Chemical Substance Release

Accidental conditions where release of a large volume of a chemical acutely toxic to human beings (a toxic inhalation hazard, or TIH) from a chemical plant, storage facility, or transportation mode results in either one or more offsite fatalities, or one or more fatalities (either on- or offsite) with offsite evacuations/shelter-in-place. This event does not include releases caused by malicious acts.

Data Summary[1]

In the following table, note that the low and high likelihoods do not correspond to the low and high impacts. In addition, low and high impacts are not necessarily correlated with each other between different impact categories.

Category	Description	Metric	Low	Best	High
Health and Safety	Fatalities	Number of Fatalities[2]	1	5	25
	Injuries and Illnesses	Number of Injuries or Illnesses[2]	0	57	790
Economic	Direct Economic Loss	U.S. Dollars (2011)[2]	$43,000	$14 Million	$330 Million
Social	Social Displacement	People Displaced from Home ≥ 2 Days[2]	0	260	5,400
Psychological	Psychological Distress	Qualitative Bins	See text		
Environmental	Environmental Impact	Qualitative Bins[3]	Moderate[4]		
LIKELIHOOD	Frequency of Events	Number of Events per Year[5]	0.61	1.6	5

Event Background

The dominant risk to human beings from accidental chemical releases is from an accidental release of a highly toxic gas, or toxic inhalation hazard (TIH), in a densely populated area.[6] The 1984 accidental release of toxic methyl isocyanate gas from the Union Carbide chemical plant in

[1] The data reported in this table represent historical U.S. accident data. This data is not representative of either the likelihood or the impacts of a catastrophic, mass-casualty chemical accident of a magnitude which has not yet occurred in the United States. The SNRA project team used historic data because a defensible estimate for the likelihood of a catastrophic accident could not be determined. For additional discussion, see Event Background section below.

[2] Low, best, and high estimates for fatalities, injuries and illnesses, direct economic loss, and number of displaced from homes for at least two days come from the low, average, and high values of the set of events meeting one of the following two threshold criteria: 1) at least one "public" fatality, defined as one fatality other or in addition to an employee fatality, caused by the hazardous material; 2) at least one fatality of any kind caused by the hazardous material, plus a reported evacuation or shelter-in-place order; this set came from the set of all reported toxic inhalation hazard (TIH) incidents reported 1994-2010 to either the EPA's RMP (Risk Management Program) accident database for fixed industrial producers and consumers of listed toxic chemicals above given threshold limits, or to the Department of Transportation's Pipeline and Hazardous Substances Administration (PHMSA)'s database of road, rail, water, and air transportation accidents. For further details see Assumptions sections below.

[3] The United States Environmental Protection Agency (EPA) convened an ad hoc group of environmental experts representing the fields of environmental science, ecological risk, toxicology, and disaster field operations management to estimate environmental impacts for this event. The comments and rankings presented in this Risk Summary Sheet have not undergone review by the EPA and only represent the opinions of the group. Estimates pertain to the potential for adverse effects on living organisms associated with pollution of the environment; they are grouped into high, moderate, low, and de minimus (none) categories.

[4] Experts provided both first and second choice categories, allowing the experts to express uncertainty in their judgments as well as reflect the range of potential effects that might result depending on the specifics of the event. The first choice represents the 'best' estimate.

[5] Frequency estimates correspond to the inverse of the number of years of the longest interval between accident events (low), the mean frequency of the accident events (best), and the greatest number of accidents within one year (high) of the set described in note 2 above.

[6] See note 11.

the city of Bhopal, India, which killed about 4,000 people immediately and 20,000 in subsequent years, is the primary historical example of the human damage such a release may cause.[7]

Across the United States, accidental releases of chemicals hazardous to human beings occur with a frequency of several times a day.[8] Of these, the largest number of historical (and recurring) accidents causing human death and injury—sometimes in the dozens or hundreds—are caused by fires and explosions from highly flammable chemicals such as propane, liquefied petroleum gas, and ammonium nitrate. However, as these fire and explosion hazards are of a different character and potential magnitude than the hazard posed by a highly toxic gas such as chlorine, hydrogen fluoride (HF), or the Bhopal chemical methyl isocyanate which could potentially kill thousands of people if released in a high population area,[9] they have not been included within the scope of this chemical substance release event analysis for the purpose of the SNRA.

Highly toxic gases may be released while transported by road, rail, or pipeline, or from a fixed facility where they are manufactured, stored, or used for further chemical processing, agricultural chemical production, meat packing, or water treatment. Of the most toxic industrial chemicals, chlorine in particular is used and transported in a total quantity much greater than all the other most toxic industrial chemicals combined: after anhydrous ammonia (which is less toxic),[10] it is the second most commonly used and transported chemical in this country.[11] Chlorine is also normally stored, used, and transported in the United States in volumes large enough to kill thousands of people if released in a densely populated area.[12] Further, like other hazardous chemicals it is routinely transported through the nation's most densely populated areas, in particular Chicago, the central hub of North America's railroad network (one out of every 25 of the nation's major rail accidents—derailments, fires, explosions—occur in Cook County, Illinois alone).[13] An insurance model of a single accidental chlorine railcar breach in the Chicago railyards projected 10,200 fatalities, with several square miles of the city's business district shut down and cordoned off for a week for investigation and recovery efforts.[14] Similarly, FEMA's

[7] [Pastel/Bhopal]. Bibliographic information for all cited references may be found at the end of this section.

[8] [Belke], appendix A. A scrolling newsfeed on the homepage of the Chemical Safety Board at http://www.csb.gov/ lists all the reported chemical accidents which occurred in the United States in the past week. A similar newsfeed with global coverage may be found on the homepage of the Mary Kay O'Connor Process Safety Center, http://process-safety.tamu.edu/.

[9] [Argonne-2000] pp 128, 132; [PHMSA].

[10] [Argonne-2000] pp 128, 132; [PHMSA].

[11] Chlorine gas, like the Bhopal chemical methyl isocyanate and many other industrial chemicals used in the U.S., is a highly toxic gas capable of killing large numbers of people at relatively low concentrations, but is used and transported in much greater quantities than any other. Anhydrous ammonia and flammable chemicals such as propane are used and shipped in comparable total quantities in storage tanks, pipelines, trucks, and railcars comparable to chlorine, under much less stringent safety standards, and are involved in a much higher proportion of fatal accidents. However, they are most frequently shipped in much smaller containers than chlorine, and by toxicity (ammonia) or blast range (propane and other flammables) they have the capability to cause many fewer deaths than chlorine even if transported in similar quantities (which is why their required storage and shipment safety standards are much lower) ([Wharton] pp 69, 129, [DoT-1992] p 7-9, [Argonne-2000] pp 4-5, 19, 67-69, 126-128, 148-150).

[12] Unlike most other chemicals which are most frequently shipped by road and pipelines, the primary hazard chlorine is shipped almost exclusively (85%) by rail, usually in standard 90 ton (18,000 gallon) tanks ([Branscomb] pp 11-12) which are of comparable size to the largest storage tanks (60,000 – 120,000 gallon) used in fixed facilities often cited in catastrophic-release scenarios (as in [FEMA-2006]). Eleven ruptures of chlorine railcars resulting in the loss of most or all contents have occurred in the 42 year period 1965-2007 which included 2.2 million rail shipments of chlorine (for comparison, the 2007 annual rate was 30,000 shipments). [ACC]

[13] 7% of the nation's rail network mileage lies within the highest population density counties, 3000 people per square mile or more ([Vanderbilt] pp 3-5]); 8% of severe rail accidents occur in these counties (the 23 most densely populated) (all derailments, fires, and explosions, 2006-2010, [FRA] database sorted by county, correlated with Census county population data). Half of these (4% of the total) occur in Cook County, IL alone. The population density of Cook County is 5800 people per square mile; the population of Aiken County, South Carolina where the 2005 Graniteville crash resulted in 9 fatalities and 631 injuries was 144 per square mile ([DoT-PHMSA] pp 33, 104). Other references calculating similar proportions include ([DoT-1992] pp 5-15-19, [DoE] pp 68-72).

DoT's most recent review noted

> DOT is aware that there are [toxic inhalation hazard] rail movements along corridors with population densities several times higher than these [four of the major hazmat rail releases of the past decade]. This coupled with the relatively favorable circumstances surrounding the four incidents leads DOT to believe that the mean of the casualties resulting from the releases analyzed is likely not the true mean of the distribution of the population of preventable releases, but rather lies in the lower end of the distribution. DOT believes that absent issuance of the proposed standards a future incident could potentially result in a larger number of casualties than experienced in recent years. ([DoT-PHMSA] p 33)

[14] [RMS] pp 54-59. This estimate of 10,200 dead (and additionally 32,400 injured) models a 90-ton chlorine railcar breach in a switchyard in Chicago, where the areas of greatest rail line and node density are surrounded by densely populated neighborhoods. Although hundreds of thousands of people

current National Planning Scenario for a catastrophic release of chlorine from a fixed plant near a medium sized city projects 17,000 dead.[15]

However, these impact models do not attempt to estimate the likelihood of such an event to occur, which was a particular requirement of the SNRA project. Compared to other types of events (for instance, nuclear plant accidents), few studies linking frequency to impact estimates have been done for catastrophic chemical accidents. Although the overall national risk to human health and life from catastrophic accidents has been quantitatively modeled in a number of studies of the transportation portion of the chemical sector as a whole, these results could not be used for the SNRA because comparable national-scale estimates could not be found for fixed facilities. Unlike the transportation sector, it does not appear that a national risk assessment attempting to answer these questions for the fixed-facility sector has been attempted since 1974.[16]

This 1974 national risk assessment for catastrophic chemical accidents[17] (performed by UCLA's School of Engineering, also referenced below by its lead author as Simmons et al 1974) was commissioned by the Atomic Energy Commission as one of a set of studies attempting to quantify the risk on a national scale of a number of different hazards (dam failure, airplane accidents, hurricanes, tornadoes, asteroids) for the purpose of comparison with the risk to the nation of civilian nuclear power.[18] However, only the risk of transporting chlorine by rail was treated in a fully quantitative manner: semi-quantitative analyses were used to assess that this risk dominated the national risk of catastrophic accidents from all TIH in the fixed and transportation sectors combined to such an extent, that the chlorine rail accident likelihood and impact estimates could be taken as a reasonable approximation to the risk of catastrophic mass-casualty accidents from the chemical industry as a whole. Although its quantitative approach was further developed in subsequent and more sophisticated studies of the transportation sector taken in isolation, and similar methods have been applied to individual chemical process plants, no public industry-wide quantitative risk assessment has been attempted in this country since.[19]

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may be within the zone of a modeled chlorine cloud (see also [FEMA-2006]), most scenarios (including both of these) realistically assume that nearly everyone is indoors at home or at work, or is able to go indoors before they are overcome: such shelter-in-place measures are known from experience to reduce the number of human casualties by ten times or more. Under circumstances where large numbers of people may be gathered for an outdoor event the fatality rate may be much higher: a similarly modeled scenario of a chlorine railcar breach within Washington DC, but set at a time when thousands of people are thronged on the National Mall for a festival or other event, estimated 100,000 fatalities. [Branscomb] p 5 footnote 9.

[15] [FEMA-2006]. This scenario modeled a deliberate release, but the consequences are similar to a catastrophic accidental release: once a large volume of gas escapes to the air, its subsequent behavior no longer depends on the cause of the breach.

[16] Accident data and worst-case scenarios reported by fixed facilities in the United States from 1995-2005 have been most extensively analyzed by [Belke], [Wharton], [Kleindorfer], and other reports from its authors available at this reference's parent site link (http://opim.wharton.upenn.edu/risk/papers.php). They do not attempt to quantitatively estimate the likelihood of the type of low-frequency high-consequence accidents within the scope of SNRA. They have, however, concluded that the extensively documented historical frequency of high-frequency but lower-consequence accidents has too low a correlation with the likelihood of high-consequence events for extrapolation from historical data to generate meaningful frequency estimates for high-consequence accidents [Elliot].

One partial list of major historical accidents involving chlorine (as well as the flammable liquefied petroleum gas and the explosive ammonium nitrate not considered here) may be found at [UK-HSE]: although worldwide in scope, it is dominated by accidents from fixed facilities which have occurred in the United States. Another list of major chemical accidents may be obtained from the UN Environmental Program's APPELL database [APPELL] by query limited to the United States and sorted by chemical involved. Other good historical sources of comprehensive chemical accident lists include [NICS], [Lees], and for pre-1974 accidents [EPA-1974].

Because of its reliance on recent historical data, this risk summary sheet for chemical accidents is essentially an update of [EPA-1974]. Along with [Simmons] which was completed in the same year (1974) these appear to have been the last and only attempts to produce a national-scale risk assessment for chemical accidents in the United States. See also [Fullwood] pp 428ff.

[17] [Simmons].

[18] These results were presented in the Nuclear Regulatory Commission's landmark 1975 Reactor Safety Study [WASH-1400], also known as the Rasmussen Report, which developed many of the techniques of probabilistic risk assessment relied upon for risk assessments today. In its quantitative approach, communication of uncertainty estimates, all-hazards scope, and deliberate comparison of different national-level risks by common metrics, chapter 6 of this report reads very similar to the SNRA.

[19] [Simmons] Being also almost 40 years old, it is unclear to what extent industry trends and practices in the years since, the last decade in particular, have rendered its inputs and assumptions out to date (although its growth projections for the chlorine industry, its prediction that this trend and population increases along rail routes would roughly cancel the risk reduction of expected safety improvements with time, and its prediction that accident trends would hence remain constant through 1990 proved accurate). As the first attempt of its kind, it relied on many simplifying assumptions

For the fixed sector, the only recent national-scale likelihood estimate for a catastrophic chemical accident comes from a 1996 regulatory impact analysis by the EPA. After including its estimated risk reduction consequent to the proposed regulation (which was enacted) fully going into effect, and incorporating its given ranges in uncertainty in its estimates of consequent risk reduction and in its basic assumptions, the EPA study's calculations give a 0.002% (1 in 50,000) to 0.4% (1 in 250) annual likelihood of a Bhopal-scale accident causing on the order of 4,000 fatalities to occur in the United States, with 0.4% being the best as well as high estimate.[20]

For the transportation sector, the National Transportation Risk Assessment done for the Department of Transportation (DoT) by Argonne National Laboratory in 2000 modeled the nation's road and rail network, routing for each of the top six toxic inhalation hazard (TIH) chemicals, accident rates and rupture probabilities for different models of train car, variation of population density along transport routes, and expected distributions of atmospheric conditions relevant to gaseous chemical dispersion to model expected ten-year frequency estimates for accidents along a range from zero to thousands of fatal exposures. The authors estimated the annual likelihood of a catastrophic chemical accident causing thousands of fatalities to be 0.0001% (one in 100,000 years).[21]

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to reduce the problem space and make tractable the large computational problem with its variables of rail traffic modeled across multiple segments, population distribution, weather patterns, railcar accident and rupture rates. Every subsequent quantitative study of hazardous material transportation hazards of a national scope located by the SNRA project team ([DoT-1988], [DoT-1992], [Argonne-2000], [DoE]), although each increasing in sophistication over the one before it, has followed this model. It reported two fatality-vs-frequency curves, one with and one without modeled evacuation: both curves are presented in figures 6-1 and 6-12 of [WASH-1400], but only the lower-fatality evacuation model is represented on the graph here.

[20] [EPA-1996] Chapter 6, pp 6-8 – 6-30. Noting that the Bhopal plant was American-owned and similar to American-owned plants in the U.S., the authors' first estimate comes from the product of the historical frequency of such events worldwide (1 in 50 years of 'the modern industrial era' since the second world war) with the proportional exposure of the United States to chemical risks (50%, as 50% of the world's annual output of chemicals and refined petroleum came from the U.S.), resulting in 1/50 x 1/2 = 0.01 or 1% in the absence of further regulation (page 6-9). This was used as their best estimate because it required the fewest number of assumptions. On an alternate assumption that the U.S. share of fatal hazardous-materials disasters decreases with the number of fatalities (the world's largest mass-casualty accidents rarely occur in the U.S.) the authors estimated the likelihood might be only 15% of this number (0.15%) (pp 6-10 – 6-11). In footnote 9 they note that if the curves on a plot of the U.S.'s share of fatal accidents (y axis) vs. the log of fatalities per accident (x axis, i.e. the numbers on the x-axis represent 101 = 10, 102 = 100, 103 =1000, 104 = 10,000) could be relied upon in the high-casualty region where the curves are projected beyond the last data point, then a 1-2% proportion might be more appropriate than the 15% they cited in the main text (15% represents the high curve for the last data point). Although the authors state that they were not confident that the curve could be projected out this far, for the purposes of reporting their total range of certainty it is used here.

For the estimate of risk reduction consequent to the RMP rule coming into effect, the authors gave the best estimate of risk reduction from both the RMP rule and new OSHA regulations due to come into effect in the same timeframe to be 60% (pp 6-18 – 6-23: because the impact estimate is essentially a point estimate for a single event, the overall risk reduction in costs from 'Large Magnitude Toxic Events' is here taken to be a reduction in frequency rather than impacts). This factor was used as their best estimate. Two alternate estimates of risk reduction in the authors' sensitivity analysis (pp 6-23 to 6-28) give what the SNRA project team calculated to be 80% and 83% total reductions in risk from the RMP and OSHA rules combined: after reduction to the one significant figure used throughout the authors' analysis in this section, these collapse to a single factor of 80%. Given the chemical industry's changes in a number of practices subsequent to these rules coming into effect, largely because of these rules (see Mitigating Factors), this range of 60-80% of risk reduction since 1996 seems reasonable. Since these are risk reductions, the overall residual risk multiplier after they are taken into account is either (100% - 60%) = 40% or (100% - 80%) = 20%.

Hence after incorporating both sources of uncertainty, the net range of annual likelihood comes to (0.01% to 1%) x (20% to 40%) = 0.002% to 0.4%. The SNRA project team took 0.4% to be the authors' best estimate because each of the factors going into it (1% base and 60% reduction) were the ones the authors selected to calculate their actual cost estimates.

Comparable likelihood estimates for a fixed-site industrial accident (but for the hazardous materials sector generally, including petroleum refining, flammables, and explosives) causing thousands of fatalities have been obtained by a fuller analysis of historical accidents for France [Rocard] and, by a full probabilistic-risk-analysis (but for only particular large concentrations of industry) for the UK (the Canvey Island studies, see for instance [Lees], [Fullwood]). Equipment failure rates which may be used for probabilistic safety analysis of chemical process plants are given in [Lees] and [FEMA-1989].

The International Atomic Energy Agency has published a procedure for conducting a regional or national quantitative risk assessment of fixed chemical sites using generic process plant and storage tank failure rates and specific chemical information [IAEA]. By allocating the number of loading and unloading operations to process plants in proportion to their reported quantities, total national amounts shipped of each chemical, and the distribution between rail and road shipments for each chemical as provided by studies such as [Argonne-2000], sufficient data exist in the public domain from Census block population and geographic population center data, RMP data available through [RTK], and chemical shipment statistics collated by the Department of Transportation and transportation studies such as those cited here to conduct such a national-scale quantitative risk assessment for catastrophic mass-casualty accidents caused by fixed facilities in the United States.

[21] [Argonne-2000] pp 11-12, chapter 5. The summary figure 5.11 and table 5.22 may be found on pp 154, 156. These tabulate estimated fatal exposures for each chemical, as well as for all six TIH chemicals combined, at the 15 minute LC-50 threshold, representing the concentration at which an expected 50% of a normally distributed human population would be dead after fifteen minutes of continuous exposure. To account for the likelihood that most of the population within this area would be partially protected by being indoors (being inside even an ordinary building offers substantial partial protection, which can be enhanced to 90% protection or greater by sealing doors and windows with tape, rolled towels, or anything which will block off routes for air exchange), the authors note that these exposure numbers should be divided by 7 to give estimates for actual

Given the frequency of major chemical accidents in the United States, whether during transport (at least five in the last decade[22]) or at fixed facilities,[23] and the routine production, use, and carriage of large volumes of hazardous chemicals in or through large population centers as mentioned earlier, other researchers have assessed the likelihood of a catastrophic release to be much greater than the estimate reported in the DoT study mentioned above. For example, a later (non-quantitative) DoT study of rail hazardous material transport qualitatively compared the frequency of accidents with the frequent proximity of transport to large population centers in this manner, and concluded it was only a matter of time before the two probabilities should overlap with catastrophic results.[24] The recent accidental rupture of the nuclear plant in Fukushima, Japan may also bring to mind the unquantified but possibly substantial risk of an external event such as an earthquake causing similar damage to a chemical plant or storage tank here, with catastrophic results: several very large concentrations of chlorine are stored on earthquake fault lines in California in highly populated counties.[25] (Note that complex, cascading events such as an earthquake triggering a chemical release are not considered in the SNRA because of the difficulty of quantifying their interdependencies; this is a limitation of the assessment.)[26]

A notable historical counterexample to these expectations of large casualty numbers from an urban chemical accident is the 1979 multiple-railcar multiple-chemical derailment, release, and fire in the Canadian city of Mississauga, a suburb of Toronto. The train accident caused several cars to burst, including a full 90 ton tank of liquefied chlorine gas (the same volume as that of the Chicago train scenario mentioned above), and several tanks of an assortment of flammable and toxic chemicals. Evacuations soon began, and continued for several days while different chemicals came into contact, reacted with each other, and caused new fires, explosions, and clouds of toxic gases, making it an exceptionally difficult disaster for the fire crews to contain. 210,000 people were evacuated from the city—three-quarters of the city's population of 280,000—and were not permitted to return for a period of three to six days. The entire city was essentially shut down for a week. Extensive federal and provincial resources were mobilized to assist the city's emergency crews, reroute traffic around the city, and coordinate the temporary resettlement and aid to the evacuated population. However, the winds happened to be blowing in the right direction to blow much of the toxic chlorine gas out over Lake Ontario and away from the city center, most of the rest burned up in reactions with the other chemicals, and the

fatalities, pp 122-123. Although their reported numbers represent totals from all accidents in a ten-year period, the right hand high-exposure end of the curve may be taken as the approximate predicted frequency of a single event having that many fatal exposures in a ten year period: because of their sharply decreasing probability, an exceptionally high casualty toll in a given ten year period is more likely to be dominated by a single catastrophic event. The six TIH chemicals were estimated by the authors to represent about 90% of the risk from TIH chemicals as a whole, p 8. It is interesting to note how chlorine dominates the high-fatality end of the combined-chemical curve (figure 5.11).

This study is similar to previous studies commissioned by DoT ([DoT-1988], [DoT-1992]).

[22] [DoT-PHMSA] Tables 3, 4, pp 62, 71.

[23] Such as the Magnablend ammonia and allied chemicals plant in Waxahachie, Texas which caught fire in spectacular fashion in October 2011 during the drafting of this sheet. Such accidents are hardly exceptional, however: see note 8.

[24] See note 8.

[25] [Tierney], [Eguchi]. There is some evidence to suggest that the Fukushima accident may not have been an outlier event, or one characteristic only of nuclear facilities: the frequency of accidental chemical releases in Japan markedly spikes in earthquake years: [Wharton] figure 1.A-2, p 42. It is interesting that these three spikes are depicted on the graph as dotted lines as though to indicate that they should be considered outlier events.

As part of the overall industrywide risk-reduction trend discussed in Mitigating Factors below, many of the largest chemical hazards in quake zones have switched or plan to soon switch to alternate or less hazardous chemical production processes. One of the highest profile examples has been Clorox, which maintained a number of bleach production plants in the hills above Los Angeles storing very large quantities of liquefied chlorine gas on-site. The company announced in 2009 that it would be converting all its bleach plants to processes using concentrated bleach as the starting material rather than pure chlorine. [SHG], [CAP-2006], [CAP-2008], [PIRG].

The question of earthquake-caused accidents at fixed facilities storing or using hazardous chemicals has been extensively studied—[Tierney] and [Eguchi] cited above are but two of a large field—but it appears no attempt has been made to quantify the risk of such an event occurring on a national scale.

This summary sheet also does not consider catastrophic chemical release due to a terrorist attack, as that is considered elsewhere. However, it is interesting to note that well before 9/11, 10% of the thousands of chemical accidents occurring in the U.S. every year were attributed to deliberate or intentional human action [EPA-1999].

[26] [Simmons] also explicitly ruled out treatment of earthquake hazards to chemical plants or storage tanks for similar reasons (p 39).

remainder, diluted by the water firefighters hosed at the ruptured tank, was frozen into a chlorine-water ice slush in the bottom of the tank by the subfreezing night temperatures of the Canadian winter. This was the worst-case imaginable scenario, a major release of highly toxic gas in a densely populated urban area similar to cities in the United States, causing massive disruption and economic loss to an entire city: yet there were no human fatalities.[27]

Since a distribution of frequency and impact estimates representing these low-probability, high-impact mass-casualty events could not be derived for the fixed chemical sector with rigor comparable to the studies producing such estimates for the transportation sector, the SNRA project team elected to rely on recent historical data of more frequent accidents which have occurred in the United States. These came from two publicly available databases of comparable quality and uniformity, the Risk Management Program (RMP) database of accidents reported to the EPA by fixed facilities under the Clean Air Act, and the Pipeline and Hazardous Materials Safety Administration (PHMSA) of the Department of Transportation's database of reported road, rail, air, and water accidents involving hazardous chemicals. Both were restricted to the seventeen year range 1994-2010 covered by the RMP database.[28]

The predicted fatality versus likelihood curves from the 1974 UCLA chlorine risk assessment (Simmons et al 1974), the EPA's 1996 Regulatory Impact Analysis (RIA) for the Risk Management Program for fixed facilities (one data point, plus uncertainties in frequency and impact[29]), and data for one-year cumulative-year totals for all TIH generated by Argonne National Labs for the 2000 Argonne NTRA are plotted in Figure 1, along with historical fatality curves for 1994-2010 for fatalities directly caused by hazardous materials for all TIH fatal accidents reported to the PHMSA and RMP databases. Note that with the exception of the EPA estimate and the historical data, these lines represent only the best estimates without uncertainty,[30] and they are not strictly comparable. In particular, the Simmons and EPA estimates and the historical data represent the annual frequency or estimated probability that an accident of that magnitude or greater will occur; the Argonne numbers represent the estimated probability that the fatalities from all accidents in a given year will total to that number or greater. As the frequency of high-fatality accidents decreases with greater fatality numbers, a large number for a given year will be more and more likely to represent the effect of one rare large accident

[27] [Mississauga], [City-Mississauga]. The identity of the slush as a semi-frozen mixture of chlorine and water was the assessment of hazardous materials experts on the scene at the time of the accident [City-Mississauga]; chemical interactions between the chlorine and water may have made the composition of the plugging slush more complicated.

For discussion of mass evacuations from chemical accidents in general, see [Cutter-1989], [Cutter-1991], [Sorensen].

[28] The EPA's Risk Management Program was established in 1999 to implement new reporting requirements from amendments to the Clean Air Act introduced after the Bhopal disaster. It requires fixed facilities producing, consuming, or storing more than a threshold quantity of a listed hazardous chemical in any single container or set of interconnected containers to report all accidents in the prior five-year period resulting in any loss of life, injury, environmental damage, evacuation or shelter-in-place orders, any economic damage outside the facility, or significant (judged by the reporting company) economic damage to the facility itself. It has been extensively studied and described by [Belke], [Wharton], [Kleindorfer], and in other papers available at the latter publication's parent site (http://opim.wharton.upenn.edu/risk/papers.php.) The EPA provided the SNRA project team with a disk containing the RMP accident databases through July 2011 for direct analysis. This database is also conveniently available on the Web through the Right to Know Network's site [RTK].

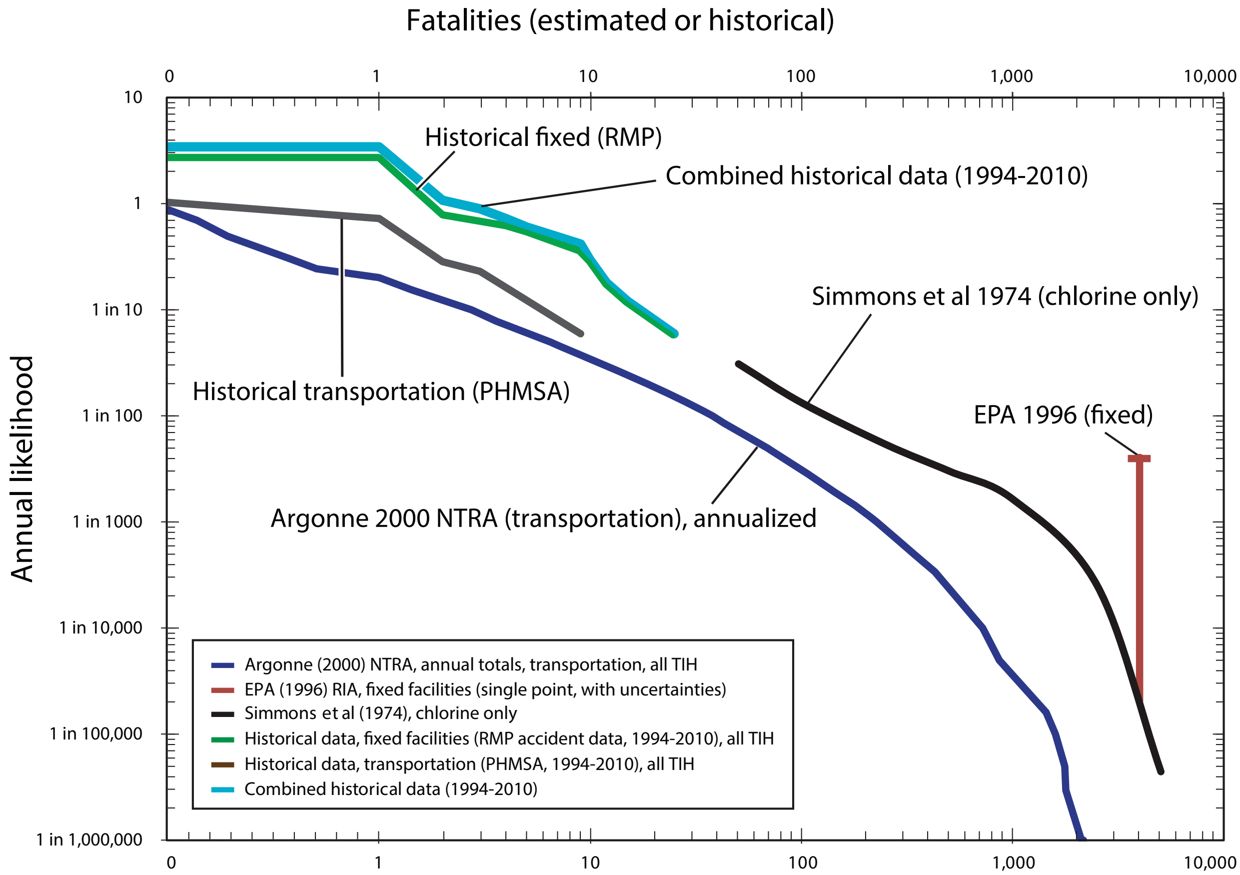
The PHMSA transportation database is available online [PHMSA-database].

[29] The likelihood (vertical) uncertainty is the range cited above, and represents the product of the uncertainty about the base likelihood of a Bhopal-style accident to occur in the U.S. (to what extent historical frequency data should be modified by an estimate of different conditions in the U.S. than in India) and the uncertainty about how much the net risk of high-consequence chemical accidents would decrease subsequent to the RMP's coming into effect in years following 1996. The impact (horizontal) uncertainty is the range represented by the estimate of "on the order of 4,000 fatalities", which for the purposes of graphing was taken to mean the range 3,500 – 4,499, the significant-figure uncertainty represented by the use of a single significant figure (this is the range which would be rounded up or down to 4,000).

[30] The uncertainty in the Argonne numbers (frequency and impact) are a factor of 3 ([Argonne-2000] p 5). The uncertainty estimates given by the UCLA Simmons et al (1974) report are a factor of 10 in frequency and a factor of 2 in impact ([Simmons] pp 3, 41, 43).

dominating the results, and so this curve will approach the estimated frequency of a single accident having that number of fatalities or greater.[31]

Figure 1



Note: The fatality scale from 0 to 1 is direct, and logarithmic above 1; the likelihood scale is logarithmic along its entire range. Fatalities are per event for historical data, the EPA's 1996 RIA (Regulatory Impact Analysis), Simmons et al (UCLA) 1974; annual yearly totals of all accidents for Argonne's 2000 NTRA (National Transportation Risk Assessment). Uncertainties are depicted only for the EPA point estimate, other curves are best estimate lines. The estimated uncertainty in likelihood and impact in Argonne 2000 is a factor of 3, in Simmons et al 1974 a factor of 10 for likelihood and 2 for impact.

The Argonne data represent 1 year totals, and total rail and road fatalities for all TIH (toxic inhalation hazard) chemicals, rather than the 10 year totals for six selected TIH chemicals as reported in the published NTRA: the line above represents actual estimated fatalities (LD-50 exposures divided by 7, see summary sheet text for reference). Historical RMP and PHMSA accident data represent all TIH accidents reported 1994-2010. Simmons et al (1974) calculated fatality estimates from chlorine transportation by rail alone, but estimated that this modality dominated the risk to the general population from fixed and transported chlorine combined: the curve here comes from the lower-fatality estimates of their evacuation model presented in figure 16 (p 53), which corresponds to the lower curve in the Rasmussen Report (WASH-1400) (see references).

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[31] The Argonne report reported ten-year totals rather than single-year totals: these also (when divided by ten) will approximate the annual estimated probability of a single catastrophic high-fatality accident for fatality levels taken above a sufficiently high selected threshold to reduce to a minimum the likelihood that a high ten-year total could represent two or more medium-sized accidents, rather than be dominated by one very large, very rare accident. In order to allow for this approximation to be valid for a larger range of impact data, Dan Brown of the original Argonne team kindly calculated single-year totals for the SNRA project team from the original study data and computer program. To extend the scope of the results to the class of chemical hazards the SNRA project team was considering, Dr Brown also extended the calculations to include estimates for all TIH chemicals transported by road and rail, rather than the top six TIH chemicals reported in the original study (which the authors estimated represented 90% of the total TIH hazard, [Argonne-2000] p 8). These data, divided by the factor of seven which the study authors themselves applied (to account for expected mitigating factors such as sheltering-in-place, pp 122-123) to convert their estimates of LC-50 fatal exposures to estimates of actual fatalities, are the data plotted in the graph above. Loading and unloading accidents may be reflected in the historical data, but were excluded from the risk assessment of the Argonne study ([Argonne-2000] pp 9-10).

In order to restrict the set of historic events to those which presented the most significant challenge to national preparedness, the SNRA project team selected those events which either 1) caused at least one fatality outside the plant or accident location, or to a member of the public or a public responder; or 2) caused at least one fatality of any kind (public, public responder, or employee), and which also resulted in an evacuation or a shelter-in-place order. These criteria excluded accidents causing fatalities only among workers, if no evacuation or shelter orders were issued. In choosing these criteria, the SNRA project team attempted to select those events which had a serious impact to public health outside the plant or industry where it occurred. These criteria, while imperfect, reflect the difference in public perception between the voluntary acceptance of the risk of occupational hazards by those who choose to work in the chemical industry, and the involuntary risk to the general public from chemical accidents.[32]

Assumptions

Frequency, fatality, injury and illness, direct economic loss, and social displacement estimates were determined from the set of all reported toxic inhalation hazard (TIH) incidents from 1994-2010 in two historical accident databases, the EPA RMP database for fixed facilities and the PHMSA database for transportation accidents. The EPA's RMP (Risk Management Program) maintains a database of accident reports from fixed industrial producers and consumers of listed toxic chemicals above given threshold limits. The Department of Transportation's Pipeline and Hazardous Substances Administration (PHMSA)'s database records road, rail, water, and air transportation accidents.

Low, best, and high estimates for fatalities, injuries and illnesses, direct economic loss, and number of displaced from homes for at least two days come from the low, average, and high values of historical incidents in this set meeting threshold criteria for the Chemical Substance Release event. Frequency estimates correspond to the inverse of the number of years of the longest interval between accident events (low), the mean frequency of the accident events (best), and the greatest number of accidents occurring within one year (high) from this set.

Environmental impact estimates were elicited from EPA subject matter experts.

Fatalities and Illnesses/Injuries

The SNRA project team used the following assumptions to estimate health and safety impacts caused by an accidental toxic inhalation hazard (TIH) chemical release event:

- The scope of this national-level event was limited to chemical accidents having the potential to cause a large number of human casualties in the brief timescale characterizing what is commonly considered to be an 'event'. As the class of chemicals having the potential to kill a large number of people in a very short period of time is comprised almost entirely of toxic inhalation hazards which are gaseous under normal conditions, only accidents involving toxic inhalation hazards (TIH) were considered to be within the scope of this event category. This choice effectively excludes accidental spills or releases of chemicals in liquid or solid form, which form the class most likely to cause environmental damage or contamination capable of causing human death and injury over long-term exposure, and also excludes accidents primarily involving chemicals hazardous by their flammable or explosive potential, such as propane, liquefied gas, and ammonium nitrate. Included were accidents caused by chemicals listed as toxic (T) in the RMP database, and classes 2.2 (non-flammable gases, selected

[32] The concept of 'voluntary' versus 'involuntary' risk is discussed in the introduction to [EPA-1974]; see also [EPA-1983].

because ammonia is classed in this category) and 2.3 (poisonous gases) in the PHMSA database.

- The set of accidents selected were those which either 1) caused at least one fatality outside the plant or accident location, or to a member of the public or a public responder; or 2) caused at least one fatality of any kind, public, public responder, or employee, and which also resulted in an evacuation or a shelter-in-place order. Within this set, no distinction was made between fatalities (onsite, offsite, employee, responder, or public).
- From the PHMSA transportation database, only fatalities and injuries reported as being caused by the hazardous substance were included.
- The databases contained many duplicate reports, largely updates to previous reports of the same accident event: these were eliminated manually once the small threshold set was generated.

Economic Loss

In addition to the generally applicable assumptions of those listed above, the SNRA project team used the following assumptions to estimate economic impacts caused by an accidental chemical release event:

- All economic estimates were inflation-adjusted to 2011 dollars.
- The direct economic damages which fixed facilities are required to report, and update for accuracy, to the RMP database are property damage to equipment or the facility itself, and all known or readily knowable property damage outside the facility. These damages do not include business interruption costs, medical or insurance costs, or litigation or settlement costs not overlapping with the above.[33]
- The direct economic damages carriers are required to report, and update for accuracy, to the PHMSA transportation database are the value of the material (spilled chemical) which was lost, physical damage sustained by the carrier (vehicles or other cargo), damage caused to public or private property, the dollar value of the response cost, and the dollar value of any remediation and clean-up cost. These damages do not include business interruption costs, medical or insurance costs, or litigation or settlement costs not overlapping with the costs listed above.[34]
- The SNRA project team added cost estimates tied to the number of injured or killed. The cost of medical care per injury/illness was taken as $6,600, for consistency with previous DHS risk assessments (including the Integrated Terrorism Risk Assessment conducted by the DHS Science & Technology Directorate to assess the risk of chemical, biological, radiological, and nuclear terrorism).
- The SNRA project team did not attempt to estimate an equivalent dollar value or a value of a statistical life (VSL) to determine an economic cost per fatality. Instead, only the countable direct contribution to the national economy of the average annual spending of one person in a year, which the SNRA project team set at $42,500, was multiplied by the number of fatalities to estimate the loss to the economy from accident fatalities.

[33] [RMP-reqts].
[34] [HMIR].

Social Displacement

For the purposes of the SNRA, social displacement was defined as the number of people forced to leave home for a period of two days or longer. Note that there are limitations to this measure of social displacement, as the significant differences between temporary evacuations and permanent displacement due to property destruction are not captured.

Social displacement estimates for the SNRA chemical accidents event come from the same historical dataset of 1994-2010 historic toxic industrial chemical accidents in the United States used for the other quantitative measures of the accidental chemical substance release event.

- There is historical precedent for very large evacuations due to chemical accidents. After Hurricane Katrina, the evacuation of 210,000 people from Mississauga was the second largest evacuation in history in North America. However, the same historical dataset used for other metrics was used for social displacement to ensure consistency of scope across measures for this event.
- The PHMSA and RMP databases include evacuation estimates. The PHMSA database additionally reports total evacuation time; the RMP database reports the total duration of the chemical substance release itself, which the SNRA project team used as a proxy for evacuation time.[35] Only two events in the historical data set, as reported in these databases, had evacuations lasting 48 hours or more (see Data Table).
- The low, best, and high social displacement estimates represent the low (0), average (260), and high (5,400) of this set.

Psychological Distress

Psychological impacts for the SNRA focus on *significant distress* and *prolonged distress*, which can encompass a variety of outcomes serious enough to impair daily role functioning and quality of life. An index for significant distress was created that reflected empirical findings that the scope and severity of an event is more important than the type of event. The equation for this index uses the fatalities, injuries, and displacement associated with an event as primary inputs; a factor elicited from subject matter experts weights the index for differing psychological impact based on the type of event, but as a secondary input.[36] The numerical outputs of this index formula were used to assign events to bins of a risk matrix for a semi-quantitative analysis of psychological risk in the SNRA.

[35] E.g. the SNRA project team assumed that people would not return to their homes while the toxic substance was still being released, and that they would return shortly thereafter.

[36] The Significant Distress Index is calculated from these inputs using a formula proposed by subject matter experts consulted for the SNRA project: $N_{SD} = C_{EF} \times (5\,Fat + Inj + ½\,D)$, where N_{SD} represents the number of persons significantly distressed, C_{EF} is the expert assessed Event Familiarity Factor, *Fat* is the number of fatalities, *Inj* is the number of injuries and/or illnesses, and *D* is the number of persons displaced (Social Displacement). In words, this formula suggests that there are 5 significantly distressed persons for each life lost; 1 for each person injured; and 1 for each 2 people displaced. This formula was constructed to reflect the empirical finding that the most severe stressor of a disaster is losing a loved one, followed by injury, followed by displacement. Uncertainty was captured by applying the index formula to the low, best, and high estimates of these three human impact metrics.

The Event Familiarity Factor is intended to capture the extent to which the event entails an ongoing threat with uncertainty regarding long term effects, is unfamiliar, or that people dread, exacerbating psychological impacts. This factor, ranging from 1.0 for familiar events to 1.3 for unfamiliar events, was provided by subject matter experts for each national-level event included in the SNRA: accidental Chemical Substance Spill or Release was given a C_{EF} of 1.1.

The numerical estimates calculated from this formula are reported in Appendix G. The semi-quantitative risk matrix is discussed in the Findings (Psychological Distress Risk).

Environmental Impact

The United States Environmental Protection Agency (EPA) convened an ad hoc group of environmental experts representing the fields of environmental science, ecological risk, toxicology, and disaster field operations management to estimate environmental impacts for this event. Estimates are based on the following assumptions:

- Experts were elicited to provide estimates in the environmental impact category based on assumptions. Actual environmental/ecological harm that occurs as a result of the events described in a given scenario may vary considerably, and will depend on numerous variables (such as chemical or biological agent, contamination extent, persistence and toxicity—both chronic and acute toxicity—or infectivity).
- EPA defined environmental consequence (impact)[37] as the potential for adverse effects on living organisms associated with pollution of the environment by effluents, emissions, wastes, or accidental chemical releases; energy use; or the depletion of natural resources.
- Experts identified the best estimate for environmental impacts as "Moderate." Experts made this estimate given that the primary set of scenarios considered for this event were releases of toxic gases which could cause large numbers of human casualties. The widespread release of a toxic gas could contaminate tens to hundreds of acres with toxic material, but not on a catastrophic scale compared with other types of disaster.
- The greater likelihood for toxic releases to happen in sparsely populated areas, although decreasing human fatalities, increases the potential for ecological damage.
- Persistence was also judged to be a possible issue. The more persistent the chemical, the greater the impact it will have on the environment. There is also a potential for water contamination (depending on the contamination, and the spread of the contaminant through water), which could elevate a chemical disaster to an environmentally high impact event.

Potential Mitigating Factors

It appears that the risk from chemical accidents has been decreasing in recent years and, should current trends continue, is expected to continue decreasing. The combination of new reporting requirements for fixed facilities in this country introduced in the years 1986-1999 following the Bhopal catastrophe, pressure from local and issue-oriented public policy groups, and sharply increased public and political attention on the potential attractiveness of chemical facilities to terrorist attack following 9/11 has resulted in a significant reduction in the quantities of highly toxic chemicals held by fixed facilities located in the most populated areas nationwide, largely due to the substitution of less toxic intermediates where possible.[38] Although attempts at directly reducing the risk from transportation accidents by regulation and rerouting have been less

[37] The 2011 SNRA referred to impacts as 'consequences' because of prior usage in quantitative risk assessment (Kaplan and Garrick [1981, March], On the quantitative definition of risk: *Risk Analysis* 1(1) 11-32). Except where it will cause confusion, 'impact' is used synonymously in this document because of pre-existing connotations of the word 'consequence' within FEMA.

[38] In addition to accidents, the EPA's Risk Management Program requires facilities holding more than a threshold quantity of a listed hazardous chemical in a single container or set of interconnected containers to submit risk assessments including modeling the impacts of the worst-case-possible scenario on surrounding populations. The number of reporting facilities substantially decreased from the first reporting period 1995-2000 to the second 2000-2005, in large part because many sites reduced the amount of chemical on-site or the amounts in any one ruptureable container below the reporting thresholds [Wharton]. Concerns about terrorists targeting chemical plants predate 9/11, and were the primary reason the EPA partially restricted the RMP data from public access [Wharton], [CRS]. Other risk reduction examples include the widespread substitution of sodium hypochlorite (concentrated bleach) for pure liquefied chlorine by water treatment facilities and the consumer bleach manufacturer Clorox, and DuPont's switching a pesticide manufacturing process from a batch production process requiring 40-50,000 pounds of the Bhopal chemical methyl isocyanate to a continuous process consuming the intermediate as it is produced, such that no more than two pounds of the chemical exists on-site at any one time [SHG] pp 3-2 – 3.4. Also see [CAP-2006], [CAP-2008], [PIRG].

successful,[39] the decreased end-user need for the most toxic chemicals at fixed facilities has also reduced the quantities being transported, reducing the overall risk from transported toxic chemicals in a similar fashion.[40]

Additional Relevant Information

Although the majority of fatal chemical accidents which have occurred in recent years have occurred in rural areas or small population centers, because road and rail traffic is so routinely routed through urban centers of high population density[41] and because of cities' dependence on water treatment plants which frequently use large amounts of chlorine,[42] some of the risk from the most catastrophic chemical accidents appears to be broadly spread among the American population. However, much of the risk appears to be geographically and socially distributed less evenly. As noted above, Chicago is at particular risk from chemical accidents by rail, and earthquake-prone regions such as California from fixed facilities. The bulk of the nation's chlorine production factories are located on the Gulf Coast:[43] although these factories withstand hurricanes on a regular basis,[44] their location increases that region's risk exposure to at least transportation accidents as their manufactures must be shipped out.[45] A risk factor particular to the fixed chemical sector, having possible social consequence as demonstrated by the government's experience of Hurricane Katrina, is the finding from studies of RMP accident data that fixed chemical facilities rated as 'highest risk' are disproportionally situated in counties having higher minority populations. This correlation persists after other demographic factors, including geographic location and poverty levels, are factored out.[46]

References

[ACC] Chlorine: ensuring rail transportation safety. American Chemistry Council, unknown year but either 2010 or 2011, at http://www.americanchemistry.com/Policy/Rail-Transportation/Issue-Brief-on-Chlorine-Rail-Transportation-Safety.pdf.

[APPELL] United Nations Environmental Program, APPELL database of industrial disasters. At http://www.unepie.org/scp/sp/disaster/database/#sources.

[Argonne-2000] A national risk assessment for selected hazardous materials in transportation. Brown et al, Argonne National Labs 2000, ANL/DIS-01-1, at http://www.ipd.anl.gov/anlpubs/2001/01/38251.pdf.

[Argonne-2007] Chang et al, 2007. Probabilistic consequence model of accidental or intentional chemical releases. Argonne National Laboratory for DHS, ANL/DIS-08/3, at http://www.dis.anl.gov/pubs/61981.pdf.

[Belke] Belke, James C, 2000. Chemical accident risks in U.S. industry – A preliminary analysis of accident risk data from U.S. hazardous chemical facilities. At http://www.epa.gov/ceppo/pubs/stockholmpaper.pdf.

[Branscomb] Branscomb et al: Rail transportation of toxic inhalation hazards: policy responses to the safety and security externality. Belfer Center, Harvard Kennedy School 2010. At http://belfercenter.ksg.harvard.edu/files/Rail-Transportation-of-Toxic-Inhalation-Hazards-Final.pdf.

[Challener] Challener, Cynthia, 2010. Hurricane season rapidly approaches: lessons learned and tips for weathering the next storm. C&M Consulting, for ChemAlliance, at http://www.chemalliance.org/featured/?sec=5&id=7017.

[39] [Branscomb] pp 7-9, 41-46 for unsuccessful rerouting attempts by local city councils, recent safety standards on new railcars not yet realized because of low turnover in railcar fleet.
[40] Recent annual shipment rates of chlorine (30,000 rail shipments in 2007) are lower than the historical average (2.2 million over 42 years, average 52,000 annually) [ACC].
[41] See note 13.
[42] [CAP-2007], map p 11. Also [PIRG], [CAP-2006], [CAP-2008], [SHG].
[43] [Branscomb] figure 1, p 12.
[44] [Challener].
[45] [DoT-1988] pp 7 to 8, page 3-12.
[46] [Wharton] pp 98, 119-122; [Elliott-2004]. See also [Cutter-1989].

[Cutter-1989] Cutter et al, 1989. The national pattern of airborne toxic releases. The Professional Geographer 41(2), pp 149-161.

[Cutter-1991] Cutter, Susan L, 1991. Fleeing from harm: international trends in evacuations from chemical accidents. *International Journal of Mass Emergencies and Disasters* 9(2), pp 267-285.

[CAP-2006] Center for American Progress, Paul Orum, 2006. Preventing toxic terrorism: How some chemical facilities are removing danger to American communities. At http://www.americanprogress.org/issues/2006/04/b681085_ct2556757.html/chem_survey.pdf.

[CAP-2007] Center for American Progress, Paul Orum, 2007. Toxic trains and the terrorist threat: How water utilities can get chlorine off the rails and out of American communities. Map, Unnecessary rail shipments of chlorine gas endanger millions, p 11. At http://www.americanprogress.org/issues/2007/04/pdf/chemical_security_report.pdf.

[CAP-2008] Center for American Progress, Paul Orum, 2008. Chemical security 101: What you don't have can't leak, or be blown up by terrorists. At http://www.americanprogress.org/issues/2008/11/pdf/chemical_security.pdf.

[City-Mississauga] Derailment: The Mississauga Miracle. City of Mississauga home site, http://www.mississauga.ca/portal/home?paf_gear_id=9700018&itemId=5500001.

[CRS] Congressional Research Service, 1999. RL30228: Accident Prevention under the Clean Air Act Section 112(r): Risk Management Planning by Propane Users and Internet Access to Worst-Case Accident Scenarios. At http://ncseonline.org/nle/crsreports/air/air-30.cfm.

[DoT-1988] Department of Transportation Office of Research and Development 1988, A risk assessment study on the transportation of hazardous materials over the U.S. railroads, DOT/FRA/ORD-88/14, http://www.fra.dot.gov/downloads/research/ord8814.pdf.

[DoT-1992] Department of Transportation Office of Research & Development 1992, Hazardous materials transportation in tank cars: analysis of risks – part I, DOT/FRA/ORD-92/34, http://www.fra.dot.gov/downloads/Research/ord9234.pdf.

[DoT-PHMSA] Department of Transportation Pipeline and Hazardous Materials Safety Administration, Notice of Proposed Rulemaking, docket no. FRA-2006-25169. Hazardous materials: Improving the safety of railroad tank car transportation of hazardous materials (PIH tank car crashworthiness performance standards), March 2008. http://mercatus.org/sites/default/files/publication/DOT%20FRA%20Tank%20Cars%20RIA.doc.

[DoE] A resource handbook on DOE risk assessment. Department of Energy 2002. At http://nepa.energy.gov/documents/DOETransportationRiskAssessment.pdf.

[Eguchi] Eguchi et al 2008, The ShakeOut Scenario supplemental study, Hazardous Materials, at http://www.colorado.edu/hazards/shakeout/hazmat.pdf.

[Elliott-2004] Elliott et al, 2004. Environmental justice: frequency and severity of U.S. chemical industry accidents and the socio-economic status of surrounding communities. *Journal of Epidemiology and Community Health* v 58, pp 24-30. At http://opim.wharton.upenn.edu/risk/downloads/archive/arch308.pdf.

[Elliott-2008] Elliott et al, 2008. Linking OII and RMP data: does everyday safety prevent catastrophic loss? *International Journal of Risk Assessment and Management* v 10 nos. 1/2, 2008. At http://opim.wharton.upenn.edu/risk/library/J2008_IntJRAM_MER,PRK_OII.pdf.

[EPA-1983] Valuing Reductions in Risks: A Review of the Empirical Estimates – Summary. EPA Office of Policy Analysis, June 1983, EPA-203-05-83-003; at http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=9100DSCZ.txt.

[EPA-1974] The Consequences and Frequency of Selected Man-Originated Accident Events. EPA Office of Radiation Programs, report date August 1974, published June 1980. At http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=9100620R.txt.

[EPA-1996] Economic Analysis in Support of Final Rule on Risk Management Program Regulations for Chemical Accident Release Prevention, as Required by Section 112(R) of the Clean Air Act. EPA, CEPPO, Office of Solid Waste and Emergency Response, June 1996. Docket A-91-73, document number A-91-73-IX-B-4. Not currently available on Web (October 2011) but may be requested by the public in person at an EPA public reading room (http://www.epa.gov/osweroe1/content/rmp/readingroom.htm) or by emailing docket-customerservice@epa.gov with a request listing the document's name, number, and docket number.

[EPA-1999] EPA, New Ways to Prevent Chemical Incidents (1999), paper EPA-550-B-99-012, p 3; at http://www.epa.gov/oem/docs/chem/incident.pdf. .

[FEMA-1989] Handbook of Chemical Hazard Analysis Procedures. Federal Emergency Management Agency, U.S. Department of Transportation, U.S. Environmental Protection Agency, 1989; at http://nepis.epa.gov/Exe/ZyPURL.cgi?Dockey=10003MK5.txt.

[FEMA-2006] FEMA's National Planning Scenario #8: Chlorine, https://www.llis.dhs.gov/content/national-planning-scenarios-final-version-213-0.

[FRA] Federal Railroad Administration, public query page, train accident database. At http://safetydata.fra.gov/officeofsafety/publicsite/Query/inctally1.aspx.

[Fullwood] Fullwood, Ralph R. Probabilistic Safety Assessment in the Chemical and Nuclear Industries. Butterworth Heinemann (Reed Elsevier), Boston 2000. LoC catalog number TK9153.F853 1999.

[HMIR] Hazardous Materials Incident Reporting, p 7. DoT PHMSA PHH50-0038-0604, at http://www.phmsa.dot.gov/staticfiles/PHMSA/DownloadableFiles/Files/reporting_instructions_rev.pdf.

[IAEA] Manual for the classification and prioritization of risks due to major accidents in process and related industries. International Atomic Energy Agency, 1996, IAEA-TECDOC-727 (Rev.1). At http://www-pub.iaea.org/MTCD/Publications/PDF/te_727r1_web.pdf.

[Kleindorfer] Kleindorfer et al, 2003. Accident epidemiology and the U.S. chemical industry: accident history and worst-case data from RMP info. *Risk Analysis* 23(5) pp 865-881. At http://opim.wharton.upenn.edu/risk/downloads/03-24-PK.pdf.

[Lees] Lees' Loss Prevention in the Process Industries: hazard identification, assessment, and control. 3rd ed., Sam Mannan ed. Elsevier Butterworth-Heinemann, Amsterdam, Boston 2005. LoC call number TP690.6 L43 2005.

[Mississauga] The Mississauga Evacuation - Final Report. Ministry of the Solicitor General of Ontario, 1981, at http://cidbimena.desastres.hn/docum/crid/Diciembre2004/pdf/eng/doc4131/doc4131.htm.

[NICS] Sheltering in place as a public protective action. National Institute for Chemical Studies, June 2001. At http://nicsinfo.org/docs/shelter%20in%20place.pdf.

[NRC data] National Response Council data, list of reported chlorine incidents 1990-2010, database downloadable from http://www.nrc.uscg.mil/download.html.

[Pastel/Bhopal] Pastel, Ross. What we have learned about mass chemical disasters. *Psychiatric Annals* v 37 (2007) p 754, at http://www.psychiatricannalsonline.com/showPdf.asp?rID=24853; for long term death toll, state reported statistic of 22,149 cited in 'How many died in Bhopal?', http://www.bhopal.net/oldsite/death-toll.html.

[PHMSA] Top consequence hazardous materials by commodities and failure modes, 2005-2009. Pipeline and Hazardous Materials Safety Administration, 2011; at http://www.phmsa.dot.gov/staticfiles/PHMSA/DownloadableFiles/Hazmat/PHSMA%20Top%20Consequence%20Hazardous%20Materials%20March%202011.pdf.

[PHMSA-database] Available at https://hazmatonline.phmsa.dot.gov/IncidentReportsSearch.

[PIRG] U.S. PIRG 2010. Chemical insecurity: America's most dangerous companies and the multimillion dollar campaign against common sense solutions. Through http://www.uspirg.org/news-releases/healthy-communities/healthy-communities/washington-d.c.-new-study---chemical-insecurity---americas-most-dangerous-chemical-companies-put-millions-of-americans-at-risk-and-spend-more-than-70m-to-fend-off-regulation.

[RMP-reqts] RMP reporting requirements, Chapter 3: Five-year accident history, pages 3-5. At http://www.epa.gov/osweroe1/docs/chem/Chap-03-final.pdf.

[RMS] Catastrophe, injury, and insurance: the impact of catastrophes on workers compensation, life, and health insurance; Risk Management Solutions, 2004; pp 54-59. At http://www.rms.com/Reports/CasualtyStudy_Final.zip.

[Rocard] Rocard et al, 1992. A socio-economic analysis of controls on land use around hazardous installations. The Geneva Papers on Risk and Insurance, 17 (no. 65, Oct 1992), pp 468-484. At http://www.genevaassociation.org/PDF/Geneva_papers_on_Risk_and_Insurance/GA1992_GP17(65)_Rocard%26Smets.pdf.

[RTK] RTKNet: the Right to Know Network. At http://www.rtknet.org.

[SHG] The safe hometowns guide: how to do a community reassessment of chemical site safety and security after September 11, 2001. Safe Hometowns Initiative, 2002. At http://www.safehometowns.org/safehometowns.pdf.

[Simmons] Simmons et al, 1974. The Risk of Catastrophic Spills of Toxic Chemicals. UCLA School of Engineering and Applied Science, for the U.S. Atomic Energy Commission Division of Research, UCLA-ENG-7425. This work is publicly available through the UCLA library and the Department of Transportation public library in Washington, DC; it is not in the Library of Congress, nor yet available in electronic form. It was also published in somewhat abbreviated form as "Risk assessment of large spills of toxic materials", in Control of Hazardous Material Spills: Proceedings of the 1974 National Conference on Control of Hazardous Material Spills, American Institute of Chemical Engineers and U.S. Environmental Protection Agency, Aug 25-28, 1974, San Francisco, pp 166-175, LoC catalog number T55.3 H3 N27 1974: although the evacuation model and results of the longer work are not included in this paper, the results are plotted (as in this summary sheet) in figure 6-12 of [WASH-1400].

[Sorensen] Sorensen, John H, 1986. Evacuations due to chemical accidents, experience from 1980 to 1984. Oak Ridge National Laboratory ORNL TM-9882, January 1986. At http://www.ornl.gov/info/reports/1986/3445600039946.pdf.

[Tierney] Risk of hazardous materials release following an earthquake. Tierney et al, Preliminary Paper #152, University of Delaware Disaster Research Center 1990; at http://dspace.udel.edu:8080/dspace/bitstream/handle/19716/524/PP152.pdf?sequence=3.

[UK-HSE] UK Health and Safety Executive, Summary of worldwide major incidents involving commonly encountered hazardous substances, 2006. At www.hse.gov.uk/foi/internalops/hid/spc/spctg26.pdf.

[Vanderbilt] Intermodal GIS network risk assessment. Vanderbilt Center for Transportation Research, 2009 or 2010, available at http://www.vanderbilt.edu/vector/?page_id=340.

[Wharton] Accident epidemiology and the RMP rule: learning from a decade of accident history data for the U.S. chemical industry. Wharton School, University of Pennsylvania, 2007. At http://opim.wharton.upenn.edu/risk/library/2007_EPA-Wharton_RMPRule.pdf.

[WASH-1400] Reactor Safety Study: An assessment of accident risks in U.S. commercial nuclear power plants. Rasmussen, Norman, U.S. Nuclear Regulatory Commission, October 1975, WASH-1400 (NUREG 75/014). Available at http://teams.epri.com/PRA/Big%20List%20of%20PRA%20Documents/WASH-1400/02-Main%20Report.pdf.

Data Table

Commodity Short Name	Date	City	State	Fixed Site or Transport	Source	'Public' Fatalities	Employee Fatalities	Total Hazmat Fatalities	Total Hazmat Injuries	Reported Loss or Damages	CPI	Adjusted (2011$)	SNRA Direct Economic Damage
Ammonia (anhydrous)	12/13/94	Pensacola	FL	Fixed	RMP	0	4	4	27	$220,200,000	1.49	$327,330,768	$327,678,968
Chlorine	4/11/96	Alberton	MT	Transport	PHMSA	1	0	1	787	$10,000,000	1.44	$14,438,815	$19,675,515
Ammonia (conc 20% or greater)	8/26/97	Lancaster	OH	Fixed	RMP	5	0	5	0	$0	1.39	$0	$212,500
Ammonia (anhydrous)	11/3/97	Sacaton	AZ	Fixed	RMP	0	1	1	1	$50,000	1.39	$69,492	$118,592
Chlorine	2/23/98	Orlando	FL	Fixed	RMP	9	0	9	1	$0	1.39	$0	$389,100
Ammonia (conc 20% or greater)	4/22/98	Centralia	KS	Fixed	RMP	12	0	12	0	$0	1.39	$0	$510,000
Ammonia (anhydrous)	10/10/98	Tacoma	WA	Fixed	RMP	5	0	5	0	$11,400,000	1.36	$15,501,879	$15,714,379
Ammonia (anhydrous)	10/26/98	Franklinton	LA	Fixed	RMP	25	0	25	0	$0	1.36	$0	$1,062,500
Ammonia (anhydrous)	1/5/00	Green River	WY	Fixed	RMP	1	0	1	2	$0	1.32	$0	$55,700
Hydrogen chloride (anhydrous) (HCl)	5/17/00	Jefferson	OK	Fixed	RMP	15	0	15	0	$300	1.32	$395	$637,895
Ammonia (anhydrous)	4/2/01	Hammond	LA	Fixed	RMP	1	0	1	12	$5,800,000	1.28	$7,419,317	$7,541,017
Chlorine	7/14/01	Newberg	OR	Fixed	RMP	0	3	3	51	$115,000	1.26	$144,818	$608,918
Ammonia (anhydrous)	10/16/01	Mesquite	NM	Fixed	RMP	1	0	1	2	$600,000	1.26	$755,570	$811,270
Ammonia (anhydrous)	1/18/02	Minot	ND	Transport	PHMSA	1	0	1	0	$0	1.26	$0	$42,500
Ammonia (conc 20% or greater)	4/11/03	Soddy Daisy	TN	Fixed	RMP	0	1	1	0	$6,015,000	1.23	$7,405,805	$7,448,305
Ammonia (anhydrous)	4/21/03	Lakewood	CO	Fixed	RMP	1	0	1	6	$100	1.23	$123	$82,223
Ammonia (anhydrous)	7/13/03	Pampa	TX	Fixed	RMP	1	0	1	3	$0	1.20	$0	$62,300
Ammonia (anhydrous)	11/4/03	Paynesville	MN	Fixed	RMP	1	0	1	1	$0	1.20	$0	$49,100
Vinyl acetate monomer[47]	4/23/04	Illiopolis	IL	Fixed	RMP	0	5	5	6	$0	1.20	$0	$252,100
Ammonia (anhydrous)	5/25/04	Seymour	IN	Fixed	RMP	10	0	10	0	$0	1.20	$0	$425,000
Chlorine	6/28/04	Macdona	TX	Transport	PHMSA	2	1	3	66	$0	1.20	$0	$563,100
Chlorine	1/6/05	Graniteville	SC	Transport	PHMSA	8	1	9	631	$8,018,600	1.16	$9,301,453	$13,848,553
Carbon dioxide (refrigerated liquid)	1/8/05	Sanford	FL	Transport	PHMSA	1	1	2	0	$0	1.16	$0	$85,000
Ammonia (anhydrous)	8/28/06	Ebensburg	PA	Fixed	RMP	10	0	10	4	$0	1.09	$0	$451,400
Titanium tetrachloride	6/27/07	Westlake	LA	Fixed	RMP	0	1	1	1	$178,000	1.09	$194,485	$243,585
Argon (refrigerated liquid)	5/20/08	Hollywood	FL	Transport	PHMSA	3	0	3	0	$0	1.05	$0	$127,500
Ammonia (anhydrous)	7/15/09	Swansea	SC	Transport	PHMSA	1	0	1	7	$700	1.04	$727	$89,427
Ammonia (anhydrous)	11/16/09	Cincinnati	OH	Fixed	RMP	2	0	2	0	$0	1.04	$0	$85,000

Commodity Short Name	Date	Evacuated (RMP)	Shelter in Place (RMP)	Public Evacuated (PHMSA)	Employees Evacuated (PHMSA)	Evacuated > 48 hours	Environ-mental Damage	Mode of Transportation (PHMSA) or Industry (RMP)	Cause
Ammonia (anhydrous)	12/13/94	2,000	80			2,000	Yes	Nitrogenous Fertilizer Manufacturing	Equipment Failure
Chlorine	4/11/96			0	0	0	No	Rail (Transportation)	Derailment
Ammonia (conc 20% or greater)	8/26/97	0	0			0	No	Farm Supplies Wholesalers	Equipment Failure
Ammonia (anhydrous)	11/3/97	30	0			0	Yes	Apiculture	Human Error
Chlorine	2/23/98	0	0			0	No	Sewage Treatment Facilities	Human Error
Ammonia (conc 20% or greater)	4/22/98	0	0			0	No	Farm Supplies Wholesalers	Equipment Failure
Ammonia (anhydrous)	10/10/98	0	0			0	No	Refrigerated Warehousing and Storage	Equipment Failure
Ammonia (anhydrous)	10/26/98	6	0			0	No	Corn Farming	Human Error
Ammonia (anhydrous)	1/5/00	6	0			0	No	Ice Manufacturing	Equipment Failure
Hydrogen chloride (anhydrous) (HCl)	5/17/00	0	0			0	No	All Other Basic Organic Chemical Manufacturing	Unknown
Ammonia (anhydrous)	4/2/01	0	0			0	No	Fluid Milk Manufacturing	Unknown
Chlorine	7/14/01	2,000	0			0	Yes	Petrochemical Manufacturing	Equipment Failure
Ammonia (anhydrous)	10/16/01	0	0			0	Yes	Corn Farming	Human Error
Ammonia (anhydrous)	1/18/02			0	0	0	No	Rail (Transportation)	Derailment
Ammonia (conc 20% or greater)	4/11/03	26	1,500			0	Yes	Flavoring Syrup & Concentrate Manufacturing	Equipment Failure
Ammonia (anhydrous)	4/21/03	20	0			0	Yes	Farm Supplies Merchant Wholesalers	Human Error
Ammonia (anhydrous)	7/13/03	0	0			0	No	Fresh and Frozen Seafood Processing	Equipment Failure
Ammonia (anhydrous)	11/4/03	0	0			0	No	Other Farm Product Raw Material Merchant Wholesalers	Human Error
Vinyl acetate monomer[48]	4/23/04	980	0			0	No	Plastics Material and Resin Manufacturing	Unknown
Ammonia (anhydrous)	5/25/04	8	4			0	No	Farm Supplies Merchant Wholesalers	Equipment Failure
Chlorine	6/28/04			0	0	0	Yes	Rail (Transportation)	Crash/Derailment
Chlorine	1/6/05			5,400	0	5,400	Yes	Rail (Transportation)	Derailment
Carbon dioxide (refrigerated liquid)	1/8/05			0	0	0	No	Highway (Transportation)	Human Error (Loading Acc.)
Ammonia (anhydrous)	8/28/06	0	0			0	No	Animal Slaughtering and Processing	Equipment Failure
Titanium tetrachloride	6/27/07	0	100			0	No	Inorganic Dye and Pigment Manufacturing	Equipment Failure
Argon (refrigerated liquid)	5/20/08			0	0	0	No	Water (Transportation)	Equip. Faiure. (Corrosion)
Ammonia (anhydrous)	7/15/09			0	5	0	No	Highway (Transportation)	Equipment Failure
Ammonia (anhydrous)	11/16/09	0	0	0	0	0	No	Farm Supplies Merchant Wholesalers	Unknown

[47] Acetic acid ethenyl ester.
[48] Acetic acid ethenyl ester.