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Risk of Earthquake-Induced Hazardous Materials Releases in Multnomah County, Oregon: Two Scenarios Examined

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With a vision of “disaster ready, everyone - everywhere”, Multnomah County’s Office of Emergency Management’s mission of working together to build resilient communities is guided by national and international best practices, research, after actions and improvement plans, and robust, meaningful engagement with our community.

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Executive Summary

Multnomah County is home to numerous industrial facilities which store or handle hazardous materials (HAZMAT). When these hazardous facilities are seismically vulnerable and located near residential areas, they pose significant threats to the health and safety of residents in the event of an earthquake. The best-known threat of earthquake-induced hazardous material releases in Multnomah County is the Critical Energy Infrastructure (CEI) Hub located along the Willamette River. Estimates suggest that during a Cascadia Subduction Zone (CSZ) earthquake, the CEI Hub may release between 65 and 194 million gallons of petrochemicals (Multnomah County, 2022). Such a catastrophic release will threaten the health of the more than 45,000 people who live or work near the CEI Hub with exposure to toxic concentrations of evaporating petrochemicals and the impacts of fires that are likely to start during the earthquake. These threats would arrive at a time when public response operations will be limited and will face significant barriers, including widespread infrastructure damage.

This report (specifically Chapter 5) deepens our understanding of the threats of earthquake-induced HAZMAT releases in Multnomah County by examining additional industrial facilities located in the Highway 30 and North Portland industrial areas beyond the boundaries of the CEI Hub and including facilities unrelated to energy infrastructure. Most of the highest-risk hazardous facilities in Multnomah County are in liquefaction zones (see Figure 2, page 67), and most of those in this study area are 'pre-existing non-conforming,' which means they are not built to sufficient seismic design requirements. These hazardous facilities store a variety of acids, potentially explosive chemicals, and toxic inhalation hazards in a variety of container types. Toxic inhalation hazard chemicals stored in aboveground storage tanks and pressurized vessels may pose substantial risks to residents of Multnomah County if they are seismically vulnerable. To exemplify this threat, selection criteria were defined (see page 70) and used to identify four of the highest-risk, seismically vulnerable hazardous facilities in the study area. Worst-case release scenarios were developed for each of these four facilities using average meteorological conditions for a summertime and a wintertime release (see Figures 4-9).

The results of the two seasonal scenarios are evidence for significant life safety risks from earthquake-induced hazardous materials releases. The models used in the scenarios demonstrate worst-case yet realistic casualty estimates for four of the facilities. The results demonstrate that a summertime release scenario (see page 79) could result in more than 330,000 irritation level exposures, 17,000 potential injuries, and more than 2,500 potential deaths, and a wintertime release scenario (see page 85) could result in more than 100,000 irritation level exposures, 18,000 potential injuries, and more than 1,100 potential deaths. These casualties would occur when decontamination capabilities are hampered by earthquake damage to water infrastructure and access to hospitals will be challenged.

Based on the results of this study, a priority recommendation is for the responsible agencies to lead a collaborative effort with public agencies, neighboring jurisdictions, and state and federal governments to conduct additional hazard assessments, pre-planning efforts, and hazard mitigation efforts. Coordination is necessary to pursue legislative action, prepare community members, and respond to HAZMAT releases or mass casualty incidents. Existing organizations, networks, and relationships should receive support and investment to enable work focusing on this hazard. It is essential that critical facilities, including hospitals and schools, in high-risk areas are informed of the hazard so that the necessary capabilities can be developed.

Efforts should be made to better understand the threats posed by earthquake-induced HAZMAT releases by conducting quantitative risk assessments for all high-risk hazardous facilities in Multnomah County to identify vulnerabilities and possible impacts. These efforts will assist in prioritizing preparedness and mitigation efforts to minimize risks to health and improve public safety.

Additionally, expanding upon existing public information efforts regarding this life-threatening hazard and the protective actions people can take for themselves and their communities is also recommended. Communities need a robust understanding of the risk and must be prepared to implement recommended protective actions like self-decontamination, sheltering in place, and evacuation prior to any hazardous materials release.

Because evacuations will likely be necessary for some HAZMAT releases or fires (e.g., at the CEI Hub). The possible use of personal protective equipment (PPE) is discussed in Chapter 5, however further assessments are necessary to assess the feasibility of the distribution and use of PPE. Following a CSZ earthquake, telecommunications to the public will be interrupted and residents will need to self-initiate protective action recommendations; it is therefore critical that these public education efforts take place prior to an incident.

Chapter 1: Introduction and Purpose

Multnomah County Emergency Management was awarded a grant through the State of Oregon, described in the funding statement of this chapter, intended to support evacuation planning for the communities potentially impacted by a catastrophic release at the Critical Energy Infrastructure (CEI) Hub due to a Cascadia Subduction Zone (CSZ) earthquake. Based on an initial analysis of the available research on the threats facing the communities alongside Highway 30 and the North Portland industrial areas, the planning team felt insufficient information was available to create an operational evacuation plan for residents. The threat of a CSZ earthquake releasing toxic inhalation hazards, including anhydrous ammonia and chlorine, had been identified by multiple reports on the CEI Hub (Multnomah County, 2022; Oregon Department of Geology and Mineral Industries [DOGAMI], 2012; Oregon Seismic Safety Policy Advisory Commission [OSSPAC], 2019). However, due to their scope limitations, none of these reports were able to provide a detailed assessment of these risks.

Inadequate knowledge of possible earthquake-induced hazardous materials (HAZMAT) releases could result in significant human harm when planning for evacuations. If members of the public are encouraged to immediately evacuate following an earthquake, then they may place themselves at greater risk of harm by leaving shelters that could protect them from gaseous chemicals. Additionally, inadequate knowledge of the possible distribution and timelines for HAZMAT releases could result in the placement of disaster resource centers (e.g., mass shelter facilities) in harm's way. To assist planning for public protective actions and response operations, this report’s Planning Team decided to focus efforts on better defining this hazard and generating a preliminary understanding of the risks residents in Multnomah County face.

In six chapters, this report examines the risks of earthquake-induced hazardous materials releases in Multnomah County. Chapter 2 conducts a systematic review of the academic literature pertaining to earthquake-induced hazardous materials releases. Chapter 3 examines the life safety risks and response challenges in Multnomah County’s most well-known threat of earthquake-induced hazardous materials releases, the CEI Hub. Chapter 4 reviews laws pertaining to fixed facilities which handle hazardous materials in the United States and in Oregon to understand the emergency management expectations placed on these facilities. Chapter 5 provides a hazard assessment for possible earthquake-induced hazardous material releases in the North Portland and Highway 30 Industrial areas. Chapter 6 reports on an Alert and Warning Exercise hosted by Multnomah County Emergency Management and the Institute for Sustainable Solutions which used the scenarios developed in the hazard assessment. Chapter 7 provides recommended next steps to Multnomah County derived from all elements of this report.

Limitations

As this report is the first to take a direct focus on the risks of earthquake-induced HAZMAT releases in Multnomah County, it should not be taken to be comprehensive nor conclusive. A variety of scope and methodological limitations should encourage planners and practitioners to view this document as a jumping off point for continued investigation and future efforts. The central limitations in this report are as follows:

Only four facilities in the North Portland and Highway 30 industrial areas which house toxic inhalation hazards are assessed in this report. This means many other facilities which use or store toxic inhalation hazards in large quantities were excluded. Also excluded were well over 1,000 other hazardous facilities in Multnomah County which store or use other hazardous materials including acids and chemicals with explosive and/or toxic inhalation characteristics, all of which may pose a threat to residents following a CSZ earthquake. *It is important to note that under the Emergency Planning and Community Right-to-Know Act[1] (EPCRA), Local Emergency Planning Committees[2] (LEPCs) must develop an emergency response plan. These plans are required to be reviewed at least annually.*

The models generated for this report's release scenarios account for only a worst-case release scenario in two wind conditions. It is impossible to know the exact quantity of hazardous materials any of these facilities will have on site at the

[1] About EPCRA: https://www.epa.gov/epcra

[2] Federal LEPC: https://www.epa.gov/epcra/local-emergency-planning-committees, Oregon LEPC: https://www.oregon.gov/osfm/fire-service-partners/pages/local-emergency-planning-committee.aspx

time of an earthquake, and there are myriad possible meteorological conditions which would affect the distribution and life safety risks of a release. These two limitations mean that this report's findings are only one possible example of the extent and distribution of toxic gasses following an earthquake.

To assess the seismic vulnerability of hazardous facilities, the Planning Team relied on building age and information around historical building codes in the State of Oregon. The building age database does not indicate if the hazardous materials storage units were in place at the time of building construction and does not indicate if significant retrofits have occurred. It is therefore possible that none or all of the selected facilities will experience a catastrophic release following a CSZ earthquake. Future, site-specific vulnerability assessments are necessary.

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Portland State University and the Institute for Sustainable Solutions are located in the heart of downtown Portland, Oregon, in Multnomah County. We honor the Indigenous people on whose traditional and ancestral homelands we stand: the Multnomah, Kathlamet, Clackamas, Tumwater, Watlala bands of the Chinook, the Tualatin Kalapuya and many other indigenous nations of the Columbia River. It is important to acknowledge the ancestors of this place and to recognize that we are here because of the sacrifices forced upon them. In remembering these communities, we honor their legacy, their lives, and their descendants.

Chapter 2: Earthquake-Induced Hazardous Materials Releases Literature Review

Research suggests that large earthquakes threaten hazardous industrial facilities which in turn pose a significant risk to people, property, and the environment, especially in unprepared urban areas (Cruz et al., 2004). Due to the wide geographic impact of earthquakes, they tend to cause simultaneous releases from many, sometimes hundreds, of hazardous facilities in the impacted area, and at the same time, earthquakes damage infrastructure lifelines critical to successful response operations and public protective actions (Girgin et al., 2019; Young et al., 2004). In terms of quantity, most releases are small, remain within the facility compound, and do not threaten the broader public. However, there are historical pretexts and present-day circumstances which suggest that large quantities of hazardous materials stored in dense urban environments pose significant risks to the public and could result in mass casualty incidents following an earthquake.

This literature review was performed on behalf of Multnomah County Emergency Management to assist with mitigation, preparedness, and response to hazardous materials (HAZMAT) releases from fixed facilities in the event of a catastrophic earthquake. The scope of this literature review is confined to factors contributing to the occurrence of earthquake-induced hazardous material releases from fixed facilities, the implications of these releases on life safety, and recommendations for mitigation, preparedness, and response.

Following the methods section, this literature review is divided into three subject areas. First, the causes, challenges, and risks for earthquake-induced HAZMAT releases are explored. Second, historical examples of earthquake-induced HAZMAT releases are presented. Third, best practice recommendations for mitigation, preparedness, and response are provided.

Methods

Articles were collected with Google Scholar using the following keywords: “Earthquake” AND (“hazardous materials” OR “HAZMAT”), “Natech,” “Natech” AND “earthquake,” (“Natural disaster” OR “earthquake”) AND (“HAZMAT” OR “Hazardous Materials”), (“natural disaster” OR “Earthquake”) AND “Technological Disaster”.

Search results were assessed for relevance to this review's purpose and scope before collection. Additional articles were gathered through the selected articles' reference lists and Google Scholar's "Cited By" tool. Recurring authors were singled out and their publication lists were examined for additional sources. For the selected examples, searches were conducted both on Google Scholar and on a standard web browser. In those cases, the goal was sufficient, rather than comprehensive, sources. Eventually, it was felt that conceptual saturation had been met and that few additional relevant articles were to be found.

A significant number of articles were excluded during this search process. The largest collection of excluded articles research quantitative risk assessment, structural engineering, or geotechnical information as these articles fall outside the scope of this literature review. Literature on quantitative risk assessments for earthquake and natural disaster induced HAZMAT releases should be the subject of future review to inform mitigation and risk assessment efforts. Non-novel research articles (e.g., some literature reviews, meta-analyses, redundant or republished articles) were excluded. Articles published before 1995 were generally excluded as their arguments are better conceptualized with improved evidence by later scholars. Additionally, the emphasis on fixed facilities means this review excludes information on HAZMAT releases that may occur from pipelines, railcars, trucks, and equipment. Articles focusing exclusively on foreign legal contexts were excluded from this literature review—future review of those regulatory frameworks may prove fruitful for mitigation and preparedness efforts. Despite these exclusions, the Planning Team is confident that the reviewed articles create an accurate representation of the academic perspective.

Description of the Literature

Research on earthquake-induced hazardous material releases began in California following the San Fernando earthquake of 1971 (Cruz & Suarez-Paba, 2019). Since then, the field of research has grown under the umbrella term "Natech," or natural disaster triggered technological disaster, which includes hazardous material releases due to any natural event (e.g., hurricanes, cold weather, wildfires, lighting, etc.). Non-seismic forms of Natech incidents are statistically more common, but earthquakes have remained a subject of study due to their history, severity, and complexity (Sengul et al., 2012).

A few limitations in the collected literature demand attention. Scholars investigating earthquake-induced HAZMAT releases point to significant gaps in the historical record, making certain quantitative assessments impossible (Lindell & Perry, 1996; Steinberg, et al., 2008). The main reasons for these gaps appear to be the prioritization of other life safety operations over the tracking of HAZMAT releases by authorities, facility owners neglecting to report information to authorities, or certain countries withholding information about disasters within their borders.

Similar limitations derive from researchers' access and methods. Researchers almost always arrive days, weeks, or years after an earthquake and must rely on field investigations, reports, interviews, surveys, etc. to assess the causes and implications of earthquake-induced HAZMAT releases. Surveys have proven to be a challenging method for Natech research as they tend to suffer from low response rates which may bias the findings by excluding companies that either went out of business or which may want to avoid disclosing information about the severity of releases. Issues of access and timeliness compound gaps in the official reports to cloud the view of history. Despite these factors, scholars have learned much.

Earthquake-Induced Hazardous Materials Releases

Earthquakes impact a wide geographic region, and they tend to cause simultaneous HAZMAT releases, both within the same facility and across facilities in the impacted region (Girgin et al., 2019). At the same time, earthquakes may damage secondary containment or safety measures, interrupt infrastructure lifelines (e.g., water and electricity), and overburden response resources (Krausmann et al., 2010; Necci et al., 2018). Damage to lifelines can in some cases lead to additional HAZMAT releases as the loss of electrical power threatens critical cooling systems (Cruz et al., 2004). Earthquakes are a less common cause of natural disaster-induced HAZMAT releases compared to, for example, hydro-meteorological disasters, but the widespread impact and the degree of damage make earthquakes perhaps the most difficult source of HAZMAT releases to prepare for and respond to (Girgin et al., 2019; Sengul et al., 2012).

Natural disaster induced hazardous materials releases pose their greatest risk in urban environments where dense populations live near industrial facilities (Cruz et al., 2004). This risk is amplified when historical land-use planning and building codes create situations in which vulnerable facilities are in hazard-prone areas and are very near residential areas (Steinberg et al., 2008). These variables create conditions in which populations are at risk of exposure to hazardous chemicals while response operations may be unable to protect life safety and perform incident stabilization.

The impact of an earthquake on a hazardous facility depends on the severity of the earthquake as it interfaces with the vulnerability of a facility. An earthquake's severity is characterized by its magnitude, depth, distance to the epicenter, geology, topography, local soil conditions, duration of shaking, etc. (Cruz & Suarez-Paba, 2019). A facility's vulnerability to an earthquake is primarily determined by its design criteria and the type of container or equipment in use. Scholars find that the damage to a facility closely correlates with the age of the facility (Krausmann et al., 2010). Older facilities experience more severe damage compared to construction built according to higher building codes or those facilities which have seismic retrofitting (Cruz & Steinberg, 2005; Krausmann et al., 2010; Cruz & Suarez-Paba, 2019).

Other variables contributing to facility vulnerability regardless of equipment or storage type include: the risk of domino effects based on proximity to other facilities (Necci & Krausmann, 2022); a lack of basic maintenance, corrosion monitoring, or modernization upgrades (Cruz et al., 2017); the risk of flooding, or the placement of a facility nearby water, either of which create conditions where stable chemicals may react with water to create toxic gasses or explosions (Necci et al., 2018); and the response capabilities, planning, and training at a facility and jurisdiction (Steinberg et al., 2004).

Storage tanks are consistently identified as the highest risk source of HAZMAT release following an earthquake due to the volume of material stored and their many seismic vulnerabilities (Cruz & Okada, 2008; Krausmann et al., 2010).

Atmospheric storage tanks, often referred to as aboveground storage tanks when referring to petrochemical storage, are those that store hazardous materials at ambient atmospheric pressure and temperature, and are the most prone to failure (Necci & Krausmann, 2022). Atmospheric storage tank containment failure may be caused by buckling, rupture of pipes and connections, tearing, shell-to-bottom detachment, support leg failure, fixed roof damage, floating roof damage, displacement, overturning, and ignition and sparking (Cruz et al., 2004; Necci & Krausmann, 2022). Pressurized storage tanks, on the other hand, are sturdier constructions that are less prone to catastrophic failure but can still suffer releases due to the rupture of pipes and connections, support leg failures, displacement, and overturning (Necci & Krausmann, 2022). Liquefaction and permanent ground deformation are of particular concern in Multnomah County's industrial districts due to their proximity to the Willamette and Columbia rivers (OSSPAC, 2013). Liquefaction occurs in areas with loose sandy soils, a high groundwater table, and strong ground shaking. This combination causes the connections between soil materials to break and the ground to act like a liquid until the shaking stops, which can cause storage tanks to sink, fail, or separate from pipes and connections (Wang, 2009).

In both aboveground storage tanks and pressurized storage tanks, those tanks which are full or nearly full at the time of the earthquake are more prone to failure due to increased weight, liquid sloshing, and overtopping (Krausmann et al., 2010). The added weight on storage tanks increases the force applied to tank walls and supports during ground shaking (Krausmann & Cruz, 2017). When aboveground atmospheric storage tanks are full or nearly full there is the risk of liquid sloshing which can cause failures in tank walls or can cause hazardous materials to spill over the top of tank walls (DOGAMI, 2012; Wang. 2009).

Fires are a critical threat to HAZMAT storage tanks following an earthquake. Petrochemical storage tanks are at especially high risk of fires caused by sparks from the earthquake shaking, but fires can threaten other chemicals as well (e.g., the ignition of sulfur in the Tohoku earthquake, Krausmann & Cruz, 2013). Fires increase the risk of further tank failures by heating the container's components such as flanges, pipe connections, or supports (Girgin, 2011). Uncontrolled fires can cause domino effects in which the fire spreads between tanks or facilities, and fires can cause over-pressurization and explosions that can further domino or otherwise threaten lives, property, and the environment (Necci et al., 2018).

Buildings, storage shelves, pipes, equipment, etc., are also susceptible to failures and account for the majority of HAZMAT releases following earthquakes, but due to the smaller quantities of materials in these components, the releases pose lower risks (Krausmann et al., 2010). Smaller spills can occur in multiple locations within the same facility and create challenges for responder access, increase the demand for resources, and risks mixing otherwise innocuous chemicals into dangerous reactions (Ricci et al., 2022).

Risks and Response Challenges Posed by Earthquake-Induced HAZMAT Releases

This section outlines general challenges to post-earthquake HAZMAT response operations. Then, the risks posed by earthquake-induced HAZMAT releases are described with a focus on life safety and a brief summary of the risks posed to the environment, industry, and the economy. Challenges specific to these risk categories are pointed out.

General Challenges in Response. A combination of facility response system failures, infrastructure damage, and resource scarcity creates conditions in which it may be exceedingly difficult to respond to HAZMAT releases to mitigate harm (Necci et al., 2018). Earthquakes often render a facility's safety equipment and secondary containment protections ineffective or useless if they are not designed to withstand the seismic event (Krausmann & Cruz, 2017). Examples include cracking in dikes or barriers intended to catch released liquid, failure of pipes intended for onsite emergency water systems, and emergency shutoff systems becoming inoperable or inaccessible (Girgin, 2011; Necci et al., 2018). Without these response systems, HAZMAT releases can increase in severity when they may have otherwise been contained.

Damage to infrastructure lifelines (i.e., energy, water, transportation, and communication infrastructure) caused by an earthquake creates further challenges to response. Electrical outages and fuel shortages, either at specific facilities or throughout a region, can lead to cascading failures in HAZMAT facilities as essential cooling, safety systems, or control systems may be inoperable (Cruz et al., 2004). There is a tendency for on-site emergency backup power to be insufficient or damaged during the earthquake (Girgin, 2011; Ricci et al., 2022). Outages in the energy grid make it more challenging for facility operators, first responders, the public, or healthcare facilities to conduct the actions necessary to minimize harm (Necci & Krausmann, 2022).

Water and wastewater treatment sites can themselves be the site of hazardous material releases (Sengul et al., 2012), and damage to these facilities and the broader water distribution systems create a scarcity in a critical response resource (Cruz et al., 2004). Response to HAZMAT fires after an earthquake is almost always challenging as damage to transportation and water infrastructure dramatically undercuts response capabilities (Necci et al., 2018). Historical examples demonstrate water shortages can combine with fire-fighting foam shortages, further increasing the difficulty of containing chemical fires (Girgin, 2011). Additionally, capabilities for victim decontamination are impacted. Decontamination depends on "irrigation with copious amounts of water," up to 5 minutes of rinsing with additional time needed in the event of ocular exposure (Jones et al., 2010, p. 153). Widespread outages in the water distribution system may make it difficult for medical professionals or members of the public to adequately conduct decontamination.

Damage to transportation infrastructure, either by broken roads, broken bridges, or debris blockages, can make it impossible for first responders and their equipment to access HAZMAT release sites (Steinberg et al., 2008). Blocked roadways and downed bridges also create significant challenges for public evacuations, discussed more below (Krausmann et al., 2010).

Damage to communication infrastructure creates several challenges to situational awareness and response coordination. Communication outages may make it impossible for HAZMAT facilities to report releases to the appropriate authorities and outages severely impact the capacity for first responders to communicate with the public (Girgin, 2011; Krausmann & Cruz, 2013; Lindell &

Perry, 1998; Ricci et al., 2022). Coordination of response resources may remain possible using emergency communication channels including radios, satellite phones, and other government channels, however the availability and bandwidth of these resources is not assured following an earthquake.

Scarcity in response resources is another challenge to response for earthquake-induced HAZMAT releases. Facilities almost always depend on support from the public sector during large spills, and neither facilities nor local authorities are generally required to plan for releases in which response resources (e.g., water) may be unavailable (Ricci et al., 2022). Resource scarcity is caused by the large geographic impact of an earthquake combined with a lack of personnel and equipment due to higher priority operations or transportation failures, and damage to structures or buildings can break response equipment and harm or otherwise interfere with response personnel (Krausmann et al., 2010; Necci et al., 2018; Steinberg et al., 2008). Combined, these variables have led well-established scholars to argue that facility response plans should assume that off-site response resources are unavailable and that facilities will need to provide their own resources and response procedures following an earthquake-induced release (Krausmann, Cruz, & Salzano, 2017b).

Risks Posed by Earthquake-Induced HAZMAT Releases. Girgin et al. (2019) explains that, practically speaking, gaseous chemicals which create toxic vapor clouds, or plumes, pose the highest risk to life safety but are likely to have the lowest impact on the environment and property. Liquid spills are likely to have the greatest impact on the environment but lower impacts on life safety and property. In each case, the risk posed by hazardous materials depends on the multiplication of its potential harm by its area of impact. For example, toxic plumes pose the highest threat to life safety because their severe health impacts multiply with the potential for a distribution over a wide geographic area.

Gaseous chemicals which create toxic vapor clouds, also known as toxic inhalation hazards, pose the greatest life safety risks in earthquake-induced HAZMAT release incidents. The United States Environmental Protection Agency (EPA) provides internationally recognized Acute Exposure Guideline Levels (AEGLs) for airborne chemicals which pose a threat to human health. AEGLs are "expressed as specific concentrations of airborne chemicals at which health effects may occur," and each chemical's AEGLs are determined by the particle density at which health effects occur for five exposure periods: "10 minutes, 30 minutes, 1 hour, 4 hours, and 8 hours" (EPA, 2022a, n.p.). Three AEGLs are defined and used across all chemicals, with level 1 being the least severe and level 3 being the most severe. AEGL 1 is defined as: "Notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not disabling and are transient and reversible upon cessation of exposure" (ibid., n.p.). Level 2 is defined as: "Irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape" (ibid., n.p.). And level 3 is defined as: "Life-threatening health effects or death" (ibid., n.p.). To demonstrate, AEGL tables and summaries of symptoms are provided for chlorine and ammonia, below.

Ammonia AEGLs and Symptoms.

Table 1: Ammonia AEGLs (EPA, 2022b).

	10 min	30 min	60 min	4 hr	8 hr
ppm					
AEGL 1	30	30	30	30	30
AEGL 2	220	220	160	110	110
AEGL 3	2,700	1,600	1,100	550	390

Ammonia is commonly used in large volumes as a refrigerant or as a fertilizer. Individuals exposed to ammonia AEGL 1 experience irritation to the eyes, throat, and nasal region (National Research Council [NRC], 2008). Exposure to AEGL 2 includes irreversible or long-term effects including, "reduced performance on pulmonary function tests, bronchitis, bronchiolitis, emphysema, and bronchiectasis" (idem, p. 60). And finally, exposure to AEGL 3 can result in, "severe irritation and burns" of the eyes, skin, mouth, and respiratory tract with the highest risk of death posed by pulmonary edema—a buildup of fluid in the lungs (idem, p. 59).

Chlorine AEGLs and Symptoms.

Table 2: Chlorine AEGLs (EPA, 2022b).

	10 min	30 min	60 min	4 hr	8 hr
ppm					
AEGL 1	0.50	0.50	0.50	0.50	0.50
AEGL 2	2.8	2.8	2.0	1.0	0.71
AEGL 3	50	28	20	10	7.1

Chlorine is used in the manufacture of chemicals, as a bleaching agent, and as a “biocide” in water and waste treatment facilities (NRC, 2004, p. 13). Exposure to chlorine at each AEGL is less distinct compared to ammonia. Minor symptoms include respiratory irritation which can increase in severity to bronchoconstriction in which the muscles of the trachea and bronchi constrict, “causing a decrease in airway diameter and a corresponding increase in resistance to airflow” (idem, p. 43). Minor and moderate symptoms, therefore, include wheezing, coughing, a tightness in the chest, and difficulty breathing. Death from chlorine exposure can occur due to a lack of oxygen caused by bronchoconstriction, pulmonary edema, and delayed death due to bronchial infection (NRC, 2004).

Risks to Life Safety. Employees working in or nearby HAZMAT facilities when an earthquake occurs are most often injured or killed by building collapse (Girgin, 2011; Krausmann et al., 2010). Deaths from fires, acid spills, and acute toxicity effects from toxic inhalation hazards have been recorded (Girgin, 2011; Necci et al., 2018). A lack of appropriate safety equipment pairs with damage to transportation infrastructure to increase the threat to facility personnel by making it difficult to respond or conduct protective actions including evacuation.

First responders are at risk of acute exposure to inhalation hazards if they lack the necessary personal protective equipment (Necci et al., 2018). Scarce resources and concurrent HAZMAT releases increase the chance of insufficient equipment available for responders (Girgin et al., 2019). A lack of situational awareness about the volume of release and its estimated dispersion can lead to personnel unknowingly entering unsafe areas, and this may be aggravated by a lack of knowledge about HAZMAT risks or symptoms in non-specialized responders (Girgin, 2011; Girgin et al., 2019). Additionally, facility, responder, and community air quality monitoring typically conducted during industrial incidents will likely not be available or will not be sufficient to the scale of releases expected in a CSZ scenario.

Members of the public are threatened by plumes of toxic inhalation hazards and the potential for both acute and prolonged exposure (Girgin et al., 2019). Additionally, smoke from HAZMAT fires can carry toxins, increasing the threat of prolonged exposure, and groundwater contamination from chemical spills may pose risks to residential areas if first responders are unable to contain or clean up the spill before they impact the community (Cruz & Okada, 2008).

Challenges for Residents to Conduct Protective Actions. Evacuation, shelter in place, decontamination, and healthcare facilities are all impeded following an earthquake (Necci et al., 2018). It has long been noted by scholars that damage to houses and apartments, including broken windows, walls, roofs, floors, and doors all inhibit the ability of the structure to be used to safely shelter in place (Lindell & Perry; 1998; Steinberg et al., 2008). A thorough search for studies and/or analysis regarding the efficacy of shelter in place following an earthquake yielded no results. Cruz and Okada (2008) argue that buildings in socioeconomically disadvantaged areas tend to be a lower quality building stock, which means they are at a higher risk of damage and therefore less likely to be effective for shelter in place.

Damage to roadways and bridges and the loss of public transportation options makes evacuating an unsafe area challenging, especially for people with access and functional needs (Girgin et al., 2019; Lindell & Perry, 1998). An additional challenge for evacuations is the possibility for people to be trapped under debris or in collapsed buildings. Those trapped are unable to leave the area, and rescuers trying to save others tend to be unwilling to evacuate, especially if those trapped are friends or family and the threat of exposure is not deemed pressing (Necci et al., 2018). For example, in the magnitude 8.0 Wenchuan earthquake in China, further discussed in the Selected Example section, evacuation was either enforced by authorities or HAZMAT exposure symptoms became so severe that the rescuers felt they had no choice but to leave (Krausmann et al., 2010).

For both protective actions, it is critical that authorities inform the public of the need to perform said action. Therefore, a compounding challenge to effective public response is widespread damage to communication infrastructure, as standard public communication channels are unavailable (Steinberg & Cruz, 2004). In the magnitude 7.6 Izmit earthquake and the Wenchuan earthquake, as examples, large evacuation orders had to be carried out in-person by response personnel, and some residents were not evacuated even after 20 hours or more of exposure (Girgin, 2011; Krausmann et al., 2010). Miscommunications also pose threats to appropriate evacuation orders. In the Izmit earthquake, a 6 km evacuation order was miscommunicated as far as 20 km away (Steinberg & Cruz, 2004). Unnecessary evacuations can result in people being left trapped under rubble who otherwise might have been saved and can create an undue burden on shelter services. Alternatively, during the Fukushima Nuclear disaster following the magnitude 9.0 Tohoku earthquake, evacuation orders were disjointed and expanded over the course of days, making some residents lose confidence in the instructions or otherwise hesitate to leave the area and forcing mass shelter sites to relocate, causing confusion (Fujinawa & Noda, 2013).

Significant challenges in the medical response operations to HAZMAT exposures following an earthquake have been noted in the literature (Girgin, 2011), however additional research is necessary. As mentioned previously, damage to water infrastructure may inhibit decontamination operations, and it is likely that medical facilities will be overwhelmed in a post-earthquake scenario (Krausmann, Cruz, & Salzano, 2017b). Even during non-earthquake-induced HAZMAT releases the number of hospitalizations required can quickly surpass local capabilities (Mackie et al., 2014).

In their analysis following the Graniteville South Carolina chlorine railway accident in which 90 tons of chlorine gas were released nearby a rural town—with a population density roughly one-sixth of Portland, Oregon, Mackie et al. (2014) found that in less than 30 minutes dozens of residents were showing up at the local hospital seeking care. Doctors were not aware of what chemical their patients had been exposed to until hours after the incident and relied on intuition and generic responses to try and provide care. Of the 529 people who eventually sought medical care, 311 were urgent cases, 71 of those required hospitalization, and 25 of those were admitted to the intensive care unit for mechanical ventilation with an average stay of three days. In total nine people lost their lives in this disaster.

Girgin’s (2011) analysis of the Izmit earthquake, discussed in greater detail below, demonstrates a similar situation. Girgin (2011) outlines how residents exposed to a major release of acrylonitrile fumes sought medical treatment at a local hospital, but the hospital was overburdened and unable to provide sufficient care. Unless knowledge and capabilities are developed, it is likely that hospitals and doctors will have to respond to HAZMAT victims without the necessary supplies and without knowledge of the chemicals at play.

***Risks to Property and the Environment*.** While not the focus of this literature review, it is worth mentioning that earthquake-induced hazardous materials releases pose significant financial and environmental risks. It is essential that thorough and timely HAZMAT cleanup occurs following release to mitigate contamination of the surrounding area and to ensure no additional life safety risks arise (e.g., groundwater contamination; Girgin et al., 2019). Costs for the environmental cleanup can quickly rise into the hundreds of millions when many small or medium-sized HAZMAT releases occur (Lindell & Perry, 1996). Facility owners face costs due to business interruptions stemming from cleaning spills and repairing facilities and equipment, and these costs may be high enough to force permanent business closure (Krausmann & Cruz, 2013). The large environmental and economic costs of earthquake-induced HAZMAT releases may far outweigh the costs of smart investments in preventative measures.

Selected Examples of Earthquake-Induced Hazardous Materials Releases

The following six examples were selected to demonstrate the impacts of earthquakes on hazardous installations and their implications for public health and response operations. In each instance the hazardous releases caused by the earthquake, the threats posed to life safety, and the relevant protective actions taken are described, concluded by mentioning notable barriers to life safety response operations. These examples were selected primarily due to their prevalence within academic literature, which allows us to better describe what happened and how it impacted people. Therefore, the selected examples are only a subset of the many earthquakes that have been recorded in the last century, and it is likely that important events have been left out. On the other hand, it is also possible that some earthquakes have been excluded because they did not contain hazardous materials releases significant enough to catch the eyes of researchers, which would result in a skewed perspective. Examples of earthquake-induced petrochemical releases and fires are not covered here and are instead located in Chapter 3 of this report on Oregon’s CEI Hub.

Loma Prieta Earthquake

On October 17, 1989, a magnitude 7.1 earthquake struck the Santa Cruz Mountains in California. This earthquake, named the Loma Prieta earthquake, caused a large amount of small and medium hazardous material spills. Releases of acids, solvents, pesticides, fertilizer, or petroleum were reported from 200 laboratories, 100 industrial facilities, and numerous shops (Young et al., 2004). The largest spills included 50,000 gallons of semiconductor fluid, between 5 and 20 thousand pounds of ammonia, and 3 million gallons of fuel from underground storage containers (Young et al., 2004). Other HAZMAT incidents included asbestos contamination in 57 buildings and extensive natural gas pipe breaks (Young et al., 2004; EERI, 1989).

HAZMAT releases from the Loma Prieta earthquake posed minimal threats to life safety. Authorities evacuated and sheltered at least ten thousand people for a couple of months due to asbestos contamination in houses (USGS, 1994). Additionally, fires due to natural gas leaks posed risks to homes and residents (EERI, 1989). Residents were able to report these fires to the authorities via telephone as the region did not experience widespread failure of the communication infrastructure (EERI, 1989). However, damage to water infrastructure created initial barriers to firefighting efforts, and significant damage to transportation infrastructure, especially highways between counties, slowed the arrival of response resources (EERI, 1989).

Northridge Earthquake

On January 17, 1994, a magnitude 6.7 earthquake struck the San Fernando Valley, California and was accompanied by two magnitude 6.0 aftershocks. Named the Northridge earthquake, this incident is estimated to have caused HAZMAT releases in 5% of the commercial facilities and 20% of the industrial facilities in the high-impact area, totaling roughly 140 releases (Steinberg et al., 2008; Young et al., 2004). A significant number of natural gas lines were also damaged, leading to structure fires (California Seismic Safety Commission, 1995). No life safety concerns were reported from these HAZMAT releases; however, the economic costs quickly rose into the hundreds of millions (Lindell & Perry, 1996). Damage to communication infrastructure and overwhelming radio traffic forced local emergency responders to rely on runners to coordinate response efforts (California Seismic Safety Commission, 1995).

Izmit Earthquake

On August 17, 1999, a magnitude 7.6 earthquake occurred on the North Anatolian Fault in the district of Izmit in the Kocaeli province in Turkey. The Izmit earthquake, also known as the Kocaeli earthquake, is estimated to have damaged at least 350 industrial firms, with an estimated 8% of those facilities having significant HAZMAT releases based on survey data (Cruz & Steinberg, 2005). Multiple notable HAZMAT releases occurred, two of which posed significant threats to life safety. Non-life-threatening releases included: 200,000 kg of anhydrous ammonia which was intentionally released to avoid over pressurization due to a loss of refrigeration; 50,000 kg of diesel fuel released into the Izmit bay from a broken fuel-loading arm; and the release of 1.2 million kg of cryogenic liquid oxygen due to tank support-column failures (Krausmann & Cruz, 2017).

The first notable release which threatened life safety occurred at a crude oil refinery where multiple above ground tanks burned for five days, releasing unhealthy smoke, and risking a domino effect explosion at a nearby LPG tank

(Girgin, 2011). Local authorities ordered an evacuation radius of 5 km to mitigate harm from the refinery fire (Steinberg & Cruz, 2004). The refinery fire receives attention in this report's chapter on the CEI Hub.

The second notable life-threatening release occurred at an acrylic fiber plant wherein 6.5 million kg of acrylonitrile was released from an above ground storage tank. Due to the evaporation rate of acrylonitrile a toxic plume formed which necessitated a 6 km evaluation radius, however some residents were exposed for more than 20 hours before being evacuated (Girgin, 2011). 27 first responders were poisoned and many more suffered exposure symptoms (ibid.). Hundreds of residents in three nearby rural towns reported symptoms of toxicity exposure; many of these people sought medical attention but the local hospital was overwhelmed by the earthquake and unable to provide sufficient care (Girgin, 2011; Krausmann & Cruz, 2017). As of now, no known return studies have been published investigating the long-term effects of these exposures. Due to earthquake damage in the containment walls, the acrylonitrile was also able to enter the environment and contaminate crops and groundwater (Cruz & Steinberg, 2005).

First responders faced barriers to response caused by damage to infrastructure lifelines. Communication was especially challenging for the acrylonitrile release. Residents were only able to be informed of the need to evacuate in-person by local authorities, and miscommunications within the response operations falsely communicated the evacuation order in a much larger radius than was intended (Girgin, 2011). Electrical outages, a lack of firefighting foam and water shortages undercut the ability of responders to contain the acrylonitrile spill or to combat fires at the crude oil refinery (Krausmann & Cruz, 2017).

Wenchuan Earthquake

On May 12, 2008, a magnitude 8.0 earthquake struck Wenchuan county in the Sichuan province, China. Known either as the Wenchuan or Sichuan earthquake, this particularly devastating earthquake displaced 5 million residents and took over 70,000 lives. The quantity or severity of HAZMAT releases following this earthquake has not been disclosed by authorities. Scholars argue that the immense human toll of this earthquake limited the resources available to respond and track hazardous materials releases, and this was exacerbated by the Chinese Government and industry's hesitancy to disclose information about the earthquake's impacts, making accurate release estimates impossible (Krausmann et al., 2010). During a field trip to investigate HAZMAT releases, Krausmann et al. (2010) argue that at least eight of the 18 facilities visited in Wenchuan assuredly had sizable releases and all but one showed signs of damage.

The most notable known HAZMAT release was from two collapsed chemical factories which are estimated to have released some 80 tons of liquid ammonia (Krausmann et al., 2010). The release of ammonia at these facilities necessitated the evacuation of six thousand people (EERI, 2008; World Health Organization, 2008; Cruz & Suarez-Paba, 2019). Extensive damage to the communication infrastructure meant that these evacuations occurred in-person, often by grassroots efforts (EERI, 2008). Extensive damage to infrastructure lifelines further limited access and capabilities for first responders (EERI, 2008).

Residents and employees from multiple locations were interviewed by Krausmann et al. (2010) and report showing symptoms of HAZMAT exposure following the earthquake. Multiple workers at one facility are reported to have died from acid bursting from pipes (ibid). London's Sunday Times newspaper provided some firsthand reports which are not corroborated by official Chinese sources (Sheridan, 2008). Sheridan (2008) interviewed civilians, among them two schoolchildren, who reported an ammonia cloud drifting into a valley and engulfing their village and injuring or killing civilians, in one location the witnesses report more than 100 children lost their lives while trapped in a collapsed school which was covered in the ammonia plume. Children attempting rescue suffered from acute exposure before eventually having to evacuate because of their symptoms (Krausmann et al., 2010).

Chile Earthquake

On February 27, 2010, a magnitude 8.8 megathrust earthquake caused by a 450 km fault rupture struck the coast of Chile and was followed by a tsunami which impacted coastal areas. In total it affected about 160,000 square kilometers in which 75% of the population of Chile resides (Zareian et al., 2012). Attempts have not been made to estimate the number of hazardous materials released caused by this earthquake, and no significant threats to life safety appear in the available literature. However, Zareian et al. (2012) report significant damage to the industrial sector of Chile's economy, with many businesses unable to operate their plants for weeks to months.

Tohoku Earthquake

On March 11, 2011, a magnitude 9.0 megathrust earthquake caused by a 500 km fault rupture struck the coast of Japan in the Tohoku region and was followed by a tsunami. In many ways the Tohoku earthquake proves the efficacy of seismic building codes as direct earthquake damage was minor compared to the severe damage caused by the tsunami (Krausmann & Cruz, 2013). A significant petrochemical release and fire occurred at Tokyo Bay, and as with the Izmit example, this spill is examined in this report's chapter on the CEI Hub. The renowned Fukushima nuclear reactor meltdown is also excluded from this analysis as the main triggering event was the tsunami, rather than the earthquake—however there is knowledge to be gleaned in the evacuation process for the Fukushima incident. Numerous smaller hazardous facilities were damaged by the earthquake, but the number of releases is unknown as the response operations focused on the Fukushima incident unless a significant threat to life safety was detected (Krausmann & Cruz, 2017).

In one notable instance, a 2 km evacuation was ordered due to the ignition of spilled sulfur and the formation of a toxic plume (Krausmann & Cruz, 2013). For Fukushima, on the other hand, evacuations were confused and disjointed. Officials originally called for a 1 km evacuation radius around the plant before increasing the radius to 20 km the next day, which forced many residents and shelter facilities to relocate multiple times and lead to a chaotic response environment (Fujinawa & Noda, 2013; World Nuclear Association, n.d.). Damage to telecommunication infrastructure was reported as a barrier to response coordination and public health interventions, and the sulfur plume created access issues for first responders combating fires at the scene (Krausmann & Cruz, 2013).

State-of-Practice Recommendations for Emergency Managers

Prevention and Mitigation Recommendations

Scholars are unanimous in their argument that the most effective mechanism to reduce the risk of natural disaster-induced hazardous materials releases is through land-use planning (e.g., Young et al., 2004; Cruz et al., 2004; Necci et al., 2018; Steinberg et al., 2008; Suarez-Paba et al., 2019). Jurisdictions should avoid placing hazardous facilities in natural-disaster prone areas, and to the greatest degree possible, hazardous facilities should be geographically distanced from residential and commercial areas and water supply sources (Cruz et al., 2017). Scholars also recognize that land-use regulations for pre-existing facilities can be prohibitively expensive or face significant social and political barriers (ibid.). If land-use planning is not an available risk reduction mechanism, scholars advocate a combination of structural hardening and organizational preparedness to minimize risks.

Cruz et al., (2017) conceptualize structural and operational measures taken to reduce the risk of natural disaster-induced hazardous materials releases into two categories: prevention and mitigation. Prevention measures reduce the likelihood of a release, and mitigation measures reduce the harm caused in the event of a release (ibid.). Both mitigation and prevention measures have consistently demonstrated efficacy in reducing the likelihood and significance of HAZMAT releases following earthquakes (e.g., Young et al., 2004; Cruz & Steinberg, 2005; Cruz & Suarez-Paba, 2019; Steinberg et al., 2008).

Specific engineering recommendations remain outside the scope of this literature review. Nonetheless, it is worth mentioning a few forms of prevention to provide a sense of the possibilities. For example, storage tanks are susceptible to failure due to buckling, liquid sloshing, floating roof sinking (or sparking), anchorage failure, pipe connection failure, etc. Proper selection of tank materials and components, proper maintenance and corrosion monitoring, proper anchoring techniques, proper support leg design, flexible pipe connections, etc. can all minimize damage to the tank should an earthquake occur and thereby reduce the risk of a release (Cruz et al., 2017).

Certain prevention measures require little structural development, instead focusing on the operational procedures in which hazardous materials are involved. Regulators and facilities can prevent domino effects and mitigate damage by separating chemicals that may cause a reaction if mixed (Cruz et al., 2004). Similar efforts should be made to locate chemicals that react with water away from flood risks or other water sources that could exacerbate a release (Necci et al., 2018). The likelihood of tank failures can be decreased by reducing the quantity of materials in a tank which lowers the total weight and provides more freeboard, which subsequently reduces the risk of liquid sloshing overtopping the tank walls (DOGAMI, 2012; Wang, 2009). Finally, facilities should pursue sustainable practices to reduce the necessary quantities of toxic chemicals and thereby reduce the risks of release (Steinberg et al., 2008).

Early warning systems and emergency shutdown procedures blur the lines between response operations and structural prevention (e.g., ShakeAlert). When activated, these systems can, for example, close valves or shutdown equipment to reduce the likelihood and magnitude of a HAZMAT release (Krausmann, Cruz, & Salzano, 2017b). In the context of earthquakes, the warning time is exceedingly short compared to the time required to perform emergency shutdown procedures, therefore it is generally assumed that any early warning system must be automated to have an effect (Krausmann et al., 2011; Krausmann, Cruz, & Salzano, 2017b). At the upper limit, earthquakes may have a warning time of 3 minutes if the facility is distant from the earthquake's epicenter, but more common are warning times between 30 and 60 seconds (Krausmann et al., 2011). On the other hand, emergency shutdown procedures can take upwards of 10 minutes (Krausmann, Cruz, & Salzano, 2017b). This combination of variables means that early warning systems for earthquakes are, "the most unfavorable situation" compared to hurricanes or flooding in which warning times may be hours or days (Krausmann, Cruz, & Salzano, 2017b). A compounding factor is the significant damage and cost incurred on hazardous installations when an automatic shutdown occurs, which means that automated systems must ensure that no false alarms occur to remain cost effective (Krausmann & Necci, 2021).

Mitigation measures supplement prevention measures to reduce the harm caused should a release occur. Per the focus of this literature review on life safety concerns, we've chosen examples of mitigation measures which can reduce the threat of toxic chemical vapors. Containment walls or dikes which capture released liquids in a smaller area can reduce the surface area of a spill and slow down the rate of evaporation; automatic water cannons and foaming systems can create a layer of materials on top of the spilled chemical to further reduce the evaporation rate; and "water curtains" can be used to contain or wash out toxic gas releases (Cruz et al., 2017, p. 220). Prevention measures are themselves susceptible to failure caused by earthquake damage, and it is imperative that they are built to the appropriate design specifications (Krausmann et al., 2011).

Emergency Response Planning Recommendations

In conjunction with prevention and mitigation measures, emergency response plans should be maintained by hazardous facilities and by government agencies with associated responsibilities. To be effective, earthquake-induced HAZMAT response plans must *take the post-disaster context into account* (Lindell & Perry, 1996; Necci et al., 2018). A prominent consideration must be the risk of multiple, simultaneous HAZMAT releases, both within the same facility and across facilities in the impacted region (Girgin et al., 2019). Widespread releases of various hazardous materials, in different quantities, leads to a strong likelihood that atmospheric concentrations of toxic chemicals will be widespread and hamper all phases of response. Comprehensive risk assessment and modeling efforts are necessary to provide sufficient information for planning purposes. Risk assessments and response plans must also consider the implications of resource scarcity and infrastructure damage to adequately understand community vulnerability, prioritize resources, and devise strategy (Cruz et al., 2004; Ricci et al., 2022). Historical examples are rife with HAZMAT response plans that proved inoperable or ineffective following a catastrophic earthquake (Cruz & Steinberg, 2005; Necci et al., 2018).

For on-site response plans, taking the post-disaster context into account means that planners should consider off-site response resources unavailable, delayed, or insufficient (Krausmann, Cruz, & Salzano, 2017b). Additionally, HAZMAT facilities located nearby one another should coordinate response plans to control the risk of possible domino effects and maximize the efficacy of their response equipment (Necci & Krausmann, 2022).

Off-site response plans must account for the myriad risks and challenges posed to the community and first responders (Krausmann, Cruz, & Salzano, 2017b). Communication plans must make provisions for the likely event that telecommunications are offline (Krausmann & Cruz, 2013); first responders must plan for transportation issues and reduced access to resources including water supply or protective equipment (Cruz et al., 2004); public protection plans must account for damage to transportation infrastructure, communication infrastructure, and shelter structures (Necci et al., 2018).

It is also essential that local jurisdictions create and maintain decontamination and medical response plans which account for the anticipated impacts of an earthquake (Cruz et al., 2004; Necci et al., 2018; Masoumi et al., 2020). Hospitals and other healthcare professionals should be made aware of the common chemicals to which they may need to respond and provide information on the best practices for treatment (Mackie et al., 2013). Alongside plans, healthcare facilities should strive to have an adequate supply of medication to treat victims suffering from HAZMAT exposure symptoms (Krausmann, Cruz, & Salzano, 2017b).

All parties who have a response role identified in emergency plans should participate in regular exercises to ensure appropriate knowledge of response operations and to improve the viability of emergency plans (Steinberg et al., 2004).

Response Preparedness Recommendations

Alongside response plans, preparedness concepts which emerge from the literature can generally be categorized as equipment or education preparedness. In terms of equipment, it is essential that first responders and facility personnel working in unsafe areas have the necessary personal protective equipment to ensure their safety (Girgin, 2011). Due to uncertainties in the boundaries of toxic plumes, along with the potential for widespread toxic conditions stemming from simultaneous hazardous materials releases at facilities not included in this report, means that it is essential that non-specialized personnel have some degree of protection to minimize the risks of unintended exposure (Necci et al., 2018).

Facilities should develop back-up capabilities to ensure safety equipment functions even if critical infrastructure lifelines are interrupted (Necci et al., 2018). For example, this could include placing sufficient generators and water or foam storage in seismically safe locations and far enough away from hazardous materials that they will remain accessible in the event of a release (Girgin, 2011). It has been noted by scholars that panic flight behavior may occur at hazardous facilities which experience significant damage, and this means that facility response mechanisms should account for a potential lack of facility personnel (Krausmann, Cruz, & Salzano, 2017b; Steinberg & Cruz, 2004).

Facility employees, first responders, and the public should all receive education specific to their responsibilities and needs. As noted, this involves the need for consistent exercising of plans to ensure first responders and facility personnel are trained in their implementation. Additionally, first responders and facility personnel must be educated in the appropriate use of response equipment and the symptoms of exposure to ensure their safety (Necci et al., 2018).

Scholars argue that before a disaster, members of the public should be made aware of the risks of hazardous material releases and educated on the appropriate responses. Arguments to this effect are briefly touched on in the literature collected (e.g., Yu & Hokugo, 2015), but the same lessons pervade the broader risk communication literature (e.g., Lindell & Perry, 2012). Girgin (2011) sums this up well:

> The public living in the vicinity of Natech prone facilities should be informed about the properties of the hazardous substances stored or processed at the facility, their health impacts, the symptoms of the various toxicity levels, how to mitigate these symptoms and the duration of exposure deemed safe and during which rescue operations could be continued. Prolonged exposure may be inevitable, but at least individuals can make an informed decision on how to act. (p. 1138)

Within certain legal frameworks it may be impossible to provide the public with information about the location of hazardous facilities or with the materials stored there, however toxic inhalation hazards have many shared symptoms, and it remains possible to share generalized knowledge of these risks (Oregon State Fire Marshal's Office, personal communication).

Conclusion

Urban environments are home to numerous facilities which store and use hazardous materials to provide goods and services critical to modern economies. These hazardous facilities are held to a high regulatory standard to ensure safe operations and to minimize the chance of a release as well as the harm caused should a release occur. However, in jurisdictions where historical land-use planning and design requirements have allowed the construction of seismically vulnerable facilities nearby high-density population centers, these hazardous facilities may pose significant threats to life safety.

The greatest threats to life safety are posed by storage tanks with large quantities of toxic inhalation hazards. When toxic inhalation hazards are released, they create toxic plumes which can travel or spread over wide geographic regions, sometimes multiple square miles depending on the quantity of release and the meteorological conditions. First responders and facility personnel are at risk of rapid acute exposure, and the public is at risk of exposure to plumes of a lower density in a wider region. Even at lower densities, toxic inhalation hazards exposure of minutes to hours can cause significant damage to health and may require hospitalization.

Because earthquakes can cause significant damage to infrastructure lifelines and the general building stock, they create challenges to response operations and public protective actions. Damage to energy, water, transportation, and communication infrastructure impedes the ability of first responders to mitigate the harm of a release and provide support to the public.

Following a standard, non-earthquake-induced, HAZMAT release, residents at risk of exposure would either be advised to evacuate an area or to shelter in place. During an earthquake incident, both actions are obstructed as homes may be damaged and therefore unusable to shelter in place, while damage to transportation infrastructure can impede public evacuations, especially for people with access and functional needs. A simultaneous loss of telecommunications creates a context within which first responders and public officials are unable to effectively communicate to the public. In multiple historical examples evacuations orders have had to take place in person by response personnel, placing a major demand on limited response resources.

In the event of widespread exposure, it will fall to first responders and medical facilities to provide decontamination and care. Decontamination requires an ample supply of water at a time when water infrastructure may be damaged. A significant portion of those exposed to toxic inhalation hazardous plumes may require hospitalization and mechanical ventilation. Hospitals and healthcare providers should be made aware of the risks of post-earthquake HAZMAT exposure and provided with the medication and equipment necessary to support those exposed. Assessments of these capabilities must consider that hospitals are likely to already be overburdened following a catastrophic earthquake.

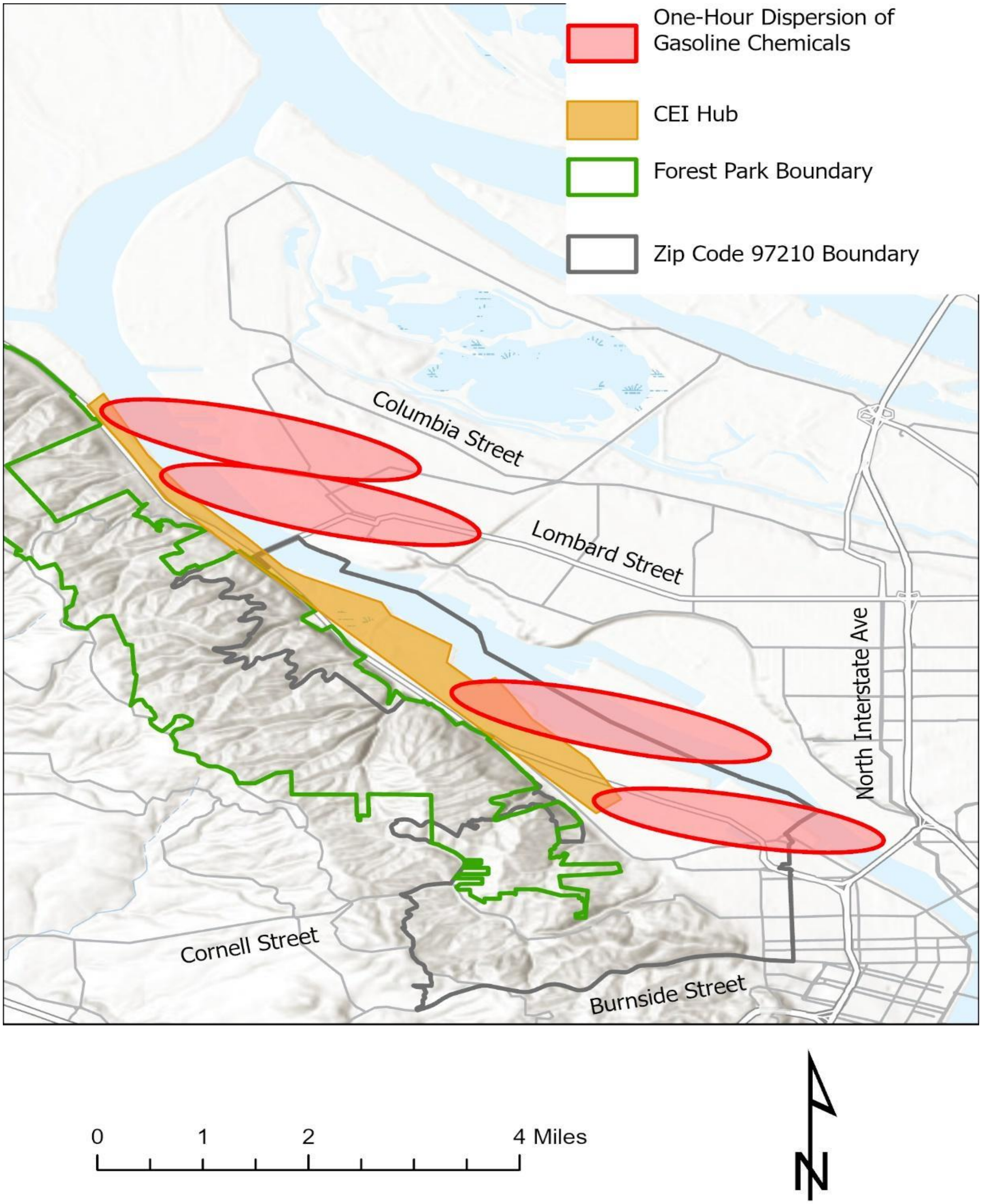
Appropriate structural measures, emergency planning and exercising, capabilities development, and public information campaigns can mitigate the risks of HAZMAT releases following an earthquake. It is advisable that in-depth quantitative risk assessments be conducted on facilities which have been identified as high-risk by qualitative measures. Policies should be pursued to encourage retrofitting and sufficient design requirements that will mitigate the chance of release, and land-use planning policies should be instituted which limit the placement of hazardous facilities in areas prone to natural disaster risk.

Chapter 3: The Critical Energy Infrastructure Hub Life Safety Risks and Barriers to Response Operations

This chapter explores the life safety implications of Multnomah County's most well-known and well-studied threat of an earthquake-induced hazardous materials spill: a catastrophic release at the Critical Energy Infrastructure (CEI) Hub that may occur following a Cascadia Subduction Zone earthquake (CSZ earthquake). The CEI Hub is located on a 6-mile stretch of the Willamette River in Northwest Portland through which 90% of Oregon's fuel supply is transported (See Figure 1, page 38; Oregon Department of Geology and Mineral Industries [DOGAMI], 2012). The age of the fuel storage tanks at the CEI Hub, the majority of which were built before the 1970s to deficient code requirements (Portland Bureau of Emergency Management [PBEM], 2019), and the location of the tanks, on soil highly susceptible to liquefaction, means a CSZ earthquake could cause a catastrophic failure resulting in the release of between 65 and 194 million gallons of petrochemicals (Multnomah County, 2022).

A release of this magnitude would pose significant life safety risks, be catastrophic to the environment, and undermine Oregon's response and recovery operations with an extended fuel shortage (Oregon Department of Energy [ODOE], 2017). More than 45,000 people live or work nearby the CEI Hub and face life safety risks from possible fires, either at the petrochemical facilities or at the neighboring Forest Park, and from exposure to toxic fumes released from burning petrochemicals, evaporating gasoline, or other hazardous materials (Multnomah County, 2022). The environmental costs are estimated to be substantial with major damage to animals and habitats along the Willamette and Columbia rivers and as far as the Oregon Coast; estimated cleanup costs range from $196 million to $2.1 billion (ibid.). The economic impacts include direct damage to facilities, halts to river navigation and fisheries, increased fuel prices, and the costs incurred by fuel shortages during response and recovery operations. Cost estimates for the impacts are not well established and likely reach into the hundreds of millions or billions of dollars. The scale of this threat necessitates continued efforts to mitigate the risk of a catastrophic failure at the CEI Hub to protect life safety and minimize harm to the environment and economy.

Figure 1: CEI Hub Geographic Region and Possible Impact Areas



After it was identified as a critical vulnerability by Wang (2009) and DOGAMI (2012), the State of Oregon began pursuing resilience initiatives for the CEI Hub spurred on by the *Oregon Resilience Plan* (Oregon Seismic Safety Policy Advisory Commission [OSSPAC], 2013). The issues surrounding the CEI Hub were brought to public attention in 2013 by Richard Read with The Oregonian who provided an overview of the CEI Hub accompanied by personal narratives expressing fear of the outcomes of a catastrophic release. Two years later in 2015, Tony Schick with Oregon Public Broadcasting did an in-depth investigation into the CEI Hub's facilities to create an interactive web-based map of the many different storage tanks, allowing people to examine the historical development of the area and explore the liquefaction risks.

Over the years, multiple policy initiatives have been pursued by local and state authorities resulting in two new regulations on some or all the petrochemical facilities at the CEI Hub. First, the City of Portland passed Ordinance 189807 which "limit[s] the size of new fossil fuel terminals and prohibit[s] the expansion of fossil fuel storage tank capacity at existing fossil fuel terminals" (n.p.). The second, Oregon Senate Bill 1567 (SB1567) was signed into law in 2022, This bill is described in more detail on page 60 of this report. Included in the facilities regulated by SB1567 are the 13 largest bulk fuel terminals at the CEI Hub who are required to submit vulnerability assessments and mitigation plans to reduce facility risk by June of 2024. SB1567 also requires the Oregon Department of Energy to develop an Energy Security Plan which will assess the State's ability to recover from a catastrophic failure at the CEI Hub and will provide recommendations for increasing fuel resilience in Oregon and strategies for conducting emergency response fuel distribution throughout the state.

This report provides a comprehensive collection of research and reports which focus on the CEI Hub. The literature was collected over multiple projects by staff at Portland State University's Institute for Sustainable Solutions and with consultation from City of Portland and Multnomah County Staff. To ensure comprehensive coverage, the reports references were examined for any additional sources. Some of the collected sources do not provide information relevant to this report's focus on life safety and response challenges. Documents which are not cited in the body of this report are briefly explained in a bibliography at the end of this chapter.

To explain the risks posed by a catastrophic release at the CEI Hub, the report begins with background information on the CEI Hub, its vulnerabilities, and the estimated impacts of a release. Then it outlines information about capabilities for response as well as the expected challenges posed by the post-disaster context. The report closes with selected examples of earthquake-induced petrochemical releases before turning to a conclusion.

What is the CEI Hub and Why is it a Risk?

Some one hundred years ago the first petrochemical storage and transportation facilities were constructed adjacent to the Willamette River using soil and fill materials gathered during the construction of the nearby Port facility (PBEM, 2021). The CEI Hub is now composed of 31 properties, currently owned by 10 companies, operating around 415 active petrochemical storage tanks with a combined capacity of 350 million gallons (Multnomah County, 2022). Alongside these tanks are all of Oregon's major liquid fuel port terminals; a collection of pipelines transporting liquid fuel, natural gas, and jet fuel; a liquified natural gas storage facility; high voltage electrical substations, local electrical substations, and many transmission and distribution lines (OSSPAC, 2013).

Researchers are concerned with the threats posed to the CEI Hub by earthquakes that could impact the region. Local crustal faults, including the Portland Hills Fault, could release an earthquake between magnitude 6 and 7 which would cause severe ground shaking and more extensive damage to Portland and the CEI Hub compared to a CSZ earthquake, but these local faults have a longer recurrence rate and are less studied compared to the Cascadia Subduction Zone (PBEM, 2016). The Cascadia Subduction Zone, on the other hand, can produce magnitude 9 or greater earthquakes and has caused 41 earthquakes in the last 10,000 years, with an earthquake on average every 250 years (Oregon Solutions, 2021). The region is overdue for the next quake as the last occurrence was in January 1700; scientists estimate that there is a 33-37% chance of another CSZ earthquake within the next 50 years (Oregon Solutions, 2021).

The CEI Hub and Multnomah County are located a good distance from the Cascadia Subduction Zone and will experience only strong to very strong ground shaking—compared to severe and violent shaking from a local crustal fault (PBEM, 2016; DOGAMI, 2018). However, much of Portland's industrial areas, including the CEI Hub, are located along the Willamette and Columbia rivers, and are therefore built on fine grained soils in locations with a high-water table (Wang, 2009). This combination means that much of these industrial areas will experience extensive damage due to ground deformation and liquefaction, which is the primary threat to the CEI Hub (DOGAMI, 2012). Liquefaction occurs when earthquake shaking breaks the bond between soil materials and allows them to mix and flow with the water present in the ground, which results in the ground behaving as a liquid prior to resettling when the shaking stops. Liquefaction and displacement threats to the CEI Hub are greatest for the facilities nearer to the river, with displacement estimates as high as 23 feet (Oregon Solutions, 2021, p. 3). Facilities located further from the river will experience less ground deformation, likely between 3 and 12 feet (DOGAMI, 2018).

The vulnerability of a hazardous facility is characterized by the structural integrity or durability of the built environment as it interfaces with the natural hazards present in the area. The central indicator used by researchers to assess the durability of petrochemical storage facilities are the building codes to which they were constructed, and which can be estimated by determining the age of the facility. The Oregon Structural Specialty Code, which covers these storage tanks, requires that tanks be built to withstand earthquakes according to design requirements based on the facilities location and the category of equipment. Historical building codes did not sufficiently account for seismic risks until 1993 and did not sufficiently account for liquefaction and displacement risks until 2004 (DOGAMI, 2012; Oregon Building Codes Division, 2012). Therefore, facilities constructed prior to 1993 are unlikely to be adequate for a Cascadia level event, facilities constructed between 1993 and 2004 "are assumed to be designed for shaking but are susceptible to failure due to liquefaction settlement and lateral spread," and facilities built after 2004 are likely to be "designed to withstand appropriate shaking and deformation" (Multnomah County, 2022, p. 9). The City

Club of Portland (2017) points out that even tanks built to current standards may not withstand the impacts of a CSZ earthquake and are designed only to maintain containment and not to retain functionality after an event.

Of the 415 active tanks, 91% were constructed before 1993[3] and are estimated to experience some degree of failure depending on local soil conditions (Multnomah County, 2022). Pipelines connected to the CEI Hub which transport gasoline, diesel, jet fuel, and natural gas are expected to endure significant damage and leaks (City Club of Portland, 2017; DOGAMI, 2012). The Olympic pipeline, for example, is a 400-mile interstate pipeline that carries gasoline, diesel, and jet fuel from Blaine, WA to the CEI Hub and is anticipated to have 250 breaks and 82 leaks along with damage to pump stations (City Club or Portland, 2017). Other local pipelines are threatened by liquefaction and landslide risks and may create life safety risks or barriers to response operations due to their collocation with roadways and other critical infrastructure (Wang, 2009).

Estimates suggest damage from a CSZ earthquake would result in the release of 95-194 million gallons of petroleum products from the CEI Hub (Multnomah County, 2022). Of these, 65% are light oils (e.g., gasoline or jet fuel), most of which would evaporate within one to two days, and 25% are medium or heavy oils which would stay in the environment until cleanup occurs (Multnomah County, 2022).

Most secondary containment facilities (e.g., berms) at the CEI Hub are pre-code and susceptible to failure (City Club or Portland, 2017). Additionally, these secondary containment facilities are designed to be sufficient in volume for a catastrophic release from the single largest tank within their bounds, and this means that multiple simultaneous releases in the same containment unit would surpass the containment volume even if those barriers remain effective (PBEM, 2019). Without sufficient and seismically resilient secondary containment units, as much as 43% of the petroleum products which may be spilled by a CSZ earthquake are at risk of flowing into the Willamette River (Multnomah County, 2022).

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[3] Or the age of the tank is unknown, and researchers therefore assume it was constructed prior to 1993 (ECONorthwest, 2022).

Researchers and first responders anticipate significant fires will break out at the CEI Hub after a CSZ earthquake (Multnomah County, 2022; Oregon Solutions, 2021). Possible ignition sources include downed power lines, sparks from floating tank roofs scraping against tank walls, machinery or vehicles operating within high concentrations of evaporated gasoline and jet fuel, and myriad other possible sources of sparks or heat within the area. The scope and location of fires will determine their impact on property and people (Multnomah County, 2022). Given the correct drought or dry conditions, fires could spread to the nearby Forest Park, which, even during a non-earthquake event, would require a statewide activation to contain and would threaten more than 70,000 people (PBEM, 2021; Portland Fire and Rescue, personal communication). Ignition of spilled petrochemicals is often employed as a cleanup mechanism following a release, and it is presumed that some fires at the CEI Hub would be allowed to burn without suppression efforts (Multnomah County, 2022). However, uncontrolled fires create a risk of domino effects which may lead to additional tank failures or cause explosions (Necci et al., 2018).

What are the Expected Life Safety Impacts of a CEI Hub Release?

A release of between 95 and 194 million gallons of petroleum products at the CEI Hub would rank among the largest oil spills in American history, and because of the post-earthquake context it will be exceedingly difficult if not impossible to quickly begin containment procedures to mitigate the spill's impacts (Multnomah County, 2022). Beginning with an exploration of the known life safety risks before briefly outlining environmental, cultural, and economic impacts of a catastrophic release at the CEI Hub.

The highest threats to life safety exist for employees working at or near the CEI Hub along with nearby residents, but the health impacts of a release will reach a much broader population in Multnomah County. The total number of people impacted will depend on the time of day at which an earthquake occurs, as more employees will be present during daytime hours compared to nighttime hours when residents are more likely to be in their homes (Oregon Solutions, 2021). Around 200 employees work at CEI Hub facilities, 1,100 employees work in nearby facilities, and a total of 16,500 residents and 31,000 employees live and work in the immediate zip code (See Figure 1, page 38; Multnomah County, 2022). These employees and residents are threatened by the possibility of fires both at the CEI Hub and Forest Park, exposure to toxic fumes from evaporating petrochemicals or other hazardous materials, as well as localized landslide risks (ibid.). People driving on Highway 30 at the time of the earthquake will face similar close-proximity risks, but exact estimates for the number of people are unknown and likely to fluctuate significantly depending on the time of day and time of year.

Residents and employees are threatened by fires, explosions, and hazardous air quality. As mentioned, fires are likely to start at the CEI Hub and may spread between facilities and into the surrounding residential communities, and it is unlikely that fire response resources will be available to contain these fires (Multnomah County, 2022). The liquified natural gas storage facility at the CEI Hub, as well as some other petrochemical storage tanks, may explode if fires are allowed to spread and envelop storage units, which may harm individuals nearby (ibid).

Air quality in the CEI Hub and downwind from the facilities will be hazardous to the health of residents. Light oils, like gasoline and jet fuel, will begin evaporating when exposed to the air, and the huge volumes anticipated to be released will result in plumes of toxic chemicals including “benzene, toluene, xylene, ethylbenzene, and others” (Multnomah County, 2022, p. 49). On the other hand, oil fires at the CEI Hub will release smoke that carries other pollutants including “VOCs, NOx, sulfur dioxide, and particulate matter” (ibid., p. 49). Models suggest that plumes may cross the river into Northeast Portland given the appropriate wind direction, and it is likely that much of Portland, OR and Vancouver, WA, will experience degraded air quality from the evaporated gasoline and smoke (ibid.). People in the immediate vicinity are at risk of acute exposure levels which may require hospitalization. As it was not the focus of their report, Multnomah County (2022) simplified their plume models to four release locations and did not model the spread of toxic plumes from other industrial facilities in the area. More facilities will need to be modeled in order to more accurately estimate impacts.

Environmental, Cultural, and Economic Impacts

A catastrophic spill at the CEI Hub would result in the contamination of air, ground, and water downstream and downwind of the facilities (Multnomah County, 2022). The estimated cost for cleanup and impacts to habitats and species ranges from $196 million to $2.1 billion (ibid.). Oil spilled into the Willamette and Columbia rivers would harm salmon and other fish species integral to indigenous peoples of the region, commercial and recreational fishing communities, along with other recreational users of these rivers (Multnomah County, 2022). Cultural impacts of a catastrophic CEI Hub release are presumed to be immense but researchers have avoided assigning a dollar figure to these impacts. Economic impacts include damage to CEI Hub facilities and halts in business operations (cost unknown); damage to residential property along the river ($11.8-$35.4 million); halts to river navigation ($11.8-$17.8 million); impacts to fisheries (cost unknown); increased fuel prices ($18.8-$120.8 million); and costs incurred by fuel shortages in response and recovery operations (cost unknown; Multnomah County, 2022).

Anticipated Challenges to Response Operations

This section explores the following five elements at play in response operations to the CEI Hub:

- infrastructure failures,
- other hazards in the area,
- containment and cleanup,
- firefighting operations, and
- evacuations and shelter in place protective action recommendations

Infrastructure Failures

A CSZ earthquake will cause widespread infrastructure damage and failures across Multnomah County and the region including electrical outages and fuel shortages, telecommunications outages, extensive damage to transportation infrastructure, damage to water and wastewater infrastructure, and will overburden or damage local hospitals (ODOE, 2017; OSSPAC, 2013; PBEM; 2016). This post-disaster context will impede all aspects of response operations in and around the CEI Hub (Multnomah County, 2022).

Other Hazards in the Area

First responders and those who live or work in the area will face additional threats to life safety, notably fires as well as a multitude of other hazardous material releases. Fires related to the CEI Hub are likely to occur and without suppression resources, these fires are likely to spread to nearby residential and forested areas igniting homes, and have the potential to harm employees, residents, and first responders, further inhibiting response and evacuation efforts. Another threat identified by DOGAMI (2012), OSSPAC (2019), Oregon Solutions (2021), and Multnomah County (2022) is the presence of toxic inhalation hazardous materials stored at or nearby petrochemical facilities, including anhydrous ammonia. These reports mention toxic inhalation hazards, but in each case a deeper analysis into the implications of these materials was beyond the project scope. This report provides preliminary insight into this hazard and corroborates the argument that gaseous chemicals stored in nearby industrial areas may spread over and around the CEI Hub (See Chapter 5). Based on this report's scenarios this is possible if the prevailing wind direction is from the northwest into the southeast, which is the standard prevailing wind direction in the summer months. Other facilities (not examined) may impact the CEI Hub in other wind conditions. For the facilities examined, the threat of plumes is highest in the first few hours after the earthquake before the chemical has had a chance to dissipate into the atmosphere. Therefore, it is likely that these risks are highest for the employees and residents nearby the CEI Hub at the time of the earthquake, as first responders will be delayed in accessing and operating in the area.

Containment and Cleanup

Alongside access issues and other hazards, operations to contain or clean up oil spills at the CEI to mitigate continued harm will be hampered by "reliance on a single provider [cleaner] for all the different facilities in the hub" (Oregon Solutions, 2021). During non-disaster times, Portland Fire and Rescue, local contractors, and facility response teams have response resources to address hazardous materials spills in Multnomah County (Alliance Solutions Group[4], personal communication). However, the combination of multiple spills/releases, telecommunication, and widespread infrastructure damage will require far more resources than will be available (Multnomah County, 2022). As this will be a Spill of National Significance, extensive national resources from a FEMA Stafford Act Response will cascade into the area at the earliest opportunity, but widespread damage to transportation systems will delay these resources, isolating insufficient local resources.

Firefighting Operations

Firefighting operations at the CEI Hub face similar barriers and resource shortfalls. Limited access caused by transportation issues and other hazards in the area will slow firefighting efforts, and even if firefighters are able to access the area, there are limited personnel and resources. Oregon Solutions (2021) reports that there are six fire stations in the vicinity of the CEI Hub, but these are likely to be focused on life safety operations within neighborhoods, rather than organizing a coordinated response to unintended releases in the CEI Hub. There are no dedicated fire brigades or firehouses responsible for the CEI Hub (ibid.). There has also been a large decrease in volunteer firefighters over the past decade, and many current firefighters live far from their service area and will be delayed in reporting to work, making sustained operations more difficult (ibid.). The final variable impeding firefighting response operations at the CEI Hub is the expected short supply of water and fuel caused by damage to Portland's infrastructure (City of Portland, 2021, ODOE, 2017). Taking these variables together, the current estimation is that firefighting operations will be delayed or insufficient and therefore unable to conduct incident stabilization to protect life safety, contain spills, control the spread of fires, and reduce the risk of a domino effect between tanks.

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[4] Alliance Solutions Group is responsible for the 2022 update to the Multnomah County Local Emergency Planning Committee's Emergency Response Plan, which outlines single-hazard response strategy and requirements.

Evacuations and Shelter in Place

The combined threat of fires and hazardous air from smoke, evaporating oils, and other chemical spills means temporary shelter in place orders and/or the evacuations of nearby residents and employees will be necessary to protect life safety. Additionally, toxic smoke and air quality may necessitate evacuations or shelter in place orders in neighborhoods across the river in North and Northeast Portland (See Figure 1, page 38). Conducting these evacuations will be extremely difficult due to damage to transportation and telecommunications infrastructure (Multnomah County, 2022). It is unlikely that first responders will be available or sufficient to convey evacuation orders house to house, and residents may need to self-activate these protective actions. The communities nearby the CEI Hub, particularly Linnton and Cathedral Park, have active community advocates who are aware of the hazards present in the area and understand the likely need to evacuate, but not all those living in the area are aware of the hazard. Continued efforts are necessary to inform these communities and to create avenues for evacuation as the current roads and trails are likely to be impassable or dangerous (Multnomah County Emergency Management, personal communication).

Selected Examples of Earthquake-Induced Petrochemical Releases

1999 Turkey, Izmit Earthquake

On August 17, 1999, a magnitude 7.6 earthquake occurred on the North Anatolian Fault in the district of Izmit in the Kocaeli province in Turkey. One of Turkey's largest crude oil refineries, the Turkish Petroleum Refineries Corp (TUPRAS) refinery, was heavily impacted by the earthquake and experienced three fires (Girgin, 2011). The earthquake damage to the facilities is distinct from what is anticipated at the CEI Hub, as the TUPRAS facility experienced minimal liquefaction and most of the damage was caused by ground shaking (ibid.). Despite these differences, important lessons can be learned from the TUPRAS incident.

The first fire occurred in an onsite warehouse facility in which shelves collapsed releasing an array of chemicals onto the ground which resulted in an ignition. Facility personnel were able to contain this fire within 30 minutes (Girgin, 2011). The second fire was caused when a refinery stack collapsed breaking open pipes carrying Naphtha, a semi-refined petrochemical, which was ignited by sparks (ibid.). Response personnel and facility employees were able to contain the fire four hours after its ignition, but the supply of fuel could not be halted and the materials reignited, requiring another 12 hours of operations before the fire was put out (ibid.).

The third and largest fire occurred when four large Naphtha storage tanks were ignited by sparks from floating tank roofs bouncing against tank walls (Girgin, 2011). Firefighters had initial success in containing the fire and the incident appeared to be stabilized until a flange on one of the tanks failed around 11 hours after the earthquake, likely due to fatigue from the heat of the fires and the deformations caused in the earthquake (ibid.). The released Naphtha caused a jet of fire to erupt, reigniting the four tanks and spreading to two additional nearby tanks (ibid.).

Electrical outages and water supply shortages, caused by damage to water pumps and water pipelines, created significant barriers to response operations and forced firefighters to eventually halt their containment efforts around 16 hours after the earthquake (Girgin, 2011). At this point officials ordered a 5 km radius around the facility to be evacuated, which was carried out in person by first responders (Steinberg & Cruz, 2004). The next day responders worked to construct a barrier between the burning tanks and large liquified petroleum gas (LPG) tanks nearby to avoid possible explosions (Girgin, 2011). On the third day, water and electricity were restored and international aid arrived to help fight the fires, which enabled five of the tank fires to be extinguished. The final tank continued to burn until the fifth day after the earthquake (ibid.).

The TUPRAS refinery fire demonstrates the challenges associated with extinguishing petrochemical fires following an earthquake, however it is worth noting a few key differences from a CEI Hub scenario. Unlike the anticipated impacts to the CEI Hub, none of the TUPRAS tanks experienced a total release of their materials onto the ground, only one petrochemical facility experienced a significant fire, the facility had a dedicated fire response team as well as onsite storage for water, and external aid was able to arrive within a few days, whereas for the CEI Hub it may be weeks before significant external resources are able to access the area.

2011 Japan, Tohoku Earthquake

On March 11, 2011, a magnitude 9.0 megathrust earthquake struck the coast of Japan in the Tohoku region and was followed by a tsunami. A significant petrochemical fire occurred at Tokyo Bay when an LPG tank's support legs failed causing the tank to collapse (Krausmann & Cruz, 2017). The tank was designed to withstand the ground acceleration experienced; however, the tank had been filled with water while undergoing an inspection which increased the weight 1.8 times, surpassing the design requirements. The initial earthquake damaged the braces supporting the tank, and an aftershock 30 minutes later caused the legs to buckle and the tank to collapse, severing pipes and releasing LPG onto the ground which eventually ignited (ibid.).

The adjacent tank experienced a boiling liquid expanding vapor explosion from the heat of the fire, and this explosion spread the fire to additional tanks and resulted in a total of five large explosions at the facility (Krausmann & Cruz, 2017). Further domino effects occurred which caused a release in a nearby asphalt tank and two additional fires on the perimeter of adjacent petrochemical facilities (ibid.). Human error contributed to the difficulty in response operations as an LPG safety valve had been locked in the open position and was unreachable in the conflagration. This pipe continued to feed LPG into the fires throughout the remainder of the incident (ibid.).

Emergency response teams made up of on-site, local, regional, and national teams worked from land and sea to control the fire (Krausmann & Cruz, 2017). It was eventually decided that the best course of action was to let the fire burn out the remaining fuel, and firefighters sprayed water on remaining LPG tanks to accelerate its evaporation. In total six people were injured, around 1100 people were evacuated, minimal air quality impacts were detected, and the explosion shockwaves damaged windows and spread debris into nearby residential areas (ibid.).

Similar distinctions between this incident and the anticipated impacts to the CEI Hub can be detected and learned from. First, the Tokyo Bay LPG fires remained accessible to first responders and significant resources were brought in from the region and nation, which will take significantly more time at the CEI Hub. Second, no significant access or infrastructure issues were reported in the Tokyo Bay fire, which provided first responders the opportunity to bring in resources and mitigate further impacts of the releases. And third, LPG is not a main chemical of concern at the CEI Hub, however this example demonstrates the risk of domino effects in which fires spread and cause additional tank failures, which is likely to occur at the CEI Hub but remains unstudied, for example, possible sources of an explosion, including at the CEI Hub's natural gas facility.

Conclusion

The CEI Hub located alongside the Willamette River in Portland OR presents a serious threat in the event of a Cascadia Subduction Zone Earthquake. The CEU Hub, through which 90% of Oregon's fuel supply is transported, is estimated to release between 65 and 194 million gallons of petrochemicals due to liquefaction and ground deformation damage from a CSZ earthquake (Multnomah County, 2022). A release of this magnitude poses significant life safety risks to the more than 45,000 employees and residents who work or live near the CEI Hub and will impact the entire region with reduced air quality (ibid.).

The greatest life safety risks stem from the high risk for petrochemical fires which may trap employees working in petrochemical facilities, spread into nearby residential areas, or ignite Forest Park. During the summer months Forest Park presents a serious fire risk given its large fuel load and the often-dry forest conditions; should a fire at Forest Park occur it would pose widespread life safety risks to more than 70,000 people and require extensive resources to contain (PBEM, 2021). Evaporating gasoline and jet fuel pose the next greatest life safety risk for facility personnel and communities downwind from the facility (Multnomah County, 2022). Those in the immediate vicinity may be exposed to toxic concentrations of these materials, and those downwind are susceptible to adverse health effects, especially for populations with existing health conditions. Well-established casualty estimates for a catastrophic release at the CEI Hub are not available and are undoubtedly challenging to model, however additional data on the possible injuries and their locations would be invaluable for response planning purposes.

Response operations to mitigate the impacts of a catastrophic release at the CEI Hub will be insufficient and face extensive barriers. Damage to infrastructure lifelines will limit access and resources to contain spills or combat fires. Other hazards in the area including hazardous gasses and spills will threaten first responder safety and place an increased burden on spill containment efforts. Insufficient response resources in the public and private sector, including limited firefighting personnel and resources, limited cleanup and containment contractors, and insufficient first responders will inhibit containment operations as well as health and medical operations to stabilize the incident and protect life safety. Evacuations and shelter in place orders may be necessary to protect people, however current avenues for egress in the surrounding communities are insufficient and may be impassable or dangerous following a CSZ earthquake. Due to the risks posed by a catastrophic release at the CEI Hub, continued mitigation and response preparedness efforts are critical.

List of Relevant Reports Not Cited in this Chapter

Multnomah County. (2022). Oregon Critical Energy Infrastructure Hub: Summary of Available Data and Report of Expected Earthquake Risk. https://multco-web7-psh-files-usw2.s3-us-west-2.amazonaws.com/s3fs-public/AppendixA-HCHA_CEI_Hub_Data_Summary_020222_0.pdf

Multnomah County (2022) presents a geotechnical analysis for the anticipated ground deformation in five geographic regions within the CEI Hub area. Each geographic region is described along with information about the facility owners and the tanks present in the area. Then an analysis provides estimates for the degree of liquefaction and surface settlement each region can expect. A comprehensive list of data sources is provided.

Oregon Solutions. (2019). Critical Energy Infrastructure Hub: Assessment Findings. http://www.orsolutions.org/wp-content/uploads/2019/03/CEI-Hub-final-3-7-19.pdf

Oregon Solutions (2019) focuses on gathering and presenting the perspectives of stakeholders and considerations for how to advance collaboration between them. Areas of inquiry include stakeholders' knowledge of the CEI Hub, perspectives on different approaches to mitigation and incentivization, and information sharing and collaboration between parties. The researchers report that challenges in garnering participation from facility owners limited their ability to answer key questions. The report concludes with a series of recommendations around convening groups to improve information sharing and to develop possible incentives to encourage CEI Hub facility owners to pursue mitigation actions.

OSSPAC. (2019). CEI Hub Mitigation Strategies: Increasing Fuel Resilience to Survive Cascadia. https://www.oregon.gov/oem/Documents/OSSPAC_CEI-Hub_report_122019.pdf

OSSPAC (2019) outlines their efforts to identify and clarify possible mitigation strategies to reduce the risks posed by the CEI Hub and post-earthquake fuel shortages. The bulk of the report is a list of recommendations to expand existing regulatory authority, foster public-private partnerships, invest in earthquake early warning systems, and identify a state agency to lead long term mitigation efforts. OSSPAC's recommendation to assign DEQ as the primary responsible agency was carried out in Senate Bill 1567 as the DEQ now oversees the ongoing vulnerability assessments and mitigation planning done by CEI Hub facilities.

PBEM. (2019). Liquid Storage Tanks at the Critical Energy Infrastructure (CEI) Hub: Seismic Assessment of Tank Inventory.

PBEM (2019) gathers and analyzes available information about the facility owners, number of tanks, and information regarding the tanks' age and storage capacity. The age and storage capacity are used to estimate how many tanks may fail and the subsequent volume of materials which would be released. The report estimates the possible cost for mitigation efforts of the largest tanks in the CEI Hub at over $300 million before concluding with next steps to fill gaps in research and clarify the estimated cost of mitigation.

Chapter 4: Laws Pertaining to Hazardous Materials in the United States and in Oregon

This chapter reviews only those laws and regulations that apply to fixed facilities which store and use hazardous materials in the State of Oregon and therefore does not include laws regulating the transportation of hazardous materials via pipelines, railcars, or other means. This collection of laws should not be considered comprehensive nor sufficient for understanding any of the laws summarized. Any facility which meets the minimum reporting requirements for quantity of material stored is subject to these regulations, however laws, rules, and codes may not apply to facilities which existed prior to the law adoption. The following summaries are explicit when the regulation requires consideration of natural disasters. Examination of these regulations shows that by and large they do not require consideration of natural disasters or earthquakes in their hazard assessments or response plans, which reflects the academic consensus (Necci et al., 2018). Oregon Senate Bill 1567 is a notable exception, passed in 2022 this bill requires bulk fuel terminals in three Oregon counties to address seismic risks, discussed more below, this may serve as a model for addressing the risks of earthquake-induced hazardous materials throughout Multnomah County.

Occupational Safety and Health Administration (OSHA)

OSHA Process Safety Management of Highly Hazardous Chemicals

Facilities must compile safety information to be provided to personnel. That safety information will include: an assessment of the hazards posed by the industrial processes, safe operating procedures, guidance to operate safety equipment, actions to be taken in the event of an exposure, the facility's evacuation plan, and the facility's emergency action plan. Facilities are also required to ensure equipment and storage containers are suitably constructed for their application, are regularly inspected, and receive any necessary maintenance to ensure regular operations remain safe.

OSHA Exit Routes and Emergency Planning

Facilities subject to the previous OSHA regulation must have an emergency action plan which includes procedures for reporting an emergency, evacuation procedures and exit routes, procedures for employees who must perform critical plant operations prior to evacuation, procedures to account for employees after an evacuation, procedures for employees conducting rescue or medical actions, and information about who at the facility is the point of contact for emergencies. Facilities must also install and operate an employee alarm system, train employees on evacuation and response procedures, and regularly review the emergency action plan.

OSHA Hazardous Waste Operations and Emergency Response

Facilities conducting the cleanup of hazardous materials or handling hazardous waste must provide engineering controls, work practices, and personal protective equipment for employee protection including a medical surveillance program. These requirements are considered fulfilled if the facility has developed equivalent programs under the EPA's Emergency Planning and Community Right-to-Know Act.

United States Environmental Protection Agency (EPA)

EPA Oil Spills Prevention and Preparedness Regulations

Within the EPA Clean Water Act, the Oil Spills Prevention and Preparedness Regulations include both the Spill Prevention, Control, and Countermeasure Rule and the Facility Response Plan Rule.

EPA Spill Prevention, Control, and Countermeasure Rule*.* The goal of this rule is to "prevent oil [or hazardous substances] from reaching navigable waters and adjoining shorelines and to contain discharges of oil [or hazardous materials]" (n.p.). To do this, facilities are required to create emergency response action plans which include facility information, response and reporting procedures, and hazard and vulnerability assessments which describe the release scenarios. Of note, the hazard evaluation must provide an analysis of the potential for a discharge, and this analysis must account for the vulnerability of a facility to a natural disaster. However, the natural disaster applies only to the likelihood of a release and is not considered in the design of response action plans or the community impact assessments.

EPA Facility Response Plan Rule*.* This rule requires facilities to "prepare a plan for responding… to a worse case discharge, and to a substantial threat of such a discharge, of oil or a hazardous substance" (n.p.). As with other response plans, this rule requires that the facility be described, the hazards and impacts be identified, and response protocols be defined. In addition to a response plan, this rule requires that a facility "identify and ensure by contract or other approved means the availability of private personnel and equipment necessary to remove" oil or hazardous substances which are spilled into the environment (n.p.).

EPA Risk Management Program Rule

This rule requires that facilities storing or using extremely hazardous substances develop a risk management plan which: "Identifies the potential effects of a chemical accident, identifies steps that facility is taking to prevent an accident, and spells out emergency response procedures should an accident occur" (n.p.). The risk management plan must include: a hazard assessment that describes the potential impacts of a release, including a worst-case scenario, on employees and on the surrounding community and environment; a prevention program that "includes safety precautions and maintenance, monitoring, and employee training measures;" and an emergency response program which includes emergency healthcare, employee training, and procedures for informing the public and relevant response agencies (n.p.).

EPA Emergency Planning and Community Right-to-Know Act (EPCRA)

EPCRA establishes a network of State Emergency Response Commissions (SERCs) who oversee Local Emergency Planning Committees (LEPCs) for each emergency planning district[5] as defined by the SERC. LEPCs are required to develop emergency response plans for public response operations for hazardous material releases from facilities in their district. Facilities who meet the hazardous substance quantity requirements[6] must notify the responsible LEPC of accidental chemical releases and submit yearly Safety Data sheets which report the amount, location, and potential risks of a release for each chemical on site. Finally, EPCRA established the Toxics Release Inventory which records the releases reported by facilities across the nation.

State of Oregon

Oregon Community Right-to-Know and Protection Act (CR2K)

CR2K is supplementary to EPCRA and establishes more stringent reporting requirements (i.e., lower quantity requirements for the quantity of materials which must be reported). CR2K places the responsibility for the SERT within the Oregon State Fire Marshal (OSFM). Facilities in Oregon are therefore required to submit their Safety Data Sheets to the OSFM. To facilitate response, planning, and community education, the OSFM operates the CHS manager as a platform for tracking the inventory of hazardous materials in Oregon. In Oregon, each county is considered an emergency planning district, and most counties support an LEPC.

Fire Code

The Oregon State Fire Marshal's *Oregon Fire Code* as well as the *International Fire Code* place requirements on facilities which use hazardous materials that are flammable or combustible. In addition to these two requirements, authorities having jurisdiction can place more stringent requirements on these facilities. It is beyond the scope of this summary to outline the many ways these fire codes interface with hazardous facilities. In summary, these codes create

[5] In Oregon, each county is considered an emergency planning district.
[6] For details regarding Hazardous Chemical Inventory Reporting: https://www.epa.gov/epcra/hazardous-chemical-inventory-reporting

requirements for facility design, spill control, secondary containment, maintenance, and response planning.

Oregon OSHA Hazardous Materials

The State of Oregon's OSHA Hazardous Materials regulation abides the nationwide OSHA requirements, outlined above, with increased stringency for certain types of hazardous materials. The number of materials covered and the specific requirements for each are beyond the scope of this summary.

Oregon Department of Environmental Quality (DEQ)

At least 10 rules are maintained by the Oregon DEQ which impact hazardous facilities and storage tanks. In general, these rules fall into contingency planning, emergency response, cleanup, and air quality. It is beyond the scope of this summary to describe all these plans in greater detail; however, three important rules are outlined below.

Oregon DEQ Oil Spill Contingency Planning and Fees Rule*.* Onshore and offshore oil facilities which handle or store more than 10,000 gallons of oil or more per day must maintain a contingency plan "for the prevention, containment and cleanup of oils spills" which enter navigable waters or threaten fisheries, wildlife, natural resources, and public or private property (n.p.). These plans must provide facility information, describe likely and worst-case spill conditions, account for the protocol to be used in the event of a spill, and demonstrate sufficient available resources to meet spill response requirements. This rule establishes an annual fee for onshore and offshore facilities which are required to develop oil spill prevention and emergency response plans to be credited towards the Oil Spill Prevention Fund.

Oregon DEQ Oil and Hazardous Materials Emergency Response Requirements*.* This rule defines the "emergency response actions, reporting obligations, and follow up actions required in response to a spill or releases," of oil or other hazardous materials, except those released from underground petrochemical storage tanks (n.p.). In the event of a spill, facilities are required to activate their contingency or emergency response plan(s). If that plan is not activated or is not activatable, facilities must warn people nearby, "undertake every reasonable method to stop the spill and contain the oil or hazardous material," respond to any medical emergencies, arrange for the continued containment and cleanup of a spill. Facilities are required to report spills, or threats of spills, which meet the minimum reporting requirements immediately to Oregon Emergency Management (n.p.).

Oregon Senate Bill 1567 (SB1567). Passed in 2022, SB1567 requires bulk fuel terminals in Columbia, Multnomah, and Lane counties with a combined storage capacity of more than 2 million gallons of petroleum products to submit seismic vulnerability assessments and mitigation plans to the Oregon DEQ by June 1, 2024. Seismic vulnerability assessments must consider the possible impacts of a Cascadia Subduction Zone earthquake's ground shaking and liquefaction risk for all elements of fuel facilities including buildings, storage tanks, secondary containment units, loading facilities, control equipment, etc. Facility risk mitigation plans must meet the rules established by the DEQ's Environmental Quality Commission which will consider provisions to reduce the risks posed by fuel terminals to public health, life safety, and the environment.

SB1567 establishes the Seismic Risk Mitigation Fund which gathers money from fees placed on facility owners, funds provided by the Legislative Assembly, and other sources to be used to review seismic risk mitigation plans and provide grants or financial assistance to terminal owners to assist in risk mitigation actions.

SB1567 also requires the Oregon Department of Energy to develop an Energy Security Plan which will assess the State's ability to recover from a catastrophic failure at Oregon's bulk fuel terminals from either physical attack, a magnitude 9.0 Cascadia Subduction Zone earthquake, or cybersecurity threats. The plan will provide recommendations for increasing fuel resilience in Oregon and strategies for conducting emergency response fuel distribution throughout the state.

Oregon Structural Specialty Code (OSSC)

The OSSC establishes the minimum requirements for the “construction, reconstruction, alteration and repair of buildings and other structures” including hazardous facilities (n.p.). Prior to 1993 the OSSC did not account for modern seismic risks in Oregon, and prior to 2004 the OSSC did not sufficiently account for liquefaction and displacement risks caused by earthquakes. Code updates are not retroactive and older facilities are not required to meet current design requirements. The OSSC defines four risk categories for buildings with Category I posing the lowest threat to human life should the structure fail (e.g., minor storage facilities) and Category IV designated as essential facilities, or which pose the highest threat to life safety in the event of structural failure. Facilities which store or use hazardous materials fall either into Category III or Category IV depending on the type of materials stores and the quantity of those materials. Category III facilities must be constructed to withstand 1.25 times the design earthquake requirements and may be operational or require minimal repair work following the design earthquake, and Category IV facilities must be constructed to withstand 1.5 times the design earthquake requirements and should be operational following the design earthquake. The design earthquake is derived using a probabilistic approach which uses USGS data for the estimated likelihood of different magnitude earthquakes in combination with local geological conditions to determine load bearing requirements and liquefaction or displacement risks. For facilities in Multnomah County, the design earthquake takes a Cascadia Subduction Zone earthquake into account (Portland Bureau of Development Services, personal communication).

Oregon’s Statewide Planning Goals and Guidelines Goal 7: Areas Subject to Natural Hazards

As part of the comprehensive land use planning system in Oregon, this goal requires local governments to adopt comprehensive land-use planning policies to reduce the risks to people and property from natural hazards. This goal prohibits the placement of hazardous facilities “in identified hazard areas, where the risk to public safety cannot be mitigated” (n.p.). Prior to the year 2001, this goal did not require consideration of earthquakes, and the goal does not place more stringent requirements for facility construction beyond those already required by the Oregon Structural Specialty Code.

Chapter 5: Hazard Assessment for Toxic Inhalation Hazardous Material Releases from Multnomah County's Highway 30 and North Portland Industrial Areas

This chapter describes research regarding the risks of earthquake-induced hazardous materials releases in Multnomah County. More than 1,100 facilities in Multnomah County store and use a variety of hazardous chemicals including acids, potentially explosive chemicals, and chemicals with toxic inhalation hazard properties.[7] The Multnomah County Local Emergency Planning Committee[8] (LEPC) performed an analysis as part of the Hazardous Material Emergency Response Plan update which identified the 70 highest-risk facilities in the County (See Figure 2, page 67; Multnomah LEPC, 2022). This hazard assessment models a worst-case release from four of these facilities located in the North Portland and Highway 30 industrial areas (See Figure 3, page 68). All four of these facilities contain toxic inhalation hazard compounds and meet criteria for seismic vulnerability (See page 70 for a description of this criteria). FEMA's Interagency Modeling and Atmospheric Assessment Center (IMAAC) provided toxic gas release models (i.e., plumes) for these four facilities using a worst-case release scenario (IMAAC, 2022). Because wind patterns can have significant seasonal variation, both wintertime and summertime models were provided. The casualty estimates for these scenarios include more than 17,000 injuries with the potential for 2,500 deaths, demonstrating the magnitude of this hazard for residents of Multnomah County. The implications of this many people being in harm's way is discussed as are the significant challenges in risk mitigation. Also considered is the variability in release scenarios that may occur and how meteorological conditions will influence the distribution of these hazardous materials.

The remainder of this chapter is organized as follows. An overview of hazardous materials in Multnomah County followed by an overview of the

[7] Toxic inhalation hazards are a class of toxic chemicals that act on the soft tissues and respiratory tract and can cause pulmonary injury and death.

[8] Under the Emergency Planning and Community Right-to-Know Act (EPCRA), Local Emergency Planning Committees (LEPCs) must develop an emergency response plan, review the plan at least annually, and provide information about chemicals in the community to citizens. See pages 57-58 of this report for a summary of EPCRA.

theoretical vulnerabilities of these facilities. A brief description of the nature of the information used in the analysis, much of which is For Official Use Only (FOUO), and the provision of the protocol used to ensure this report can be shared with a broader audience. Then, the population of facilities within the area of study is described before turning to the methods used for facility selection and plume modeling. At this point limitations in the research are discussed. The next section describes and contemplates the release scenarios and plume models to explore the variety of possible outcomes and to learn about the hazard. A discussion of the implications of these findings and recommendations for areas of future research is also included. Lastly, the outcomes of an alert and warning exercise conducted using these scenarios is provided, followed by the conclusion.

Cascadia Subduction Zone Earthquake

Multnomah County is at risk of catastrophic damage caused by a magnitude 9 or greater Cascadia Subduction Zone (CSZ) earthquake (Oregon Department of Geology and Mineral Industries, [DOGAMI], 2018). Information on the impacts of a CSZ earthquake is widely available and detailed elsewhere in this report. Therefore, this section provides a summary of the impacts most relevant to hazardous materials releases and to communicating and supporting protective action recommendations.

A CSZ earthquake will have significant impacts on much of Multnomah County's built environment (Oregon Seismic Safety Policy Advisory Commission [OSSPAC], 2013). Most notable is the damage to transportation infrastructure like roads, bridges, buildings, and telecommunications infrastructure. Failures in these systems will impede the ability of first responders to reach areas containing hazardous facilities or for operators at these facilities to communicate information about releases to first responders, and first responders will therefore be unable to determine the type and extent of hazardous materials releases. Without this critical information, public agencies will be unable to determine appropriate protective actions, and those agencies would be unable to communicate those actions to the impacted communities without standard telecommunications. Because first responders will be unable to reach impacted areas to render aid, members of the community will need to evacuate or shelter in place without assistance. Damage to water infrastructure will be widespread and will impede the ability for residents and first responders to conduct decontamination operations. Finally, a CSZ earthquake will cause widespread damage to building stock (DOGAMI, 2018), which will undermine the function of these structures to be used for shelter in place by residents (Steinberg et al., 2008).

Hazardous Facilities in Multnomah County

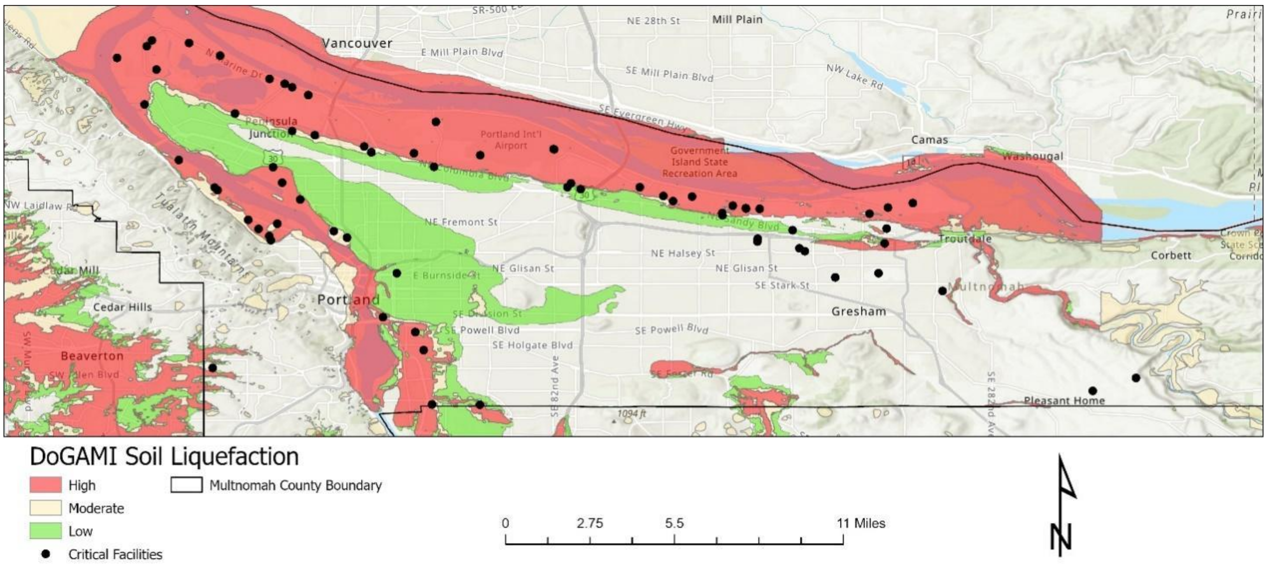
Multnomah County is home to more than 1,100 Tier II facilities, which are facilities that meet the minimum reporting requirements for the quantities of hazardous materials as required by Oregon's Community Right to Know and Protection Act (Portland Fire & Rescue HAZMAT team, personal communication). Tier II facilities contain a variety of different hazardous materials including acids and materials with explosive and/or toxic inhalation hazard characteristics in a range of quantities, some as low as 5 gallons with others housing more than 2 million gallons. This means that the risks posed by Tier II facilities in Multnomah County range from no off-site risks to extensive off-site risks which could impact thousands of residents.

Facilities which store or use hazardous materials are vulnerable to seismic events if the equipment, tanks, pipes, and secondary containment units which house these materials are not built, maintained, and operated to sufficient seismic codes and standards. Facilities built prior to 1993 were not required by Oregon's Building Code to account for modern seismic risks (Oregon Building Codes Division, 2012). Facilities built prior to 2004 do not sufficiently address liquefaction and permanent ground displacement risks (DOGAMI, 2012).

The type of equipment or storage unit(s) at a hazardous facility, as well as backup and secondary containment capabilities, contributes to a facility's degree of vulnerability to a seismic event. Above ground storage tanks which house materials at atmospheric pressure are the most vulnerable to seismic events, including liquefaction and permanent ground displacement risks (Necci & Krausmann, 2022). Pressurized storage tanks and/or cylinders are less prone to catastrophic failure in a seismic event compared to atmospheric storage tanks as tank walls and edges must be more robust to maintain high internal pressures. However, these pressurized vessels can still be damaged and release materials due to pipe or connection failures, support leg failures, displacement, and overturning, all of which can occur due to either ground shaking or liquefaction (ibid.). Pipes and connections between storage tanks or equipment may break open due to liquefaction and lateral spread, ground shaking, or the collapse of structures or objects which land on the pipes (Krausmann et al., 2010). Materials stored on shelves or in small containers are at risk of falling and breaking open, resulting in sometimes numerous small spills which create additional challenges in first responder access and which risks mixing otherwise innocuous chemicals into dangerous reactions (ibid.). Facilities which depend on refrigeration to maintain containment of hazardous gasses, by keeping them in liquid form, are at risk of release due to power outages or failures in backup power supply systems (Krausmann & Cruz, 2017; Portland Fire and Rescue, personal communication). Secondary containment units including water curtains or containment walls not built to current seismic design requirements (i.e., pre-existing non-conforming) or that were not built considering the potential for simultaneous tank failures within the same unit, are at risk of being rendered inoperable and failing to safely contain a release (Cruz et al., 2017).

Liquefaction and permanent ground deformation are of particular concern in Multnomah County's industrial districts due to their proximity to the Willamette and Columbia rivers (OSSPAC, 2013). Liquefaction occurs in areas with loose sandy soils, a high groundwater table, and strong ground shaking. This combination causes the connections between soil materials to break and the ground to act like a liquid until the shaking stops, which can cause storage tanks to sink, fail, or separate from pipes and connections (Wang, 2009). Historical land use planning and economic decision making has resulted in most of Multnomah County's industrial districts being established alongside the Willamette and Columbia rivers where land is more affordable and access to maritime transportation is readily available. Unfortunately, this means a significant portion of Multnomah County's Tier II facilities are in liquefaction zones (Figure 2) with the potential for lateral spreading that can cause permanent ground deformation of up to 17 feet (DOGAMI, 2018) compounding the risk of failure. The top 70 highest risk Tier II facilities identified by the Multnomah County LEPC (2022) are superimposed on the DOGAMI (2018) liquefaction risk map below.

Figure 2: Multnomah County Top 70 Tier II Facilities Overlaid on DOGAMI (2018) Liquefaction Map for Dry Soil Conditions.



Protocol for Protected and Classified Information

Much of the information and data used for this analysis is considered For Official Use Only (FOUO), protected, or classified information by government agencies (Oregon State Fire Marshal's Office, personal communication). Safeguarding details about specific types of chemicals, and the number of possible casualties a release may cause, helps to minimize the risk of this information being used to intentionally cause harm. "Some information is restricted from the public because it's confidential. This information may be released through a public records request under ORS 453.327[9], the state fire marshal may require an individual to provide their name, address, and proof of identity when necessary to protect public safety and welfare."[10] Information is considered protected or classified when represented in a plume model, including the name of a facility, the facility's exact location, the type of material shown in the plume model, and the quantity of

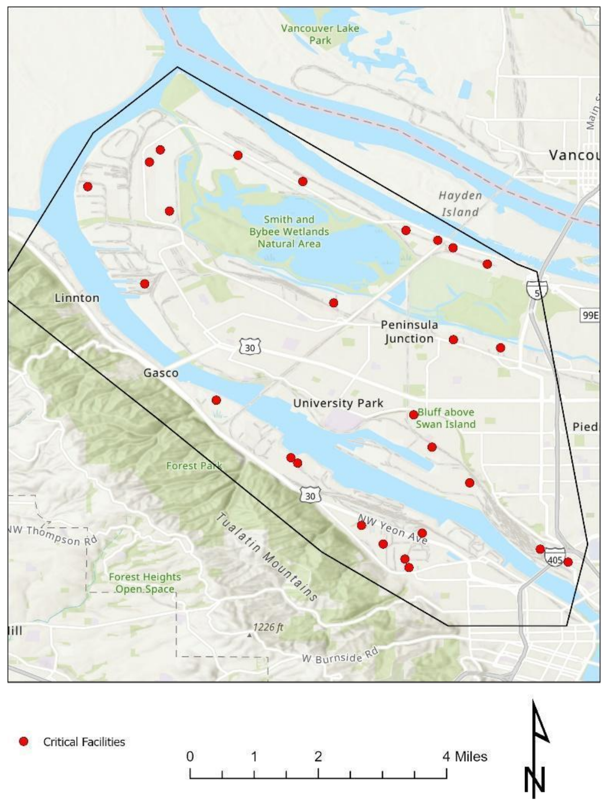
[9] https://oregon.public.law/statutes/ors_453.327
[10] https://www.oregon.gov/osp/programs/sfm/Pages/HazMatStorageInfo.aspx

material shown in the plume model. To abide by these information protection requirements and enable a broader distribution of these findings, this report and the scenarios employ pseudonyms for facilities (e.g., Facility 1), pseudonyms for the hazardous materials (e.g., Chemical 1), quantities for hazardous materials stored at a facility are not included nor shown in any plume model.

Description of Facility Population Within the Study Area

The scope of this research project was limited to the facilities along Highway 30 and the North Portland industrial areas. This region, shown in Figure 3, contains 27 of the Multnomah County LEPC's (2022) identified top 70 Tier II facilities. The facilities in this target area store a variety of chemicals including hydrochloric acid, sulfur dioxide, hydrogen chloride, thionyl chloride, anhydrous ammonia, diesel, toluene, sulfuric acid, and other miscellaneous chemicals. Storage unit types include metal or plastic drums, plastic totes or bins, pressurized cylinders, above ground tanks, and rail cars.

Figure 3: Tier II Facilities Within Study Area



According to Metro's Regional Land Information System (n.d.), nine of the facilities in the target area are listed as constructed prior to 1993, seven are listed as constructed between 1993 and 2003, four are listed as constructed after 2004, and seven do not have facility age listed and are therefore assumed to be constructed prior to 1993.

According to the DOGAMI (2018) peak ground acceleration estimates for a CSZ earthquake, of the 27 facilities examined: one facility is in a peak ground acceleration zone of 0.20g to 0.25g; 15 facilities are in peak ground acceleration zones of 0.25g to 0.3g; and 11 facilities are in peak ground acceleration zones of 0.3g to 0.35g. Based on the Mercalli Intensity Scale calculations provided by DOGAMI (2018) which estimate perceived shaking and damage potential (including liquefaction impacts) six facilities are likely to experience very strong to severe shaking and moderate to moderate/heavy damage, and 21 facilities are likely to experience severe shaking with potentially heavy damage. A CSZ earthquake is expected to produce prolonged ground shaking which would exacerbate these damage levels.

Information and Data Sources

The following sources were used to inform this hazard assessment and to develop the most realistic scenarios possible. Information regarding the process for accessing these sources can be found in the accompanying chapter on HAZMAT planning resources for Multnomah County.

- Informal interviews with local and state hazardous materials experts, emergency managers, regulatory authorities, and engineers.
- Oregon State Fire Marshal's (OSFM) office and the Community Right to Know Hazardous Substance Manager (CHS Manager) software: information regarding the location of facilities and the type and quantity of materials stored at a facility.
    - The CHS Manager is available through the OSFM's website. Only parties affiliated with emergency response planning and response, or those affiliated with official research institutions, can access FOUO information. Citizens or residents can access information on facility name, location, and type of material stored.
- Oregon Metro's Regional Land Information System (2022) dataset: data regarding the age of facilities, which can be accessed via Metro's website.
- Multnomah County Local Emergency Planning Committee's (2022) *Hazardous Material Emergency Response Plan*: the top 70 highest risk facilities.
    - Personnel affiliated with emergency planning and response can access the LEPC's emergency response plan by contacting the Portland Fire

and Rescue HAZMAT Coordinator or the Oregon State Fire Marshal's LEPC Program Coordinator.

- Portland State University's literature review on earthquake-induced hazardous materials releases: helped define the framework for the facility selection process.
- FEMA's Interagency Modeling and Atmospheric Assessment Center (IMAAC) managed by the Defense Threat Reduction Agency: Plume modeling and guidance regarding how to read and understand plume models.
    - Local, state, and federal officials can request IMAAC support by contacting their Technical Operations Hub (IMAAC@fema.dhs.gov).
    - Requests for modeling must include at least: the facility address, the type and quantity of material released, and the real or selected date and time at which the release occurred—which IMAAC uses to determine meteorological conditions for the release. Requests may include the speed at which a release occurs and the presence or absence of secondary containment berms.

Methods for Facility Selection and Plume Modeling

A qualitative and modified version of the Rapid Natech Risk Assessment outlined by Cruz and Okada (2008) was employed to identify high-impact and vulnerable facilities for realistic worst-case release scenario models for the study area. The decision to pursue a worst-case scenario situation was chosen to help inform the placement of and safe timing for opening shelters and other CSZ earthquake response operations. The Rapid Natech Risk Assessment method assigns each HAZMAT storage tank with a risk index score derived from the multiplication of the HAZMAT release likelihood times the anticipated impacts of that release.

The HAZMAT release likelihood of a tank is determined by combining assumptions about the presumed severity of the natural hazard with assumptions about the durability of the storage container. In quantitative forms this would involve the use of fragility curves for a known piece of equipment with the anticipated natural hazard intensity. For the qualitative approach used in this study, a facility was determined to be seismically vulnerable if it was built prior to 2004 and the hazardous materials are stored in above ground storage tank(s) or pressurized cylinder(s). Additionally, only facilities that store toxic inhalation hazards were included, which means that facilities storing acids or potentially explosive materials were not examined in this study. Based on these criteria, eight possible facilities were identified as appropriate for further analysis.

In a full application of this methodology, the anticipated impact of a release would be determined by the combination of the risk of potential cascading effects, the possible population impacted by a tank's release, and other critical facilities impacted by a tank's release. This report's analysis did not consider the risk of cascading effects as this would require additional quantitative and geospatial analysis that fell beyond the scope of this report. Because there is minimal variance in the estimated number of impacted critical facilities provided by Multnomah LEPC (2022), this factor was not included in selection criteria. Therefore, the primary selection criteria for the highest risk facilities in the target area was the estimated population at risk provided by the Multnomah LEPC's (2022) preliminary plume modeling. Based on this value, four facilities were selected from the eight vulnerable facilities, identified above, as posing the most significant off-site risk. Catastrophic release scenarios from these four facilities were sent to IMAAC for plume modeling. IMAAC (2022), *Chemical Releases at Various Locations in Portland, OR, Revision B* prepared for the Institute for Sustainable Solutions at Portland State University, contains the results of this modeling process.

The IMAAC modeling process combines geographic data on an area's topography, the location of a release, the type and quantity of material releases, the speed of release, and the meteorological conditions at the time of release to calculate the path of a gas cloud prior to its dissipation. To develop worst-case scenario models, the research team provided IMAAC location information on the four facilities selected. To maintain this study's worst-case assumptions, the maximum storage quantity for hazardous materials at a facility was given, rather than the average quantity of hazardous materials. For the speed of release, a catastrophic release resulting in total loss of containment taking less than 10 minutes was used (versus a slow release with an extended duration of exposure).

For the meteorological conditions at the time of the modeled releases, two dates were used that reflect the average prevailing wind direction in Multnomah County for the winter and summer months. Other wind events, for example, a strong westerly wind, could result in comparatively more casualties due to the pathway of a release. However, higher winds may also result in a lower concentration of gas at any given point and thereby result in fewer casualties. The array of possible meteorological conditions is discussed further in this chapter's limitation section. Due to the uncertainty involved, the planning team followed recommendations provided by emergency managers and hazardous materials experts and used average wind conditions rather than speculating on possible worst-case wind conditions.

In Multnomah County during the summer months from April through August the average wind direction is from the northwest into the southeast with an average wind speed between 4 and 9 miles an hour (Midwestern Regional Climate Center [MRCC], n.d.). To represent a summertime release scenario, July 24, 2022, at 5PM was used as the example date and time of release. On this date, the wind was 5 miles per hour into the southeast, the temperature was 90°F, and there was a mild overcast with low humidity (MRCC, n.d.). During the winter months from October through March, the average wind direction in Multnomah County is between six and 10 miles per hour from the southeast into the northwest (MRCC, n.d.). To represent a wintertime release scenario, January 2, 2022, at 12PM was used as the example date and time of release. On this date, the wind was 10 miles per hour into the Northwest, the temperature was 28°F, and there was an overcast with low humidity (MRCC, n.d.).

With the information provided, IMAAC (2022) developed plume models for each facility for both a summertime and wintertime release scenario. Each model provides estimations for the number of individuals impacted in each of the Acute Exposure Guideline Levels: AEGL 1 (short-term irritation), AEGL 2 (long-term health impacts) and AEGL 3 (life-threatening health effects or death). As part of the modeling process, IMAAC (2022) was able to provide wintertime and summertime plume models for a simultaneous release from Facility 1 and Facility 3 because they store the same type of hazardous material. These models provide insight into the possible implications of compounding and/or consecutive releases, discussed below.

IMAAC's modeling software assumes a completely unsheltered population and the casualty estimates reflect this assumption (i.e., residents are not inside a shelter and not wearing personal protective equipment). While this assumption is considered a limitation in the estimation of casualties, there is reason to argue that a largely unsheltered population may be representative of a post-earthquake scenario. The first variable contributing to this is damage to the general building stock, as broken windows, doors, etc. will reduce the efficacy of a building to serve to shelter in place (Cruz & Okada, 2008). Second, well established post-earthquake protective action recommendations are to "go outside and quickly move away from the building" after the shaking stops if the building is damaged during the earthquake, which would place survivors outside (Ready.gov. n.d.). Third, the well documented occurrence of "milling" behavior among victims of a disaster in which residents work to "define unfamiliar situations" by talking to neighbors or family members and contemplating what to do, can delay the initiation of protective action recommendations (Wood et al., 2018). And fourth, disaster survivors often begin emergency search and rescue operations or otherwise assist neighbors and others nearby (Necci et al., 2018).

The plume models were provided by IMAAC as GIS layers which were used to review a variety of geospatial datasets including GIS layers for hospitals, schools, nursing homes, and other critical facilities, as well as the consideration of social vulnerability indicators related to demographics. Critical facility datasets proved to be incomplete and defining what is a critical facility fell beyond the scope of this study. For training purposes and to ensure a robust understanding of the potential issues and level of risk, the scenario maps include schools and hospitals. The plume models indicate the HAZMAT releases will impact a large geographic region spanning many census tracts with wide ranges in socioeconomic and social vulnerability variables. To explore these vulnerabilities, readers are advised to use Oregon Metro's Social Vulnerability Toolkit.

Limitations

A variety of constraints must be considered while interpreting this report's scenarios. This section details limitations in the following areas: compounding and cascading exposures, meteorological, population impacts, and storage tanks.

Compounding and Cascading Exposures

This study considered only a single type of material from each of the four selected hazardous facilities and excludes the majority of facilities in Multnomah County from analysis all together. Therefore, this report's analysis does not consider the impacts from the multitude of hazardous storage vessels containing a wide variety and quantity of chemicals throughout the area of study and all of Multnomah County, which is why our priority recommendation is additional risk assessment and modeling. Scenarios included in this report should not be considered a comprehensive look at the possible life safety risks stemming from earthquake-induced hazardous materials releases following a CSZ earthquake. Significant research remains to understand both the breadth of this hazard in Multnomah County and the risks associated with each facility.

Significant uncertainties also exist for the plume models and their life safety implications. Current capabilities of predictive modeling software are limited to producing models with only one type of hazardous material. Plumes in this report's wintertime release scenario from Facility 2 and Facility 3 overlap extensively. It is unclear what multiple concurrent or in-succession exposures to any level of AEGL would mean for a person's health. It may be the case that significant overlap between the AEGL 1 pathway for two plume models could result in more serious health effects than would otherwise occur. Discussion of the summertime release scenario provides some insight into the possible outcomes of overlapping plumes using IMAAC's (2022) combined model for Facility 1 and Facility 3.

Due to the project scope, a variety of outcomes of earthquake-induced hazardous materials were not explored and are deserving of future investigation. One such consideration is the possibility that cascading impacts and/or failures may have on facilities near one another (i.e., a domino effect). For example, fires at a petrochemical facility spreading to a nearby facility which may have otherwise been resilient to earthquake impacts and causing additional releases. Additionally, the risks posed by hazardous material spills to the local water supply and other environmental and economic impacts were not addressed in this report.

Meteorological

There are a variety of possible meteorological conditions which may be present at the time of an earthquake, each having specific and, in some cases, significant impacts. As previously mentioned, Multnomah County has certain average prevailing wind conditions, but there is also the possibility for: no winds, high sustained winds, high gusty winds, winds from abnormal directions, etc. all of which would result in the distribution of hazardous materials in different directions and in different concentrations compared to the scenarios in this report. Additionally, there is uncertainty introduced by the possibility of rain events or high-humidity days. Moisture and rain can interact with toxic gasses and chemicals, in some cases reducing the spread or health impacts of a gas and in others causing an innocuous chemical to become dangerous (Portland Fire and Rescue, personal communication). Future investigation into the risk of hazardous materials releases in Multnomah County following an earthquake would benefit from a greater study of this variability.

Population Impact Uncertainty

The timing of the CSZ earthquake, whether during working hours or during a time when most people are home, will have significant implications regarding the number of casualties. Additionally, the assumption of an entirely unsheltered population and the issues of compounding releases also introduce uncertainty in the casualty estimates. No literature was found that quantifies the expected viability of structures to provide shelter from hazardous gasses following an earthquake. Widespread damage to building stock will reduce the effectiveness of using these structures for sheltering, but to what degree remains unknown (Steinberg et al., 2008). In addition to the protective action recommendation to leave a damaged building post-earthquake, there are many other reasons why people would be outside after an earthquake (e.g., "milling" or conducting search and rescue), and this may support the assumption of an unsheltered population. Continued research in this area is essential to accurately estimate the life safety implications of earthquake-induced hazardous materials releases.

Storage Tanks

The quantity of hazardous material present in a facility is transient and it is impossible to know how much will be present at the time of a CSZ earthquake. Therefore, this report took the worst-case assumption and used the facility's maximum quantity for modeling purposes, which may overestimate the geographic and life safety impacts of releases at these particular facilities. Additionally, the storage vessel's seismic vulnerability is based on multiple assumptions which should receive continued investigation. For example, the building age dataset provided by Oregon Metro's Regional Land Information System (2022) does not indicate if the hazardous materials storage unit or equipment was in place at the time of facility construction, which translates to a lack of confidence that the data reflects the seismic design requirements to which a storage unit was constructed. It is also unknown if facilities have been retrofitted, and, if so, to what degree. Continued investigation of this hazard with an approach that assesses each facility individually and includes direct outreach and contact with facilities and relevant permitting and regulatory authorities is recommended.

How to Read Plume Models

The United States Environmental Protection Agency (EPA, 2022) provides internationally recognized Acute Exposure Guideline Levels (AEGLs) for airborne chemicals which pose a threat to human health. Three AEGLs are defined and used across all chemicals, with level 1 being the least severe and level 3 being the most severe. AEGL 1, represented as yellow, is defined as: "Notable discomfort, irritation, or certain asymptomatic non-sensory effects. However, the effects are not permanently disabling, they "are transient and reversible upon cessation of exposure" (ibid., n.p.). Level 2, represented as orange, is defined as: "Irreversible or other serious, long-lasting adverse health effects or an impaired ability to escape" (ibid., n.p.). And level 3, represented as red, is defined as: "Life-threatening health effects or death" (ibid., n.p.). See Chapter 1, page 20 of this report for more information on AEGLs.

The plume model maps shown in the scenarios (Figures 4-9) do not represent the total area covered by a plume at a given time, rather these models represent the pathway that a cloud of gas may travel prior to dissipation. For the four releases used in the scenarios, IMAAC (2022) noted that the plumes will have dissipated into the atmosphere within two to three hours after release, and that it will take less than 10 to 15 minutes for the plume to pass any given location on the map. This modeling is based on catastrophic, instantaneous releases in which all of the material stored is released at once, which is unlikely. More likely, there will be continuing sources of high concentrations of toxic compounds beyond those stated here both in terms of the duration prior to evaporation or release and the duration it takes for the chemicals to dissipate to less unhealthy levels.

We provide three maps for each of the summertime and wintertime release scenarios. The first map provides the four HAZMAT releases, modeled separately. The second map provides the four HAZMAT releases with Facility 1 and Facility 3 being modeled as a simultaneous release. And the third map provides the four releases, modeled separately, and containing only AEGL 2 and AEGL 3 impact zones for clarity.

Post-CSZ Earthquake Hazardous Materials Release Scenarios

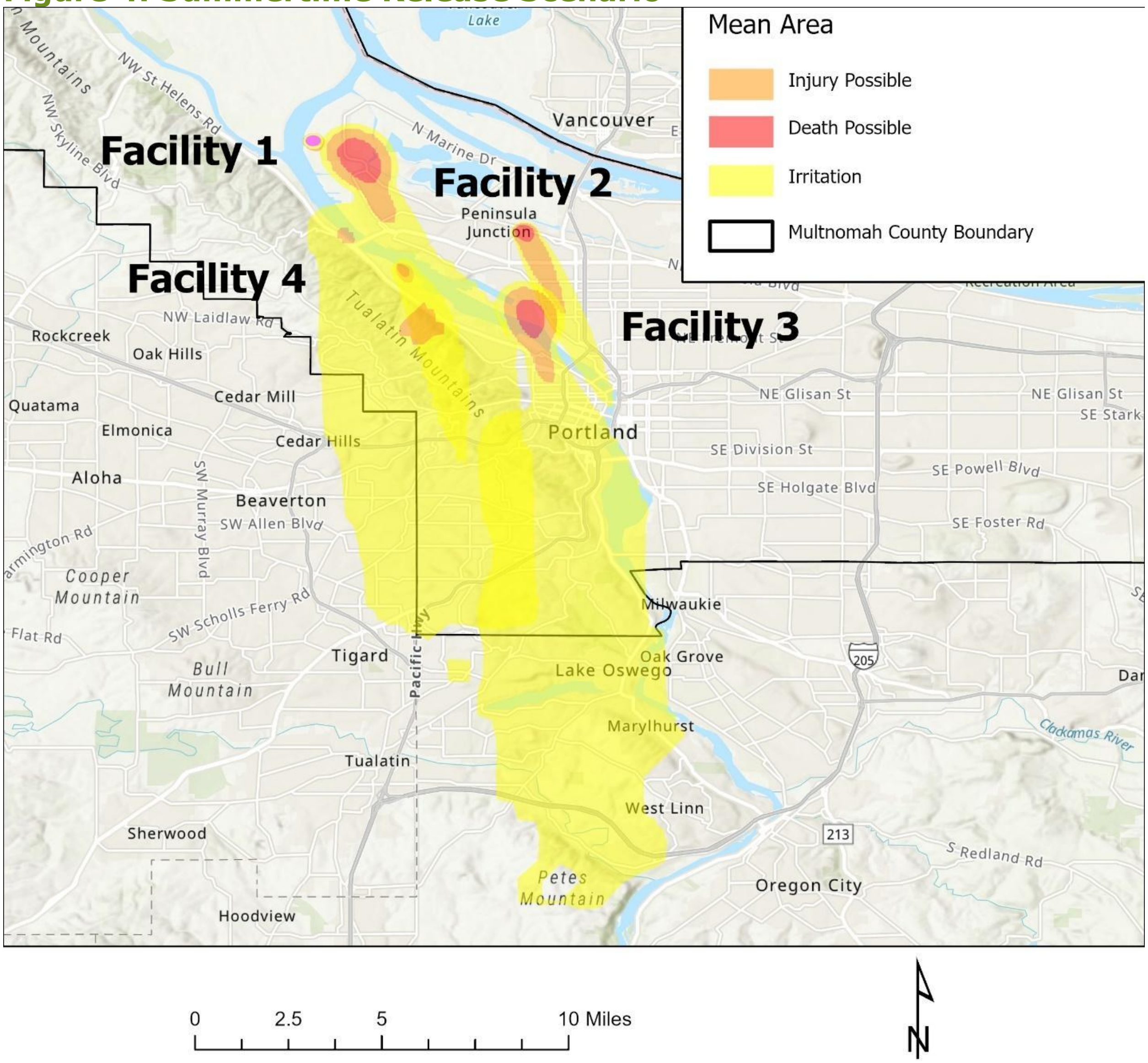
The subsequent sections describe the summertime and wintertime scenarios in a contemplative way. Rather than emphasizing the specific pathways for gas clouds and their implication on different things like government and response capabilities, the discussion instead seeks to learn from the models to glean a deeper understanding of the hazard and its possible variability. Certain assumptions persist across all possible scenarios that are worth reiterating here:

- If you are not in the area of possible exposure in these maps, it does not mean you do not have the same risk, it just means you are not captured in this scenario.
- AEGL 1 (temporary irritation) will impact a very broad population with significant symptoms that will require decontamination.

- Fires and other hazardous material releases, including from the Critical Energy Infrastructure Hub, will further reduce air quality for much of Multnomah County and will exacerbate the health impacts of exposure to toxic inhalation hazards.
- Transportation infrastructure including roads and bridges are expected to be significantly damaged which will impede the ability of community members to evacuate and to acquire medical care.
- Telecommunication outages will impede:
    - the ability for first responders to determine accurate information about hazards,
    - the ability of first responders to communicate appropriate protective action recommendations,
    - the ability for facility operators to report spills or leaks to the public agencies,
    - and the ability to coordinate efforts between government agencies who play a role in response.
- HAZMAT releases will occur immediately following an earthquake before response operations have had time to organize and muster resources. Aftershocks and cascading impacts (e.g., domino effects or prolonged power outages at large refrigeration facilities) may lead to subsequent HAZMAT releases and further delays in response mobilization.
- Damage to structures will undermine the effectiveness of buildings to shelter the population due to broken windows, doors, etc.
- Hospitals will likely be rendered partially or fully inoperable while simultaneously being inundated with patients without sufficient resources to appropriately provide care to individuals exposed to hazardous gasses (OSSPAC, 2013).
- Widespread damage to water infrastructure will inhibit decontamination capabilities for community members and first responders.
- Community members are likely to be outdoors in the process of “milling” with family and neighbors or conducting search and rescue operations (Necci et al., 2018; Wood et al., 2018).

Summertime Release Scenario

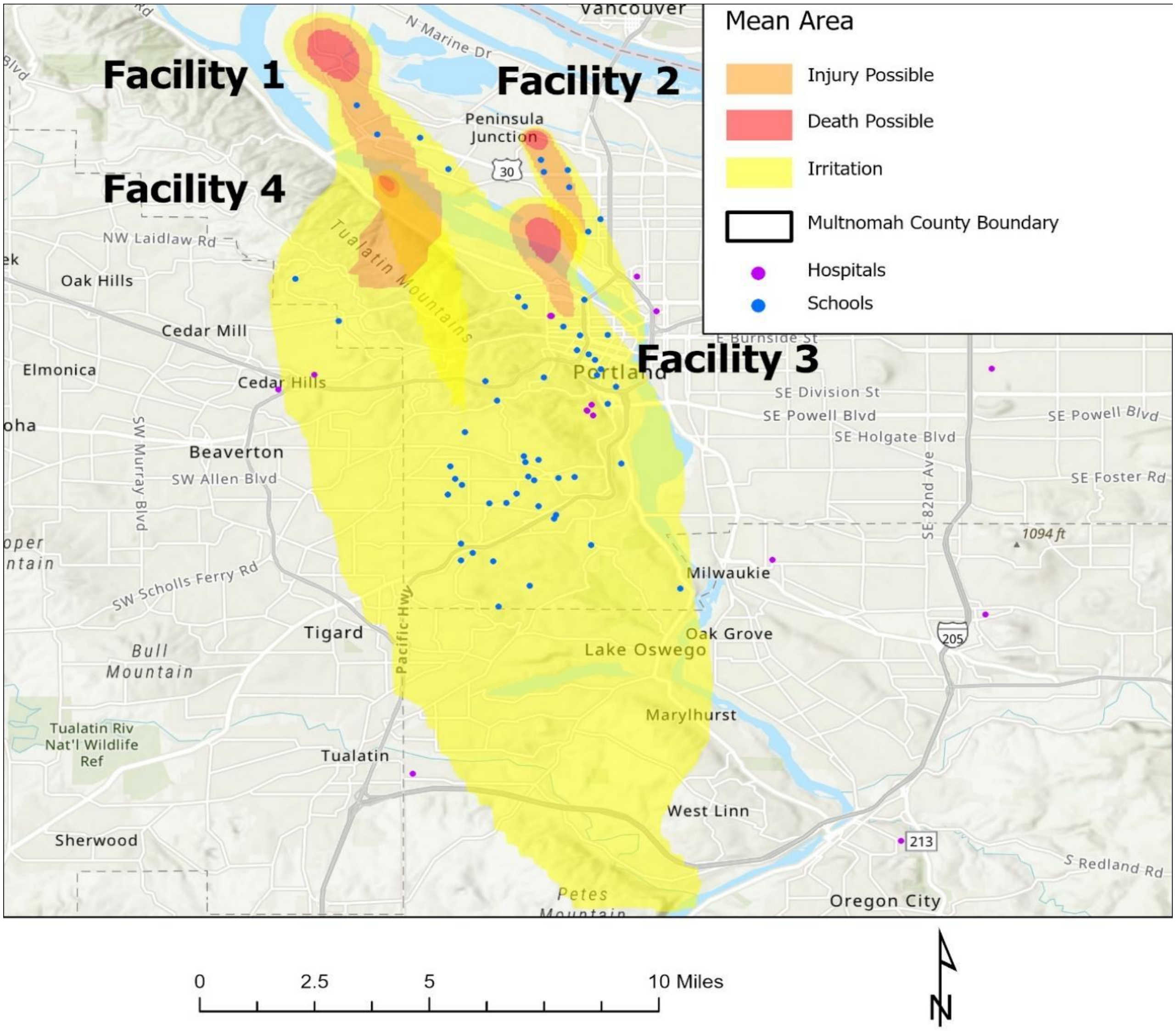
Figure 4: Summertime Release Scenario[11]



July Scenario	AEGL 3 (Potential Deaths)	AEGL 2 (Potential Injuries)	AEGL 1 (Reversible Irritation)
Facility One	535	3284	107626
Facility Two	541	5138	21830
Facility Three	1649	9263	205615
Facility Four	38	81	2062

[11] Areas not in the AEGLs represented in this model are not necessarily out of harm's way. This model only represents one possible wind direction and speed.

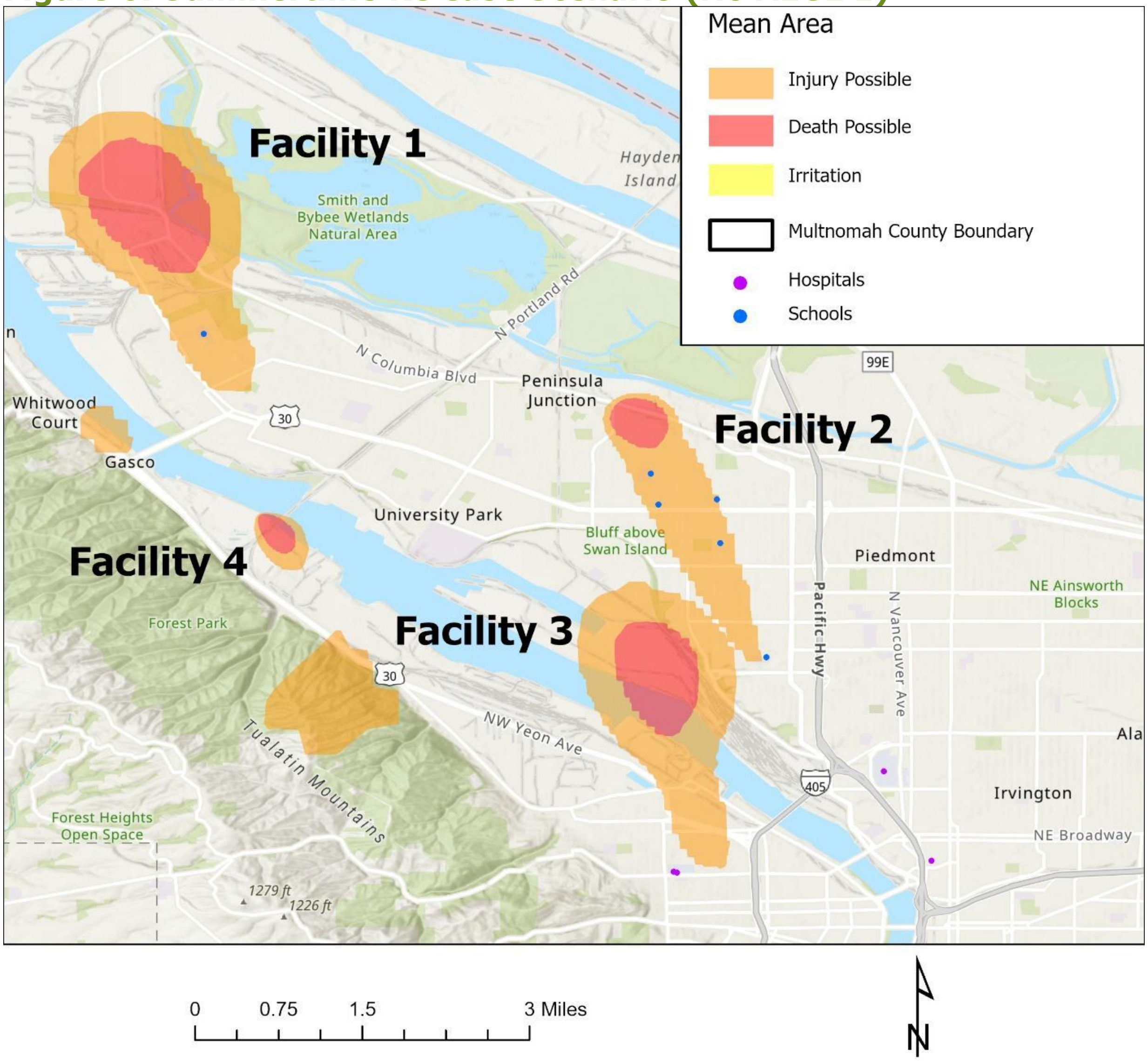
Figure 5: Summertime Release Scenario, Combined Release Modeling for Facilities 1 & 3[12]



July Scenario	AEGL 3 (Potential Deaths)	AEGL 2 (Potential Injuries)	AEGL 1 (Reversible Irritation)
Facility 2	541	5138	21830
Facility 4	38	81	2062
Facilities 1 & 3	2200	20000	330000

12 Areas not in the AEGLs represented in this model are not necessarily out of harm's way. This model only represents one possible wind direction and speed.

Figure 6: Summertime Release Scenario (No AEGL 1)[13]



July Scenario	AEGL 3 (Potential Deaths)	AEGL 2 (Potential Injuries)	AEGL 1 (Reversible Irritation)
Facility One	535	3284	107626
Facility Two	541	5138	21830
Facility Three	1649	9263	205615
Facility Four	38	81	2062

[13]Areas not in the AEGLs represented in this model are not necessarily out of harm's way. This model only represents one possible wind direction and speed.

Modeled for an average summer day with winds at 5 miles per hour into the southeast, a temperature of 90°F, mild overcast, and low humidity. This scenario highlights the immense life safety risks posed by earthquake-induced releases of toxic inhalation hazards into residential areas, the dangers posed by slower moving or stagnant air, the possible influences of topography, and the variability in impact from different chemical types.

As Figure 4 shows, the modeled release could result in more than 17,000 injuries and 2,500 deaths. The location of facilities and the direction of wind contribute to the potential casualties caused by a release. For example, compare Facility 2 across the two scenarios. In the summertime release scenario Facility 2 could injure more than 5,000 people and kill more than 500, whereas in the wintertime scenario Facility two is estimated to injure less than 500 people and kill less than 50. This somewhat extreme range is the result of the facility's location and seasonal norms regarding wind direction which results in the plume traveling either directly into residential areas or with fewer impacts into non-residential areas.

It is noteworthy that the total estimated potential deaths seen in the summertime scenario (>2,500) is greater than the potential deaths estimated for the wintertime scenario (>1,100; Table 2), even though the estimated injuries are greater in the wintertime scenario. The main variable contributing to this variability is wind speed. Because the summertime release scenario has a relatively low wind speed, the hazardous gasses move slowly and spread out in more of a radial pattern, as seen in Facility 1 and Facility 3. Because the wind speed is lower the hazardous gasses remain in a higher concentration for longer and the length of exposure is also likely to be higher. This same reduced wind speed contributes to the extreme number of residents who will experience AEGL 1 exposure levels in the summertime release scenario. This demonstrates the risks associated with an earthquake occurring during stagnant weather or during a “heat dome” as happened during June 2021. When wind speeds are low hazardous gasses may persist at ground level for extended periods of time.

The summertime scenario demonstrates the potential implications of topography on the distribution of toxic inhalation hazards. Two abnormalities can be seen in Figure 6, directly south of Facility 4 and directly west of Facility 4 there are small patches of EAGL 2 exposure concentrations. These plumes are not the result of a release at Facility 4, rather they are gasses released from Facility 1. The material released from Facility 1 is heavier than air when in a gaseous state. This means it will travel along the ground and will sink into low topographical spaces. Having been pushed south by the wind, the modeled gas appears to have increased in concentration and duration of exposure due to it contacting the natural barrier provided by the Portland Hills. The implications of this sort of topographical variance require additional study. Valleys or low points in Multnomah County are at an unquantified greater risk of prolonged exposure due to the properties of different hazardous materials, and topography will further influence the actual distribution of materials, possibly channeling gasses along hills and corridors.

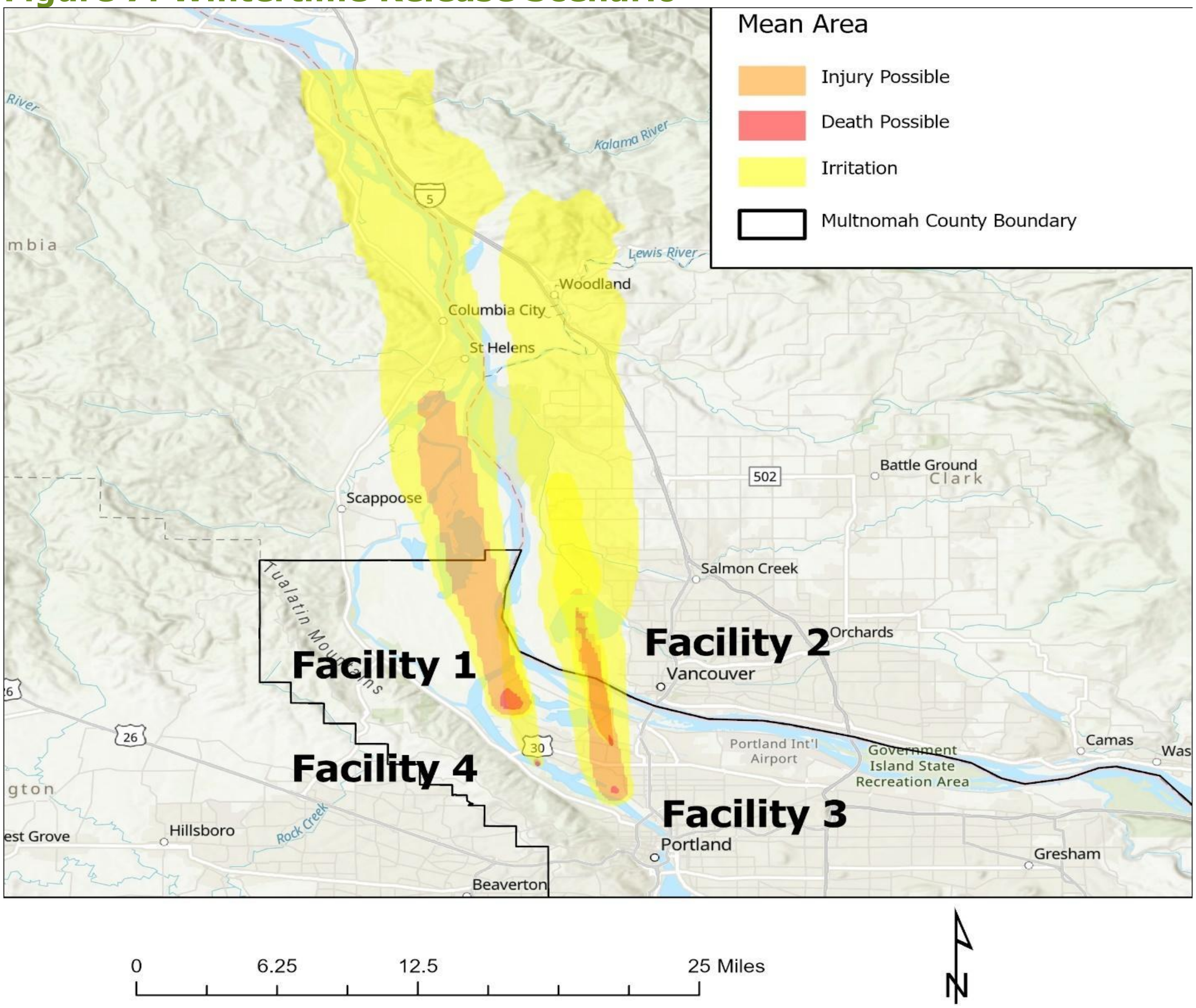
Plumes from Facility 1 and Facility 3 demonstrate the widespread risk of AEGL 1 (short-term irritation) exposures. Based on these models, as many as 330,000 residents may be exposed at AEGL 1 as far as 20 miles away.

Two points for the scale of possible exposures are emphasized. First, after evacuating the hazard area, those exposed to toxic inhalation hazards need to then decontaminate with copious amounts of clean water and a change of clothes. The United States Department of Homeland Security’s (DHS, 2014) manual for *Patient Decontamination in a Mass Chemical Exposure Incident*, advises decontamination must occur quickly to minimize adverse health impacts. Evidence in this area is sparse, but from what is available, DHS (2014) proposes a time window for effective decontamination from “minutes to hours in most cases” (p. 35). Given the constraints of a post-earthquake scenario, it is likely that most exposed residents will need to conduct “self-care” decontamination if it is to take place within this window (DHS, 2014). Self-care decontamination “can be conducted with or without readily available equipment or supplies; it mainly depends on patient’s knowing what to do either on their own or through instructions from responders” (DHS, 2014, p. 32). The number of residents impacted in this scenario is evidence that Multnomah County should consider public education campaigns on protective action recommendations, including self-care decontamination, to ensure residents can act on their own to minimize threats to their health and the health of their families or neighbors.

The second point of emphasis for the scale of exposures in the summertime scenario is the chance for significant overlap in hazardous materials plumes of the same or different materials. AEGL exposure guidelines are derived from the combination of the concentration of the material and the duration of exposure. If multiple chemicals overlap at AEGL 1 concentrations and therefore increase the total concentration of hazardous materials, or if this overlap increases the duration of exposure, then it can be deduced that there is a risk those exposed residents may move into an AEGL 2 exposure and face more serious health impacts requiring hospitalization. IMAAC (2022) was able to provide some indication for the increased risk of overlapping plumes by modeling a simultaneous release from Facility 1 and Facility 3 which store the same material. When modeled together, the AEGL 2 exposure estimates for these two facilities increase by between 8,000 and 9,000 residents and the AEGL 1 estimates for these two facilities increase by nearly 20,000 residents. The current state of the science does not provide sufficient information to calculate the AEGL implications of compounding plumes of different materials, and as Figure 5 shows, all four plumes in the summertime scenario have significant overlap. Taken together, it is fair to assume that the life safety risks of compounding or consecutive releases may be significant and continued research is necessary to improve the state of the science and to provide recommendations to medical experts and residents alike on how to provide care to individuals exposed to multiple toxic gasses.

Wintertime Release Scenario

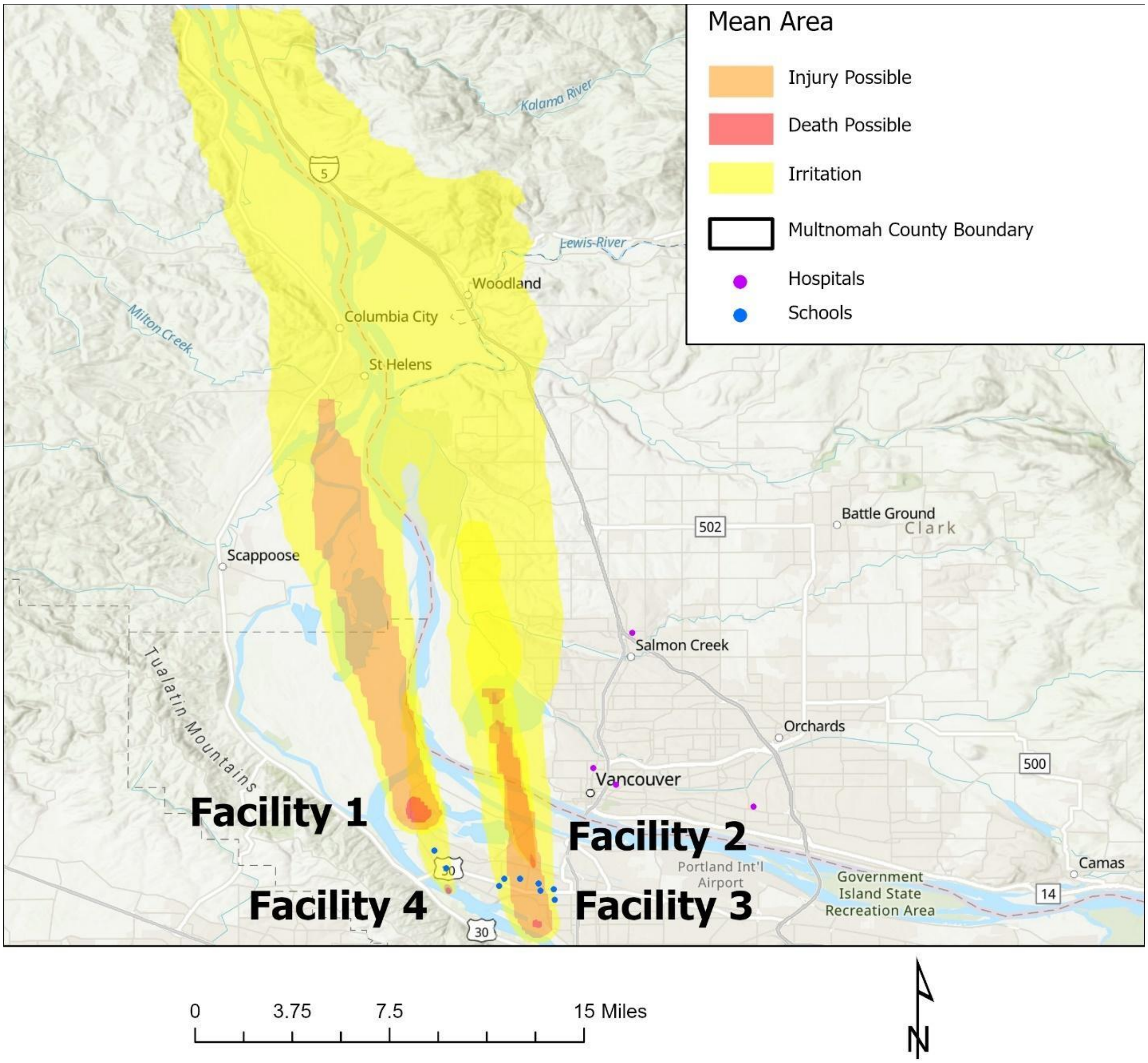
Figure 7: Wintertime Release Scenario[14]



January Scenario	AEGL 3 (Potential Deaths)	AEGL 2 (Potential Injuries)	AEGL 1 (Reversible Irritation)
Facility One	812	3510	26885
Facility Two	37	355	3772
Facility Three	389	14742	60382
Facility Four	19	45	8820

14 Areas not in the AEGLs represented in this model are not necessarily out of harm's way. This model only represents one possible wind direction and speed.

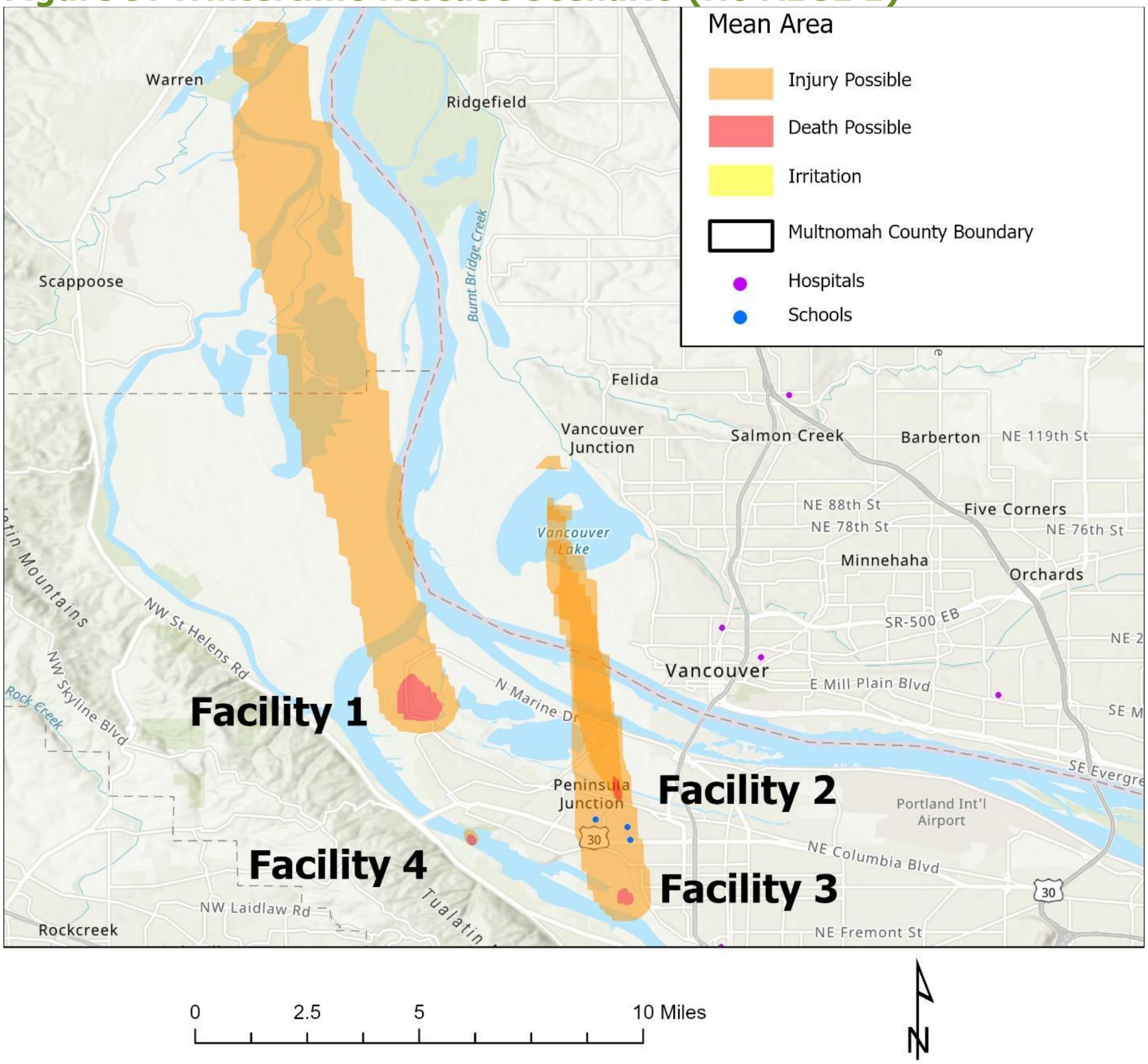
Figure 8: Wintertime Release Scenario, Combined Release Modeling for Facilities 1 & 3[15]



January Scenario	AEGL 3 (Potential Deaths)	AEGL 2 (Potential Injuries)	AEGL 1 (Reversible Irritation)
Facility 2	37	355	26885
Facility 4	19	45	8820
Facilities 1 & 3	1100	19000	86000

15 Areas not in the AEGLs represented in this model are not necessarily out of harm's way. This model only represents one possible wind direction and speed.

Figure 9: Wintertime Release Scenario (No AEGL 1)[16]



January Scenario	AEGL 3 (Potential Deaths)	AEGL 2 (Potential Injuries)	AEGL 1 (Reversible Irritation)
Facility One	812	3510	26885
Facility Two	37	355	3772
Facility Three	389	14742	60382
Facility Four	19	45	8820

[16] Areas not in the AEGLs represented in this model are not necessarily out of harm's way. This model only represents one possible wind direction and speed.

This scenario modeled an average winter day with winds at 10 miles per hour into the northwest, a temperature of 28°F, overcast, and low humidity. This wintertime scenario demonstrates certain similarities to the summertime release scenario. However, this discussion focuses on some core differences from the summertime scenario including the distance and direction traveled by plumes, the risks of plumes traveling across jurisdictional boundaries, and the risks of overlapping AEGL 2 plumes.

The first notable characteristic of the wintertime release scenario is the greater distance traveled by the plumes. This is due to wind speed being double that of the summertime release scenario. The different distances stemming from this increase in wind speed are stark, with the summertime release scenarios traveling between 3 and 5 miles downwind of the facility at AEGL 2 concentrations, while for the wintertime release scenario the plume from Facility 1 travels roughly 15 miles at AEGL 2 concentrations and plumes for Facilities 2 and 3 travel between 5 and 10 miles. When a plume travels further, the possibility for more exposures increases, however there is also reduced risk for AEGL 3 exposure as the materials concentration will decrease from its initial height at a more rapid pace. Similarly, with higher winds or slight changes in direction the possible impacts of a hazardous material release can change dramatically. In this case, if the wind modeling choice had been only a few degrees more to the west, the plume from Facility 1 could have rolled over Scappoose or Warren, OR instead of passing over the less populated wetland areas adjacent to the Columbia River.

Stemming either from the distance traveled by a plume or by the location of a facility, there is a risk that toxic gasses may spread beyond Multnomah County into neighboring jurisdictions. The reverse is also true in that earthquake-induced hazardous materials releases in Vancouver, WA, for example, may be pushed south into Multnomah County based on wind conditions. The possibilities for cross-jurisdictional impacts mean that inter-governmental coordination is critical for planning, mitigation, and response operations. County and State governments in Oregon and Washington have a mutual interest in reducing the risk of releases from Tier II facilities in all locations.

The third element of the wintertime scenario considered is the risk of overlapping plumes at AEGL 2, as seen from Facility 2 and Facility 3. No information was found in academic or government literature which investigates the health implications of multiple AEGL 2 exposures. In this case, the specific risks from these overlapping models are comparatively small as the estimated population who would be impacted by both plumes is less than 500 residents. However, given alternative wind conditions it is possible that such overlaps may be more severe. To demonstrate the dangers of overlapping plumes, in this wintertime release scenario residents north of Facility 2 would experience exposure to concentrations of Chemical 2 high enough to cause severe symptoms including constriction of the airways and burning of the eyes, nose, mouth and lungs. Once the toxic cloud of Chemical 2 passed, the impacted population would need immediate hospitalization and decontamination. It is likely that these individuals would be debilitated to the degree that they would have trouble evacuating to a hospital on their own. Likely within 30 minutes, another cloud of gas, Chemical 3 from Facility 3, would then roll over this same population. As has been previously argued, if multiple chemicals overlap at AEGL 2 concentrations and therefore increase the total duration of exposure or concentration of materials, then it can be deduced that those residents may move into an AEGL 3 exposure (life-threatening injury or death).

Discussion

The central finding of this research is the extent of life safety risks posed by earthquake-induced hazardous materials releases in Multnomah County. The investigation focused on four of the most dangerous facilities in the North Portland and Highway 30 Industrial area which is an area of considerable interest and hazard mitigation at a state level (See Chapters 3 and 4 of this report for information on the Critical Energy Infrastructure Hub and recent legislative initiatives). Local agencies have engaged in exercises that led to this report. While some agencies are aware of the potential for casualties related to Hazardous Materials release post CSZ earthquake, fostering awareness of this hazard could help in beginning the process of determining appropriate protective action recommendations and the associated public messaging and education. Inclusive collaborative discussions and further study will also help enable the appropriate prioritization of resources for mitigation, preparedness, and response efforts.

Considering the distribution of industrial facilities along the County's northern border on the Columbia corridor (Figure 2) and comparing the summertime release scenario (Figure 4) to the wintertime release scenario (Figure 7) it can be argued that winds into the south or southwest will result in greater life safety risks in Multnomah County compared to winds into the north or northwest. This is because most of the top 70 Tier II facilities are located on the northern edge of Multnomah County and winds into the south will carry these materials deeper into the County rather than north and out of the County. Based on the same argument, winds into the north or northwest would mean that the northern industrial districts of Multnomah County pose significant threats to Vancouver, WA, and other Oregon Counties. Furthermore, industrial facilities which may be located on the southern edge of Vancouver, WA may pose additional threats to Multnomah County residents if the wind is into the south or southeast. This possibility of cross jurisdictional releases necessitates robust coordination between these jurisdictions to prepare for and mitigate this hazard.

The implication of the casualty estimates of more than 17,000 injuries with the potential for 2,500 deaths, are dire. Yet these numbers are likely a conservatively low estimate since only four sites are represented, which can be seen, for example, by considering the life safety threats of a catastrophic CEI Hub release described in Chapter 3. The Graniteville South Carolina chlorine railway accident resulted in 311 urgent cases, 25 of which required mechanical ventilation for an average duration of three days (Mackie et al., 2014). To use even this very rough estimation of 12.5% of injuries requiring ventilation would result in more than 2,000 people requiring extended hospital care and mechanical ventilation for these four hazardous facilities alone. Considering the current constraints on healthcare facilities and the estimated constraints following an earthquake, injuries from these exposures would surpass healthcare capabilities.

The summertime scenario in which more than 300,000 people may be exposed to AEGL 1 concentrations demonstrates the importance of the need for seismic safety standards at these facilities, decontamination operations, and public information campaigns. The United States DHS (2014) estimates an effective decontamination window as small as minutes to hours following exposure to minimize health impacts. In this time window, public emergency response operations will be in the initial phases of organization and will not be able to provide decontamination resources at this scale. Most residents, especially those with less severe exposure[17], will be best served by conducting self-care decontamination in which they flush their eyes with copious amounts of warm water, wash their bodies, and put on clean clothing (DHS, 2014). However, with widespread damage to the water infrastructure the public's ability to conduct decontamination procedures will be severely hampered.

Health and medical personnel and emergency managers should also consider the significant mental health impacts hazardous materials exposures may have on the public. The trauma of these incidents is well documented among victims of chemical warfare. These people experience a great deal of psychological trauma and long-term physical harm, and victims in Multnomah County will face a similar reality should they be forced to watch neighbors, friends, and loved ones suffer or die while they themselves are experiencing horrific physical symptoms from hazardous material exposures.

Conclusions and Recommendations

Multnomah County is home to more than 1,100 Tier II facilities which store or use a variety of hazardous chemicals, including toxic inhalation hazards. Due to historical land use development, many of these hazardous facilities are in Multnomah County's industrial areas alongside the Columbia and Willamette rivers, placing them at high risk for earthquake-induced damage and especially liquefaction and lateral spread. This report selected four hazardous facilities from the North Portland and Highway 30 industrial areas (See Figure 3, page 68) which met the criteria for seismic vulnerability (See page 70), and which pose a significant life safety risk. Each of these four facilities store toxic inhalation hazards

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[17] It is critical that severe exposures receive thorough decontamination and medical care in a timely manner.

in above ground storage tank(s) or pressurized cylinder(s) and were constructed prior to sufficient seismic building code requirements.

Plume models were developed for a worst-case simultaneous release scenario from these four facilities with meteorological conditions that correspond with an average summer day and an average winter day in Multnomah County. The models were used to determine worst-case, yet realistic casualty estimates. The findings were that a summertime release scenario (See page 79) could result in more than 330,000 irritation level exposures, 17,000 injuries, and more than 2,500 potential deaths, and a wintertime release scenario (See page 85) could result in more than 100,000 irritation level exposures, 18,000 injuries, and more than 1,100 potential deaths. These casualties will occur at a time when decontamination capabilities are hampered by earthquake damage to water infrastructure and access to hospitals will be nearly impossible.

Residents who are exposed to hazardous materials should be advised to conduct self-care decontamination as soon as possible, within minutes to hours to reduce the health impacts of exposure (DHS, 2014). Decontamination involves flushing the eyes with copious amounts of warm water, washing the body, and donning clean clothing (DHS, 2014). There are certain hazardous materials which are reactant to water and exacerbated by standard decontamination procedures, however these chemicals are less common. DHS (2014) argues that self-care decontamination is accessible and effective if the public knows how to perform those actions, or a first responder can communicate this information to them. As telecommunication systems will receive significant damage from a CSZ earthquake, it is advisable that public information campaigns communicate appropriate protective action information to residents prior to the disaster.

It is also advisable to communicate shelter in place and evacuation guidelines to the public prior to a CSZ earthquake so that residents can conduct protective actions without telecommunication guidance from public agencies. Each of these protective actions face barriers to implementation. For example, windows and doors may be broken on houses thereby reducing their effectiveness to function for shelter in place. For evacuations, the speed at which toxic inhalation hazards can be released and move casts doubt on the viability of immediate evacuation, especially with extensive earthquake damage to Multnomah County's transportation infrastructure. The importance and complexity of communicating these protective action recommendations to the public are discussed further in Chapter 6 which reports on the outcomes of an Alert and Warning exercise conducted with this hazard scenario.

The scenarios developed demonstrate only two possible meteorological conditions in a small subset of the total hazardous facilities in Multnomah County. Continued research is necessary to identify and assess high-risk facilities for seismic vulnerability and possible impacts to the community, and to understand the implications of alternative meteorological variables including different wind and rain conditions.

Based on these scenarios and the location of hazardous facilities in Multnomah County, it is likely that hazardous materials releases will cross jurisdictional boundaries. Additionally, releases outside of Multnomah County may threaten residents here. Robust collaboration and coordination between these jurisdictions will be essential to mitigate and respond to this hazard.

Chapter 6: HAZMAT Alert and Warning Exercise Summary

On October 12, 2022, Multnomah County and the Institute for Sustainable Solutions hosted an alert and warning exercise using the summertime and wintertime release scenarios described in Chapter 5 of this report. The goals for the exercise were to:

1. Share information regarding potential HAZMAT risk after a Cascadia Subduction Zone (CSZ) earthquake for Multnomah County's northern and western industrial areas.
2. Communicate limitations and uncertainties regarding CSZ earthquake induced HAZMAT models.
3. Facilitate discussion to develop Next Steps Document that outlines:
    a. list of policy level issues
    b. potential concerns regarding messaging content,
    c. potential pre and post incident messaging elements (supplies, training, protective action recommendations (PARs), etc.)
    d. identification of additional research needed,
    e. possible capability and supply development areas.
    f. any critical issues, decisions, requirements, or questions that should be addressed.
4. Build a mutual understanding of the potential geographic scope and impacts of post CSZ HAZMAT risks.

To achieve these goals, 15 public information officers, first responders, and communication experts from Multnomah County, the City of Portland, Portland State University, the Oregon Department of Transportation, and the Regional Disaster Preparedness Organization (RDPO) were convened.

Planning Team Attendees:

Alice Busch – Multnomah County Emergency Management
Luke Hanst – PSU, Institute for Sustainable Solutions
Molly Kramer – PSU, Institute for Sustainable Solutions
Tyren Thompson – PSU, Institute for Sustainable Solutions
Yumei Wang – PSU, Institute for Sustainable Solutions

Participants:

Anna Bergman – Multnomah County Emergency Management
Brendon Haggerty – Multnomah County Environmental Health
Brianne Suldovsky – Portland State University
Bryan Proffit – Portland Fire and Rescue
Denis Theriault – Multnomah County Communications Office
Geoffrey Bowyer – Oregon Department of Transportation
Jessica Morkert – Multnomah County Communications Office
Julie Sullivan-Springhetti – Multnomah County Communications Office
Katy Wolf – Portland Bureau of Emergency Management
Laura Hall – Regional Disaster Preparedness Organization
Lauren Frank – Portland State University
Marty Schell – Portland Police Bureau
Nadege Dubuisson – Multnomah County Environmental Health
Sarah Hurawits – Multnomah County Department of Transportation
Shon Christensen – Portland Fire and Rescue

Participants were informed of the hazard and relevant information from both a presentation and situation manual which included: an overview of hazardous material threats in Multnomah County; a description of the methods for facility selection and plume modeling; a tutorial on plume models, toxic inhalation hazards, and Acute Exposure Guideline Levels (AEGLs); descriptions of Protective Action Recommendations (PARs); and an overview of this report's post-earthquake hazardous materials release scenarios. After the presentation, exercise attendees participated in a facilitated discussion, the results of which are provided in this chapter.

Possible Capability Development Areas

Participants were prompted to discuss possible areas of capability development related to post-earthquake response operations including the detection and reporting of hazardous materials release and the communication of this information to the public.

Air Quality Monitors and HAZMAT Release Detection Systems

The facilitators proposed the idea of establishing air quality monitors to detect HAZMAT releases. Portland Fire and Rescue (PF&R) provided additional background: PF&R relies on pre-planned knowledge about what the facility contains, the likely material that has been released, and rapid plume model generation in route to response more than they rely on air quality monitoring equipment. However, some facilities may already have some on-site sensors.

PF&R explained that wall mounted or handheld sensors at a facility transmit directly to the facility's main office and may set off alarms. The usefulness of these sensors will depend on on-site response personnel being there (not after-hours), having the ability to respond, and having the ability to report this information to PF&R. Many HAZMAT facilities rely on PF&R as their primary response resource and do not staff on-site teams. If employees receive information from a wall mounted sensor, they must then be able to report it, and this usually occurs through telecommunication channels which will be unavailable after a CSZ earthquake. One participant suggested the Oregon Health Authority function as a model, as they have provided each hospital with satellite phones with regular testing and protocols for immediate reporting after an earthquake.

Additional issues with permanent air monitors include:

- Technology does not exist to test all chemicals in the same sensor.
- Sensors require regular maintenance (~6-12 months).
- Sensors rely on telecommunications to transmit data to responders. After a CSZ earthquake this may not be possible.
- The ability to detect releases does not equate to any public agency having the resources or capability to respond before exposures occur.
- Stationary monitors established in high-risk regions may not be flexible enough for the distributed nature of this hazard.
  - One participant proposed the use of drones with air quality sensors, and others mentioned different forms of mobile sensor.

This discussion led to questions of responsibility and feasibility; who owns, monitors, interprets, and/or deploys these resources and how many would there need to be?

Pre-Planning and Exercising

Participants articulated the need for more multi-discipline, multijurisdictional exercises that are informed by, and include the breadth of responders, including, but not limited to: HAZMAT teams, Portland's Emergency Coordination Center, Multnomah County and neighboring counties (environmental health, behavioral health, human services, emergency management), transportation, law, DEQ, EPA, OEM, OSFM, LEPC, and community members. Including these intersecting agencies will strengthen relationships and inform the development of protocols. Participants were supportive of using a scenario that closely aligns with realistic impacts of a CSZ earthquake and includes multiple simultaneous releases. Participants also recommended (and expressed a willingness to assist with) earthquake exercises for HAZMAT facilities staff to assist in further identification of any potential policy, procedure, staffing, equipment and training gaps.

Pre-planning was determined to be critical in some areas, but the degree of variability in the possible sources of the hazard, as well as the many meteorological conditions, means accounting for each potential scenario would require extensive efforts and may not provide much utility. Participants were supportive of the development of an initial template IAP and communications plan and agreed that continued pre-planning is necessary to determine the highest risk areas in Multnomah County. These efforts will help identify mitigation considerations for Disaster Resource Center air quality.

Alert and Warning Systems

Radio*.* The radio could prove to be a critical mechanism to inform people of protective action recommendations following an earthquake. There is a need for continued effort to ensure that residents have a radio and know that they should use it following an earthquake. Some pre-scripted messages exist but work remains to create messages which are accessible and useful for the public. This system also relies on knowing where a release has occurred and what populations need to be warned.

Signage. Signs or other publicly posted materials came up multiple times in the discussion with mixed feelings. No consensus was reached regarding messaging for signs, ideas included: shelter in place zones, plume zones, evacuation zones. It is unknown how many signs would be needed or where they would need to go as the hazard is still largely unknown across the County. Participants were also concerned that signs would likely lack actionable information and would require a robust public education effort to ensure communities understood and had access to additional information. Other short notice hazards like tsunamis could provide models for sign implementation.

Volunteers. Multnomah County partners with The City of Portland's Neighborhood Emergency Team (NET) volunteer program. PBEM's NET volunteers receive some training on hazardous materials releases, but they are not trained to be ambassadors about hazard information to the public. More training and opportunities for these and other community volunteers could assist in building capacity for a public education and outreach campaign regarding HAZMAT risks and protective actions.

Sirens. Sirens were not seen as a feasible idea both because they require the information from sensors to function, which may not exist, and because they don't provide enough information for residents to make an informed decision about what the siren means and what protective action to take. Participants expressed that sirens may be confusing and scary, especially if wide regions were impacted simultaneously. Loudspeakers with pre-recorded messages were also mentioned, challenges were noted regarding how to determine what information would need to be shared and what languages it would need to be shared in.

Risk Index. Participants discussed the feasibility of communicating (and pre-planning) this hazard by developing a risk index to be featured on real estate information disclosures and other communication mediums. There is a lack of clarity for how detailed this index could be, however it remains likely that populations more distant from the Columbia corridor and Willamette River would have a lower risk index score due to the distribution of high-risk hazardous facilities identified by the Multnomah County LEPC (2022). It would be important to find avenues to share this risk index with renters, and information conveyance to houseless populations would be a challenge.

Hazardous Facility Actions and Next Steps

Participants stressed that these hazardous facilities provide critical goods and services to the local community and are integral to Multnomah County's economy. Therefore, the goal should be to mitigate the hazard in place without relocating facilities or displacing any residential populations. At this point discussion turned towards regulation as a heavily favored approach to mitigating this hazard. Earthquake-induced hazardous materials release, aside from the CEI Hub, are not well known among the public, therefore this hazard should be made more visible to encourage requests for regulations and mitigation from the State. Exercise participants felt that perhaps the best protective action recommendation for residents may be to lobby their local representatives and fight for money and policy to support hazard mitigation.

Due to the similarities between the life safety risks of the CEI Hub and other hazardous facilities in Multnomah County, participants expressed a strong desire for the social and political networks responsible for Senate Bill 1567 to push for similar, statewide regulation of all hazardous facilities. The DEQ recently concluded rulemaking for Senate Bill 1567 which regulates the largest fuel terminals in Columbia, Lane, and Multnomah counties to require seismic vulnerability assessments and mitigation plans. At the time of this report, there is no program at DEQ that is funded or staffed to assess all hazardous materials facilities. The DEQ Program created by passage of SB 1567 covers large fuel storage facilities only and additional regulation will be necessary to expand the DEQ's purview to all hazardous facilities. One such example of quick regulatory action can be seen in 2016 when it was found that glass factories in Oregon were causing heavy metal contamination of the air in nearby residential areas, the DEQ moved quickly to introduce regulations, and the glass factories are still operational (Zarkhin, 2016).

It is important to note that at the time of this report, the DEQ Emergency Response Program has the ability to assess hazards from hazardous materials as they pertain to emergency response to hazardous materials spills, a regulatory authority that DEQ shares with the Oregon State Fire Marshal's Office. The regulation of safe hazardous materials storage is the purview of the Oregon State Fire Marshal and local Fire Marshal, the safe use of chemicals is the purview of Oregon OSHA, while the regulation of wastes generated from commercial enterprises is within DEQ's statutory responsibilities. DEQ has delegated authority from the US EPA for implementation of the Clean Air Act and implements a permit program discharge of hazardous air pollutants.

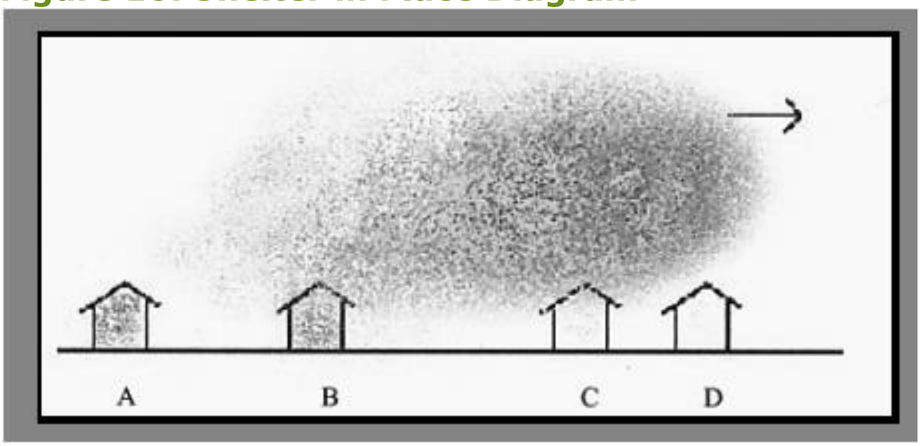
Protective Action Recommendations

Participants were prompted to think of initial ideas for messaging content or areas of concern related to each of the following protective action recommendations (PARs):

- Evacuations: Participants noted that following a CSZ earthquake, barriers to accessing the area, and therefore an inability to determine hazardous material types, concentration, and spread, undermines the ability to determine the location and timeline of evacuation recommendations. Additionally, the same damage to transportation and telecommunications infrastructure that challenge access for determining the appropriate protective action, will also hamper professional rescuers from assisting the community with evacuations.
- Shelter in Place: Participants were also concerned with the use of shelter in place. While the appropriate use of shelter in place is likely to be an effective mechanism to protect members of the public when air monitoring is possible and when buildings are structurally sound. The post CSZ earthquake environment is anticipated to damage many structures beyond their ability to provide adequate protection via a sealed environment.
- Other significant challenges that will impede the widespread implementation of Shelter in Place, include:

- Emergency management conceptualizations of shelter in place are continually expanding to include more different applications and implementations while at the same time participants stressed that public knowledge of the meaning of shelter in place is universally lacking in Multnomah County and beyond.
- Residents must be made aware that shelter in place loses efficacy over time and after the hazard has passed people should exit their shelter to the cleaner air outside (See Figure 10)

Figure 10: Shelter in Place Diagram



- A lack of pre-planning and the diversity of possible meteorological conditions makes it difficult or impossible to pre-determine what neighborhoods or populations should begin sheltering in place after an earthquake, and it is assumed that this information would need to be shared prior to the earthquake as damage to telecommunications will similarly impede first responders' ability to communicate hazards to the public.
- Participants were concerned with the implications of the Milling effect in which residents talk with neighbors or family members before deciding to take protective action, which could lead to exposure to toxic inhalation hazards.
- The duration for which people should stay inside is difficult to determine; people who leave shelter too quickly may be exposed to releases which occurred elsewhere or further upwind and staying indoors for an unnecessary time both creates life safety risks due to

HAZMAT which have entered the shelter and creates life safety risks for those people who require search and rescue efforts.
    - It is not known how well houses or other structures will serve as shelter in place locations following an earthquake.
- Personal Protective Equipment (PPE): PPE is effective for hazardous materials releases but pose myriad challenges in widespread public use, including:
    - PPE requires regular fit testing, proper use, and grooming standards to ensure effectiveness.
    - Specific types of equipment and filter cartridges are needed depending on the hazardous materials which have been released, which is likely to be unknown or a mixture of chemicals following an earthquake.
    - Plastic deteriorates causing a 6-year shelf life for PPE.
    - Residents must have the PPE readily available at the time of the earthquake or hazardous material release.
    - PPE is expensive, and participants felt that because people struggle to store enough water it is unreasonable to expect residents to purchase their own PPE.
    - Questions arose around the public acquisition of PPE to be distributed to residents, including:
        - Which populations or regions are prioritized to receive PPE?
        - Which agency would be responsible for providing and tracking PPE?
        - Could PPE be assigned to houses? If so, what happens when people move?
- Decontamination:
    - Residents need to be informed that they may experience significant AEGL 1 (irritation) symptoms, but these symptoms do not necessitate a hospital visit and instead those exposed should decontaminate when the air quality improves.
    - Participants felt that residents should begin storing water for more than just drinking and sanitation and should include additional supplies for decontamination. This is a challenge as although the standard 2

gallons water per person per day is simplistic, it has been the primary message to the public for many years now.

- Other Possible Protective Action Recommendations:
    - Residents should be encouraged to bolt their homes to their foundations to improve shelter resilience for shelter in place actions.
    - Residents should be encouraged to join the NETs and support local community resilience efforts.
    - Residents should be encouraged to lobby their representatives to begin mitigating the risks of earthquake-induced hazardous materials releases.

Considerations for Messaging Content and Dissemination

The life safety risks of earthquake-induced hazardous materials releases in Multnomah County are so significant that participants felt regulation requiring facilities to become seismically resilient was the most effective avenue forward. Without dissent towards this position, other participants argued that there is still a need to determine what to do and what to tell the public in the interim period before the hazard is mitigated. There is a need for a plain language explanation of the hazard with actionable steps to be made available. Of particular concern are the terms hazardous materials and shelter in place. The words "hazardous materials" do not always exist in other languages or carry the same connotations which can make it challenging to convey the dangers and seriousness of an incident. On the other hand, exercise participants expressed that shelter in place is poorly understood by most communities in Portland who understand it to mean "stay inside," which is not sufficient for the need to enter as sealed a space as possible and eventually leave the shelter when it is right to do so.

Participants expressed that the sharing of hazardous materials information could be accompanied by general information about earthquake hazards in Multnomah County to derive additional benefits from the outreach. Information about the hazard could be distributed online and with postcards to high-risk communities which would encourage people to pursue more information about the hazard and about protective action recommendations. The State of Oregon and the counties included in the Regional Disaster Preparedness Organization are working on best practices for alert and warning and are developing accessible and multilingual templates, and these initiatives will be important to engage with for future information dissemination concerning this hazard.

Participants stressed the importance of public education campaigns to accompany any capability developments undertaken. Residents must be educated on the meaning of public messaging to ensure that they respond with the appropriate actions. For example, people would need to know what a sign, siren, or automated message means they should do and how they should do it. Japan provides one such model of public education with the development of their earthquake early warning systems, which was accompanied by both infrastructure development and social integration to ensure effectiveness.

Key Exercise Takeaways and Future Research Needs

- It is critical to define actions the public can take to mitigate this risk or protect themselves after a disaster before beginning widespread public messaging.
    - With the current state of this hazard, a favored action recommendation is to lobby local representatives to push for State regulation of these facilities.
- Structural mitigation of these facilities appeared to participants as the most cost-effective mechanism to reduce the threat compared to public messaging, however there is a need to define communication and begin outreach to protect residents in the interim period before this mitigation has occurred.
- Continued uncertainty in the distribution of hazardous facilities and the variability of hazardous material release impacts due to meteorological variability creates challenges to pre-planning and preparedness efforts.
- Questions remain about how to message this hazard to elected leadership in an accurate and effective way.

Chapter 7: Recommended Next Steps

These recommendations are derived from this report's literature reviews, hazard assessment, exercise, and discussions with experts and advisors. From these sources, the report team recommends the following:

Hazard Analysis and Pre-Planning

- Supplement existing natural hazard mitigation plans with updated hazard vulnerability assessments to include hazardous materials (prioritizing highest risk hazardous facilities).
    - Account for additional meteorological conditions, including wind directions and precipitation events.
    - Assist in the identification of the highest-risk regions.
    - Determine methods to mitigate/address air quality issues in human services support facilities following a CSZ earthquake, including disaster resource centers and shelters.
    - Inform and prepare critical facilities in high-risk areas.
    - Consider ways to accurately illustrate hazard areas on maps.
- Perform quantitative risk assessments at a countywide level and at each high-priority hazardous facility to determine the likelihood of releases and possible impacts; use these results to prioritize mitigation efforts.
    - We recommend future analyses begin with *Natech Risk Assessment and Management* by Krausmann, Cruz, and Salzano (2017). This volume is among the most current references with contributions from 19 leading scholars in this field. The volume includes chapters dedicated to quantitative risk assessments for hazardous industrial facilities along with case studies of their application.
- Research the following:
    - Life safety implications of overlapping hazardous plumes—repeated exposures to Acute Exposure Guideline Level (AEGL) 2 (injury possible) and AEGL 1 (irritation) or simultaneous exposures of different materials at AEGL 1 or AEGL 2 leading to higher total concentrations of airborne hazardous chemicals.

  - The average efficacy (and duration) for houses and other structures to be used for sheltering in place following an earthquake.

Public Communication, Alert and Warning, and Protective Action Recommendations

- Develop a bi-state (Oregon and Washington) public education campaign regarding potential post CSZ earthquake HAZMAT hazards that is appropriately contextualized. *This report represents a point in time and only a fraction of the HAZMAT hazards, in a finite area of one county.*
  - Develop accessible and multilingual plain language explanations of the risks and protective actions the public can take related to earthquake-induced hazardous materials releases.
  - Consider the creation of detailed accessible online information that clearly articulates the complexities of hazardous materials related incidents and related protective actions.
  - Collaborate with potentially impacted communities to co-create messaging regarding plume models versus risk area (point in time) expression of hazard.
- Expand existing public agency communications strategies to ensure capability for post-CSZ earthquake information sharing that takes into consideration the potential constraints related to technology and power interruption.
- Build upon Regional Disaster Messaging Workgroup efforts (with state and federal partners) designed to determine community understanding of risks and willingness and capability to perform protective actions.
- Work collaboratively with potentially impacted communities to co-create an educational campaign related to CSZ earthquake-induced Hazardous Materials incidents.
  - Consider the creation of pre-scripted plain language translated messages that can be vetted by impacted communities to ensure robust understanding.

- **Protective Action Recommendations:**
  - Develop a multi discipline team that includes, but is not limited to equity, community representation, communications, health, transportation, law, emergency management, and HAZMAT expertise to create uniform plain language messaging regarding protective action recommendations.
  - **Shelter in place:**
    - Determine the communities' understanding of, and capacity to perform "shelter in place" actions. Work collaboratively to build capacity.
      - Articulate the duration that 'shelter in place' may be effective.
    - Create educational campaigns that bring together first responders, transportation, equity, health, and communications teams regarding "shelter in place'' (constraints, time and other limitations, life safety implications). Ensure various disciplines are coordinated in their definitions, descriptions, and recommendations regarding this protective action.
  - **Evacuations:**
    - Build upon existing evacuation plans to develop evacuation messaging that articulates the specific challenges related to post CSZ earthquake impacts (like the potential for significant ground deformation/displacement that will likely hamper travel by vehicle, fires, etc.).
      - Provide recommendations for ways to effectively accomplish evacuation.
      - If possible, include where community members can go once they have successfully evacuated.
    - Articulate the potential/likelihood that first responders will be unable to assist in evacuation support in areas susceptible to ground deformation.

        - Use pre-planning (response and mitigation plans) to include information regarding hazardous materials release scenarios that create immediate life safety risks that in non-CSZ earthquake environments would result in 'shelter in place' recommendations.
    - **Decontamination:**
        - Increase the accessibility of decontamination information. Ensure communities at risk understand when and how to adequately perform decontamination procedures.
            - Work with health and chemical subject matter experts to determine all possible alternatives and options for widespread public decontamination efforts when copious amounts of water are not available due to infrastructure damage caused by an earthquake.
    - **Personal protective equipment (PPE):**
        - Further investigate the type or types of PPE that may be most appropriate to address multiple simultaneous hazardous materials releases.
        - Determine cost estimates for acquisition of PPE and examine the feasibility of distribution/provision of PPE to impacted communities.
        - Ensure information regarding the complexities of PPE is part of educational and informational campaigns.

Inter & Intra-Government Outreach and Coordination

- Determine which agencies have the authority needed to address issues identified in this report. Identify any gaps in capabilities or capacity to address this report's recommended next steps.
    - Consider the development of tiered multi discipline standing teams (policy, operations, and communications) to ensure coordination.
- Continue to share this report with local, regional, state of Oregon, Washington State, and federal agencies that have roles and responsibilities

related to hazardous materials incidents (prevention, mitigation, response, and recovery).

   - Coordinate and collaborate to accomplish the following:
      - Identify hazardous facilities outside of Multnomah County which could impact Multnomah County residents.
      - Ensure other jurisdictions are aware of the threats posed to their residents by hazardous facilities in Multnomah County.
      - Jointly pursue prevention, mitigation, preparedness, and response planning efforts to ensure maximum effectiveness.
- Communicate with neighboring Local Emergency Planning Committees (LEPCs) to exchange available information and knowledge gaps on the risks of earthquake-induced hazardous materials releases. Share the information developed in this report, and coordinate future prevention, mitigation, and response preparedness efforts.
- Continue to host and increase the breadth to ensure multijurisdictional / multi-discipline participation in exercises for post-earthquake hazardous materials releases:
   - Account for the post-disaster context and employ multiple simultaneous release scenarios.
   - Engage facility operators to aid them in articulating and addressing any problem areas.

Hazard Mitigation

- Increase engagement with the Multnomah County LEPC to accomplish the following:
   - Share earthquake hazard information with industry representatives.
   - Propose solutions for mitigating the risks of earthquake—or other natural hazard—induced hazardous materials releases with industry representatives, assuming that the greatest threats to residents come from the release of large quantities of toxic inhalation hazards.
   - Ensure that LEPC meetings remain inclusive of industry representation and participation to enable future collaboration.

    - Propose solutions to reduce the risk of major fires following catastrophic hazardous materials releases (e.g., a catastrophic failure at the CEI Hub igniting Forest Park).
- It would benefit residents if Multnomah County developed a strategy for drafting and advocating for a bill to be passed by the Oregon legislature to require the Oregon Department of Environmental Quality to conduct a statewide study of the multi-hazard vulnerabilities and the possible life safety impacts of hazardous materials releases from industrial facilities.
- Multnomah County should consider local ordinances to improve the safety of facilities handling hazardous materials for all natural hazards.

Health and Medical

- Support hospitals in developing capabilities necessary to respond to possible mass casualty incidents involving widespread exposure to toxic inhalation hazards.
- Develop decontamination and medical response plans for the possibility of earthquake-induced hazardous materials releases. These plans must take the post-disaster context into account and assume that water and transportation infrastructures will be insufficient or unavailable.

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