

# **Risk Management Practices at Industrial Facilities during the Turkey Earthquake of August 17, 1999: Case Study Report**

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## **Abstract**

The Turkey earthquake of August 17, 1999 offered a unique opportunity to study risk management practices and emergency response to accidental releases of hazardous materials triggered by seismic movement. While there has been some attention devoted to releases from pipeline breaks during earthquakes, until recently there has been little consideration of earthquake-related hazardous materials releases at industrial facilities. This paper results from a study of hazardous material releases in 18 industrial facilities in the industrial region of Kocaeli, Turkey, one of the hardest hit areas. Through a series of interviews to plant managers and engineers, and visits to the plant sites, as well as interviews of government officials, the authors document the performance of risk management practices, such as mitigation measures, and emergency response to hazardous material releases during the earthquake.

The study results indicate that hazardous material releases are a real threat to life and property inside industrial facilities as well as to nearby residential areas. Some of the more significant examples of hazardous materials releases triggered by the earthquake include: the air release of 200 metric tons of hazardous anhydrous ammonia to avoid tank over-pressurization due to loss of refrigeration capabilities; the leakage of 6500 metric tons of toxic acrylonitrile (ACN) into air, soil and water from ruptured tanks; the spill of 50 metric tons of diesel fuel into Izmit Bay from a broken fuel loading arm; the release of 1200 metric tons of cryogenic liquid oxygen caused by structural failure of concrete support columns in two oxygen storage tanks; and the enormous fires, liquid petroleum gas leakages, and oil spills at the Tupras oil refinery.

The study identified several strategies to make highly populated, industrialized cities safer and more resilient to earthquake threats. These include seismic-resistant construction codes for buildings and other structures, specifically those pertaining to industrial facilities such as open structures, containment vessels, storage tanks, piping, connections, and pipe racks; enforcement of regulations pertaining to seismic-resistant construction codes and other environmental and public safety laws; risk management practices and mitigation measures in industry which account for the possibility of seismic hazards; emergency management programs in industry and government that take into account the simultaneous effects of the earthquake and possible hazardous materials releases; land use planning as a mitigation strategy to reduce the impact of joint earthquake and hazardous materials releases on urban communities; and the appropriate government structure, organization, and political context in which to effectively manage joint natural and technological emergencies.

## **Introduction**

The Turkey earthquake of August 17, 1999 was one of the strongest earthquakes ever to hit an industrialized region. The earthquake had a magnitude of  $M_w$  7.4 and caused over 15,000 deaths and 40,000 injuries. It is estimated that 214,000 residential units and 30,500 business units either collapsed or were lightly to heavily damaged leaving more than 250,000 people homeless (USGS, 2000). The earthquake not only cost thousands of lives, but also caused direct and indirect economic losses estimated at \$16 billion USD (Tang, 2000; Erdik, 2000).

The strong ground motion severely affected lifelines and infrastructure, as well as industrial facilities, triggering unprecedented hazardous materials releases. The earthquake affected the industrialized areas of Izmit (Kocaeli), Golcuk, Avcilar, Yalova, Adapazari, and Karamursel (Turkey-US Geotechnical Reconnaissance Team, 1999). The industrial sector was hit hard by the quake. Over 350 large and medium industries in the Izmit Bay area of Turkey were affected, and applied for government funds to compensate for losses caused by the earthquake (Izmit Chamber of Commerce, 1999). A report prepared by the Kocaeli Governor's Environmental Director's Office listed 58 industrial facilities in the Kocaeli region alone that suffered moderate to heavy damage during the earthquake; many of them reported having releases of hazardous substances also (Kocaeli Governor's Environmental Office, 1999).

The devastation wreaked by this earthquake was horrific; however, the earthquake does offer an unprecedented opportunity to study the potential for earthquakes to trigger hazardous material releases in industrialized environments. The investigation presented in this paper focuses on the effect of the earthquake on hazardous materials produced or stored in the earthquake area, the performance of hazmat mitigation measures, and the emergency response associated with releases of these materials during the quake.

## **Research Methods and Data Collection**

Data for this project were obtained from interviews conducted at nineteen of the largest industrial facilities in the affected area that experienced extensive structural damage. These facilities were identified from a wide variety of sources including the Izmit Chamber of Industry, the Environmental Director's Office for the Kocaeli Region, Middle East Technical University, and other information gathered by our collaborators at Ege University. Information was also obtained from various documents collected during our investigation; in the following sections of the paper, all uncited information may be assumed to derive from verbal information obtained during the interviews.

At each plant, we interviewed the plant manager or a facility engineer; the interview was structured around a survey instrument which asked questions regarding the type of materials stored at the facility, mitigation and process control measures for release and dispersal of hazardous materials in effect at the time of the earthquake, and the performance of these mitigation and control measures during the earthquake. The survey

also included questions regarding emergency management plans for hazardous materials releases in the facility, and asked for an assessment of how successful these were in the context of the earthquake.

### Case Study Reports and Analysis

We visited and interviewed a total of nineteen industrial facilities. These plants are located in the areas of Gebze (two plants) and Korfez (three plants) to the east of Izmit, in the heart of Izmit one kilometer or less from the shoreline (three plants), to the north of Izmit (one plant), in the industrial corridor along the road to Ankara to the west of Izmit (six plants) and in Yalova (two plants). Figure 1 indicates the location of these facilities. Although fourteen industries visited reported having some problems with hazardous materials during the earthquake, we present here detailed information about the two cases that we believe are most significant because of the potential they exhibited for impacting public health and safety, and the level of difficulty experienced in responding to the simultaneous natural and technological disasters. We first discuss some general findings about the facilities visited, and then follow with detailed reports on the two case studies.

### General Findings

The nineteen plants visited represent a variety of industry types including petrochemical and oil refining (3), chemical (6), biotechnology (3), metallurgical (2), rubber (2), textile (1), construction (1), and hazardous/solid waste treatment (HSWT) (1). Fourteen of the facilities considered themselves large-size facilities and five considered themselves medium-size facilities. The large-size facilities generally employed more than 200 people. Seven of the facilities were multinationals, the rest were Turkish. All of the facilities visited, except the HSWT plant, suffered some damage during the earthquake.

**Figure 1. Industrial facilities visited in the Kocaeli region in Turkey.**



Note: Red and yellow dots indicate location of industrial facilities visited. Yellow dots represent Tupras (on the right) and AKSA (on the left).

Nine of these facilities suffered substantial hazardous materials releases, and an additional five acknowledged having “minor” releases that were cleaned up quickly, or dispersed rapidly into the environment without causing any adverse effects.

Some of the more prominent examples of hazardous materials releases triggered by the earthquake include: the intentional air release of 200 metric tons of hazardous anhydrous ammonia to avoid tank over-pressurization due to loss of refrigeration capabilities; the leakage of 6500 metric tons of toxic acrylonitrile (ACN) into air, soil and water from ruptured tanks; the spill of 50 metric tons of diesel fuel into Izmit Bay from a broken fuel loading arm; the release of 1200 metric tons of cryogenic liquid oxygen caused by structural failure of concrete support columns in two oxygen storage tanks; and the enormous fires, liquid petroleum gas leakages, and oil spills at the Tupras oil refinery.

All the facilities surveyed were affected by loss of electrical power and communications capabilities, as well as the lack of sufficient personnel to respond to the emergency situation in their factories. Emergency water systems and back-up power generators existed in all of the facilities visited at the time of the earthquake. However, during the earthquake seven facilities suffered loss of water supply and five did not have access to an emergency water system. The loss of electrical power was in part responsible for failures in emergency water systems (inability to operate emergency water pumps and foam sprayers), as well as general damage to the emergency water systems themselves (mainly caused by pipe breaks or ruptures).

### **Risk Management and Emergency Management Practices at Industrial Facilities Affected by the Kocaeli Earthquake**

All of the industrial facilities visited had implemented some measures to mitigate the effects of possible hazardous materials releases during normal operation. The use of containment dikes, for example, was apparent at almost all the sites. However observations indicated that some may not have sufficient capacity to contain the contents of the tanks. Thirteen facilities reported the use of restraining straps or chains and the strapping and anchoring of emergency equipment. Nevertheless, unsecured small propane and LPG gas cylinders, as well as unsecured barrels containing hazardous materials, were observed in almost all facilities that handled them.

Eight of the facilities claimed to have performed off-site consequence analysis, but only three had identified populations at risk to a hazardous material accident.<sup>1</sup> Nine of the industries visited said they carried out risk analysis to determine what series of events might lead to a hazardous material release or a fire/explosion in their plants, yet only one of the facilities had considered the effects of seismic ground motion in their risk analysis.

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<sup>1</sup> However, owing to translation difficulties between English and Turkish, it is not certain that either this question or the question referring to off-site consequence analysis were fully understood by the interviewees.

Structural design and/or retrofitting for earthquakes characterized only seven of the facilities visited, and in most cases, earthquake-resistant construction existed only in the newer parts of the plants. However, even design for earthquake loading did not always prevent structural failure; a 115-meter concrete stack designed to earthquake resistant codes collapsed and helped trigger the four-day Tupras refinery fire. Table 2 summarizes the mitigation measures in place at the industrial facilities visited.

All of the industrial facilities interviewed had emergency management plans in place that included training programs for staff and workers on the use and handling of hazardous materials (including maintaining material safety data sheets) and response to hazardous substance releases, fires and explosions. However, only four facilities had earthquake emergency management plans in place at the time of the earthquake. All facilities visited had on-site fire fighting teams. Seven said they had specific teams for air releases, and eight said they had specialized teams to respond to spills. Three of the companies had teams that could respond to any of these types of emergencies.

The practice of risk management activities by these facilities can be attributed in part to the fact that many of the interviewed industries are either certified or about to be ISO 14000 certified, and partly to the fact that facilities are required by Turkish environmental law to carry out mitigation measures to prevent or reduce the risk of accidental hazardous materials releases. Although environmental laws regulating hazardous materials do exist, a general lack of awareness of these laws persists.

### **Case Study 1: Tupras oil refinery and adjacent fertilizer plant**

Tupras is a state-owned oil refinery producing 11.5 million metric tons/year of naphtha. It is the largest refinery in Turkey and is located in Korfez in the midst of a heavy industrial area surrounded by residential communities. In addition to adjacent fertilizer and chemical plants, there are five natural gas and LPG distribution facilities near the refinery. Given the proximity of these industrial facilities to one another, the large fires at Tupras posed great risks of explosions and hazardous materials releases at nearby industrial facilities and neighborhoods.

For the people of Korfez and nearby Derince, the earthquake was the first disaster, but the huge fires and threat of a hazardous material release at the fertilizer plant next door became a major concern for those who survived the earthquake and were trying to simultaneously rescue family and friends. As many of the people interviewed put it, this was the apocalypse: “We want to share our experience of this catastrophe so that people in other parts of the world will be better prepared. We don’t want anyone to have to go through something similar again....” In the following sections, we discuss the damage and emergency response at the refinery and the adjacent fertilizer plant, and provide a short commentary on the events at these plants and the neighboring area.

***Earthquake Effects on the Tupras Refinery.*** The refinery was operating at full capacity on the morning the earthquake occurred. The earthquake collapsed a 115-meter-high reinforced concrete stack in the crude oil area, breaking and cutting 63 product and utility

pipelines, and a charge heater. The engineers we spoke with believe that the combination of the broken lines, the impact of the falling stack, the high pressure in the lines, and the 350 degree temperature of the charge heater were responsible for the enormous fire which ensued. Because of insufficient and inoperable valving, flow from the product lines could not be shut off. The fire was put out after four hours, reignited around noon, put out, and then reignited again at about 6 pm that evening. In addition to the fire in the crude unit, there were fires in the naphtha tank farm and a smaller fire in the main warehouse which the plant managers believe was started when chemicals, stored in glass containers, fell from storage racks and reacted.

The plant has a total of 45 storage tanks in three tank farm areas (for naphtha fuel, crude oil, and liquefied petroleum gas (LPG)). The most affected was the naphtha tank farm area where an enormous fire melted six steel storage tanks and consumed more than 18,000 m<sup>3</sup> of naphtha. It is believed that sparks, caused by metal-to-metal contact of the vibrating floating-roofs and the tank shells, ignited four tanks. Leaking naphtha from a damaged flange on one of the four tanks ignited and flowed downstream through the refinery's drainage system, spreading the fire to two additional naphtha tanks. Thirty of the forty-five tanks in the tank farms suffered damage. Typical damage to tanks included elephant-foot buckling of tank walls, bulging of tank tops due to sloshing of liquid, cracking of tank roof-shell wall joints, and damage to roof seals. A small amount of LPG leaked from a broken flange connection, but no ignition occurred.

Tupras managers reported two incidences of hydrocarbon spillage into the Bay of Izmit. The first was from a ship at the loading/unloading naphtha port terminal which tore loose, breaking pipe connections causing a leakage of naphtha. The second incident involved the release of approximately 35 metric tons of LPG into the bay at the jetty, when a LPG loading/unloading arm broke due to the earthquake.

In the days following the earthquake, there was a thick layer of oil at the southern shoreline of the Bay of Izmit between Karamursel and Degirmendere, at the small fishing harbor of Guzelyali (Tsunami Research Group, 1999). According to the Tsunami Research Group report, the entire harbor was covered with a 2-15 cm thick layer of oil, which they believe probably came from the Tupras refinery across the bay. Their assumption is based on the fact that the day before they arrived at this site (August 20, 1999) there had been strong north-to-northeast winds which probably blew the oil straight from the refinery to the southern shore of the bay.

***Emergency Response at Tupras.*** Immediately after the earthquake, operators shut down as many processing units as they could and closed operable valves to reduce the flow of product to the fires. Many plant personnel were unavailable to aid in these efforts however, as they had fled the plant in fear or to find family and friends. Response was greatly hampered by the loss of power supply, minimal or no water pressure due to water supply pipeline breaks, and the loss of communications (no phone lines, no access to mobile phone lines, no internet access). There was much confusion at the refinery and little direction on how to proceed until senior managers arrived at the plant from their

homes at about 3:25 a.m. Entrance to the plant was also hindered by access roads which had buckled under the seismic loading.

Emergency response centered on containing the fires using foam spray. The power from the main grid to run these systems had been lost when the earthquake struck. Emergency power generators were used instead but were not started immediately for fear that LPG or other flammable gas leaks would lead to additional fires. The available pumps and power however, could only supply one-half of the pressure required, making it difficult for the spray to reach the fires. The 3000 metric tons of on-site fresh water supply (required to mix with the chemical agent to form the fire-fighting foam) were quickly consumed. Additional water supply was taken from the emergency water supply available at a nearby petrochemical facility, as well as from water brought in by trucks and saltwater pumped from the Bay of Izmit.

It took four days to put out the fire in the naphtha tank farm. External firefighting efforts at Tupras did not arrive until three hours after the earthquake Turkish personnel as well as foreign ground and air support teams combated the fire. Aircraft flew over the blaze between large clouds of black smoke and sprayed chemicals to douse the flames and cool neighboring naphtha tanks to prevent them from burning. However, in several cases external help was made to wait outside the company's doors until needed, wasting precious time and resources that were much needed elsewhere. This fact brings to attention once more the problems encountered because of lack of coordination and communication problems. In interviews, local government officials questioned the effectiveness of the highly centralized government in responding to the fire in a timely manner. In an example of poor coordination, some equipment such as hoses and fire trucks could not be attached to the Tupras water system because of differences in fire fighting system codes. The fire department equipment in Istanbul's system is based on German codes, while the Tupras refinery fire system is based on US codes.

Attempts to clean up the oil spills into the Bay of Izmit began on the first day. A one-kilometer radius floating oil-barrier was positioned in the bay to confine the oil. Help in the spill clean-up came from teams from Holland, the United Kingdom, and Istanbul. The teams worked for one week and ultimately collected 600 cubic meters of oil from the surge pools and 300 cubic meters of oil from the sea.

A major concern for the emergency responders at Tupras was keeping the fire in the naphtha tank farm from spreading to nearby tanks at the onsite LPG storage area, as well as the ethylene and LPG storage tanks in neighboring industrial facilities. The possibility of additional fires or the explosion of any of the seven 5000 m<sup>3</sup> LPG spherical pressurized storage tanks posed a great threat to other industrial facilities in the area and nearby residents. Furthermore, the imminent danger of continued fires, and/or explosions was a threat to the nearby fertilizer plant storing ammonia. As a Tupras manager explained, "All we could do really was to try to cool down the remaining tanks so they wouldn't burn too or spread to other tank farms."

***Earthquake Effects on the Fertilizer Plant.*** This urea fertilizer plant is adjacent to Turpras. It is a privately owned industrial facility employing more than 200 workers. The plant suffered moderate to heavy structural damage, although no hazmat releases occurred during the earthquake. Losses include cracking of all refractory vessels (ceramic vessels that hold material inside vertical ovens) and tearing of anchor bolts holding vessels down; deformation of transportation belts used in production lines; breaking of joints in many of the steel constructions; structural damage to packaging building; and total collapse of management building. Furthermore, an underwater pipeline measuring 1.6 meters in diameter, which was used to transport saltwater for the cooling water system, suffered structural damage resulting in leakage at the flanges. The plant's port terminal also suffered heavy damage. More than 50 meters of pier was totally submerged. Anchor bolts failed on a 400-metric-ton urea-ammonia storage tank containing 270 tons of the material. Luckily, there were no leaks.

***Emergency Response at the Fertilizer Plant.*** With fuel tanks at the adjacent Tupras refinery in imminent danger of exploding, the fertilizer plant was shut down immediately after the earthquake and the staff was evacuated. Before leaving, the valves on the two refrigerated ammonia tanks were opened and allowed to bleed ammonia to the atmosphere. This action was necessitated by the complete loss of electrical power at the plant and insufficient capacity of emergency power generators to supply power to the refrigerating unit of the ammonia tanks. Fearing an intolerable build-up of pressure in the tanks as the ammonia warmed, workers allowed 200 metric tons of ammonia to escape over a 48-hour period.

***Discussion.*** The enormous fire at Tupras not only threatened LPG and crude oil tank farms at Tupras, but also the adjacent fertilizer plant storing 13,000 metric tons of ammonia, a nearby petrochemical facility, and LPG tank farms at neighboring distribution facilities. Concern over the possibility of explosions and hazardous materials releases at these facilities caused government officials to recommend the evacuation of an area five kilometers in radius from the refinery. However, concern was much more widespread. In our interviews at factories located to the east of Izmit, we learned that personnel at plants as far as nineteen kilometers from Tupras had also evacuated. The evacuation forced residents and search teams to abandon rescue activities in Korfez (Yarimca) and Derince for two days, leaving people trapped in buildings and under debris. It is still not known, and probably may never be known, how many people might have been saved if search operations had not needed to be cancelled because of the technological disaster at the oil refinery.

A manager at the petrochemical plant next door to Tupras stated: "Everything at Tupras went wrong; they had bad luck." Tupras was prepared for an accidental release of a hazardous material, a fire, or an explosion during normal circumstances. However, as Reitherman (1982) notes, an earthquake-triggered hazardous material release is complicated because the earthquake affects response capabilities, as well as being the cause of the release. This was particularly true in the case of Tupras. The earthquake caused problems, such as loss of electrical power, damage to water supply pipelines, blocked access roads, and lack of communications hindered the response to the

technological disaster. According to one of the Tupras managers interviewed, “We could not even ask for help; we were totally cut off from the rest of the world.” After the first few hours, thanks to short wave radios, communication at Tupras was made possible. Onsite roads and offsite access routes to and from Tupras and the fertilizer plant were almost impossible to use. Emergency help had to be brought in by boat or helicopter.

Another contributing factor to the difficult situation was the general shortage of workers to respond to the emergency. During our interviews it was made clear that it was very difficult to find people who could stay and help with the response efforts. At Tupras, as well as in the nearby petrochemical facility, managers reported they locked all access gates so that no one could leave or enter the factory. Workers were asked to work twelve or sixteen hours to help deal with the emergency, and could not leave until a replacement arrived.

It is not clear how the release of two hundred metric tons of ammonia during the two day period affected nearby residents. Fortunately, all weather data indicates that winds were predominantly from land to sea (coming from the North). This can also be confirmed by the observation that oil, which had spilled at Tupras and other facilities on the north shore, appeared on the south coast of the Marmara Sea (area near Golçuk and Yalova) in the days following the earthquake. In informal conversations, residents of Derince and our translator recalled a strong pungent odor in the air, but were unsure of what was causing the smell. The last thing they could think about was the odor. They were far more concerned with saving family, relatives and friends and evacuating the area.

## **Case Study 2: AKSA Chemical Plant in Yalova**

AKSA is a large acrylic fiber manufacturing facility located in Yalova on the southern shore of the Marmara Sea, which produces large quantities of acrylonitrile (ACN), a highly toxic and flammable compound. The ACN is stored in eight tanks at the plant; the three partly-full tanks suffered major damage as a result of the earthquake. ACN leakage occurred in three ways from these tanks: one tank’s outlet pipe broke; the second had a leak at the base of the tank; and the third tank’s roof ruptured, leading to an air release (ACN is stored as a liquid but volatilizes easily). Concrete containment dikes around the tanks cracked, and the liquid ACN flowed through the storm water drainage channel into the Bay of Izmit.

***Emergency Response at AKSA.*** The leaking ACN was discovered at about 8 a.m. In the confusion following the earthquake, due to the failure of the electricity system and the resulting loss of lighting, the plant employees were not immediately aware of the leakage. Even the distinctly acrid odor of ACN was not reported until morning. Emergency response centered around preventing volatilization of ACN from the open tank, the ACN pools in the tank farm, and the ACN in the drainage channel by spraying foam on the liquid ACN. Since power had been lost, diesel generators were employed to supply power for the sprayers, however, fear of ignition of the ACN from the emergency generator sparks delayed activation of the generators until 11 am. From 9 am to 11 am, foam was applied manually. Even with the generators working, only portable spraying

units could be used on the fire; the spray nozzles which ring the tanks could not be activated by the reduced amount of power supplied by the generators. In addition, the water transmission line into the plant was broken, so AKSA personnel were forced to use seawater to mix with the foaming agent, which made the agent less effective.

Eventually, AKSA ran out of foaming agent and requested additional supplies from the government and nearby industrial facilities. Delivery was hampered because the road to the plant was impassable, so supplies and personnel reached the plant by sea or helicopter. Meanwhile, beginning at about 10:30 am, AKSA staff began to control the ACN runoff to the Bay of Izmit. People in the immediate area of the plant began to evacuate after AKSA managers informed the government at 11 am that there was a dangerous ACN release. Ultimately, it took 40 hours from the time the earthquake struck to stem the liquid and gaseous releases from the plant.

Environmental damage due to the ACN release included the death of all animals on the grounds of the plant and all vegetation within 200 meters of the tanks. No one at the plant or in the neighboring community died due to the release, although a simple modeling exercise using EPA's RMP Comp model<sup>2</sup> provides estimates that an air release of 6500 metric tons of ACN over 48 hours would yield a toxic plume of 6.6 km in radius. This is the area around the plant in which people would be exposed to an ERPG-2<sup>3</sup> or greater levels of ACN (i.e. levels that a person can be exposed to ACN for 30 minutes before suffering adverse health effects). Although authorities in Yalova had established a protection zone of 1.2 km around the plant, some development had nevertheless occurred within the area. The RMP Comp model results show that the area affected was much larger than the designated protection zone. Therefore, people living outside the protection zone around the plant were likely exposed to uncomfortably high concentrations of carcinogenic ACN.

The ACN also affected the sea in the Bay of Izmit Bay, as well as soil and groundwater in the area. There was little reported fish kill, although this is surprising because ACN is highly toxic. There is concern, however, about the long-term effects of ACN on the ecosystem of the Bay of Izmit and faculty from the University of Istanbul are engaged in long-term monitoring of the Bay. The groundwater under the tanks reached ACN concentrations in the thousands of ppm, but under a continuing pump-and-treat regimen the concentrations have dropped into the hundreds of ppm.

### **Concluding Remarks**

This study has provided first-hand evidence that earthquakes act as a triggering mechanism for *multiple and simultaneous hazardous materials releases*. When this happens, hazmat problems compete with the earthquake disaster for emergency

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<sup>2</sup> The RMP Comp model was developed by the CAMEO Team at the Hazardous Materials Response and Assessment Division, NOAA, and the Chemical Emergency Prevention and Preparedness Office of the United States Environmental Protection Agency (EPA).

<sup>3</sup> ERPG values are put out and updated annually by the American Industrial Hygiene Association (AIHA).

resources, greatly hampering search and rescue operations. Although all the industrial facilities visited had various types of mitigation measures in place to reduce the risk of hazmat releases, these did not prevent them from occurring. Furthermore, none of the facilities interviewed had addressed the particular problems associated with joint earthquake and hazmat disasters. In industry, emergency response plans did not particularly address earthquake scenarios, and more importantly did not specifically address or prepare workers and managers for the specific conditions that exacerbate an emergency situation during and following an earthquake. These include loss of electrical power, loss of water supply systems, an overall upset to all process units in production, loss of boiler and cooling capabilities, lack of communication systems and access roads, and a general sense of confusion and unavailability of personnel to respond to the earthquake-caused problems.

The proximity of Tupras and AKSA to residential areas, and in particular of Tupras to other industrial facilities which handle highly flammable and toxic chemicals aggravated the situation in both cases. There is a need for land use planning mitigation strategies to deal with joint earthquake and technological disaster threats in highly urbanized industrial regions. This is well stated by Christou et al. (1999) in an article about land use planning methodologies in the Europe and elsewhere:

“...establishments able to cause major accidents ...with consequences extending outside their borders should be separated from residential and commercial areas by *adequate* distances.”

Christou et al. also note that the “domino effect” of a technological disaster escalating as it crosses to neighboring plants, as threatened to occur at Tupras and the adjacent fertilizer plant, can be avoided by the appropriate siting of industrial facilities. The adoption of land use planning and siting requirements in densely populated regions is vital in order to protect people, property and the environment.

In summary, the study confirmed several strategies that should be pursued in order to make highly populated industrialized regions safer and more resilient to joint earthquake-technological disaster threats. These include the development of:

- Risk management practices and emergency response plans by industry that take into account the simultaneous effects of the earthquake and possible simultaneous and multiple hazardous materials releases.
- Emergency response plans by government (or emergency response responsible party) that take into account the government structure, organization, and political context within which joint natural and technological emergencies are managed; as well as emergency response plans that consider the complex set of problems that are common during a hazardous materials release (s) during or following an earthquake.
- Land use planning requirements as a mitigation strategy to reduce the risk of joint earthquake and hazardous materials releases.

And of course we also recommend:

- The use of seismic-resistant construction codes for buildings and other structures, specifically those pertaining to industrial facilities such as open structures, containment vessels, storage tanks, piping, connections, and pipe racks.
- Enforcement of laws and regulations pertaining to seismic-resistant construction codes and other environmental and public safety laws;
- Enforcement of risk management practices and mitigation measures in industry to account for the possibility of seismic hazards.

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