at risk. One of the most important of these is past experience with the type of disaster for which a warning has been issued (Perry et al., 1981). Another aspect of past experience is with previous warnings. The literature provides only ambivalent support for a "cry wolf" syndrome, that is, if warnings are issued and the predicted event does not materialize, one consequence may be reduced motivation to respond in future warnings. The impact of false alarms on future warning response is complex and various mitigating factors including fear, the media of warning communication, imminent expectation of disaster, and source credibility may operate to reduce the dampening effect of false alarms on future response (Turner et al., 1986).

The studies cited above were based on warnings of greater length than any which will be produced by the technology employed in Mexico. Having a few seconds in contrast to hours or weeks of warning will introduce new and possibly important response variables. Mileti and Fitzpatrick's (1993) observation, for example, that people do not respond with protective actions upon first hearing a warning bears close examination in the context of earthquake early warning. The impact of prior experience, particularly the disastrous earthquake of 1985 and the activities of groups which emerged in its aftermath, must be closely examined as potential influences on warning response behavior.

METHODS

The primary data for this study were obtained through in-depth interviews with the providers and current users of the
Although some minor damage occurred, there were no deaths, injuries, or structural collapse in Mexico City. The earthquake caused damage.

The ensuing evacuations, according to Department of Education and response readiness in the schools has been a key component of Mexico's seismic safety program, and the successful execution of this evacuation was considered the most significant payoff of the early warning system in this earthquake.

A total of forty-six radio stations are equipped with receivers that carry the alert signal from SAS. In eighteen of these stations, the warning, which consists of a clearly identifiable tone and the statement “alerta sísmica, alerta sísmica” is automatically broadcast without the intervention of human operators. In the remainder of radio stations, a diskette must be inserted into broadcasting equipment in order to play the alert message. According to the public officials with whom we spoke, all participating radio stations relayed the alert message on September 14.

In the Mexico City community of El Rosario, towers broadcast a clearly audible signal when the SAS is activated and this system functioned without difficulty at 8:04 on September 14, providing residents of the community adequate time to evacuate their apartments. A community organization had been created after the 1985 earthquake disaster that conducted training in appropriate response actions including those which should be taken in a warning situation. Residents indicated that they and others around them were frightened when the signal sounded but responded by turning off gas and lights and evacuating their buildings according to established procedures and with the assistance of residents assigned to direct people to the pre-designated evacuation routes and outdoor assembly locations. No one with whom we spoke reported witnessing behavior such as running, shoving, or other actions associated with extreme fear and flight reactions.

In an effort to raise awareness of the SAS and provide instructions on how best to respond to an alert, the government of Mexico City developed and disseminated a brochure to two million households. This brochure describes how the early warning system works and gives instructions as to how residents should respond to an alert as well as advice on preparedness activities and actions to take during an earthquake and after the shaking has ceased. The section of the brochure that addresses activity during the alert period recommends: turning off utilities, opening emergency doors, helping children, older persons and others requiring assistance, and either taking cover inside or evacuating the building using pre-designated routes (not elevators).

The Aftermath of September 14: Expansion or Stasis for SAS?

A plausible hypothesis in the aftermath of the September 14, 1995 alert was that individuals, organizations, and communities would seek greater participation in the SAS program and that the public and private organizations that cooperate to provide earthquake early warnings for Mexico City would aggressively move toward expansion of SAS. It must be recalled that SAS is an experimental program and that coverage is not universal. The September alert was widely interpreted as successful and could have saved many lives had the earthquake caused damage.

Based on our interviews and other documentation, there appears to be neither a strong surge of public demand for participation nor an aggressive strategy by the Mexico...
City government to expand SAS to new segments of the population. Although we were somewhat surprised by this finding, our investigation revealed political, economic, sociological, and technical factors that make the future of SAS uncertain. Clearly, there are factors or conditions which contribute to a future comprehensive deployment of SAS as well as its potential stagnation or even abandonment.

Perhaps the most compelling reason for the further deployment of SAS, and a key factor in its initiation, is the legacy of the September 19, 1985 earthquake. This legacy includes the heightened awareness of the risk of major damage and loss of life in future earthquakes, advocacy for effective programs of preparedness and mitigation, and major changes in the philosophy of civil protection in Mexico. In the aftermath of this earthquake, there were militant demands for programs to reduce hazards and one of these programs was the SAS. There is also widespread belief among residents of Mexico City that many buildings in the city were damaged and thereby weakened in 1985 without being repaired or strengthened to withstand future earthquakes.

There are also reasons why there is neither advocacy nor widespread demand for expanded access to SAS. The SAS radio receivers are expensive, approximately $2,000 US and many organizations, the school district, and community-based organizations find this cost prohibitive. Government agencies indicated that they were unable (or unwilling) to subsidize the expansion of SAS due to the expense. During our visit to CIRES, we were shown a prototype receiver which is smaller, more mobile and far less expensive (approximately $300) than the first generation of receivers. This innovation may prove to be an important incentive to further deployment of SAS.

Mexico City's earthquake early warning system had a strong advocate in former Regent (the equivalent of city mayor) Manuel Camacho Solís. It was under Camacho's administration that the SAS was initially deployed on an experimental basis. Camacho's departure from office, motivated by the desire to run for Mexico's presidency, created a two-fold problem for SAS. His absence from the regency left SAS without a powerful ally and Camacho's departure from the PRI, Mexico's dominant political party, to run as an opposition candidate may have jeopardized the future of SAS, a system closely identified with the former Regent. There is no elected official in Mexico of Camacho's stature or who has stepped forward as an advocate of SAS. In addition, SAS has never enjoyed a consensus endorsement by the engineering and seismological communities within Mexico City's two main universities.

Potential advocacy might come from two other sources, the media, or the public. Despite the extensive participation of Mexico City's commercial radio stations in conveying the SAS message to the public, there does not seem to be a concerted effort on the part of the media to push for an extension of SAS. Currently, 46 of 52 radio stations are equipped to convey SAS messages when triggered. Televisa, Mexico's largest telecommunications organization, which controls the city's television station and six radio stations, has declined to participate in SAS. We monitored the print media for articles that appeared in the aftermath of the September 14, 1995 alert and, in the coverage obtained, failed to find a clear statement of advocacy for further deployment of the SAS.

The Mexican economy is in the midst of a crisis with devaluation of the peso, rising prices, and serious unemployment. An even more salient issue is the political situation in which highly visible public scandals and widespread dissatisfaction with one party dominance has led to greater demands for democratization and reform. Although the memories of September 19, 1985 are still vivid for many residents of Mexico City, the present political and economic crises and the every day manifestations of them have pushed the seismic safety issue into relief, at least for now.

Mitigation and Life Safety as Objectives of SAS

The two major potential benefits of an earthquake early warning system are life safety and hazard mitigation. A warning that strong ground motion is approaching a populated area provides an important advantage in that protective actions can be taken to reduce the risk of injury such as the evacuation of vulnerable structures, locating safe areas within structures, exiting elevators, or moving away from other sources of danger. Although the life safety factor might also be considered mitigation, we would like to distinguish the two and define mitigation as actions in response to an alert that alter processes to reduce the likelihood of damage and disruption. The type of actions visualized here include automatic shutdown procedures, redirecting telecommunications to avoid area overloads, and other actions.

Holden et al. (1989) focused heavily on hazard mitigation in their assessment of the feasibility of implementing an earthquake early warning system in California. The major types of facilities for which data were available were fossil-fuel and hydroelectric power plants, electrical distribution substations, oil processing and refining facilities, water treatment and pumping stations, natural gas processing stations, manufacturing facilities, and large commercial facilities, including hospitals. The database consisted of observations from 82 facilities damaged in 17 earthquakes. The conclusion drawn from these observations was that "with very few exceptions, earthquake warning does not appear to be of significant value in the mitigation of damage to engineered structures or their internal components" (Holden et al., 1989, p. 30). The engineers who conducted this portion of the study noted that the only potential application of EWS was in an area not included in their study, personnel safety. Their conclusion was that personnel safety could be improved by early warning systems in every type of manned facility examined.

If life safety and hazard mitigation are viewed as alternative (though obviously related) benefits of an earthquake early warning system, both the providers and users of SAS have unequivocally chosen life safety as the primary system...
objective. The SAS deployment in schools, the audible signal in El Rosario and as broadcast by 46 Mexico City radio stations is clearly directed at life safety. In other applications where we expected to see mitigation as the principal objective (i.e., the Metro and national electric power utility), life safety concerns also prevailed. Interviews with transportation engineers at the metro and with utility operators revealed that the principal concern was for the safety of passengers and personnel, respectively, for these organizations.

System Reliability: The Specter of False Alarms and Missed Events
There are two types of potential error in the operation of earthquake early warning systems. False alarms involve the activation of an early warning system for earthquakes with magnitudes below some predetermined threshold or events (e.g., microwave noise, etc.) that are not earthquakes. A second and far more dangerous error is a missed event, a situation in which the system fails to announce the approach of dangerous ground motion to which the population is exposed without warning.

The potential consequences of these errors have been the subject of considerable discussion and have factored heavily in debates over the social value of earthquake early warning systems (Holden et al., 1989; National Research Council, 1991). The conventional wisdom is that false alarms may be quite detrimental to those organizations whose warning period response involves curtailing processes that are vital to large numbers of people (e.g., utilities), taking action that negatively affects corporate profits or serves to compromise the credibility of authorities who issue the alert. It has also been argued that frequent false alarms result in the propensity of people to ignore future warnings, the “cry-wolf syndrome” as it is sometimes called. The consequences of a missed event, assuming that an earthquake early warning system has become an established element of public safety, could be catastrophic if lives could have been saved.

According to Espinosa-Aranda et al. (1995), a total of 287 events were detected and recorded between August 1991 and September 1995. Fifteen of these earthquakes were greater than magnitude 5, the threshold for restricted (non-public) warning. During this period, the SAS experienced three technical failures, one missed event and two false alarms. The missed event occurred on October 24, 1993 and involved a M6.7 event for which there was no public alert due to a software error. This event did not cause damage or injuries in Mexico City. The other two system failures were false alarms. The consequences of these errors are unknown as there were no studies or after-action assessments (other than technical) to determine their impact, if any, on public policy or perceptions.

Information obtained in our interviews suggests that when life safety is considered the primary objective of an earthquake early warning system, false alarms are likely to have a less deleterious impact on response to future alerts than might be expected in systems in which mitigation is primary. A senior Mexico City Department of Education official told us that the district considers a possible false alarm as simply another opportunity to drill faculty and students and that the temporary disruption in the instructional program is a small price to pay for increased confidence in response readiness. This readiness to tolerate false alarms was shared by other SAS users as well. We might hypothesize that if the SAS is eventually linked to systems whose curtailment or alteration causes significant disruption of services or financial loss, tolerance for false alarms will drop significantly. The relatively high false alarm tolerance we observed might also be traceable to the disaster subculture of Mexico City, the legacy of 1985, and perhaps to Mexican culture in general.

Behavioral Response to Imminent Alerts
A common predilection, probably fueled by media portrayals of behavior in crisis situations, is to assume that any imminent warning involving a large number of people will be accompanied by confusion, chaos, and panic. But years of disaster research have revealed that human response to the threat or actual occurrence of disaster is largely controlled, rational, and adaptive (Drabek, 1986). The operation of SAS and the activation of the system on September 14, 1995 provide an opportunity to revisit some of the insights contained in this literature and to separate stereotype from reality.

Much of the literature on warning behavior centers on disasters for which lengthy warning times are available (e.g., hurricane, tornado, volcanic hazard, etc.). For example, Perry et al. (1981) found that beliefs and actions in response to warnings were affected by various qualities of message content, and Mileti (1975) observed that multiple messages contributed to belief and action. But SAS messages have little content and the time frame of a few seconds makes multiple messages impossible. It appears, however, that the SAS signal and repeated phrase “Alerta Sismica!” during the signal is widely recognized as an officially issued warning from credible authorities.

One finding which is not warning-time-dependent is the important role played by prior experience with the type of disaster for which a warning is issued. The finding of Perry et al. (1981) that the probability of undertaking adaptive behavior in response to a warning was greatly enhanced among those who had experienced a damaging event in the past is clearly applicable to the Mexico City situation. The catastrophic 1985 earthquake has been a major factor in the propensity of Mexico City residents to take SAS warnings seriously and to respond adaptively. We might also speculate that the importance of this recent past experience with a major earthquake disaster would, as Turner (1986) suggests, reduce the dampening effect of false alarms on response to future earthquake warnings.

Mileti and Fitzgerald’s (1993) observations regarding information seeking and confirmation prior to taking action in response to a warning suggest that timely response to SAS warnings could be problematic. That is, a few seconds of
warning provide little time for interaction with others or confirmation of the message through multiple channels. To some extent, the immediate reactions of others nearby provide cues which undoubtedly affect response behavior. The immediate behavior of parents, informal leaders, and, where organized response to SAS alerts has been established, designated response coordinators is important for the adaptive response of others. Unfortunately, our data permit only speculation on many of these important findings from past studies and additional research is needed to examine behavior in imminent warning situations.

Preliminary findings of a study of behavioral response to the September 14, 1995 alert are quite suggestive that an imminent warning can produce adaptive responses. Arjonilla (personal communication, 1996), in comparing the behavioral response of schoolchildren in institutions equipped with SAS receivers and those without, found that children in SAS-equipped schools showed fewer stress-related symptoms (e.g., fear, distraction, restlessness, etc.), were able to return to and refocus on the academic program more quickly, and were less likely to be removed from school by parents on the day of the earthquake than were students at the non-SAS-equipped schools.

CONCLUSIONS AND OBSERVATIONS: EWS IN MEXICO AND THE US

Geography of EWS: Mexico City and Southern California
While the tectonic setting of the Mexican capital is ideal for an early warning system, critics of EWS have pointed out there are many earthquakes in the US, including several recent damaging southern California earthquakes (e.g. San Fernando, 1971; Whittier Narrows, 1987; Sierra Madre, 1991; and Northridge, 1994), for which the Los Angeles metropolitan area would have received little or no early warning, had there been a system in place. There are scenarios, however, in which an EWS could provide as much warning as was received in Mexico City, such as an event on the southern San Andreas fault. Major earthquakes on the San Jacinto, Garlock, and Whittier-Elsinore faults might also be preceded by enough warning to take protective actions. Possibly as many as one in three earthquakes likely to cause damage and casualties in the Los Angeles area might be preceded by warnings of various lengths in an EWS based on networks in southern California (L. Jones, personal communication, 1995).

Life Safety and Mitigation as Objectives of EWS
Based on our study, we would suggest that any policy-level decision regarding the development, pilot deployment, and ultimate operation of a publicly available earthquake early warning system in the United States must be made with careful consideration of both life safety and hazard mitigation. It appears that in the presence of a relatively prevalent earthquake subculture such as exists in Mexico City, community consensus may be built around life safety as the sole justification for an EWS. It is extremely unlikely, however, that EWS can be justified solely as a means of avoiding financial losses in a commercial and industrial setting or of providing industry with large financial savings derived from mitigative actions undertaken within a few seconds.

Reliability Factors and the Actual and Perceived Impact of System Errors
The lesson of both SAS in Mexico City and real-time seismic information programs in California is that experimental deployment of a new technology and its transition to operational status requires a well-considered strategy and a long view of benefits, risks, and consequences. Based on information assembled in this study and previous research, we suggest that the impact of system errors is likely to be minimized if an early warning system is first carefully introduced to a well-briefed and receptive audience of experimental users and, when experimentation has achieved an acceptable level of technical reliability and public acceptance, a transition is made into an operational mode. The essential point here is that an earthquake early warning system will never be error-free and that the most critical variable is the achievement of a consensus among users as to its indispensability to public safety.

The Social Demography of Acceptance: Mexico City and Southern California
Our observations regarding the potential for public acceptance of an EWS in the United States are at variance with the assumption that an earthquake early warning system must provide the private sector with mitigation opportunities that translate into millions of dollars in savings. Based on our interviews and the social science disaster research literature, it appears that the presence of a constituency or "culture of acceptance" for a new technology like earthquake early warning or real-time seismic information is a more critical factor than its ability, at least initially, to pay dividends. This constituency is likely to emerge in a disaster-experienced population (a disaster subculture) and must be nurtured through advocacy and must be supported by the major institutions in the community (i.e., the media, local government, and community leaders). Both northern and southern California have experienced recent damaging earthquakes, state and local governments have sponsored programs to promote public awareness and preparedness, the news media have been supportive of new technologies to reduce earthquake hazards, and the scientific community has provided advocacy. Thus, our conclusion is that the current environment is conducive to the introduction of an experimental program to provide earthquake early warnings in California.

The Organizational Basis for EWS
Mexico City's SAS is a cooperative venture between a private non-profit organization, Centro de Instrumentacion y Registro Sismico (Cires) and the government of Mexico City (Direccion de Obras Publicas and Dirección de Protección Scientific).
Civil). This cooperative effort has proven advantageous in the experimental phase of SAS, although there has been an apparent lack of vision on the part of the government in developing a strategic plan for moving SAS from the experimental to the fully operational phase of development. The organizational scheme most likely to result in a pilot earthquake early warning system in California is also a public-private partnership. The Tri-Net group (made up of public and private institutions) proposes to enhance the real-time capabilities of the Southern California Seismic Network, including the capability of providing earthquake early warnings. Additional participation would be needed, including that of state and local emergency services organizations. Given the regional scope of a major earthquake, the California Office of Emergency Services (OES) would most likely issue public warnings and public education and planning would be a joint responsibility of OES and local government.

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E QE International, Inc.
Center for Advanced Planning and Research
18101 Von Karman Ave., Suite 400
Irvine, California 92612

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