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Estimating the Economic Impacts of Terrorist Events at Individual Chemical Facilities: Initial Results

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EXECUTIVE SUMMARY

The U.S. Congress enacted Section 550 of the *Homeland Security Appropriations Act of 2007, P.L. 109-295,* to direct the U.S. Department of Homeland Security (DHS) to identify and secure the Nation's high-risk chemical facilities. Within DHS, the Infrastructure Security Compliance Division (ISCD) is responsible for implementing the Chemical Facility Anti-terrorism Standards (CFATS) regulatory process. Part of this process requires determining whether and how facilities should be regulated based on how critical they are to the national economy. ISCD partnered with Sandia National Laboratories (SNL) to develop a method for identifying economically critical chemical facilities.

SNL first conducted a comprehensive review of historical chemical-facility events to understand the types of impacts caused by disruption to a chemical facility. It then reviewed potential methods for measuring the economic criticality of chemicals and facilities and ultimately developed a methodology based largely on the *economic impacts* literature. Research was then conducted on specific alternative approaches for estimating how the loss of a chemical facility could cause national-level economic impacts. The method identifies national economic impacts by measuring the costs of four primary impact types:

1. Cleanup and decontamination of the chemical facility or affected area,
2. Repair or replacement of chemical facility equipment,
3. Local business interruptions caused by the chemical event and cleanup, and
4. Chemical supply-chain interruptions.

These impacts are used in a macroeconomic model to estimate the total economic impact on the U.S. economy. The method does not include the impacts of morbidity and mortality, since analysis of historical events suggests their economic impacts to be comparatively small and human-life effects are considered under the CFATS public health and safety (PH&S) regulations.

The method was applied to specific scenarios, including terrorist events at a chemical facility (e.g., explosion, fire, or release of a toxic substance) and the theft of chemical substances from a chemical facility for nefarious use in another location (Ackerman *et al.,* 2007). Detailed impact modeling of events at 100 CFATS chemical facilities was conducted, at the plant, supply-chain, and macroeconomic levels. These calculations provide an initial but representative understanding of potential impacts.

SNL's general finding is that terrorist events at a chemical facility are not likely to cause national-level economic impacts, but that impacts could be significant at the local level. The initial results suggest average gross domestic product (GDP) impacts for onsite and offsite events in the hundreds of millions of dollars and billions of dollars, respectively, with nearly 25 percent of the GDP impact occurring in the first year. These impacts are relatively small compared with other national-level events, such as:

- The terrorist attacks of September 11, 2001 (9/11), which created an estimated $124 billion in economic impact from cleanup, business interruption, and reduced travel (Carter and Cox, 2011);
- Hurricane Katrina, with an estimated economic impact that ranged from $96 billion (White House, 2006) to $250 billion (Swiss Re, 2007); and
- The economic recession of 2007-2009, which resulted in a GDP contraction of $850 billion, or 5 percent of U.S. GDP.

The reasons for small national impacts from chemical facility events are at least twofold: first, the U.S. economy and Chemical Sector are each very large: GDP is over $17 trillion and the gross output of chemical products is $794 billion (U.S. DOC, 2012). The analytical results suggest that economic impact of the potential worst-case chemical incidents is a small fraction of the Chemical Sector output.

Second, the majority of chemicals are bought and sold in competitive commodity markets that typically have excess production capacity. As confirmed by the SNL analysis of historical events and its own Chemical-Sector simulations, the price effects of these events are minimal and supply-chain substitutions often adequately replace lost chemical production capacity over short time intervals.

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1 INTRODUCTION

1.1 The Chemical Facility Anti-terrorism Standards

The U.S. Congress enacted Section 550 of the *Homeland Security Appropriations Act of 2007, P.L. 109-295,* which directed the Department of Homeland Security (DHS) to identify and secure the Nation's high-risk chemical facilities. Pursuant to this congressional mandate, DHS issued the Chemical Facility Anti-Terrorism Standards (CFATS), also known as the Final Rule, which defines the process by which chemical facilities are regulated. The DHS Infrastructure Security Compliance Division (ISCD) is responsible for implementing the CFATS regulatory process outlined in the Final Rule. The Rule currently regulates facilities that hold particular chemicals of interest (COIs), listed in Appendix A of the Final Rule, based on the risks they pose to human health. More broadly, however, the Final Rule defines a chemical facility as high risk (and therefore a candidate for CFATS regulation) if it has the potential to cause:

> significant adverse consequences for human life or health, national security, and/or critical economic assets if subjected to terrorist attack, compromise, infiltration, or exploitation (Public Law 6 CFR 2).

To address the additional potential for regulating facilities based on potential impacts to critical economic assets, ISCD partnered with Sandia National Laboratories (SNL) to develop and apply an economic methodology that can estimate potential economic consequences of an attack on one of the nation's chemical facilities.

1.2 Assessing the Economic Consequences of a Chemical Incident

The U.S. Chemical Sector is large and complex; it contributes high economic value to the nation. Thousands of chemical firms with almost 800,000 employees produce tens of thousands of chemical, adding hundreds of billions of dollars to the U.S. gross domestic product (GDP) (American Chemistry Council, 2013). Chemical facilities also support important government missions, such as ensuring the country has clean drinking water and safe and effective pharmaceuticals.

The potential economic *consequences*,[1] or impacts, on the U.S. economy of chemical incidents include near-term human exposure, unavailability of goods and services due to supply-chain disruptions, cross-sector business disruption, longer-term chronic health issues, environmental

[1] The DHS Risk Lexicon (U.S. DHS, 2010) defines *economic consequence* as "[an] effect of an incident, event, or occurrence on the value of property or on the production, trade, distribution, or use of income, wealth, or commodities."

impacts, and psychological trauma. Injuries and fatalities resulting from an attack have associated medical and funeral costs, and remediation efforts require resources. There are immediate economic consequences of an incident (property damage) as well as derivative, or cascading, consequences that may develop over time as a result of an incident (e.g., changes in production and exchange of goods). Finally, there may be positive impacts in commodities and employment associated with remediation industries following an incident, in addition to the myriad negative impacts identified above.

Part of the challenge, then, in developing a measure of economic consequence or criticality is selecting one that addresses the majority of direct and indirect economic impacts of a terrorist event on a chemical facility, using defensible industry-accepted practices. Based on comprehensive literature review and research into the national economic impacts of a chemical facility disruptive event, SNL developed an analytical approach (and accompanying data) for estimating the consequences of these events and ultimately the criticality of these facilities.

1.3 Project Accomplishments

This project developed a defensible approach for estimating the potential national economic consequences of terrorist events at individual U.S. chemical facilities. First, SNL conducted a comprehensive review of methods that could be used to define and measure the economic criticality of chemicals and facilities. It then developed a candidate approach focused on chemical supply-chain disruptions that could result in significant national economic impacts. This preliminary approach was tested on a set of chemicals and facilities.

Based on these first findings, SNL expanded the approach to include additional, more regional and dynamic sources of economic impact. This new method leveraged detailed modeling of hypothetical chemical incidents and analysis of historical events to provide a more comprehensive understanding of the local-then-national economic consequences of a terrorist event. Terrorist events at a chemical facility considered include explosion, fire, or release of a toxic substance and the theft of chemical substances from a chemical facility for nefarious use in another location.

SNL tested the expanded approach, which included analyses of 100 worst-case chemical incidents involving domestic chemical facilities, either onsite at the chemical facility or in major metropolitan areas. The selected chemical facilities are representative of the different classes of chemicals in the U.S. Chemical Sector and the facilities that produce and use them. National economic impacts were estimated as the collective effect of constituent impacts caused by cleanup time and costs and business interruption costs. For onsite incidents, facility replacement costs and chemical supply-chain impacts were estimated, if available. These analyses suggest the potential range of economic impacts and suggest the primary factors that determine economic impact.

As initial validation of the refined approach, SNL compared the initial model estimates of impact to a set of domestic historical chemical incidents, including accidents and terrorist events. Most of the events analyzed were highly publicized at the time they occurred and are considered some of the most catastrophic chemical incidents on record. The information gathered informed the model inputs and assumptions and provided a source of validation of the model results.

1.4 Purpose and Scope of This Report

This report documents and discusses, in detail, the implications of the method, modeling tools, modeling results, and historical event analysis. Section 2 describes the economic-impact methodology. Section 3 then describes the initial model results and compares these results qualitatively to a set of real-world historical events. Section 4 summarizes and concludes the report.

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2 ECONOMIC IMPACT METHODOLOGY

To support ISCD in developing a method for assessing the economic criticality of domestic chemical facilities, SNL developed a methodology that estimates the potential economic impacts of a terrorist event on a chemical facility. Terrorist events are either *onsite* events – such as an explosion, fire, or release of a toxic substance – or *offsite* events, specifically the theft of a chemical substance from a chemical facility for nefarious use in another location. Figure 2-1 outlines the economic-impact methodology.

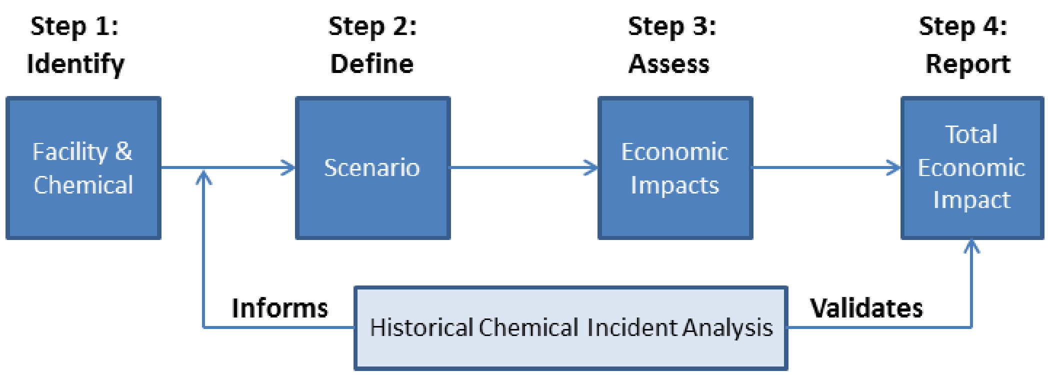

Figure 2-1. Economic-impact Methodology

Following the diagram from left to right, analysis involves first selecting a particular facility and chemical of interest and then defining an onsite or offsite incident involving the chemical used at that facility. Next, a set of tools are used to estimate the economic impacts of this incident on both the local and national economies. Finally, economic impacts are reported in ways that inform ISCD.

The economic-impact methodology is based on the general framework of *economic-impact analysis*,[2] which estimates how changes in the underlying structure of an economy changes other economic activity such as sales, profits, productivity, employment, income, prices (including inflation), and tax revenues. Impacts themselves are measured as the difference between the baseline values of activity and the new values under the changed conditions. These difference-based impacts are for a particular unit of analysis—a firm, city, county, region, state, country, or the world—and include changes over time—a week, month, year, or longer—and within Sectors—Critical Manufacturing, Food and Agriculture, Transportation Systems, etc. While the

[2] Economic-impact analysis is part of the consequence component of threat-vulnerability-consequence risk in approaches such as Sandia National Laboratories' (2014) and part of broader loss-estimation approaches, such as those in Tierney *et al.* (1999).

economic analysis conducted by SNL for this project uses a particular set of tools, these tools are representative of the wider set of economic tools available for estimating these types of economic impacts.

The SNL methodology focuses primarily on capturing *supply-side* shocks to the economy, for which loss of productive capacity causes direct and indirect losses of output in many economic sectors. The SNL model also considers *capital shocks*, for which loss of productive capital (damage to the plant) or its value (through devaluation) affects the longer-term, broader productive capital base in the economy. The model does not directly include *demand shocks* (although demand is impacted by reductions in employment, income, and investment brought on by the event). Nor does it include *labor shocks* due to morbidity/mortality effects.

Specifically, the methodology focuses on four specific sources of economic effect:

1. The cleanup time and costs of a chemical release (which affects when local economic activity can resume),
2. The interruptions to businesses in the vicinity of the release,
3. The chemical supply-chain impacts to suppliers and buyers of the facility's chemicals, and
4. The repair or replacement of chemical facility components.

These effects are used in a general-equilibrium simultaneous-equation world[3] macroeconomic model to estimate the indirect economic impacts on the U.S. economy.

2.1 Literature Review

Others have used conceptually different approaches for estimating economic impacts (Hallegatte and Przyluski, 2010). SNL analysts reviewed these approaches and provided an overview for each approach, the advantages of that approach compared to the others reviewed, and example applications.

2.1.1 Case Studies, Surveys, and Data Analysis

The most basic economic-impact methodology is the analysis of historical data – through case studies or surveys – on the economic changes that occur due to a disruptive event. The

[3] Only U.S. variables were manipulated. However, including the entire world provides a more complete picture of the total economic impact, especially considering the global links of the U.S. chemical industry.

advantages of this approach are that the economic-impact data are real, not estimated, and include many of the industry-specific details about disruption and impact that are missing from many other modeling approaches. (See Section 4 for historical examples of the kind of detail available in this approach.) Disadvantages include that the data are often too limited to make broader quantitative/statistical analysis or conclusions about impacts.

For chemical-facility events, a common approach is chemical-plant *domino effects* studies, such as Khan and Abbasi (1999), Darbra *et al.* (2010), Clini *et al.* (2010), Abdolhamidzadeh *et al.* (2011), Kadri *et al.* (2014), and Krausman and Cruz (2013). Many of these studies do not directly estimate economic losses to the plant, but describe what happened in detail and thereby provide means of better estimating direct physical effects. There are also broader chemical-facility risk approaches such as Tixier *et al.* (2002).

Examples of approaches used for assessing the economic impacts of natural disasters include Kroll *et al.* (1991), Tierney (1997), Dalhamer and Tierney (1998), Boarnet (1998), and Webb *et al.* (2002).[4]

2.1.2 Econometric Models

Econometrics-based economic-impact models use data and statistical (often causal) relationships between economic components (e.g., income and spending) to estimate the response of the economy to disruptions and other changes to the economy. Common methods use *vector auto-regressions* and other time-series techniques that compare *ex post* (after-event) and no-event data[5] to estimate the change in economic activity as a result of a disruptive event. Advantages of this approach include that it is based on real data and can estimate confidence intervals for the estimated impacts. Disadvantages include the effort involved with using large amounts of data, the need to capture how the real-world economic structure and behaviors change over time, and the fact that most models are macroeconomic in nature and are too aggregate and statistically uncertain to capture the economic effects of small events such as a terrorist event on a single chemical facility.

[4] Examples of non-U.S. studies of GDP impacts include the Benson and Clay (2001) analysis of hurricanes on the Dominican Republic GDP and Benson and Clay (2003) analysis of droughts on the Malawi GDP.

[5] When used to analyze the impacts of a real event, econometric techniques are used to estimate what the economic performance would have been had there not been a disaster: i.e., to “train” the econometric model for a forecast period where there is no disaster.

Example models available to the public include the FAIRMODEL (Fair, 2013) and the Oxford Model (Oxford, 2012). Table 2-1 lists example econometrics-based impact analyses of disruptive events.

Table 2-1. Econometrics-based Economic Impact Studies

Publication	Analysis
Li *et al.* (2014)	Impacts of the Fukushima earthquake on the Japan trade
Carroll *et al.* (1996)	Impacts of Nevada chemical plant explosion on residential property values
Hendricks and Singhal (2005)	Impacts of supply-chain disruptions on company valuations
Simmons (1996)	Impacts of pipeline explosion on residential property values
Cavallo *et al.* (2010)	Economic impact of the Haiti earthquake
Guimaraes *et al.* (1996)	Impacts of Hurricane Hugo using a South Carolina State econometric model and the FAIRMODEL (Fair, 2013) national baseline forecast
Xiao (2011)	Impacts of 1993 Midwest flooding on local employment and income
Noy (2009)	Impacts of natural disasters on country GDP

An important new method is econometric stochastic network analysis, in which supplier-buyer network data are used to estimate how the structure of these networks affect economic impacts. Examples include analysis of the Great East Japan Earthquake by Todo *et al.* (2013).

2.1.3 Input-Output Models

Economic input-output (IO) models capture how consumption and output in given sectors of the economy create demand for output in other sectors. These models often include high-fidelity social accounting matrices and industry make-use data based on published government data sources, but IO models typically lack methods for capturing price effects, how commodities are exported to or imported from other regions, and impacts over time. Still, they are the most common modeling approach and are "useful in providing ball-park estimates of very short-run response to infrastructure disruptions" (Rose, 2005).

Comprehensive reviews of IO modeling and its application can be found in Leontief (1986) and Rose and Miernyck (1989). Discussion of the IO literature pertaining to natural disasters and terrorist events can be found in Rose *et al.* (1997), Rose and Benavides (1998), Bockarjova *et al.* (2004), Burrus *et al.* (2002), Clower (2007), Okuyama (2003), Haimes and Jiang (2001), and Horowitz *et al.* (2005). Chemical-sector IO methodologies include CIRA (2012); broader homeland security models include CREATE NIEMO (Gordon *et al.*, 2008), REAcct (Vargas and Ehlen, 2012), and FastEcon (LANL, 2014).

2.1.4 Computable General Equilibrium Models

Computable general equilibrium (CGE) models have similar foundations as IO modeling, but the CGE models have the added advantages of capturing dynamic supply- and demand-side price effects and household optimizing behavior, over time. Reviews of CGE models include Partridge and Rickman (2006). Specific models include Hallegatte and Przyluski (2010) and the Koopman *et al.* (2002) USITC USAGE model. Table 2-2 lists example CGE-based economic-disruption analyses.

Table 2-2. CGE-based Economic Impact Studies

Publication	Analysis
Dixon *et al*. (2010)	Analysis of U.S. border closures
Giesecke *et al*. (2012)	Analysis of a radiological dispersal device (RDD) attack, which captures physical effects very similar to a chemical release
Rose and Guha (2004)	Analysis of the electric power-related economic losses of an earthquake
Rose *et al.* (2009)	Analysis of reductions in airline demand after 9/11
Rose and Liao (2005)	Analysis of water disruptions

2.1.5 Agent-based Computational Economic Models

Agent-based computational economics (ACE) is a modeling approach in which individual firms and households interact dynamically in markets, supply chains, and other parts of the economy.[6] Compared with traditional economic approaches in which economic behavior and markets are constant-flow (IO) or optimized (CGE), agent-based models often assume bounded rationality of the individual economic actors and include actor algorithms ranging from simple rules (e.g., buyer behavior) to complex optimizations (plant-level operations), as agent enterprises and households adapt to changing conditions.

The comparative advantages of ACE include a sizeable increase in the number and types of economic behaviors and dynamics that can be modeled, but at the expense of becoming increasingly large, time-consuming to build, and difficult to validate. Reviews of ACE approaches include Arthur (1994) and Tesfastian (2003). ACE economic-impact analyses include Henriet *et al.* (2012), Henriet and Hallegatte (2008), and Hallegatte (2012), which simulate production supply shocks at the firm level, using disaggregate IO data; and Ehlen *et al.*

[6] Seminal work in agent-based modeling include Palmer *et al.* (1994), Axelrod (1997), and Epstein and Axtell (1996).

(2007), which uses similar data to simulate firm-level responses to disasters. The APIO model (Hallegatte, 2014) and SNL N-ABLE™ model (Ehlen *et al.*, 2013) are examples of ACE with IO constructs, inventory and price dynamics, and household behaviors.

2.1.6 Conclusions of Literature Review

Important qualitative conclusions drawn from this literature review form the basis for the SNL model. First, the majority of economic impacts captured in these models and analyses are *supply-side shocks* that impact output in economic sectors, whether at the local, supply-chain network, regional, or national levels. Other effects, such as labor, capital, or demand shocks; impacts to markets and property values are much smaller.[7]

2.2 Selected Methodology

The selected methodology is based on key findings developed by SNL during chemical-sector economic model development. Different methodologies have been developed, depending on the particular economic impact assessment needed, the measures of economic impact needed, the existence and sophistication of data, and the availability and appropriateness of models.

At the beginning of the model development process, ISCD requirements dictated that economic criticality be defined only as "significant national economic impacts." SNL efforts focused on developing a defensible economic model that could capture how disruption of a single chemical facility or metropolitan area could cascade through the national economy. (The issue of defining significant impacts was conducted through comparison of other large-scale disruptive events: e.g., Hurricane Katrina.) This effort included identifying particular chemicals that were important direct and/or indirect contributors to GDP (including high multiplier effects)—suggesting an IO modeling approach to supply-side impacts—and then identifying the domestic facilities that make these chemicals.

Over the course of the entire effort, SNL developed facility-to-country supply-side models using IO, agent-based, and agent-to-IO approaches and tested them against a range of Appendix-A chemicals and CFATS-regulated facilities. Application of this model and comparison of results against other estimates suggest strongly that it is extremely unlikely to generate significant national economic impacts from the loss of a single domestic chemical facility. Chemical Sector-specific supply-chain and commodity chemicals market-price effects are insignificant on a national scale. Secondly, existing methodologies do not capture the relatively small effects of a

[7] Notable exceptions include the 9/11 grounding of air travel and subsequent severe reduction in air travel demand, and post-Japan-tsunami reductions in demand for Japanese produce.

single facility on the broader economy; traditional economic models and measures aggregate over large areas and long periods.

2.2.1 Modeling Requirements

Prior modeling efforts suggest that a terrorist event on a chemical facility that is insignificant to the national economy could be significant or critical to the local economy. Using the ISCD language, if a city is a critical economic asset and if an individual chemical facility could cause impacts that are significant to the city, then the facility could be deemed critical.

To address this insight, the proposed methodology was expanded: first, the methodology needed to capture impacts at the local level. Second, given that some of the effects cause adjustments over long periods, the model needed to address the dynamics of impact over time. Third, ISDC CFATS data include estimated capital replacement costs reported by chemical plants. The estimated size of these costs (or capital losses) suggests that capital shocks are real and could have large indirect economic effects; the model should address these. Finally, given mandates ISCD has for determining risks across the Chemical Sector, the model should include impacts to other chemical facilities through chemical supply-chain effects. Table 2-3 lists the differing requirements of the original methodology and the current methodology.

The area of impact has changed from national impacts to local and then national impacts. The estimates of impact have moved from a single national impact (in GDP) to first-year and then ten-year impacts. These increases in fidelity are designed to increase the ability of ISCD to evaluate impacts in important ways.

Table 2-3. SNL Economic Model Factors: Initial and Current Requirements

Impact Analysis Factor	Initial Methodology	Current Methodology
Analysis Region	Nation	Local area; Nation
Analysis Sectors	From Chemical Sector to all Sectors	From Chemical Sector and local economy to all Sectors
Study Period of Analysis	First year	First year; first 10 years
Dynamic Impacts?	No	Yes
Measure of Impact	GDP	GDP

2.2.2 The Impact Scenarios

The methodology is designed to estimate the economic impact of a terrorist event at a particular chemical facility. The methodology does this by defining two general categories of terrorism scenarios—onsite or offsite—to represent the seven Security Issues defined in CFATS Final Rule Appendix A (defined below in Table 2-4) and then accessing data on the particular event's geographic location. These prototypical scenarios generate a set of modeling data and parameters to estimate economic impacts. Although the prototypical scenarios were created with the CFATS Security Issues in mind, the method is designed to allow analysis of a variety of chemical incidents.

Table 2-4. CFATS Security Issues

Security Issue	
Release–Toxic	Chemicals that, if released, could result in the threat of a poisonous inhalation hazard.
Release–Flammable	Chemicals that, if released, could result in a flammable gas or a volatile flammable liquid.
Release–Explosive	Chemicals that pose an explosive threat.
Sabotage or Contamination	Chemicals that, if combined with readily available materials, could result in human health impacts; e.g., chemicals that release a poisonous gas when exposed to water.
Theft and Diversion–CW/CWP (chemical weapon or chemical weapon precursor)	Chemicals identified by the Chemical Weapons Convention as chemical weapons and their immediate precursors with no other industrial use or those that are easily converted into chemical weapons and consequently are potential targets for theft or diversion.
Theft and Diversion–EXP/IEDP (explosives and improvised explosive device precursors)	Chemicals and their precursors that pose an explosive threat and consequently are potential targets for theft or diversion.
Theft and Diversion–WME (weapons of mass effect)	Chemicals that are poisonous gases under atmospheric conditions and consequently are potential targets for theft or diversion.

The following sections describe in detail the key scenario data and parameters that affect economic impacts.

2.2.2.1 *Size and Shape of Area Impacted*

Whether caused by a single chemical release within a city or *domino effects* (the cascading effects of industrial accidents) of an attack on a chemical facility, the chemical release is assumed to spread over a wide geographic area. The area impacted is a function of the amount of material used in the incident, the location of the incident, weather conditions, and other factors. Large buildings or other infrastructures can influence the area impacted, and weather conditions can lessen or exacerbate the severity of the incident: for example, wind can disperse and dilute a release or spread a fire.

To expedite initial calculations on a large number of scenarios, a uniform spatial area of impact was selected. The size and shape of the area capture a worst-case scenario, based on historical examples of chemical incidents, which are described in Appendix A, and the U.S. Department of Transportation Emergency Response Guidebook (DOT, 2012), which provides first responders with guidelines to estimate areas to quarantine following a chemical spill or release. A persistent chemical can travel 1 mile from its point of release, especially on a windy day. Similarly, in the absence of wind, obstructions, or terrain variation, it is possible for a fire, explosion, or release to impact a circular area. Thus, a circular area with a 1-mile radius was selected as the size and shape of the scenario impact area, although a circular area of this size is very unlikely. For purposes of the analysis, the entire area is assumed to require decontamination.

2.2.2.2 *Location of Area Impacted*

The location of the exposure/release area is an important determinant of economic impact. For example, an explosion, fire, or toxic chemical release in an open field will require less cleanup and interrupt less business activity than the same incident in a dense urban area. Differentiating the indoor area from the outdoor area is also important, especially when estimating cleanup costs, as the decontamination of indoor spaces is generally significantly more costly than outdoor spaces. Again, motivated by capturing worst-case scenarios, urban areas with high densities of people and business activity were selected for the offsite scenarios. Intersections in each city were selected to capture a worst-case event.

2.2.2.3 *Type of Incident: Explosion, Fire, and Release*

For a given quantity of chemical, an explosive or flammable chemical is likely to impact a smaller area than airborne release. The release of a toxic chemical will result in a number of additional activities, including decontamination and toxicity sampling, but perhaps less physical damage than a fire or explosion. However, a fire or explosion would likely require significantly less toxicity sampling and chemical-based decontamination, but might result in more physical damage.

The release of a toxic chemical may require cleanup or remediation of the surfaces and materials that were exposed to the chemical and thus interrupt business activity for a longer period. A helpful chemical property to consider is whether the chemical can be considered to be *persistent* or *non-persistent*. Non-persistent chemicals naturally, or in a relatively short amount of time, become less dangerous, through either dilution or reaction. Persistent chemicals do not readily or quickly become less dangerous. For example, the chemical nerve agent VX is an oily, nonvolatile liquid that can remain harmful for many weeks after being dispersed. However, another nerve agent, sarin, is a highly volatile liquid under normal atmospheric conditions, but naturally evaporates, disperses, and eventually becomes harmless (Somani, 1992).

The release of non-persistent chemicals generally requires very little cleanup, while the release of persistent chemicals can require extensive cleanup. Extensive cleanup takes more time and results in longer business interruptions. When cleanup is necessary, the methods and technologies used in the cleanup process are largely independent of the type of chemical released. For example, sampling to determine extent and levels of toxicity do not depend on the chemical substance being tested. Furthermore, the chemicals used to decontaminate the toxic substance are also largely independent of the chemical released. These factors allow accurate estimation of cleanup cost without knowledge of the chemical released. To capture worst-case scenarios, chemical decontamination was assumed necessary for all incidents; in other words, chemicals were assumed to be persistent.

While the real range of chemical release area, toxicity, and cleanup requirements varies significantly between the COIs and Security Issues in the CFATS Appendix A, some initial assumptions were required for the modeling. Further work should be done to refine the area associated with chemical release.

2.2.3 Potential and Modeled Sources of Economic Impact

Terrorist events at a chemical facility causing economic impacts in many ways; Table 2-5 lists many of the potential impacts cited in the literature.

Table 2-5. Potential Economic Impacts of a Terrorism Act on Chemical Facility

Economic Impact
Medical costs due to injuries
Funeral costs due to fatalities
Economic value of lost human life
Chemical cleanup costs*
Interruption of local business activity*
Capital replacement costs *
Damage to environmental resources
Supply disruptions in chemical supply chains*
Changes in company stock prices
Changes in property valuation
Changes in inter-industry supply and demand
Changes in consumer risk behavior and spending
New technology investments
Costs of new business regulations/policies

Based on the literature review, the SNL model uses a subset of these impacts, noted with an asterisk (*) in Table 2-5. The terrorism-related chemical release generates economic impacts the following ways:

- The release itself causes a chemical vapor cloud that damages the surrounding area (a chemical facility for onsite events and a metropolitan area for offsite events).
- The release causes evacuation of people from the chemical plant and surrounding businesses and homes.
- Cleanup of these chemicals causes further business interruptions to the local community.
- Cleanup, capital damage, and business interruptions directly impact the regional and national economies through the chemical supply chain of which this facility is a part, and indirectly the full set of sectors in the economy.

Many impact types were not included in the model due to other studies not finding significant impact from them. For example, Carroll *et al.* (1996) and Simon (1996) found very small property valuation decreases from adjacent industrial accidents. Changes in consumer risk behavior and spending were not included because, as noted in Giesecke *et al.* (2012),[8] these are likely significant only when uncertainty and dread are high (Fischhoff, 1978), neither of which are assumed for the selected scenarios.[9] Mortality is considered in current CFATS regulations based on health and human safety, to include mortality in the economic analysis would double-count these impacts. Furthermore, mortality and morbidity were not included, in part due to lack of specific data sources, and in part to findings in the literature (e.g., Giesecke *et al.,* 2012) that these impacts are insignificant.

Some factors that are not necessarily significant in other studies were included in the selected impacts due to their potential utility to ISCD. Capital costs are included because these data are readily available from the CFATS Top Screen. Supply-chain impacts are included because of their importance in potential future work on the supply-chain effects of ISCD facility performance requirements and their role in national impacts.

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[8] Giesecke *et al.* (2012) specifically surveyed consumers and found that many would continue economic purchases of professional services and electronics in an RDD-affected area, but may never purchase food from or have a vacation in the affected area. Significant consumer effects (other than fresh produce, which is often replaced daily) are unlikely in the selected scenario.

[9] Larger events, such as 9/11, can significantly decrease consumer demand; relevant studies include Gordon *et al.* (2007) and Rose *et al.* (2009).

2.2.3.1 *Cleanup Time and Costs*

Cleanup costs are the costs associated with restoring affected areas to safe conditions. Given that these activities must be completed before economic activity can resume, the amount of cleanup time is one of the primary determinants of economic impacts. Cleanup procedures themselves are not necessarily regulated or codified; as noted in Giesecke *et al.* (2012), "decisions on cleanup options may involve tradeoffs between public safety levels and the costs and economic impacts of decontamination." Examples of methods for estimating cleanup time and costs include Volcheck *et al.* (2006) and Hoette *et al.* (2011).

2.2.3.2 *Chemical Facility Replacement Costs*

The second economic impact considered is the cost to replace damaged chemical facility equipment. A terrorist event at a chemical facility will very likely result in significant damage to production equipment, which will need to be repaired and/or replaced in order to return to operation.

2.2.3.3 *Business Disruption Costs*

The third economic factor is disruption to businesses in the area of the chemical release. For onsite events, these are businesses near and around the chemical facility itself; for offsite events, these are businesses within the affected metropolitan area. Both events cause *supply-side shocks* to business activity in the surrounding area. (Section 0 discusses the most common supply-side economic-impact methodologies).

2.2.3.4 *Chemical-Sector Supply-chain Impacts*

The fourth economic impact modeled is the loss of a chemical facility on the chemical supply chain in which it operates. Loss of key chemical facilities could cause supply-side shocks to downstream chemical plants and other chemical consumers.

2.2.3.5 *Indirect Macroeconomic Impacts*

The macroeconomic effect of the four sources identified above are then modeled as the set of indirect and induced impacts to the rest of the domestic economy. *Indirect impacts* are losses to supplier and buyer firms in other sectors. *Induced impacts* are losses due to lost income of workers.

2.3 Analytical Steps

The methodology estimates the potential economic impacts of terrorist events at a particular facility, using a specific set of steps. These steps are described below.

2.3.1 Step 1: Identifying Facility and Chemical

The first step is to select a chemical facility that is a candidate for regulation under CFATS. The facility could be any manufacturer, distributor, or consumer of chemicals. The facilities analyzed in section 3.2 Results were selected from those with completed CFATS Top-Screen surveys and thus were registered in the CFATS systems. However, the methodology allows analysis of chemical facilities that are not CFATS candidates for regulation.

2.3.2 Step 2: Define the Terrorism Scenario

The second step is to define the particular terrorism scenario from the list of potential CFATS Security Issues (Table 2-4). The first choice is between an onsite and offsite scenario. Onsite scenarios occur at the facility identified in Step 1. Offsite scenarios can occur anywhere away from the chemical facility and should be selected based on the intent of the analysis. In the present analysis, the economic impacts of worst-case events were sought, and thus the offsite locations were selected to be major urban centers. Although the current analysis employed several assumptions that eliminated the distinguishing characteristics of the Security Issues within the onsite/offsite categories, the methodology was designed to capture these differences. For example, an onsite explosion or fire will likely result in greater physical damage but impact a smaller area than an onsite release. The inputs to each tool used in Step 3 can be tailored to each Security Issue or other disruptive event.

2.3.3 Step 3: Estimate Economic Impacts

Once the facility and scenario are selected, five constituent tools are used to estimate the component and overall economic impacts of the incident. The tools are used in the workflow in Figure 2-2 (a more detailed version of Figure 2-1) to estimate the net GDP impact of the terrorist act. While the tools used herein are part of the state-of-practice in economic modeling, they are not specifically required by the methodology; other, similar tools can be used to estimate impacts.

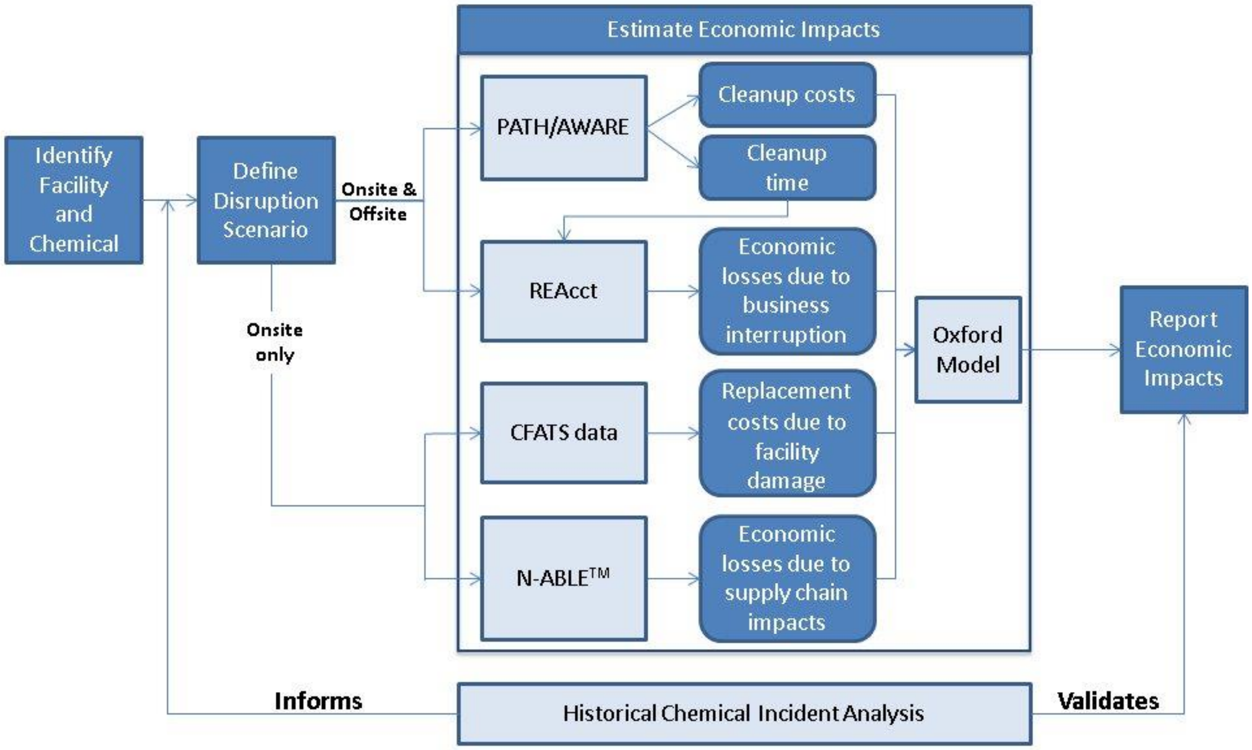

Figure 2-2. Economic-impact Methodology: Detailed Workflow

The PATH/AWARE tool (Hoette *et al.*, 2011) estimates cleanup costs and cleanup time. Cleanup time is used in REAcct (Vargas and Ehlen, 2014) to estimate the direct economic impacts to businesses. For onsite events, the CSAT Top-Screen is used to estimate facility replacement costs, and the N-ABLE^{TM} ACE model (Ehlen *et al.*, 2014) is used to estimate supply-chain impacts. Finally, the Oxford Economic Model (Oxford, 2012) is used to estimate national GDP impacts of the constituent PATH/AWARE, CSAT capital replacement, REAcct, and supply-chain direct impacts. (See Appendix B for detailed descriptions of the constituent models.)

2.3.4 Step 4: Reporting Results

The final step is to report the results of the analysis, including both:

1. A description of the facility, chemical, and scenario and the estimated constituent direct economic impacts, and
2. The estimated total (direct plus indirect) U.S. economic impact, in GDP.

To facilitate comparison of results across different facilities and scenarios, the GDP impacts are reported as first-year impacts and the sum of impacts over the 10-year period (calculated in present-value terms).

2.4 Data Quality and Modeling Assumptions

Two main sources of chemical facility data were relied upon: the CSAT Top-Screen surveys and a robust chemical database at SNL consisting of proprietary and open-source information that has been vetted by experts and used in a variety of work for various customers and peer-reviewed publications. The economic data is from the U.S. Department of Commerce Bureau of Economic Analysis (BEA) and is at the county level. Implementing the data in the models required several important assumptions, listed below.

2.4.1 Area Impacted

1. A circular area with 1-mile radius is used in modeling all hypothetical scenarios. An event of this magnitude would also likely have political and psychological impacts regardless of the economic impacts; however, these non-economic impacts are not considered in this analysis.
2. Traffic intersections in the middle of large urban centers are selected for the offsite scenarios. This level of location detail is captured in modeling the cleanup costs, while the business interruption costs are normalized at the county level. (See the Cleanup and Business Interruption assumptions below.)

2.4.2 Cleanup

1. Chemical decontamination is necessary for all incidents. The entire area impacted, indoor and outdoor, would need to be decontaminated.
2. Manufacturers of essential equipment would quickly increase production to meet demand, and all needed equipment would be onsite within 2 months of the incident.
3. Statistical sampling would be used to verify the remediation of the buildings most severely impacted by the chemical incident, while all remaining buildings would rely on an optimized decontamination process in conjunction with judgmental sampling.

2.4.3 Business Interruption

1. The BEA data is at the county level, so REAcct employment impacts are estimated based on the percentage of the county that is within the 1-mile radius area.
2. Cleanup starts from the perimeter of the area and works toward the center. The rate of cleanup (the size of the crew conducting cleanup) is constant over time. As a result, over time the area experiencing business interruption becomes smaller; in other words, businesses located furthest away from the chemical incident will reopen before those at the center of the incident. For each scenario the affected area would decrease by 25 percent after each quarter of the calculated disruption time.

2.4.4 Facility Replacement

1. The upper-bound replacement cost from the Top Screen survey is used; for example a cost of $500 million is assumed if the facility selected the category of "$100,000,000 – 499,999,999."
2. Due to a lack of clarity in the facility replacement question in the Top-Screen survey, the most expensive potential interpretation is assumed.

2.4.5 Supply-chain Disruption

1. The supply-chain disruption lasts nine months and impacts all key chemicals at the facility.
2. The supply-chain model estimates a lost mass of chemical production. An average cost of $1,500 per metric ton of chemical was assumed in order to estimate a total economic impact of the supply disruption.

2.5 Uncertainty Analysis

The impact methodology itself introduces uncertainty to the estimates of impact, through the particular data used, assumptions made, and constituent models. As described in Walker *et al.* (2003), *uncertainty* is "any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system." A key component of the methodology, then, is a process for identifying these uncertainties and using them to help set confidence bounds on the estimates of impact.

Uncertainty analysis is typically composed of three elements:

1. Uncertainty Identification: identifying the sources of uncertainty and their potential qualitative effects on model(s) results,
2. Sensitivity Analysis: determining how changes in the model(s) inputs affect model(s) outputs, and
3. Uncertainty Quantification: measuring how uncertainty propagates through the model(s) used.

Uncertainty is introduced into any model along a number of categorical lines. For the economic impact model, the categories of uncertainty include:[10]

[10] As another viewpoint, Walker *et al.* (2003) categorize uncertainty based on (i) location – where in the model system it occurs; (ii) level – the degree of uncertainty, from total knowledge to total ignorance; and (iii) nature – whether it is due to imperfect knowledge (epistemic) or inherent randomness (variability).

- *Parametric uncertainty* – key data and parametric assumptions used by the models, sometimes described as uncertainty due to lack of knowledge;
- *Structural uncertainty* – whether the models used have inherent biases relative to the physical, chemical, and economic processes they are attempting to model; and
- *Stochastic uncertainty* – uncertainty in actual outcomes (e.g., economic impacts) caused by the inherent random nature of the physical, chemical, and economic processes; sometimes described as uncertainty due to inherent variability in the system.

Table 2-3 lists some of the key sources of uncertainty introduced by the impact model.

Table 2-6. Potential Sources of Uncertainty in the Economic Impact Model

Type/Source
Parameter Uncertainty
Size of impacted area
Persistent versus non-persistent chemicals
Extent of physical damage
Extent and duration of business interruptions
Worst-case physical damage (use of largest replacement cost)
Structural Uncertainty
PATH/AWARE estimates of cleanup time based on crew size and the availability of resources
REAcct indirect impact multipliers
Economic impact averaged at county level

Many of the uncertainties within the SNL model are directly caused by conditions in the Chemical Sector and economy. For example, most chemical-facility incidents involve *domino effects*, or "an incident which starts in one item and may affect nearby items (e.g., vessels containing hazardous materials) by thermal, blast, or fragment impact" (CCPS, 2000).

Sensitivity analysis is the process of assessing how sensitive the model results are to changes in the input data and parameters (Iman and Helton, 1988). Uncertainty quantification estimates the potential uncertainty in model outcomes given these parameter, structural, and stochastic uncertainties. Sometimes called *forward uncertainty propagation*, the uncertainty is quantified by assigning uncertainties to the input data and parameters and generating probability distributions of output. Methods for uncertainty quantification include Lee and Chen (2009), Helton *et al.* (2006), and Morris (1991).

2.6 Limitations of Use

There are a number of key limitations to use of the methodology. None of them limit the use of the methodology for the current set of regulated (or potentially regulate-able) chemical facilities, but it is worth understanding what these limitations are and why. Most notably, the model is not appropriate for scenarios where there are significant price-based economic impacts either through the local economy or through chemical supply chains. (It uses an IO model [REAcct] and supply chain model [N-ABLE] that do not include price effects at these two levels.) While the literature review did not find chemical-facility scenarios to create large price-based economic impacts,[11] the potential exists for these to occur, for example within the crude oil and derivatives parts of the Chemical Sector. When prices are a prime factor of impact, econometric models and CGE models are more appropriate for estimating economic impacts. (See Section 2.1 for a discussion of econometric and CGE models.)

[11] By large impacts, we mean the combined effects of large price changes across large quantities of chemical(s). If price changes are large but quantities small or vice versa, then economic impacts are likely insignificant. Hallegatte (2012) suggests that price effects are generally small during disasters.

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3 INITIAL ESTIMATES OF ECONOMIC IMPACT

Using the methodology described in the previous section, SNL estimated the economic impacts of 100 potential terrorism events at CFATS-regulated facilities. This section summarizes these first estimates of potential economic impact, describes how they vary based on facility and other characteristics, and specifies the primary determinants of those impacts. The implications of these estimates on the future refinement of the methodology are also considered.

3.1 Sample Set of Facilities, Chemicals, and Scenarios

Table 3-1 summarizes the selected CFATS facilities based on key characteristics.

Table 3-1. Characteristics of 100 Modeled Terrorism Events

Characteristic	Count
Onsite/Offsite	
Onsite Events	86
Offsite Events	14
Onsite: Physical Health and Safety Tier	
Facility Tier 1	9
Facility Tier 2	20
Facility Tier 3	16
Facility Tier 4	19
Facility Tier 5	22
Onsite: Security Issue	
Release-Toxic	54
Release-Flammable	31
Release-Explosive	1

The analysis uses facilities currently regulated under CFATS for COIs listed in Appendix A of the CFATS Final Rule. The CFATS facilities considered were identified as high-risk facilities in the current CFATS process due to their potential to cause significant public health consequences. The analysis, therefore, did not identify additional high-risk facilities; rather, it provided understanding of the economic risk posed by the currently regulated CFATS facilities. Many of these combinations of geography and facility represent worst-case conditions.

3.2 Results

For each of the 100 scenarios covered, GDP impacts were estimated for the first year and each of the first 10 years after the terrorist event. Figure 3-1 and Figure 3-2 display the range of GDP impacts across all facilities, for first-year and 10-year impacts, respectively. Each bar in each figure represents a scenario. Each impact estimate includes the effects, if they apply, of cleanup and business interruption costs, facility replacement costs, and supply-chain losses.

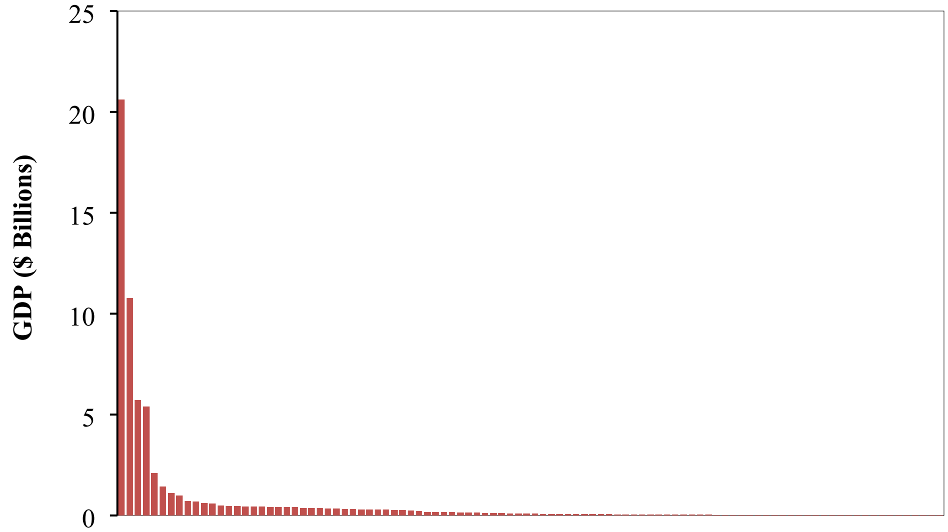

Figure 3-1. First-Year GDP Impacts ($Billion), by Facility: 100 Scenarios

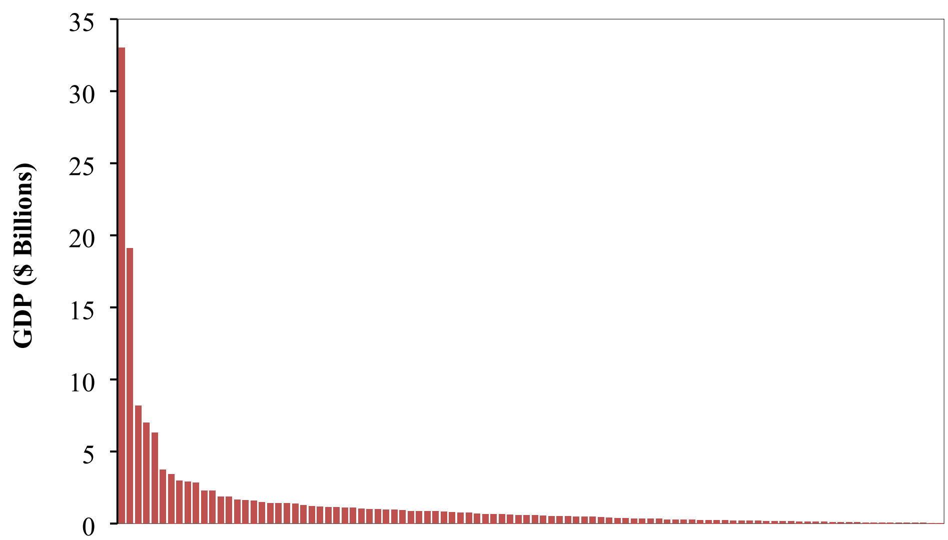

Figure 3-2. 10-Year GDP Impacts ($Billion), by Facility: 100 Scenarios

First-year GDP impacts range from $2 million to $20.6 billion; 10-year impacts range from $38 million to $33.0 billion. The distributions of first year and 10-year impacts shown in the figure suggest that GDP impacts are an empirical example of the *power law*:[12] the majority of impacts are small, but there are a few cases of large impact.

3.2.1.1 *Impacts by Year*

Figure 3-3 illustrates the average GDP impact over time. The majority of economic impacts across the facilities occur in the first year, when cleanup activities and associated business disruptions are the largest.

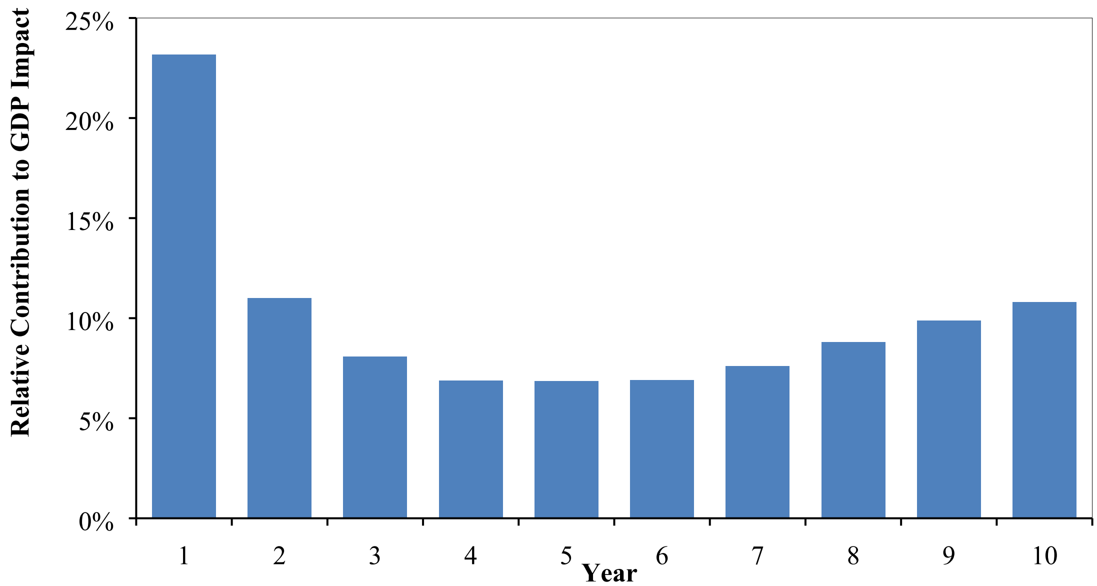

Figure 3-3. Average Distribution of GDP Impacts, by Year: 100 Scenarios

Out-year GDP impacts (after the cleanup and facility-replacement activities are complete) are caused largely by longer-term ripples through the economy from multiyear capital adjustment processes and indirect (inter-sectoral) and induced (personal income-based) adjustments in the macroeconomy. As suggested by the increase in impacts over years 7 through 10, there are long-term effects that do not diminish by the 10th year, but for analytical reasons SNLs bound the impact period to the first 10 years.[13]

[12] As explained below, this could also be considered an *economic size distribution* (Kleiber and Kotz, 2003), given that these impacts are found to be a function of the size of the local economy in which they occur.

[13] The *macroeconomic impulse response* (Lütkepohl, 2008) in Figure 3-3 – (i) a large first-year impact followed by (ii) significant reduction and then (iii) long-term rebound – is representative of the economic response. This dynamic is typical of econometric models such as the Oxford Model; other models such as strict input-output models will not show this dynamic.

3.2.1.2 *Scenario Type*

To illustrate the breakdown of impacts by scenario type and impact period, Figure 3-4 displays the first-year and years 2-10 GDP impacts by scenario type (onsite, offsite), and Table 3-5 summarizes the distribution of impacts for the two types of events. Inspection of the figure suggests that the largest potential economic impacts come in the first year, from offsite events. As illustrated by the figure entries with red bar components, there are a few events for which capital replacement-based GDP impacts are the dominant factor of impact; otherwise, they are a minor component of overall impact.

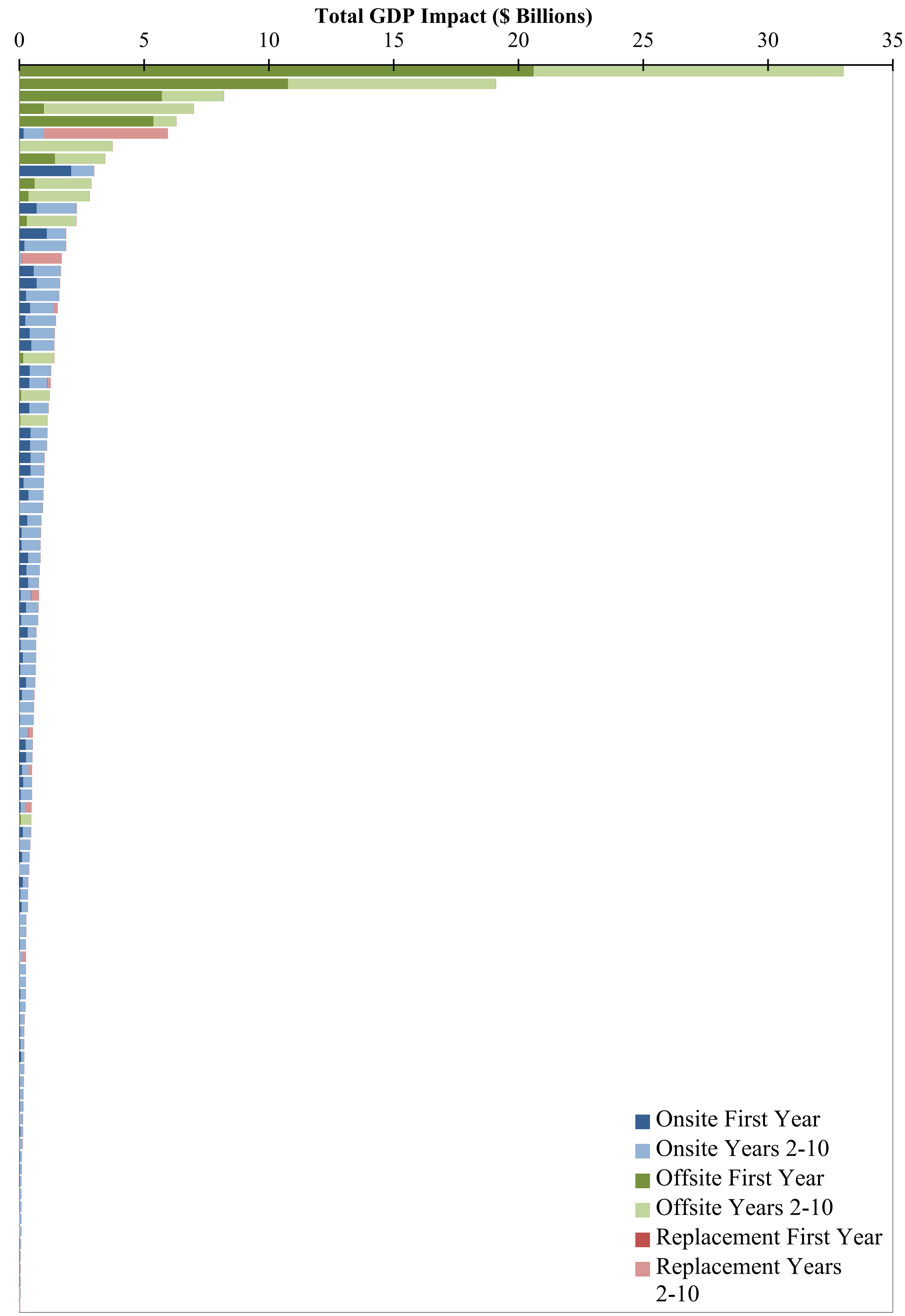

Figure 3-4. First-Year GDP Impact, by Onsite/Offsite Event: 100 Scenarios

The average first-year and 10-year GDP impacts for onsite events are $185 million and $630 million, respectively. The average first-year and 10-year offsite impacts, however, were much larger, at $3.33 billion and $6.64 billion, respectively.

Table 3-2. Minimum/Average/Maximum First- and 10-year Economic Impacts ($Million), by Scenario Type

	First Year			First 10 Years		
Scenario Type	Minimum ($M)	Average ($M)	Maximum ($M)	Minimum ($M)	Average ($M)	Maximum ($M)
Onsite	9	185	750	38	630	2,990
Offsite	24	3,330	20,600	470	6,640	33,020

These data suggest that the potential economic impacts of theft and diversion scenarios are significantly greater than onsite scenarios, because the chemical is exposed to a much larger population and economic density.

3.2.1.3 *Structural Determinants of Impact*

Based on analysis of direct structural effects and 10-year GDP impacts, an estimated 85-percent (on average) of the national impacts are derived from the local GDP losses from business interruption,[14] which themselves are driven by cleanup time and costs. To understand the structural drivers of 10-year impacts better, SNL investigated the relationships between input parameters and total economic impact.

Figure 3-5 and Figure 3-6 illustrate the relationship between impacted indoor area (from PATH/AWARE) and 10-year GDP, in linear-linear and log-log plots, respectively. The figures suggests that impacted indoor area is a strong predictor of economic impacts.

[14] Econometric *t*-statistics are significant at the 95-percent level and the correlation coefficient between REAcct results and 10-year GDP impacts is 0.85.

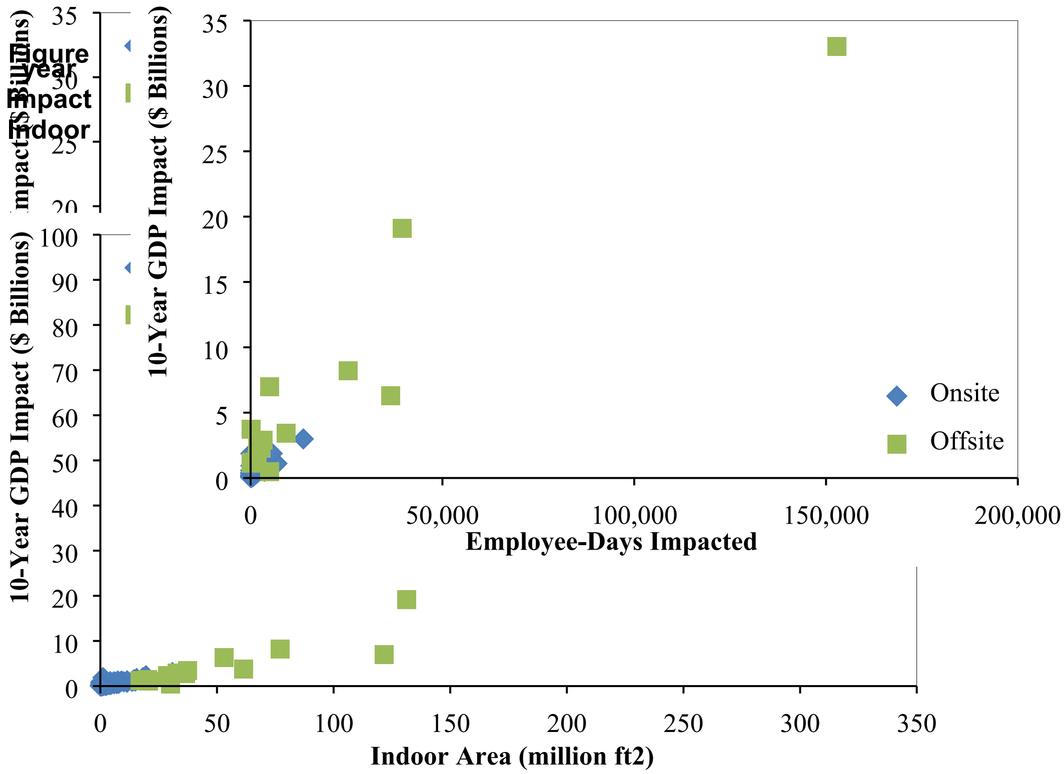

Figure 3-5. Ten-year GDP Impact vs. Indoor Area

Figure 3-6. Log 10-year GDP Impact vs. Log Indoor Area

Figure 3-7 and Figure 3-8 similarly show the relationship between affected workforce (estimated from the REAcct model) and 10-year impacts, in linear-linear and log-log plots, respectively. These figures suggest that impacted workforce is also a strong predictor of economic impacts. The number of employee-days impacted is the number of employees multiplied by the number of days of the disruption.

Figure 3-7. Ten-year GDP Impact vs. Workforce Affected

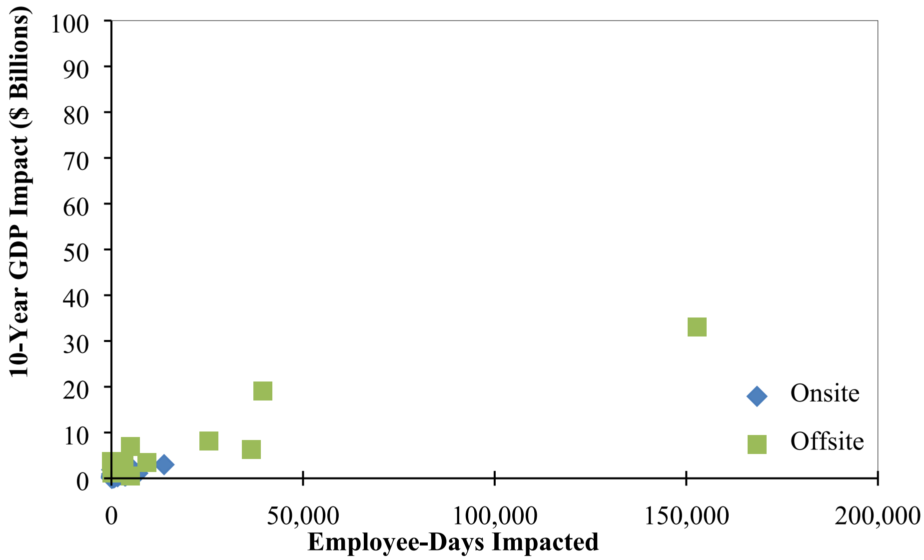

Figure 3-8. Log of 10-year GDP Impact vs. Workforce Affected

The significant variance among the first-year GDP impact for both the onsite and offsite scenarios can be attributed to the dynamic differences between business-interruption impacts and capital impacts. Business interruptions are direct impacts to GDP and experienced immediately during the actual event. The businesses interrupted are not able to operate, at least at full capacity, and the economy suffers directly and indirectly through this lost productivity. When the business interruptions are over—in this case, when the cleanup process is completed—the most significant impacts to GDP soon end.

Impacts to capital have a fundamentally different impact on the economy. Facility replacement costs are capital impacts. These impacts can have a positive economic effect initially. For example, the cleanup process requires that equipment and materials be purchased and people employed to analyze samples, remove debris, and clean contaminated surfaces. These activities will temporarily stimulate the economy. However, over many years the negative economic impact will become more significant. The funds allocated to clean up the impacted area enable a return to pre-incident productivity. If those funds had been available for new capital investments, output would have increased.

3.3 Direct-Impact Components

3.3.1 Cleanup Activities

The cleanup costs and time were estimated based on PATH/AWARE parameters that include indoor decontamination technology, type of sampling, and resource availability. These parameter values were set based on the review of historical domestic large-scale toxic chemical releases and subject-matter expertise. Table 3-3 and Table 3-4 provide examples of the cleanup parameters and costs associated with an offsite and onsite event from the set of 100 events.

Table 3-3. Building Cleanup Area, by Type of Building: an Offsite and Onsite Event

Type of Building		Offsite (City)	Onsite (Facility)
Residential	Number of Buildings	6,842	4,839
	Area (square feet)	58,879,525	7,415,665
Commercial	Number of Buildings	4,926	820
	Area (square feet)	60,711,244	6,901,642
Industrial	Number of Buildings	770	297
	Area (square feet)	6,078,611	3,814,242
Public	Number of Buildings	658	73
	Area (square feet)	5,743,351	830,743
Total	Number of Buildings	13,196	6,029
	Area (square feet)	131,412,731	18,962,292

Table 3-4. Example Breakdown of Cleanup Costs: an Offsite and Onsite Event

	Location	Offsite (City)	Onsite (Facility)
	Area (square miles)	3.14	3.14
	Decontamination Method	Fumigation	Fumigation
Outdoor	Characterization	$35,700	$68,550
	Waste Removal	$5,016,600	$9,576,500
	Decontamination	$90,000	$170,000
	Clearance Sampling	$22,815	$43,810
Indoor	Characterization	$2,028,950	$276,300
	Waste Removal	$74,367,700	$9,726,450
	Decontamination	$3,220,800,000	$495,800,000
	Clearance Sampling	$678,951	$97,960
Total	Total Outdoor Cost	$5,165,115	$9,858,860
	Total Indoor Cost	$3,297,875,601	$505,900,710
	Total Cost	$3,303,040,716	$515,759,570
	Total Time (Days)	754	353

Cleanup time is primarily a function of resource availability, the number of samples collected, and the type of sampling conducted (e.g., *judgmental* or *statistical sampling*[15]). Resource

[15] *Judgmental sampling* is non-statistical sampling in which the location to sample is based partly on expert opinion; it is less time- and resource-intensive than statistical sampling. *Statistical sampling* is random and systematic in order to provide specific confidence levels of decontamination throughout the area of concern.

availability parameters include number of workers, decontamination units, decontamination materials, and the number of samples that can be processed in a day. Changes in resource availability can have significant impacts on cleanup time while having little impact on cleanup cost: for example, adjusting parameters within PATH/AWARE can change the cleanup time for a given scenario from several years to approximately one year, yet result in less than a 1-percent change in the overall decontamination cost. Changing the number of samples collected, the amount of waste removed, the number of fumigation units available, and the type of sampling can significantly affect the cleanup time.

No wide-area decontamination efforts were performed on any of the historical large-scale chemical releases reviewed in Section 4, and thus it is likely that a real chemical incident would require the cleanup of significantly less than 3.14 square miles (the area of a circle of 1-mile radius, which is the area assumed to be in need of cleanup in the present analysis). However, for chemical incidents that involve the aerosolized release of chemical warfare agents or other toxic and environmentally persistent chemicals, it is possible that large areas would be decontaminated. The need to decontaminate a large area could also be driven by public safety and public perception (i.e., the public perceives an area to be in need of cleaning); however, there are no reports of chemical releases that resulted in the decontamination of square miles. Consequently, a decontamination area with a one-mile radius captures a worst-case scenario.

The observed outcomes of this analysis are dependent to a certain extent on the default input parameter values, so a different set of parameter values would likely yield slightly different estimates for the cleanup cost and time. However, for estimating cleanup cost and time needed for the overall analysis, the parameter values used in this analysis are appropriate. In the event of an actual chemical incident, a more detailed analysis that includes parameter values specific to the incident would be needed.

Two key assumptions mitigate the challenge of estimating cleanup time for large-scale scenarios such as those considered in the present analysis. First, manufacturers of fumigation units and other needed equipment would quickly increase production to meet demand, so all needed equipment would be onsite within 2 months of the incident. This assumption is reasonable based on the response witnessed in national-level events such as the 1995 World Trade Center bombing, when manufacturing priority was given to parts needed in the building restoration (see Section 4). Second, statistical sampling will be used to verify the remediation of the buildings most severely impacted by the chemical incident, while all remaining buildings will rely on an optimized decontamination process in conjunction with judgmental sampling. The building information is from HAZUS, the Federal Emergency Management Agency's (FEMA's) methodology for estimating potential losses from disasters. Waste removal is the most significant cost for outdoor cleanup; decontamination is the most costly aspect of indoor cleanup.

Cleanup costs ranged from $12 million to $626 million, while cleanup time ranged from 32 days to 369 days for the onsite scenarios. The offsite scenarios were more costly and required longer cleanup times, ranging from $404 million to $3.3 billion and 91 days to 754 days. Figure 3-9 shows the duration of cleanup activities and business interruption for onsite and offsite events.

Although all incidents were assumed to occur outdoors, incidents were also assumed to impact all building indoor space. Although this is unlikely in a real event, it captures a worst-case scenario, as indoor cleanup is significantly more costly than outdoor. The onsite cleanup costs are similar to those from the historical case studies in Section 4: hundreds of millions of dollars. Based on the cleanup costs of onsite and offsite scenarios, it can be concluded that cleanup costs are correlated with indoor square footage. Cleanup costs are greatest in scenarios located in metropolitan or urban areas with high building density.

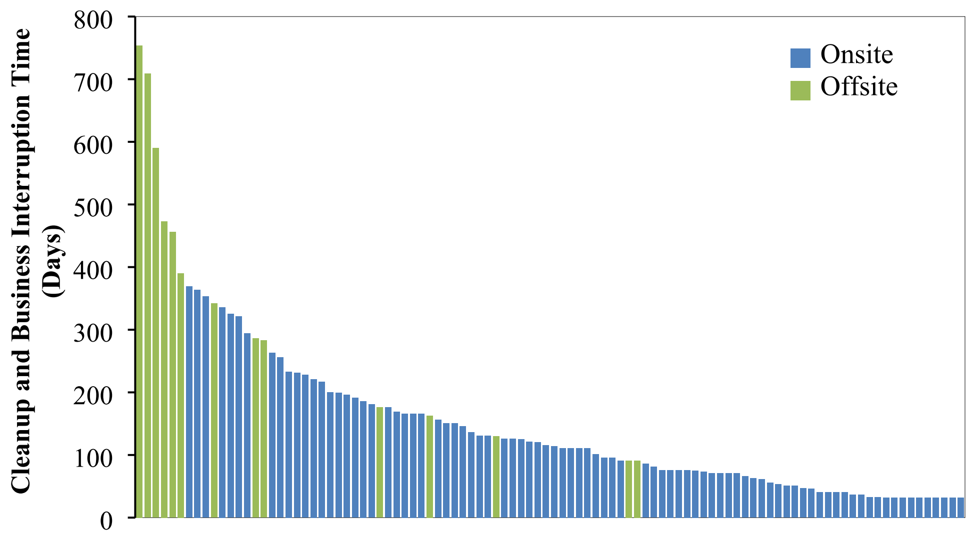

Figure 3-9. Duration of Cleanup and Business Interruption

The average indoor area in need of decontamination in the offsite scenarios (70 million square feet) is very large; over 10 times the area of the Pentagon and five times the area of the World Trade Center complex. It is very unlikely that an event that impacted an area of 1-mile radius would contaminate all indoor space of all buildings in that area. Sampling would be required to determine the extent of contamination, but the sampling would likely verify that a significant portion of the indoor area was not in need of decontamination, resulting in a significant reduction in the cost of decontamination, the key factor in cleanup. It also limits the waste removal cost.

The ability of an adversary to disperse the amount of material needed to require the decontamination of this much indoor area is very unlikely—making this truly a worst-case scenario. A very high level of sophistication would be required to carry out such an attack, including acquisition or synthesis of the necessary volume of material and the effective dispersal of the material, all while remaining undetected.

3.3.2 Business Interruption Costs

Figure 3-10 and Figure 3-11 list the total GDP impact from business interruption for onsite and offsite scenarios in linear-linear and log-linear figures, respectively. The GDP impacts range from less than $1 million to $2.08 billion for the onsite scenarios and $7 million to $30.9 billion for the offsite scenarios. As expected, the largest business interruption impacts occur in dense urban areas. As noted in Section 3.2, this distribution of impacts is similar to a power law distribution, likely due to an underlying power law *economic size distribution*, or a power law of basic economic structure (population size) or activity (business size).

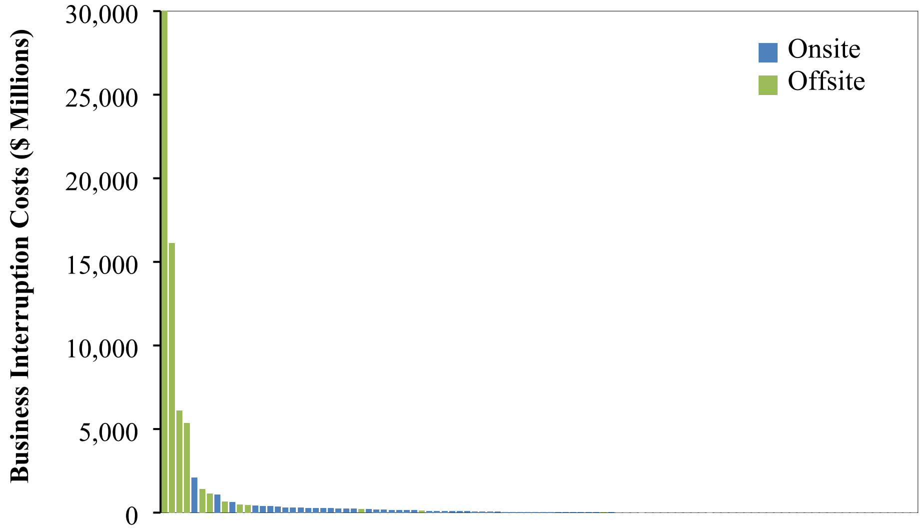

Figure 3-10. Business Interruption Impacts

Figure 3-11. Log of Business Interruption Impacts

Table 3-5 shows more detail on how industries are impacted by the disruption for an offsite incident; the sectors are based on the North American Industry Classification System (NAICS). The results are largely as expected; for example, the urban chemical incident had very little impact on agriculture and a significant impact on finance and insurance. Generally, finance, insurance, and other similar industries require less land area to operate than industries like agriculture and mining. Finance and insurance can be thought of as having a high economic density or being high-value economic activity. These high-value economic activities often occur in office buildings in major urban centers, and their disruption will be more costly than the disruption of industries with low economic densities.

Table 3-5. Business-Interruption Impacts, by Industry: an Example City

NAICS Industry ID	Industry Name	Direct GDP ($Millions)	Indirect GDP ($Millions)	Total GDP ($Millions)
3	Agriculture; forestry; fishing; and hunting	0	0	0
6	Mining	58	66	124
10	Utilities	305	300	604
11	Construction	193	379	573
14	Wood products	1	2	3
15	Nonmetallic mineral products	2	3	5
16	Primary metals	0	0	0
17	Fabricated metal products	4	7	11
18	Machinery	1	1	2
19	Computer and electronic products	15	16	31
20	Electrical equipment; appliances; and components	3	5	8
21	Motor vehicles; bodies and trailers; and parts	0	1	1
22	Other transportation equipment	7	13	20
23	Furniture and related products	4	8	12
24	Miscellaneous manufacturing	9	14	23
26	Food and beverage and tobacco products	33	74	107
27	Textile mills and textile product mills	2	3	5
28	Apparel and leather and allied products	16	26	42
29	Paper products	3	6	10
30	Printing and related support activities	9	19	28
31	Petroleum and coal products	0	0	0
32	Chemical products	29	49	78
33	Plastics and rubber products	0	1	1
34	Wholesale trade	251	362	612
35	Retail trade	419	615	1,034
36	Transportation and warehousing	88	134	222
45	Information	857	1,432	2,289
51	Finance and insurance	1,325	2,279	3,604
56	Real estate and rental and leasing	1,950	1,730	3,679
60	Professional; scientific; and technical services	1,621	2,656	4,277
64	Management of companies and enterprises	267	469	737
65	Administrative and waste management services	246	409	654
69	Educational services	154	269	423
70	Health care and social assistance	517	915	1,432
75	Arts; entertainment; and recreation	182	311	492
78	Accommodation and food services	385	652	1,038
81	Other services; except government	188	360	548
83	Federal Civilian	244	468	712
85	State and Local Government	816	1,563	2,379
	Total	**10,203**	**15,616**	**25,818**

3.3.3 Replacement Costs

The facility replacement cost data was taken from the Chemical Security Assessment Tool (CSAT) Top-Screen survey. Facilities reported replacement costs if they answered YES to the following question:

> Does this facility account for 35% or more of the domestic production of any chemical (including Appendix A and non-Appendix A chemicals) and supply the chemical(s) to any sector of the U.S. economy excluding these critical infrastructure sectors: Defense Industrial Base, Energy (electricity generation only), Public Health or Healthcare, and/or Public Drinking Water? (CSAT, 2010)

If a facility answered NO to the question shown above, no replacement cost values were entered in the Top-Screen survey. Less than one percent of all Top-Screen surveys contain data on replacement costs. Of the 86 facilities selected for analysis in this work, 10 contained replacement costs in the Top-Screen survey.

The replacement cost is reported by selecting 1 of 9 possible ranges of replacement cost in the Top-Screen survey, as depicted in Figure 3-12. However, what the replacement cost represented was not clear. For example, did the range selected represent replacement of the chemical plant, the entire chemical complex, or just the production line specifically related to the chemical production capacity that represents 35 percent of national capacity? Furthermore, a single facility often had multiple ranges selected. To address these uncertainties, three cost calculations were conducted:

1. The largest replacement cost range indicated by a facility on a Top-Screen survey.
2. The sum of all replacement costs indicated by a facility on a Top-Screen survey.
3. The replacement cost most applicable to the COI, as judged by experts. (If no clear COI could be identified, then a zero replacement cost was used).

What is the estimated replacement cost of the production unit(s) for this chemical at this facility?

Replacement Cost(s) of Production Units [Q:9.5-765]

- ○ > $1,000,000,000
- ○ $750,000,000 - $1,000,000,000
- ○ $500,000,000 - $749,999,999
- ○ $100,000,000 - $499,999,999
- ○ $50,000,000 - $99,999,999
- ○ $25,000,000 - $49,999,999
- ○ $12,000,000 - $24,999,999
- ○ $6,000,000 - $11,999,999
- ○ < $6,000,000

Figure 3-12. CSAT Top-Screen Survey

Table 3-6 lists the figures used from the Top Screen for computing the economic impacts resulting from capital replacement. The largest replacement cost was used when determining the effect of including replacement cost in the total economic impact.

Table 3-6. Chemical Facility Replacement Costs

Highest Cost Per Facility ($Millions)	Summation of Cost ($Millions)	Applicable Chemicals ($Millions)
50	62	50
50	50	0
500	2,161	0
500	606	606
100	100	100
50	50	0
100	118	100
50	50	50
6	60	18

As shown in Figure 3-4, the first-year impact of including the replacement cost is minimal, which can be attributed to the immediate economic stimulus of rebuilding the damaged facility: materials are purchased and people are hired to complete the work. Over a ten-year period, however, the negative GDP impact of the replacement is more noticeable. The money that was spent to rebuild the facility could not be used more productively. In other words, the money spent to replace the facility returned the facility to pre-incident conditions and did not ultimately enhance the ability of the company to do business.

Although only 9 of 86 scenarios included a replacement cost, the overall findings do not change: offsite incidents are more costly than onsite and the total GDP impact for onsite incidents is in the billions of dollars. This lack of dramatic change in GDP impacts when replacement costs are included is not unexpected. The largest option for replacement cost is greater than $1 billion, which is a reasonable upper category for the cost of construction of a large chemical facility, and is of the same order of magnitude as most of the cleanup and business interruption costs. Typically, the larger the cost of the repair, the longer the period over which this cost is borne. Fires and explosions generally result in more physical damage than the release of a toxic substance, while a toxic substance will likely result in the need for greater decontamination. Repair of damage and decontamination can be assumed to offset each other to some degree, depending on the type of incident. It is thus extremely unlikely for an incident to result in decontamination and repair costs both on the order of $10 billion.

3.3.4 Offsite Replacement Cost

Replacement costs for offsite scenarios—for example, rebuilding buildings or other infrastructure damaged by an explosion—were not considered in the analysis. These costs were not included due to the lack of detailed and specific data for each location considered. However, anecdotal evidence from the historical incidents discussed in Section 4 suggests that rebuilding damaged buildings will be similar in cost to the worst-case onsite scenarios. Construction of One World Trade Center is estimated at $3.9 billion (Brown, 2012), making it the most expensive office building tower ever. The Burj Khalifa, the tallest building on earth, cost an estimated $1.5 billion (Brown, 2012). In contrast, the repair of damages to the Alfred P. Murrah Building in Oklahoma City was estimated in the hundreds of millions of dollars (Kennedy, 2014).

3.3.5 Supply-chain Disruption

The economic impacts of chemical supply-chain disruptions resulting from onsite chemical incidents were analyzed using N-ABLE™ in concert with SNL's extensive expertise in chemical supply-chain analysis. The historical case studies provide examples of large-scale chemical plant accidents that resulted in disruptions to a portion of domestic production capacity of key chemicals. The economic impacts of supply-chain disruptions are typically negligible, unless the disruption affects a significant capacity of a chemical of which very large amounts are consumed. The economic impacts from supply-chain disruptions for the majority of the scenarios analyzed are also then negligible.

Five specific scenarios were analyzed. As a worst-case scenario, a nine-month disruption to one of the largest domestic chemical complexes was simulated; the largest volume chemicals produced were all assumed to be disrupted. A disruption of nine months was selected based on subject matter expertise and analysis of the historical chemical incidents discussed in Section 4. Disruptions lasting longer than approximately nine to twelve months can be expected to be significantly mitigated through imports and substitution. In the instances in which supply-chain disruptions can cause economic impacts, SNL's supply-chain analyses of similar facility-level disruptions suggest average 1-year GDP impacts of about $100 million to $200 million.

For the worst-case scenario, the model estimated the economic impact of supply-chain disruption to be approximately $500 million in lost GDP. This loss occurred during the first year after the incident. The loss directly to the facility was an estimated $1.4 billion in lost GDP; however, the output response by the rest of the domestic Chemical Sector to mitigate the disruption was an estimated $900 million. This example illustrates the resiliency of the domestic chemical supply chain; in a worst-case scenario involving the disruption of one of the largest chemical production complexes in the country, the value of more than 60 percent of the lost production was recovered by other domestic players. This recovery can be assumed to occur within the first 1 to 3 months of the disruption—a time period that is often of the same order as mitigation of the impacts by supplies, inventories, and in-route shipments. In other words, supplies and in-route shipments will largely mitigate the amount of time needed for other companies to increase production.

These estimates were based on the model's predictions of the mass of lost production from the facility and the mass of increased production by the rest of the domestic chemical sector. The mass of chemicals produced by individual facilities is based on detailed plant-level data and can be assumed to be precise. To convert mass of chemicals to dollars, an average price of $1,500 per metric ton ($0.68 per pound) of chemical was assumed for all chemicals disrupted. This average price was based on actual prices of many of the largest volume chemicals included in the model.

The supply-chain disruption simulation included 123 chemicals of which 16 are produced at the disrupted facility. The modeled supply chain was built from these 16 chemicals using stoichiometry to move upstream and downstream from these original 16. Production and consumption values in the model are based on real data. See Ehlen *et al.* (2013) for a detailed explanation of the model.

3.3.5.1 ***Supply-chain Impacts in the Macroeconomic Model***

The inclusion of the lost GDP from N-ABLE™ into the macroeconomic model produces expected results. For example, a $200-million disruption to a large chemical production facility increases the first-year GDP impact by $175 million, but has a negligible impact on GDP over years 2-10 years. The $200-million supply-chain impact was assumed to be equally distributed over the first year ($50 million per quarter, in the Oxford Model). These results, combined with SNL's extensive expertise in chemical supply-chain analysis, confirm that supply-chain disruptions will not have a national-level economic impact. The results also verify that not including a detailed and individualized supply-chain analysis for each facility is appropriate.

3.3.5.2 *Example Calculations*

In comparison with other potential supply-chain disruptions previously studied using N-ABLE™, the consequences of the disruption to a large facility are very small. Figure 3-13 shows the overall decrease in production from a worst-case hurricane impacting the chemical manufacturing area along the Houston Ship Channel. In Figure 3-13 each color band represents a chemical. The disruption begins at day 100 and lasts for 90 days. A 90-day disruption was used in this hurricane scenario because it was assumed to be appropriate for the damage caused by the hurricane. Likewise, 9 months was used in the five disruptions considered presently because the damage from a terrorist incident was assumed to be greater than damage from a hurricane.

At the beginning of the disruption, production immediately drops by about 6 million metric tons (MTs). Over the next 30 days, production continues to decrease as inventories are consumed, resulting in a minimum production volume of 8 million metric tons per day. This gradual decrease is the indirect impact, the result of lost production at facilities outside the impacted area due to the unavailability of chemicals. A gradual recovery of certain chemicals begins approximately 40 days after the beginning of the disruption. In contrast to the noticeable decrease in chemical production shown in Figure 3-13, a similar figure showing the disruption to the individual facilities considered was unresolvable from the inherent noise of the system modeled.

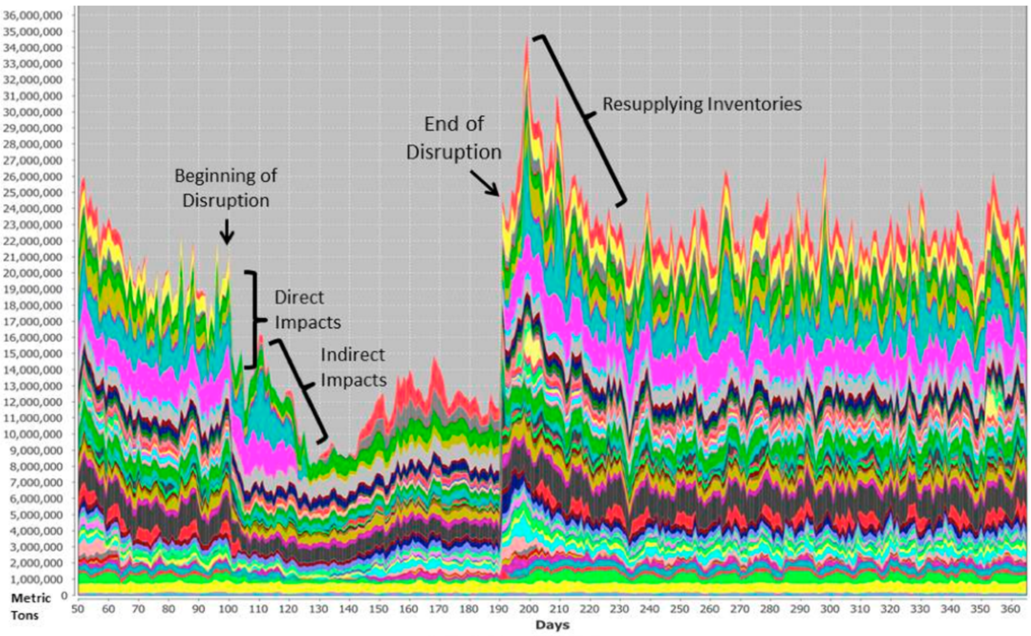

Figure 3-13. Chemical Facility Production (MT), by Chemical: 9-month Disruption

3.4 Discussion

As investigated in previous years, SNL's research has not found chemical facilities that if disrupted could cause significant national economic impacts. The initial results (presented above) concur with the earlier work. First, the *economic multiplier* effect that translates local economic impacts (business disruption, cleanup, facility replacement) to national economic impacts (through supply chains and the general macroeconomy) is an estimated 1.15, which is low compared to other multipliers (BEA, 1992).

Second, the SNL review of 12 historical chemical accidents, described in detail in Appendix A, suggests that most impacts of chemical accidents are local and likely smaller than the scenarios considered for this report.

Chemical sector and national economic resilience to these local impacts is largely due to actions that chemical producers and consumers can take to mitigate or prevent impacts. At chemical plants, chemicals suppliers and buyers directly impacted by a chemical-facility disruption shift suppliers, inventories, and sales to continue operations. Analysis of historical events suggests that a disrupted chemical facility will invoke *force majeure* on existing contracts to release both parties from contractual obligations. The impacted facility then works with its suppliers and buyers to identify alternate avenues for the affected chemicals until restoration of its own normal operations.

In merchant chemical markets, price determines an efficient allocation of supply to demand, including during acute disruptions to supply or demand. Analysis of historical chemical events—

including those impacting large U.S. oil refineries—suggests that merchant chemical markets increase prices of chemicals in the short term, effectively adjusting supply and demand through domestic and international merchant markets. Furthermore, domestic merchant chemical markets have become even more resilient to disruption due to the increased global chemical trade.

In chemical supply chains, independent chemical companies continuously adjust their own supply chains due to changes in production, shipments, prices, buying, and selling. Supply chains can sometimes substitute for the chemicals used in chemical end products by using alternate recipes that use the same feedstock chemicals but alternate chemical process paths. This individualized, uncoordinated rationalization by all firms involved in chemical production or consumption is normal and very effective at mitigating cascades caused by a disruption at a chemical facility.

In the broader national economy, many nonchemical companies are increasingly able to purchase chemicals from non-U.S. sources, thereby enabling consumers to purchase the same chemical-based products from other sources, purchase other goods entirely, or delay a purchase until the supply returns. In many cases, end consumers are unaffected by a disruption in chemical production.

While these impacts may not be significant at the national level, they could be devastating to smaller local economies that rely heavily on the chemical facility for employment and income. Business interruption impacts are the likely largest contributor to impact, in particular for offsite events in which exposure to persistent chemicals in large metropolitan areas could significantly affect business activity.

3.5 Alternative Next Steps

The following alternatives offer potential courses of action based on the present work. For each alternative for which work is performed, that work is generally focused on improving the detail of the existing work and operationalizing the analysis for application to a large number of facilities. However, if ISCD determines that additional sources of economic impact (e.g. cost of death and injuries) and/or a more detailed understanding of how an incident could affect non-national-level economies (i.e., local and regional economies) are necessary, the alternatives can be adapted to meet these needs.

Each successive alternative offers increasing detail and individualization of analysis and results. The more detailed and individualized the results, the more appropriately additional factors can be included in the analysis and the results be applied to understanding regional- and local-level economic impacts. Except where explicitly stated, the cost estimates for each alternative do not include the addition of other sources of economic impact or understanding how the results could impact local or regional economies.

3.5.1 Alternative 1: No Action

No additional work regarding the potential economic impacts of domestic chemical facilities would be conducted. This is the best alternative if the decision is made that economic factors will not be used by ISCD in regulating chemical facilities under CFATS. ISCD was required to consider economics as a potential factor in regulation, but was not required to include it in their calculations to determine a facility's level of risk. The five-year ISCD-SNL collaboration on the potential economic impacts of the chemical sector may satisfy the legislative requirement. Finally, the present work strongly suggests national-level economic impacts are highly unlikely; even extremely improbably, worst-case events are small compared with national GDP, the economic output of the Chemical Sector, and historically significant economic events like recessions. Negative economic impacts associated with cleanup, business interruption, and facility replacement mainly occur at the local level, while the dynamic and robust Chemical Sector mitigates the potential national-level impacts of supply chain disruptions.

***Feasibility/Achievability*:** N/A

***Effectiveness*:** Based on SNL's findings that national-level economic impacts from a terrorist event involving a domestic chemical facility are unlikely, this alternative might be an effective option.

***Pros*:** The resources required to implement another alternative could be leveraged to meet other ISCD needs, effectively increasing the safety and resiliency of the Chemical Sector. Future data-gathering of economic information from chemical facilities becomes unnecessary, hence simplifying future data requirements.

***Cons*:** This option leaves ISCD open to potential criticism.

***Cost*:** N/A

3.5.2 Alternative 2: Limited Action

As a limited action alternative, SNL suggests assigning all CFATS facilities into a limited number of categories based on a simplified algorithm (or evaluation). The categories would be a tiering system. This simplified algorithm would be based on key parameters identified in the present work, such as population, indoor area, and facility replacement cost. This alternative would leverage the existing analysis and would require only a limited amount of additional work to develop a simple algorithm for assigning facilities to categories. Each key parameter would be weighted and an equation developed to combine the results of the parameters to give each facility a score. The parameter weights and equation could be easily modified to give a logical and appropriate distribution of facilities.

***Feasibility/Achievability*:** This alternative has a high degree of achievability. The existing work can be leveraged to develop a simple algorithm for categorizing facilities. The rating and grouping of facilities can be completed through simple tools (e.g., Excel) and would not require specific expertise to run multiple models once the algorithm is developed. The data requirements for this alternative are also relatively minor: existing CSAT, tiering engine, and government-available data (e.g., surrounding area population) may be sufficient in most cases. Following the present work, appropriate assumptions can be made to group facilities and reduce the burden of scenario-specific data requirements. Thousands of facilities could be easily and efficiently processed through the algorithm and provide a basic understanding of the potential economic impacts of chemical facilities.

***Effectiveness*:** This alternative would provide a simple understanding of the potential economic impacts of chemical facilities and provide a basis for comparing facilities. Based on the findings of the present study that national-level impacts are unlikely, this alternative may provide an effective method to address the potential economic impacts of chemical facilities. This alternative is attractive if public health and safety concerns are determined to be the primary factor in identifying a facility for regulation while also giving ISCD the ability to use economic impacts to refine a facility's regulatory status.

***Pros*:** This alternative would provide a limited but tangible method to address economic impacts. Improvements to the algorithm could be made in future years in response to improved understanding of the key parameters and changes in data.

***Cons*:** Like the No Action alternative, this option could leave ISCD open to potential criticism for being too generic and not providing the level of detail required to understand and differentiate facilities' potential to cause economic impacts. The proposed binning is not as scientifically rigorous as modeling facilities individually. Furthermore, the binning would rely on many assumptions and further obfuscate individual chemical facility characteristics.

***Cost*:** Minimal cost, on the order of 1 to 2 full-time employees (FTEs). Developing the algorithm would take less than a year. Ideally, economic data would be reviewed on a periodic basis (every year to every few years) to ensure the algorithm is up-to-date.

3.5.3 Alternative 3: Moderate Action

The Moderate Action alternative builds on the Limited Action alternative, with additional work that focuses on providing greater resolution of the potential economic impacts of each chemical facility. SNL suggests modifying the area of impact. Rather than the uniform 1-mile radius, the size of the area impacted would be one of a limited number of possibilities based on chemical characteristics and the approximate quantity of chemical at each location. Modification of the area of impact requires data on the quantity of a chemical that a facility reports in its Top-Screen survey. Additionally, the chemical would be given a classification based upon its properties.

As part of this alternative, SNL suggests that ISCD improve the facility replacement cost data collected in the Top-Screen survey to indicate clearly what is represented in the cost and gather this information for all facilities. Each facility would then be categorized, as in the Limited Action alternative, using an enhanced algorithm based on these more detailed scenario characteristics. Creating the customized area of impact and using homogenous facility repair and replacement data are the next steps necessary to improve the understanding of economic impacts.

Feasibility/Achievability**:** This alternative has a medium-high degree of achievability because it is largely based on the present work; the additional work suggested does not represent significant challenges in data acquisition or implementation. Modifying the area of impact to be a function of chemical quantity and property is fairly simple and the required data are available. Refining the Top-Screen survey as suggested is also fairly simple, but full implementation might require multiple years because all facilities will need to resubmit a Top-Screen survey.

Effectiveness**:** This alternative would provide a solid understanding of the economic impacts of chemical facilities and a detailed basis for comparing facilities. This option also allows the algorithm to be applied to each facility using more specific data inputs than the Limited Action alternative. Based on the present findings that national-level impacts are unlikely, this alternative would provide a defensible, thorough, and effective method to address the potential economic impacts of chemical facilities. This alternative is attractive if ISCD identifies economic impacts as a significant component of the risk posed by domestic chemical facilities and wants the capability to evaluate the risks of facilities accurately based on both health and economic risk.

Pros**:** This alternative would provide a valuable level of detail in a simple and cost-effective way. The enhanced resolution of the area of impact would also provide insight into local economic impacts.

Cons**:** As in the Limited Action alternative, a simple algorithm is used in place of detailed models thereby reducing the accuracy of the results for each facility. An algorithm is not as scientifically rigorous as modeling facilities individually. Furthermore, the algorithm would rely on many assumptions and potentially obscure individual chemical facility characteristics.

Cost**:** This alternative would likely take 1 to 2 years to develop and implement and require 4 to 5 FTEs. Similar to the Limited Action alternative, reviewing data periodically to ensure accuracy of the algorithm is recommended.

3.5.4 Alternative 4: Further Action

As a Further Action alternative, SNL suggests implementing the method and models used in the present study to estimate the potential economic impacts for each facility regulated by CFATS. This alternative would include the refinements of the area of impact and the changes to the Top-Screen questionnaire to collect homogenous facility repair and replacement data for all facilities. If the SNL models and tools are not used, ISCD must determine appropriate equivalent models and tools.

***Feasibility/Achievability*:** This alternative has a medium degree of achievability. Strategies for implementing this alternative include the training and education of individuals to run the various models and understand the results, regardless of whether the model execution occurs at SNL, ISCD, or a third-party site. Transitioning the analysis capability from SNL to ISCD would require additional model development so that the tools are operational outside a research and development environment. Potential difficulties include intellectual property issues associated with using the SNL models outside SNL, finding equivalent models of equivalent fidelity if the SNL models are not used, operationalizing the SNL models or their commercial equivalents, and defining clear and defensible economic impact thresholds. While the SNL models are sound and effective models, they are not designed to provide thousands of runs quickly.

***Effectiveness*:** This alternative would provide a more granular and accurate result for each facility compared to the algorithms of the Limited and Moderate Action alternatives.

***Pros*:** This alternative would provide a more defensible, thorough, and effective method to address the potential economic impacts of chemical facilities. This alternative would demonstrate a serious commitment to understand and include economic impacts in the regulation of chemical facilities.

***Cons*:** Based on the results of present work, this alternative could be viewed as unnecessary. Furthermore, it would require a significant effort to re-evaluate and re-categorize the more than 4,000 existing CFATS facilities. A rolling implementation of this alternative, in which a facility is not reassessed until an updated Top-Screen is submitted, could take many years to complete.

***Cost*:** This alternative could take 2 to 3 years to develop and implement followed by another 2 to 3 years for full implementation for all CFATS regulated facilities, if a rolling implementation is chosen. Costs would be much greater than the Moderate Action alternative, perhaps as much as 6 to 8 FTEs plus licensing fees for commercial software and data.

3.5.5 Alternative 5: Full Action

This alternative would build on the action offered in the Further Action alternative, while adding detail, technical rigor, and scenario-specific analyses. Enhancements to this alternative include an even more customized area of impact that takes into consideration specific chemicals present at each location. The size and shape of the impacted area would be in concert with the area of impact used by health and human safety and tailored to the geography, building landscape, and the potential interaction of multiple chemicals onsite. The economic analysis would work hand-in-hand with current health and human safety metrics. Broadening the number of sources of economic impact would be considered, including medical costs.

***Feasibility/Achievability*:** This alternative has a medium-to-low degree of achievability. Although the methodology developed in the present study would support this option, this alternative would require a significant amount of additional development. Challenges associated with acquiring data with the desired level of detail could present delays or other problems. The current approach for modeling public health impact is being revised, and the implementation of this alternative would be contingent on the outcome of that effort.

***Effectiveness*:** This alternative, if realized, would provide the most rigorous and detailed understanding of the economic impacts of chemical facilities. It would be highly effective in providing a regulatory framework.

***Pros*:** Such a thorough and detailed approach would be technically sound and defensible. Estimating economic impacts using the same scenario information (i.e., plume or blast area) as used in the public health analysis would provide consistency in the overall analysis, thereby rendering evaluations of the two types of impacts much easier.

***Cons*:** Based on the present work, this alternative could be interpreted as excessive and unnecessary. This analysis would likely be classified. As with the Further Action alternative, the time and cost to re-evaluate and re-categorize all CFATS facilities would be significant.

***Cost*:** This alternative would add at least one more year to the Further Action alternative at a much greater cost. The effort would require an estimated 10 to 12 FTEs.

4 SUMMARY AND CONCLUSIONS

4.1 Summary

SNL developed a methodology for estimating the economic impacts of a terrorist event at a chemical facility. Prior efforts focused on macroeconomic impacts solely from chemical supply-chain disruptions. This early work suggested that national economic impacts were small when compared with the size of the national economy, the size of historically significant economic events (e.g., recessions), and the size of other Chemical Sector disruptive events (e.g., Hurricane Katrina).

SNL did find that impacts could be significant at the local level, however: that is, large relative to the local economy. SNL therefore expanded the methodology to include four component economic-impact types that capture the potentially significant local economic impacts better. These costs are chemical cleanup costs, chemical facility replacement costs, business-interruption impacts, chemical supply-chain impacts, and indirect macroeconomic effects. SNL's methodology leverages the detailed modeling of hypothetical incidents and analysis of historical events to provide a thorough and comprehensive understanding of the potential economic consequences of a terrorist event at a domestic chemical facility.

4.2 Conclusions

The analysis and results fulfilled the needs of the project in five ways. First, the work suggests that a range of potential economic impacts exist from a terrorist event at a chemical facility. Second, the approach suggests the primary factors that cause economic impacts are indoor areas that require decontamination and the interruption of high-value business activity. Third, the analyses show that even worst-case scenarios are very unlikely to result in national-level economic impacts, although significant impacts are likely at the local level. Fourth, this methodology is general enough that facilities not considered in this work can be analyzed and other potential sources of economic impact could be included in the approach. Finally, ISCD can use these results to begin determining whether and how to regulate chemical facilities based on potential economic impact.

This work provides a seminal understanding of economic criticality, understanding that will improve with time as industry and government gain further knowledge of the Chemical Sector and its economic and infrastructure interdependencies. These future improvements are dependent on the regular review of data and methods to ensure the accurate reflection of the Chemical Sector and the national economy. There are inherent challenges associated with this type of analysis, and future improvement depends on detailed and up-to-date data on chemical production, consumption, and trade; infrastructure; and economic activity.

The types of terrorist events modeled in this study—domestic wide-area chemical incidents requiring extensive cleanup, decontamination, and infrastructure repair and resulting in significant business interruption and chemical supply-chain impacts—have never occurred. SNL sought a broad understanding of potential sources of possible economic impact and their magnitudes. Although no modeling approach is completely accurate, the one developed by SNL is state-of-the-art, adaptable to a variety of modeling tools, and could be used to estimate the effect of a future event.

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APPENDIX A. HISTORICAL EVENTS

To inform and validate the modeling of the hypothetical chemical incidents and verify the findings, SNL analysts investigated historical chemical incidents. Table A-1 lists the historical incidents analyzed. Most of these events were highly publicized at the time they occurred and are considered the most catastrophic domestic chemical incidents on record. Special attention was devoted to determining the potential economic impacts caused by each incident, including cleanup costs, businesses interrupted by the incident, facility replacement costs, and supply-chain impacts. This comparison suggests that the economic-impact methodology includes key factors affecting economic impacts.

Historical events are characterized as onsite or offsite. The subsection detailing each category begins with relevant conclusions and describes how they informed the model development process.

Table A-1. Historical Chemical Incidents Analyzed

Facility/Setting	Event	Location	Date
Onsite Incidents			
Chevron Refinery	Fire	Richmond, CA	August 6, 2012
El Dorado Chemical Plant	Explosion	El Dorado, AR	May 15, 2012
BP Refinery	Explosion and Fire	Texas City, TX	March 23, 2005
Shell Deer Park Complex	Explosion and Fire	Deer Park, TX	June 22, 1997
ARCO	Explosion and Fire	Channelview, TX	July 5, 1990
Phillips 66 Complex	Explosion and Fire	Pasadena, TX	October 23, 1989
Offsite Incidents			
Highway Accident	Ammonia Spill	Houston, TX	May 11, 1976
Customer Storage Accident	Ammonia Spill	Seward, IL	April 23, 2007
Train Accident	Chlorine Spill	Graniteville, SC	January 5, 2006
Train Accident	Chlorine Spill	Macdona, TX	June 28, 2004
World Trade Center	Bombing	New York, NY	February 26, 1993
FBI Building	Bombing	Oklahoma City, OK	April 19, 1995

A-1. Onsite Incidents

Four important conclusions can be drawn from the historical onsite incidents and other scenarios studied during the course of this analysis:

1 Significant physical damage is almost always on the order of hundreds to a couple of thousand feet in radius; reports of physical damage in areas greater than 1 mile are rare, and damage at this distance is generally minor.

2 Maximum cleanup and replacement costs were generally in the hundreds of millions of dollars.

3 Business interruptions for large-scale incidents are typically in the hundreds of millions of dollars; no business interruption costs greater than $1 billion were identified, and business interruption costs are frequently insured. A chemical company's business interruption losses do not necessarily equal national economic losses due to the ability of the overall economy to mitigate these losses—for example, through other chemical facilities increasing production.

4 National economic impacts from supply-chain disruptions are minor, even when significant portions of domestic capacity are lost for months to years.

A-1.1. *Chevron Refinery Fire – Richmond, California, 2012*

The Chevron Richmond Refinery is a 2,900-acre petroleum refinery located in Richmond, CA, on San Francisco Bay in an area of mixed urban and industrial development. The facility was owned and operated by Chevron Corporation and employed more than 1,200 workers.[16] Prior to the fire, the refinery had the capacity to refine 245,000 barrels of crude oil per day,[17] which included approximately 16 percent (963,000 barrels[18]) of the West Coast's daily gasoline consumption of gasoline. Chevron refineries provide about 20 percent of California's gasoline and about 68 percent of the jet fuel used by Bay Area and Sacramento airports. The Richmond refinery is one of the largest of the 14 oil refineries in California that produce a particular blend of gasoline required under California state law.[19]

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[16] Geneviève Duboscq, "Chevron Access Needed for Richmond Bay Trail Link," The Berkeley Daily Planet, 27 March 2007, http://www.berkeleydailyplanet.com/issue/2007-03-27/article/26643?headline=Chevron-Access-Needed-for-Richmond-Bay-Trail-Link&status=301, accessed 11/6/2013.

[17] Dylan Tokar, "Gas prices increase after Richmond refinery fire," The Daily Californian, 15 August 2012, http://www.dailycal.org/2012/08/15/gas-prices-increase-after-richmond-refinery-fire/, accessed 11/6/2013.

[18] Terry Collins, "Experts: Richmond fire will boost gas prices," Associated Press report appearing in The Monterey Herald, 7 August 2012, http://www.montereyherald.com/business/ci_21256153/experts-richmond-fire-will-boost-gas-prices, accessed 11/6/2013.

[19] Dylan Tokar, "Gas prices increase after Richmond refinery fire," The Daily Californian, 15 August 2012,

Incident

According to the U.S. Chemical Safety Board (2013), on August 6, 2012, an 8-inch pipe from the #4 crude distillation unit ruptured, releasing flammable hydrocarbon process fluid, which partially vaporized into a large cloud and ignited at 6:33 p.m., approximately two minutes after the release.[20] The resulting fire was brought under control within five hours. (See Figure A-1.) The fire resulted in a large plume of unknown and unquantified particulates and vapor traveling across the Richmond area. A shelter-in-place order was issued at 6:38 pm for the cities of Richmond, San Pablo, and North Richmond; the order was lifted that night at 11:12 p.m., after the fire was fully under control. Bay Area Rapid Transit (BART) closed the Richmond, El Cerrito del Norte, and El Cerrito Plaza stations during the shelter-in-place order. [21]

Health Impacts

Six Chevron employees suffered minor injuries during the incident and subsequent emergency response efforts. In the weeks following the incident, nearby medical facilities received more than 15,000 members of the public seeking treatment for ailments including breathing problems, chest pain, shortness of breath, sore throat, and headaches. Approximately 20 people were admitted to local hospitals as inpatients for treatment.[22]

Economic Effects

According to Tokar (2012) gasoline prices increased $0.30 or more a gallon to more than $4 a gallon following the refinery fire. Part of the price increase is attributed to increases in crude oil prices. According to the California Energy Commission, the decrease in production at the Richmond refinery was offset by an overall increase in production across the state—461,000 barrels of crude oil were added to state refinery production between August 3 and August 10. [23]

Two months after the incident, other California refineries shut down for maintenance. These shutdowns drove gasoline prices higher and caused retail stations to close. Average gasoline price in California was $4.535 a gallon, compared to the national average of $3.788 a gallon.[24]

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http://www.dailycal.org/2012/08/15/gas-prices-increase-after-richmond-refinery-fire/, accessed 11/6/2013.

[20] "Chevron Richmond Refinery Fire Interim Investigation Report," U.S. Chemical Safety Board, 19 April 2013, http://www.csb.gov/assets/1/19/Chevron_Interim_Report_Final_2013-04-17.pdf, accessed 11/6/2013.

[21] Kristin J. Bender and Daniel M. Jimenez, "Massive fire at Chevron refinery in Richmond fully contained; shelter in place lifted," Contra Costa Times, 6 August 2012, http://www.contracostatimes.com/california/ci_21250598/large-fire-burning-at-chevron-refinery-richmond, accessed 11/6/2013.

[22] "Chevron Richmond Refinery Fire Interim Investigation Report," U.S. Chemical Safety Board, 19 April 2013, http://www.csb.gov/assets/1/19/Chevron_Interim_Report_Final_2013-04-17.pdf, accessed 11/6/2013.

[23] Dylan Tokar, "Gas prices increase after Richmond refinery fire," The Daily Californian, 15 August 2012, http://www.dailycal.org/2012/08/15/gas-prices-increase-after-richmond-refinery-fire/, accessed 11/6/2013.

The West Coast is particularly vulnerable to spikes in gasoline prices because it is poorly connected to the refineries along the Gulf Coast, where most of the country's refining capacity is located. Inventories of gasoline in the region at the time of the incident were already low compared with the rest of the country.[25]

Chevron agreed to pay $2 million in fines and restitution and pled no contest to six charges filed by the California Attorney General's Office and the Contra Costa District Attorney's Office, including failing to correct deficiencies in equipment and failing to require the use of certain equipment to protect employees from potential harm.[26]

Figure A-1. Fire at Chevron's Refinery in Richmond, California, 2012[27]

A-1.2. *El Dorado Chemical Nitric Acid Plant Explosion – El Dorado, Arkansas, 2012*

El Dorado Chemical Company (EDC), a subsidiary of LSB Industries, operates a 150-acre facility in El Dorado, Arkansas. The facility produces multiple chemicals and employs

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[24] Anna Matherne, "Refinery outages lead to retail gasoline shortages in California," ICIS News, 5 October 2012, http://www.icis.com/Articles/2012/10/05/9601614/refinery-outages-lead-to-retail-gasoline-shortages-in-california.html, accessed 11/21/2013.

[25] Terry Collins, "Experts: Richmond fire will boost gas prices," Associated Press report appearing in The Monterey Herald, 7 August 2012, http://www.montereyherald.com/business/ci_21256153/experts-richmond-fire-will-boost-gas-prices, accessed 11/6/2013.

[26] "Chevron pays $2m fines and pleads no contest to Richmond fire charges," Associated Press report appearing in The Guardian, 5 August 2013, http://www.theguardian.com/business/2013/aug/05/chevron-fines-charges-richmond-fire-california, accessed 11/6/2013.

[27] KNTV, NBC Bay Area, http://photoblog.nbcnews.com/_news/2012/08/06/13151533-fire-erupts-at-chevron-oil-refinery-in-richmond-calif, accessed 1 March 2014.

approximately 150 people. The production facility is located on 1,400 acres of rural land owned by EDC. The production facility is not immediately adjacent to areas of high business activity or population density. EDC produces a variety of agrochemical and industrial products, including both regular and concentrated nitric acid, sulfuric acid, and both agricultural and industrial grade ammonium nitrate. EDC uses ammonia as its primary feedstock, delivered by pipeline, and its products are transported to market by truck or rail.[28] At the time, the El Dorado facility was the largest producer of concentrated nitric acid for the U.S. market.[29]

Incident

On May 15, 2012, a reactor exploded in the concentrated nitric acid plant. The explosion caused significant damage to the plant and surrounding equipment.[30] The concentrated nitric acid plant, which represents 20 percent of the nitric acid manufactured at the facility, was completely destroyed. Other portions of the facility suffered varying degrees of repairable damage. The three regular nitric acid plants required 30 to 90 days to repair. The two ammonium nitrate plants suffered relatively little damage, but production was severely curtailed due to the lack of nitric acid feedstock.[31] The sulfuric acid plant sustained substantial damage and was offline for approximately seven months.[32] There were no impacts to people or infrastructure offsite.[33]

The concentrated nitric acid plant was not repaired. A new 1,100-ton/day regular nitric acid plant is under construction, along with a nitric acid concentrator plant that concentrates a portion of the output. The new facilities, which are expected to be operational by mid-2015, cost approximately

[28] El Dorado Chemical Company website, http://www.lsbindustries.com/edc, accessed 11/25/2013.

[29] LSB Industries SEC filing: "DEF 14A · For 6/24/04 · EX-99," 24 June 2004, http://www.secinfo.com/d1R95.114.b.htm, accessed 12/4/2013.

[30] LSB Industries News Release: "LSB Industries, Inc. Reports That Its El Dorado Chemical Facility Suffers Damage And Had To Cease Production At This Facility," 15 May 2012, http://investors.lsbindustries.com/phoenix.zhtml?c=114410&p=irol-newsArticle&ID=1718656, accessed 11/25/2013.

[31] LSB Industries News Release: "LSB Industries, Inc. Updates Status Of Its El Dorado Chemical Facility – Anticipates Resumption Of Limited Production In Approximately 30 Days," 6 June 2012, http://investors.lsbindustries.com/phoenix.zhtml?c=114410&p=irol-newsArticle&ID=1718653, accessed 11/25/2013.

[32] LSB Industries News Release: "LSB Industries, Inc.'s El Dorado Facility Signs Contract for a New Nitric Acid Plant, and Completes Reconstruction and Resumes Production at Its Sulfuric Acid Plant," 4 December 2012, http://investors.lsbindustries.com/phoenix.zhtml?c=114410&p=irol-newsArticle&ID=1764274, accessed 11/25/2013.

[33] LSB Industries News Release: "LSB Industries, Inc. Updates Status Of Its El Dorado Chemical Facility – Anticipates Resumption Of Limited Production In Approximately 30 Days," 6 June 2012, http://investors.lsbindustries.com/phoenix.zhtml?c=114410&p=irol-newsArticle&ID=1718653, accessed 11/25/2013.

$120 million.[34] LSB Industries settled an insurance claim for losses and damages for $113 million. [35]

Health Impacts

There were no injuries from the incident.[36]

Economic Impacts

Concentrated nitric acid, used to produce several specialty chemicals, including flame-resistant fibers, gaskets, fuel additives, ordnance, carbon filters, and other chemical products is a very small part of the overall nitric acid market.[37] LSB Industries was forced to declare *force majeure* following this even,[38] and concentrated nitric acid supply in the U.S. tightened significantly in the month following the explosion. To satisfy certain customer product requirements, LSB Industries purchased nitric acid and sulfuric acid on the open market and resold them at a loss.[39] At least one purchaser of concentrated nitric acid from the El Dorado facility subsequently declared *force majeure*, as did their customers, and, in some cases, their customers' customers.[40,41] The domestic supply of regular nitric acid did not appear to be significantly impacted by this event.

LSB Industries had business-interruption insurance that helped to cover certain lost profits.[42] However, the event reduced LSB's operating income for the second quarter by approximately $7

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[34] LSB Industries News Release: "LSB Industries, Inc.'s El Dorado Facility Signs Contract for a New Nitric Acid Plant, and Completes Reconstruction and Resumes Production at Its Sulfuric Acid Plant," 4 December 2012, http://investors.lsbindustries.com/phoenix.zhtml?c=114410&p=irol-newsArticle&ID=1764274, accessed 25 November 2013.

[35] LSB Industries News Release: "LSB Industries, Inc. Announces Conclusion of Insurance Claim," 25 October 2013, http://investors.lsbindustries.com/phoenix.zhtml?c=114410&p=irol-newsArticle&ID=1868732, accessed 25 November 2013.

[36] LSB Industries News Release: "LSB Industries, Inc. Updates Status Of Its El Dorado Chemical Facility – Anticipates Resumption Of Limited Production In Approximately 30 Days," 6 June 2012, http://investors.lsbindustries.com/phoenix.zhtml?c=114410&p=irol-newsArticle&ID=1718653, accessed 25 November 2013.

[37] LSB Industries website, http://www.lsbindustries.com/indacid, accessed 22 January 2014.

[38] "LSB Industries, Inc. Quarterly Report 10-Q Filing - 6/30/2012," http://www.morningstar.com/invest/filings/286174-xnys-lxu-lsb-industries-inc-quarterly-report-10-q-filing-6-30-2012.html, accessed 25 November 2013.

[39] LSB Industries News Release: "LSB Industries, Inc. Reports Results for the 2012 Third Quarter and Expects an Improved 2012 Fourth Quarter," 6 November 2012

[40] Puritan Products Blog post: "Nitric Acid--Force Majeure," 29 June 2012, http://www.puritanproducts.com/blog/2012/6/29/nitric-acid-force-majeure/, accessed 25 November 2013.

[41] Avantor Performance Materials, letter to customers: "Notice of Force Majeure - Nitric Acid," 27 June 2012 www.avantormaterials.com/WorkArea/DownloadAsset.aspx?id=4295002897&libID=4295003641, accessed 25 November 2013.

million.[43] Combined negative impact to operating profit resulting from lost sales and extra expenses was approximately $9 million[44] and $4 million[45] for the third and fourth quarters of 2012. Monthly negative effect on operating income will be approximately $1 million to $2 million at the El Dorado facility, until the new regular nitric acid plant and the nitric acid concentrator are constructed and begin production.[46]

A-1.3. *BP Refinery Explosion and Fire – Texas City, Texas, 2005*

The BP Texas City facility is the third-largest oil refinery in the United States and BP's largest refinery worldwide, with a capacity of 460,000 barrels per day.[47,48] Located 30 miles southeast of Houston on a 1,200-acre site, it produces gasoline, jet fuels, diesel fuels, and chemical feed stocks. The refinery mainly serves markets in the Southeast, Midwest, and along the East Coast, and produces approximately 2.5 percent of the gasoline consumed in the United States. The refinery employs approximately 1,800 BP workers; at the time of the incident, approximately 800 contractor workers were also onsite.[49]

Incident

On March 23, 2005, at 1:20 p.m., the BP refinery suffered one of the worst industrial explosions and fires in recent U.S. history. The incident occurred during the startup of an isomerization unit—a unit that converts low-octane molecules into high-octane molecules for addition to gasoline. A combination of events resulted in the release of hot flammable liquid, estimated at 7,600 gallons, some of which vaporized. The vapor was ignited approximately two minutes after

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[42] LSB Industries News Release: "LSB Industries, Inc. Reports That Its El Dorado Chemical Facility Suffers Damage And Had To Cease Production At This Facility," 15 May 2012 http://investors.lsbindustries.com/phoenix.zhtml?c=114410&p=irol-newsArticle&ID=1718656, accessed 25 November 2013.

[43] LSB Industries News Release: "LSB Industries, Inc. Reports Results For The 2012 Second Quarter," August 8, 2012, http://investors.lsbindustries.com/phoenix.zhtml?c=114410&p=irol-newsArticle&ID=1745519, accessed November 25, 2013.

[44] LSB Industries News Release: "LSB Industries, Inc. Reports Results for the 2012 Third Quarter and Expects an Improved 2012 Fourth Quarter," 6 November 2012

[45] LSB Industries News Release: "LSB Industries, Inc. Reports Results for the 2012 Fourth Quarter and Year," February28, 2013, http://investors.lsbindustries.com/phoenix.zhtml?c=114410&p=irol-newsArticle&ID=1790814, accessed November 25, 2013.

[46] Ibid.

[47] "BP America Refinery Explosion Final Investigation Report," U.S. Chemical Safety Board, March 2007, http://www.csb.gov/assets/1/19/CSBFinalReportBP.pdf, accessed November 12,2013.

[48] "Fatal Accident Investigation Report,0, BP America, December 2005, http://www.bp.com/liveassets/bp_internet/us/bp_us_english/STAGING/local_assets/downloads/t/final_report.pdf, accessed November 12, 2013.

[49] "BP America Refinery Explosion Final Investigation Report," U.S. Chemical Safety Board, March 2007, http://www.csb.gov/assets/1/19/CSBFinalReportBP.pdf, accessed November 12, 2013.

release. The CSB investigation cited organizational and safety deficiencies at all levels of BP as the cause of the incident.[50]

The burned area of the plant was estimated to be approximately 4.6 acres (0.007 square miles), as shown on Figure A-2. The most severe blast damage occurred within the isomerization unit. Surrounding buildings also had blast damage, but of a much lower magnitude. Fifty storage tanks located approximately 250 feet from the explosion also sustained varying degrees of structural damage.[51] A shelter-in-place was issued that required 43,000 people to remain indoors. Windows were shattered in homes and businesses located north of the refinery, up to three-quarters of a mile away.[52]

Health Impacts

The incident killed 15 people and injured 180. Of the injured, 66 were hurt seriously enough that they had days away from work, restricted work activity, or medical treatment.[53]

Figure A-2. Explosion and Fire at BP's Refinery in Texas City, Texas, 2005[54]

[50] Ibid.
[51] Ibid.
[52] Ibid.
[53] Ibid.
[54] What Went Wrong: Oil Refinery Disaster, Popular Mechanics, September 14, 2005,

Economic Impacts

Restoration and repair of the refinery was estimated at $200 million.[55] Shortly after the incident, BP paid a $21.3-million fine to the U.S. Department of Labor's OSHA and entered into a four-year agreement to repair hazards at the refinery. In 2009, following an inspection of safety practices at the Texas plant, OSHA issued BP an additional $87.4-million fine for violations that BP had failed to correct after the explosion and for new violations.[56] Total fines and legal payouts have cost BP more than $2 billion. The company also has spent more than $1 billion on safety and infrastructure improvements at the Texas City refinery and another $500 million to make fixes under a 2010 settlement agreement with OSHA.[57]

Trading prices for gasoline, methyl tertiary butyl ether (MTBE), and benzene increased slightly (2 percent to 3 percent) in the days immediately following the accident.[58] Other chemical prices appear to have been unaffected by the accident.

A-1.4. *Petrochemical Explosion and Fire – Deer Park, Texas, 1997*

The Shell Deer Park Manufacturing Complex is a large petroleum refining and chemical manufacturing facility on 1,400 acres approximately 15 miles east of Houston, Texas. The facility, which employs approximately 2,400 people, is located on the Houston Ship Channel, adjacent to other chemical manufacturing and oil refining facilities. The nearest residential neighborhoods are located in Deer Park, immediately south, and in Channelview, approximately two miles north.[59] At the time of the incident, the facility had capacity to produce 862,000 metric tons per year of ethylene (approximately four percent of U.S. capacity) and 417,000 metric tons per year of propylene (approximately two percent of U.S. capacity).[60]

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http://www.popularmechanics.com/technology/gadgets/news/1758242, accessed March 1, 2014.

[55] Price-Kuehne, C. (Ed.), "The 100 Largest Losses 1972 – 2011 Large Property Damage Losses in the Hydrocarbon Industry," 22nd ed., Marsh Global Energy, 2011, https://usa.marsh.com/Portals/9/Documents/100_Largest_Losses2011.pdf, accessed November 12, 2013.

[56] "BP agrees to pay record $50.6m fine for Texas explosion," BBC News, August 12, 2010, http://www.bbc.co.uk/news/business-10960486, accessed November 13, 2013.

[57] Sam Hananel, "BP Texas City Refinery: Company To Pay Additional $13 Million For 2005 Explosion," Associated Press, posted July 12, 2012, by The Huffington Post, http://www.huffingtonpost.com/2012/07/12/bp-texas-city-refinery-fines_n_1668173.html, accessed November 13, 2013.

[58] "Refinery Blast: US gasoline, petchem prices finish higher," ICIS News, March 24, 2005, http://www.icis.com/Articles/2005/03/24/663461/BP-Refinery-Blast-US-gasoline-petchem-prices-finish.html, accessed November 25, 2013.

[59] "EPA/OSHA Joint Chemical Accident Investigation Report: Shell Chemical Company, Deer Park, Texas," U.S. Environmental Protection Agency, June 1998, http://www.epa.gov/oem/docs/chem/shellrpt.pdf, accessed November 21, 2013.

[60] Joe Kamalick, "US ethylene plant fire will boost prices," ICIS News, June 25, 1997, http://www.icis.com/Articles/1997/06/24/18923/us-ethylene-plant-fire-will-boost-prices.html, accessed November 21, 2013.

Incident

On Sunday, June 22, 1997, at approximately 10:07 a.m., a violent explosion and large fire occurred in a unit that produces ethylene and propylene. A check-valve failure resulted in a large flammable vapor cloud that eventually ignited, causing an explosion and fire that burned for approximately 10 hours.[61] The explosion was felt and heard more than 10 miles away, and adjacent residential property sustained minor damage. Residents within approximately one mile were advised to remain indoors during the incident. The smoke plume from the fire migrated toward the northwest; however, concentrations of contaminants in the path of the smoke plume were found to be below federal and state limits.[62]

The production unit experienced extensive damage, and the production lines of other chemicals, including butadiene, were also damaged. Butadiene production resumed approximately five weeks after the incident[63] and production of ethylene and propylene resumed approximately eight months after the incident.[64]

Health Impacts

There were no fatalities from the explosion or fire, although several workers received minor injuries.[65]

Economic Impacts

Following the incident, inventories of butadiene were near record-low levels, and butadiene prices increased from $0.20/pound in May and June to $0.22/pound in July. Production of ethylene at other facilities worldwide increased to help mitigate the loss of the Shell facility, with an average operating rate estimated to have been 95 percent during June, up 4.4 percent from May.[66] Inventories of ethylene were not as tight as butadiene following the incident. Spot market

[61] "EPA/OSHA Joint Chemical Accident Investigation Report: Shell Chemical Company, Deer Park, Texas," U.S. Environmental Protection Agency, June 1998, http://www.epa.gov/oem/docs/chem/shellrpt.pdf, accessed November 21, 2013.

[62] Ibid.

[63] Angela Macdonald-Smith, "Shell Deer Park butadiene unit back up," ICIS News, August 4, 1997, http://www.icis.com/Articles/1997/08/04/34262/shell-deer-park-butadiene-unit-back-up---source.html, accessed November 21, 2013.

[64] Gary Taylor, "Shell Deer Park plant to reopen 5 Feb," ICIS News, 23 January 1998, http://www.icis.com/Articles/1998/01/23/51276/shell-deer-park-plant-to-reopen-5-feb.html, accessed November 21, 2013.

[65] "EPA/OSHA Joint Chemical Accident Investigation Report: Shell Chemical Company, Deer Park, Texas," U.S. Environmental Protection Agency, June 1998, http://www.epa.gov/oem/docs/chem/shellrpt.pdf, accessed November 21, 2013.

[66] "Deer Park repercussions," ICIS News, July 21, 1997, http://www.icis.com/Articles/1997/07/21/44404/deer-park-repercussions.html, accessed November 21, 2013.

prices for ethylene and propylene increased by 0.5-1.5 cents/pound, from 20-21 cents/pound before the outage, but this price increase was smaller than historical fluctuations in the year prior to the incident.[67]

Figure A-3 and Figure A-4 show the U.S. spot market prices for ethylene and chemical-grade propylene for the years prior to and following the incident. There are three main grades of propylene (in order of increasing propylene purity): refinery, chemical, and polymer. Shell's Deer Park facility is a major producer of chemical-grade propylene. In both figures, the red line indicates the date of the incident.

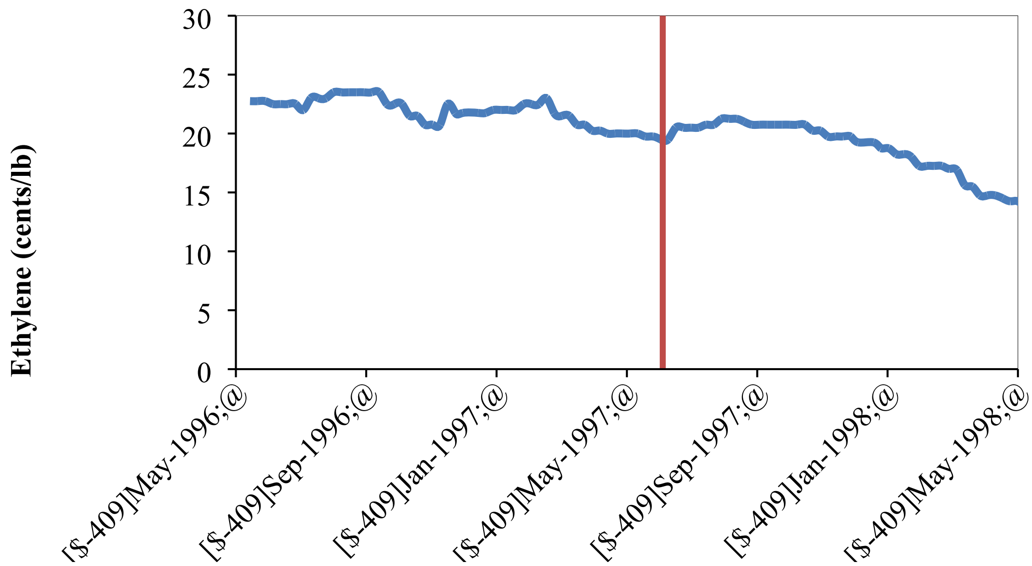

Figure A-3. Price of Ethylene on U.S. Spot Market[68]

[67] ICIS Chemical Price Report, "Ethylene in US Gulf Spot Del (Pipeline)," Reed Business Information Limited, 2014.
[68] ICIS Chemical Price Report, "Ethylene in US Gulf Spot Del (Pipeline)," Reed Business Information Limited, 2014.

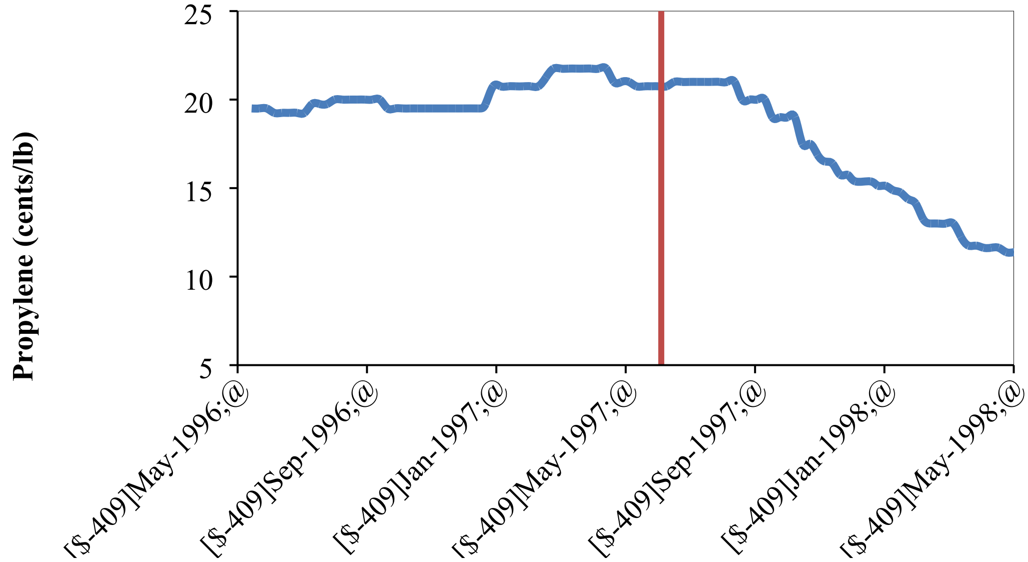

Figure A-4. Price of Chemical-grade Propylene on U.S. Spot Market[69]

Both ethylene and propylene can be produced from multiple feed stocks originating from crude oil, natural gas, and other materials. Shell's Deer Park facility is able to use both crude and natural gas feed stocks. To relativize the ethylene price by the price of its raw materials and isolate the effect of the supply disruption on price, the prices of crude oil and natural gas are plotted in Figure A-5. The plots are based on weekly crude oil and monthly natural gas prices.

Shell declared *force majeure* on its worldwide ethylene, propylene, and butadiene contracts within a week of the incident.[70] To mitigate the lost production, Shell increased production at a similar facility in Norco, Louisiana; borrowed inventory from other producers; and purchased from the spot market.[71] Repair of the facility cost approximately $125 million;[72] costs associated with offsite impacts are unknown. Shell paid fines of $350,000 to the EPA[73] and $130,000 to OSHA.[74]

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[69] ICIS Chemical Price Report, "Propylene (C Grade) In US Gulf Spot Cars," Reed Business Information Limited, 2014.

[70] Joe Kamalick, "Shell Chemical declares force majeure," ICIS News, 26 June 1997, http://www.icis.com/Articles/1997/06/25/18940/shell-chemical-declares-force-majeure.html, accessed 21 February 2014.

[71] Ibid.

[72] Larry Terry, "Shell Deer Park cracker expected onstream this week," Chemical Week, 4 February 1998, 160(5), p. 13.

[73] Mike Sheridan, "Shell settled with US EPA to 'avoid lengthy litigation'," ICIS News, December 10, 2001, http://www.icis.com/Articles/2001/12/10/153030/shell-settled-with-us-epa-to-avoid-lengthy-litigation.html, accessed November 21, 2013.

[74] Gary Taylor, "Shell pays $130 000 fine in Texas blast," ICIS News, December 18, 1997, http://www.icis.com/Articles/1997/12/18/46647/shell-pays-130-000-fine-in-texas-blast.html, accessed November

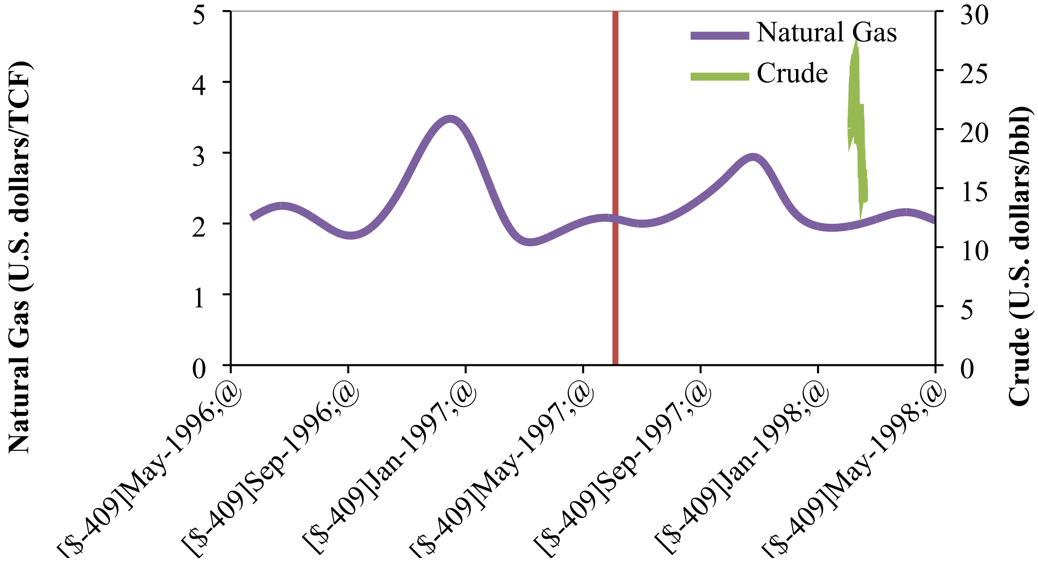

Figure A-5. Price of Crude Oil and Natural Gas[75,76]

A-1.5. *Petrochemical Explosion and Fire – Channelview, Texas, 1990*

The ARCO Channelview facility, now owned by LyondellBasel Industries, is located on 514 acres in Channelview, Texas, a mixed urban and industrial area approximately 20 miles east of Houston. At the time of the incident, the facility produced:

- 600 million pounds per year of propylene oxide (17.5 percent of U.S. capacity),
- 1.77 billion pounds per year of ethyl benzene (18 percent of U.S. capacity),
- 125 million pounds per year of urethane polyols (17 percent of U.S. capacity; production is now owned and operated by Bayer Materials Science), and
- 1.4 billion pounds per year of styrene monomer (15 percent of U.S. capacity).

Additionally, the facility was the world's largest producer of MTBE, a gasoline additive widely used at the time of the incident, at 27,500 barrels per day.[77]

21, 2013.

[75] U.S. Energy Information Administration, Natural Gas, http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm , accessed March 21, 2014.

[76] U.S. Energy Information Administration, Spot Prices for Crude Oil and Petroleum Products, http://www.eia.gov/dnav/pet/pet_pri_spt_s1_w.htm, accessed March 21, 2014.

[77] Robert Suro, "Explosion Kills 17 at Petrochemical Plant in Texas," The New York Times, 7 July 1990.

Incident

At approximately 11:30 p.m. on July 5, 1990, a 900,000-gallon tank containing plant wastewater and hydrocarbons exploded. Only about 65 of the 500 employees were onsite at the time of the explosion. The tank was located in a utility area set apart from main production operations. The fire was extinguished after approximately four hours.[78] The blast destroyed two steel tanks and charred an area the size of a city block. The explosion caused considerable damage to the plant utilities area, and the plant was shut down for six months. The accident did not cause the release of any dangerous materials, and there was no evacuation of people living in the area.[79] The explosion broke windows in residential homes adjacent to the plant.

Health Impacts

Seventeen workers were killed and five others injured. There were no injuries to neighboring residents.[80]

Economic Impacts

The plant's shutdown impacted the price of propylene oxide, propylene glycol, MTBE, and styrene.[81] The loss of styrene production was followed by 4-5 months of spot market prices fluctuating 10-25 percent higher than normal; however, there had been similar price fluctuations prior to the incident,[82] which is consistent with reports that styrene supply had been tight in the preceding months. Figure A-6 shows the U.S. spot market price of styrene for the year prior to the incident and the year following; the red line indicates the date of the incident. The price of styrene is dependent on the price of crude oil and natural gas, and Figure A-7 shows the price of these two raw materials during the same time period.

[78] Ibid.
[79] Ibid.
[80] Ibid.
[81] Andrew Wood and Shelina Shariff, "Fallout from Channelview explosion keeps on coming," Chemical Week, 24 June 1990, p. 9.
[82] ICIS Chemical Price Report, "Styrene in US Gulf Spot + FOB Export," Reed Business Information Limited, 2014.

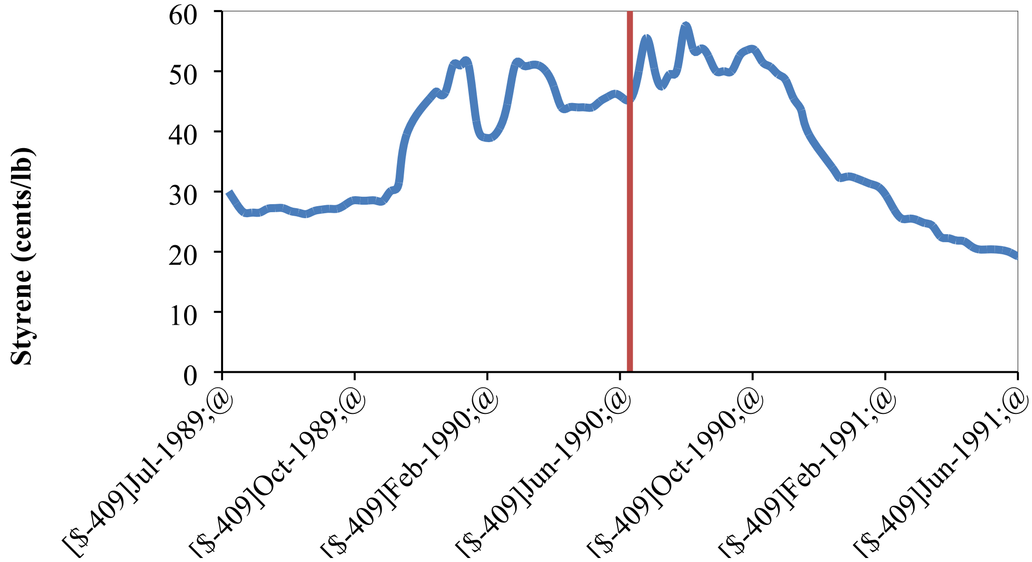

Figure A-6. Price of Styrene and Crude Oil on the U.S. Spot Market[83]

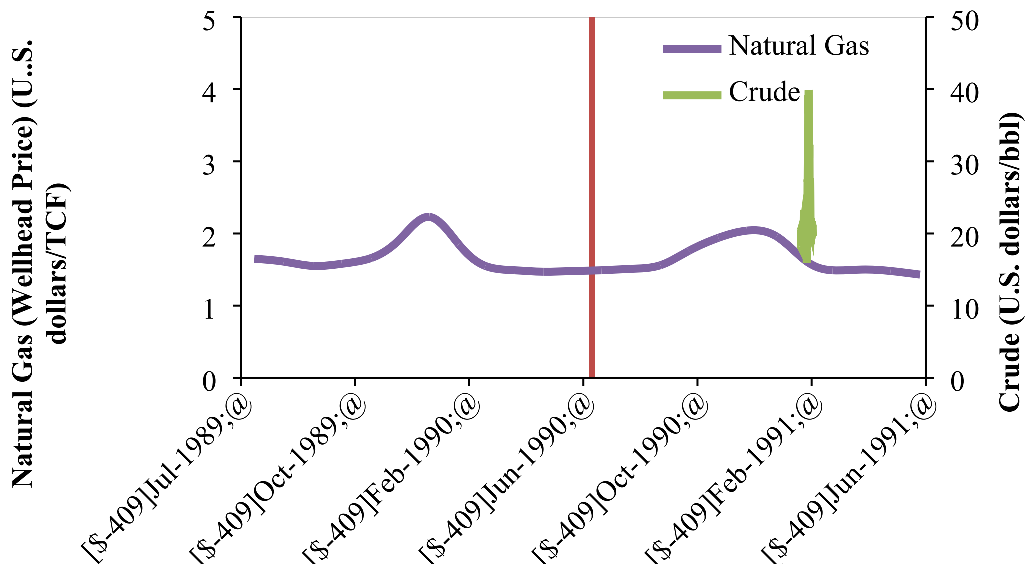

Figure A-7. Price of Crude Oil and Natural Gas[84,85]

The loss of the facility's MTBE production was blamed for a small increase in gasoline prices (approximately one cent per gallon, an increase of less than two percent at the time of the

[83] ICIS Chemical Price Report, "Styrene in US Gulf Spot + FOB Export," Reed Business Information Limited, 2014.

[84] U.S. Energy Information Administration, Natural Gas, http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm, accessed March 21, 2014.

[85] U.S. Energy Information Administration, Spot Prices for Crude Oil and Petroleum Products, http://www.eia.gov/dnav/pet/pet_pri_spt_s1_w.htm , accessed March 21, 2014.

incident) in both the United States and Europe.[86,87] ARCO paid a $3.48-million fine to OSHA for violations of federal safety law; this was the largest fine allowable at the time of the incident.[88] Projections for lost business to ARCO were approximately $200 million.[89] This loss to ARCO does not mean the economy necessarily suffered an equal loss, as the Chemical Sector responded to mitigate the loss—for example, by increasing production at other facilities.

A-1.6. *Petrochemical Explosion and Fire – Pasadena, Texas, 1989*

The Phillips 66 Houston Chemical Complex (now owned by Chevron Phillips Chemical) is located on 800 acres in Pasadena, Texas, an urban and industrial area approximately fifteen miles east of Houston. The facility produced a variety of petrochemicals and employed approximately 1,500 people. Important chemical production at the facility at the time of the incident was 1.5 billion pounds of high-density polyethylene (HDPE) (19 percent of U.S. capacity), 500 million pounds of polypropylene (10 percent of U.S. capacity), and 180 million pounds of a butadiene-styrene copolymer.[90]

At approximately 1:00 p.m. on October 23, 1989, 85,000 pounds of flammable gas composed primarily of ethylene and isobutane was released through an open valve during regular maintenance of a polyethylene reactor. Within two minutes the gas cloud reached an ignition source and exploded. A second major explosion occurred 10-12 minutes later, when two 20,000-gallon isobutane storage tanks exploded. A third major explosion occurred 20-45 minutes after the initial explosion, when another polyethylene reactor catastrophically failed. The resulting fire was brought under control within approximately 10 hours and extinguished within 24 hours of the initial explosion.[91]

Two polyethylene plants, covering an area of approximately 16 acres (0.025 square miles), were completely destroyed, and process units sustained minor damage.[92] A two-mile section of the Houston Ship Channel, which connects the Port of Houston to Galveston Bay, was temporarily closed by the Coast Guard. More than 700 students of a nearby school were evacuated after the

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86 "ARCO Petrochemical unit blast jolts markets," Oil & Gas Journal, July 16, 1990, p. 28.
87 Frank Swoboda, "Settlement set in '90 plant blast," The Washington Post, January 4, 1991.
88 Ibid.
89 Simon Reynolds, "The price of tragedy rises - Industrial risk rates are out of step with the new size of losses," Financial Times (London), September 9, 1991.
90 Hayes, T.C., "Reverberations for Industries But Not for U.S. Households," The New York Times, October 25, 1989.
91 U.S. Department of Labor Occupational Safety and Health Administration, "Phillips 66 Company Houston Chemical Complex Explosion and Fire," April 1990.
92 Clough, I. (ed.)," The 100 Largest Losses 1972 – 2009 Large Property Damage Losses in the Hydrocarbon Industries," 21st ed., Marsh Energy Practice, 2009.

explosions blew out cafeteria windows, although no evacuations of residential areas were ordered. The explosion shattered windows in Pasadena's downtown district three miles away.[93] Debris from the plant was found six miles from the site.[94]

Health Impacts

Twenty-three workers were killed and more than 130 were injured. One-hundred and twenty-four people were taken to hospitals, with 35 admitted for treatment, including six in serious or critical condition.[95] The mixture of flammable gases ignited, dissipated, and did not pose a significant threat to the public or environment.[96]

Economic Impacts

At the time of the incident, the plant produced 19 percent of the domestic consumption of HDPE and return to full production of polyethylene took approximately two years. Other processes resumed normal production within a few weeks of the incident.[97] This business interruption cost was estimated at $700 million, while property damage, cleanup, and repair costs were estimated at $680 million.[98,99] This incident is the largest single-owner property damage loss to date in the petrochemical industry.[100] In addition, a fine of $4 million was paid to OSHA.[101]

Figure A-8 shows the price of polyethylene the years before and following the incident. The red line indicates the date of the incident. Prior to the incident, demand for HDPE had leveled off after two years of rapid growth; prices had fallen 30 percent.[102] The explosion was followed by price increases of approximately $0.04/pound, an increase of approximately 10 percent. While there was a falling price trend for HDPE that ended at the time of the explosion, that trend matched a similar halt in falling ethylene prices—the precursor to HDPE. The reduction in price

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93 Suro, R., "Plastics Plant Explodes; Many Missing," The New York Times, October 24, 1989.

94 U.S. Department of Labor Occupational Safety and Health Administration, "Phillips 66 Company Houston Chemical Complex Explosion and Fire," April 1990.

95 Suro, R., "Little Hope Held by Texas Rescuers," The New York Times, October 25, 1989.

96 U.S. Department of Labor Occupational Safety and Health Administration, "Phillips 66 Company Houston Chemical Complex Explosion and Fire," April 1990.

97 Clough, I. (ed.)," The 100 Largest Losses 1972 – 2009 Large Property Damage Losses in the Hydrocarbon Industries," 21st ed., Marsh Energy Practice, 2009.

98 These estimates are in 1989 dollars; $680 million is equivalent to approximately $1.3 billion in 2009 U.S. dollars.

99 Clough, I. (ed.)," The 100 Largest Losses 1972 – 2009 Large Property Damage Losses in the Hydrocarbon Industries," 21st ed., Marsh Energy Practice, 2009.

100 Ibid.

101 "Oil Company to Pay $4 Million Over Texas Blast," The New York Times, August 23, 1991.

102 Hayes, T.C., "Reverberations for Industries But Not for U.S. Households," The New York Times, October 25, 1989.

6-9 months after the incident can be credited to new capacity. Figure A-9 shows the price of HDPE raw materials, crude oil, and natural gas, during the same time period as Figure A-8.

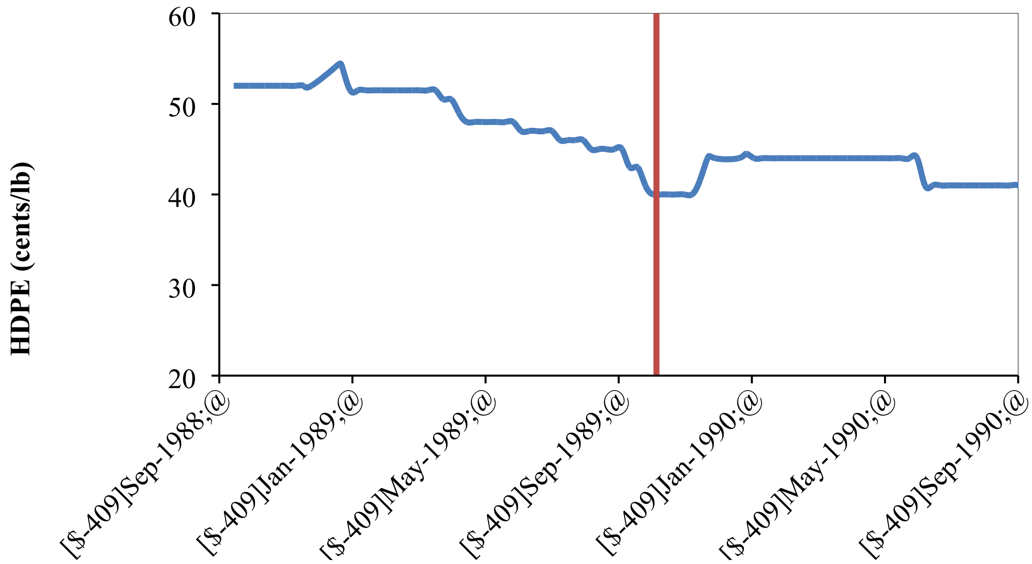

Figure A-8. Price of HDPE on U.S. Market[103]

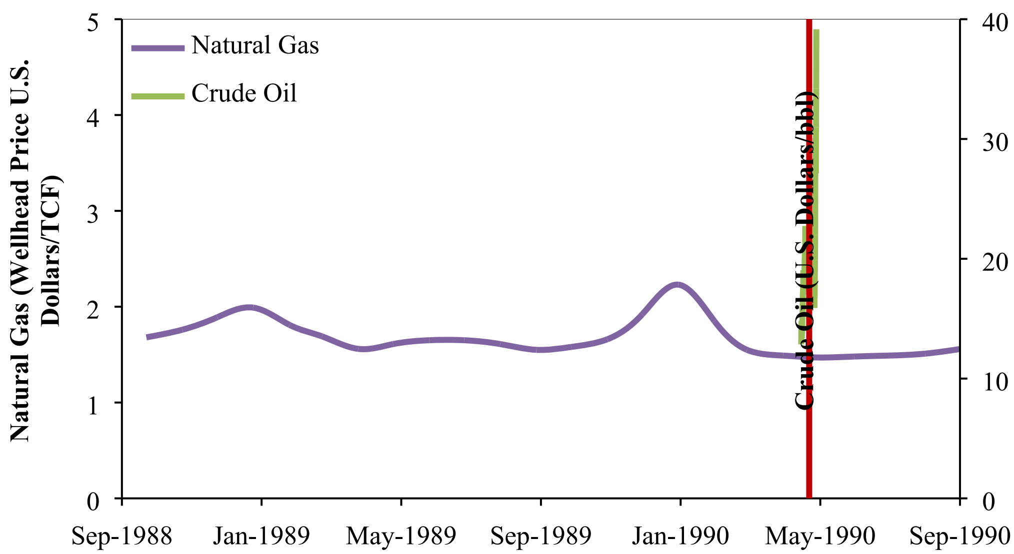

Figure A-9. Price of Crude Oil and Natural Gas[104,105]

[103] ICIS Chemical Price Report, "Polyethylene: HDPE (BL/MDGL) In US Gulf Domestic Bulk Del USA," Reed Business Information Limited, 2014.

[104] U.S. Energy Information Administration, Natural Gas, http://www.eia.gov/dnav/ng/ng_pri_sum_dcu_nus_m.htm, accessed March 21, 2014.

[105] U.S. Energy Information Administration, Spot Prices for Crude Oil and Petroleum Products,

A-2. Offsite Incidents

Six important conclusions can be drawn from the historical offsite incidents and others studied during the course of this analysis:

1. Non-persistent chemicals require minimal cleanup.
2. Even very toxic chemicals, such as ammonia and chlorine, dissipate quickly outdoors; fatal concentrations naturally dissipate in a matter of minutes.
3. Offsite incidents do not have supply-chain impacts; the loss of a finite volume of material, apart from the loss of production capabilities, is not sufficient to cause supply-chain impacts.
4. Equipment losses tend to be small.
5. Wide-area business interruptions tend to be very short in duration.
6. Explosions that result in extensive building damage are generally the most costly type of offsite incident.

A-2.1. Ammonia Spill – Houston, Texas, 1976

On May 11, 1976, approximately 7,500 gallons (19 tons) of ammonia were spilled on a Houston interstate highway when a tanker truck crashed, falling 15 feet from an overpass ramp.[106] Ammonia is transported as a compressed gas under low temperature and/or high pressure. The sudden breach of containment resulted in an explosion that resulted in the immediate release of the full volume of ammonia. The ammonia gas penetrated cars and buildings.

Based on injuries and known toxicity levels, ammonia levels were estimated to reach approximately 6,500 parts per million (ppm) within 200 feet of the accident. Ammonia at this concentration is fatal within a few minutes. The immediately dangerous to life or health (IDLH) concentration for ammonia is 300 ppm, while a four-hour exposure at 30 ppm is expected to cause notable discomfort, but no disabling health effects, according to Acute Exposure Guideline Levels, (AEGL) level 1.[107] A wind of 7 mph spread and dissipated the vapor cloud. The vapor

http://www.eia.gov/dnav/pet/pet_pri_spt_s1_w.htm, accessed March 21, 2014.

[106] For a detailed description of the accident see National Transportation Safety Board, Highway Accident Report Number: NTSB-HAR-77-1, April 14, 1977.

[107] EPA Emergency Response Air Monitoring Guidance Tables, http://www.uscg.mil/hq/nsfweb/foscr/ASTFOSCRSeminar/Presentations/RemovalandResponseTech/AirMonGuidanceTables09Ed2.pdf, accessed February 26. 2014.

cloud was dispersed about five minutes after the accident and ammonia levels were normal within 2.5 hours. Figure A-10 is a photograph of the ammonia cloud shortly after the accident.

Health Impacts

Six people were killed in the accident: five from inhalation of ammonia. An additional 178 people were within 1,000 feet of the release and sought medical treatment, of which 78 required hospitalizations.

Figure A-10. Photograph of Ammonia Spill Shortly After Release[108]

Economic Impacts

Economic impacts were minimal. The truck was completely destroyed and a few other vehicles were damaged by debris. The bridge and roadway also required repair. First responders used a water-based fog spray to wash the area. Natural dispersion negated the need for any additional remediation or decontamination. Business interruption was limited to those people directly impacted on the road and the loss of the ammonia.

[108] Photo: Carroll Grevemberg, Grevy Photography, New Orleans. Taken from Erik Slotboom, Houston Freeways: A Historical and Visual Journey, 2003, www.houstonfreeways.com, accessed February 26, 2014.

A-2.2. Ammonia Spill – Seward, Illinois, 2007

Incident

A hose burst while transferring ammonia from a storage tank to a tanker truck and resulted in the release of an estimated 20 tons (approximately 8,000 gallons) of ammonia at an agriculture supply store in Seward, Illinois.[109] The release occurred during the late afternoon of April 23, 2007. The town of Seward (population approximately 200) was evacuated, and two other nearby towns were placed under voluntary evacuation. Residents were allowed back into their homes the following day.[110]

Health Impacts

Ten people were injured. No one was killed.

Economic Impacts

Economic impacts were minimal. A small number of local businesses and an elementary school were closed for approximately two days; the school was cleaned and ventilated before reopening.[111] Portions of the spill were captured on camera. Stills from that video are presented below in Figure A-11.

Figure A-11. Ammonia Leak in Seward, Illinois; Eight Seconds Elapsed Between Each Frame[112]

[109] Attorney General Madigan Takes Action Against Company Involved in Seward Ammonia Leak, Illinois Attorney General Press Release, May 11, 2007, http://www.illinoisattorneygeneral.gov/pressroom/2007_05/20070511.html, accessed February 26, 2014.

[110] "3 towns evacuated from ammonia leak," USA Today, April 24, 2007, http://usatoday30.usatoday.com/news/nation/2007-04-24-illinois-ammonia_N.htm, accessed February 26, 2014.

[111] Businesses Affected by Ammonia Leak, http://www.mystateline.com/story/d/story/businesses-affected-by-ammonia-leak/11157/7Al2HvaQSkSPIMxSWFd53A, accessed February 26, 2014.

[112] http://www.youtube.com/watch?v=qIi4_Poo2HY, accessed February 26, 2014.

A-2.3. Chlorine Spill – Graniteville, South Carolina, 2005

Incident

The worst chlorine leak in U.S. history occurred early in the morning of January 6, 2005, in Graniteville, South Carolina. A moving train was accidentally diverted onto an industrial track and collided with a stationary train. The moving train included three tank cars of chlorine; one car burst after being derailed. The tank car held 90 tons of chlorine (about 14,000 gallons).

Chlorine has an IDLH of 10 ppm and four-hour AEGL-1 of 0.5 ppm.[113] Based on human observation and the locations of those killed, a cloud of chlorine extended at least 2,500 feet to the north, 1,000 feet to the east, 900 feet to the south, and 1,000 feet to the west.[114] A 1-mile radius evacuation zone was created, necessitating the evacuation of 5,400 people for several days following the accident.

Health Impacts

Nine people were killed by inhalation of chlorine gas. Another 554 reported respiratory ailments, of who 75 received treatments.

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113 EPA Emergency Response Air Monitoring Guidance Tables, http://www.uscg.mil/hq/nsfweb/foscr/ASTFOSCRSeminar/Presentations/RemovalandResponseTech/AirMonGuidanceTables09Ed2.pdf, accessed February 26, 2014.

114 National Transportation Safety Board, Railroad Accident Report NTSB/RAR/-05/04 Collision of Norfolk Southern Train 192 with Standing Norfolk Southern Local Train P22 With Subsequent Hazardous Materials Release at Graniteville, South Carolina, January 6, 2005, http://www.ntsb.gov/doclib/reports/2005/RAR0504.pdf, accessed February 26, 2014.

Figure A-12. Train Derailment and Chlorine Release Near Graniteville, South Carolina[115]

Economic Impacts

The accident and release occurred in an industrial area that included a textile mill, which ultimately closed despite efforts to clean and restore it. This closure resulted in the loss of 4,000 jobs.[116] Other local businesses were interrupted while the town was evacuated and while cleanup was conducted. Several railroad cars were also destroyed and the chlorine was lost, but no supply-chain impacts occurred. The economic impact to the small town of Graniteville was significant.

A-2.4. Chlorine Spill – Macdona, Texas, 2004

Incident

At 5:03 a.m. on June 28, 2004, two trains collided near Macdona, Texas, leading to the derailment of 35 railcars. Macdona is a mixed rural and suburban area within the San Antonio metropolitan area. The accident occurred about 1 mile from Macdona and 17 miles from downtown San Antonio. A railcar containing 90 tons (about 14,000 gallons) of chlorine derailed

[115] Photograph by Andrew Davis Tucker, taken from "10 Lessons Learned from Past Rail Accidents," Popular Mechanics, http://www.popularmechanics.com/science/4322631, accessed February 26, 2014.

[116] Georgia Tech Research Institute, Chlorine's Casualties and Counsel, http://www.gtri.gatech.edu/casestudy/chlorines-casualties-and-counsel, accessed February 26, 2014.

and breached. Chlorine gas quickly covered an area of with a radius of at least 700 feet.[117] The chlorine vapor drifted with the wind toward San Antonio. Several employees of Sea World, approximately 10 miles away, reported chlorine vapors.[118] Over the course of about three days, 60 tons of chlorine was released.

Health Impacts

Three people were killed in the accident, including two from chlorine inhalation. An additional 43 people were hospitalized due do chlorine inhalation.

Economic Impacts

Damages to the railroad equipment were approximately $6 million. Cleanup costs were estimated to be $150,000. No business interruption occurred, aside from that of the two trains, and no supply-chain impacts occurred.

Figure A-13. Train Derailment and Chlorine Release Near Macdona, Texas[119]

[117] National Transportation Safety Board, Railroad Accident Report NTSB/RAR/-06/03 Collision of Union Pacific Railroad Train MHOTU-23 with BNSF Railway Company Train MEAP-TUL-126-D with Subsequent Derailment and Hazardous Materials Release Macdona, Texas, June 28, 2004. http://www.ntsb.gov/doclib/reports/2006/RAR0603.pdf, accessed February 26, 2014.
[118] Ibid.
[119] Ibid.

A-2.5. Bombing – New York City, New York, 1993

Incident

Known as the first World Trade Center bombing, a truck bomb exploded below the North Tower of the World Trade Center on February 26, 1993. The 1,500-pound bomb[120] was designed to collapse the North Tower into the South Tower, bringing down both buildings. Both buildings remained standing, but the parking garage below the North Tower was significantly damaged, with the blast crater measuring 130 feet by 140 feet at its widest point.[121] An estimated 2,500 tons of debris required removal after the blast;[122] Figure A-14 shows the damage. The New York City Fire Department responded with approximately 45 percent of its on-duty staff and maintained a presence at the scene for 28 days.[123]

Figure A-14. Damage to World Trade Center[124]

[120] Craig Whitlock, "Homemade, Cheap and Dangerous," The Washington Post, July 5, 2007, http://www.washingtonpost.com/wp-dyn/content/article/2007/07/04/AR2007070401814_pf.html, accessed March 3, 2014.

[121] U.S. Fire Administration/Technical Report Series, "The World Trade Center Bombing: Report and Analysis," New York City, New York, February 1993.

[122] Ibid.

[123] Ibid.

[124] Skyscrapercity, The World Trade Center, http://www.skyscrapercity.com/showthread.php?s=138d3bb99a99b94a14e6e84ab7283a17&t=1440718, accessed March 3, 2014.

Health Impacts

Six people were killed and 1,042 people were injured. However, only 15 people received traumatic injuries directly from the blast; most were injured during evacuation of approximately 50,000 people from the World Trade Center complex.[125]

Economic Impacts

More than 3,000 workers were employed in continuous shifts to clean 10 million square feet of office space. Vendors around the country interrupted their scheduled production to provide needed parts and equipment; impacted office space began to be reoccupied two weeks after the explosion.

A-2.6. Bombing – Oklahoma City, Oklahoma, 1995

Incident

At 9:02 a.m. on April 19, 1995, a truck full of explosive materials was detonated intentionally outside the Alfred P. Murrah Federal Building in downtown Oklahoma City. At the time of the attack, it was the most destructive act of terrorism committed in the United States. The Murrah Building was almost completely destroyed by the 5,000-pound bomb.[126] Figure A-15 shows the destruction. A total of 324 buildings within a sixteen-block radius received some degree of damage. Two-hundred and fifty-eight buildings suffered broken windows, 25 received structural damage, 10 others completely collapsed, and 86 cars were destroyed.[127]

Health Impact

One-hundred and sixty-eight people were killed and 680 others were injured in the explosion.

Economic Impact

The physical damage from the explosion was estimated at $652 million,[128] including cleanup, repairs, and replacement of buildings. Business interruption costs are difficult to estimate, but likely are small. No supply-chain impacts occurred.

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[125] Ibid.

[126] Craig Whitlock, "Homemade, Cheap and Dangerous," The Washington Post, July 5, 2007, http://www.washingtonpost.com/wp-dyn/content/article/2007/07/04/AR2007070401814_pf.html, accessed March 3, 2014.

[127] Maryann Haggerty, Okla. City Businesses Assess Damage, Cost of Rebuilding, Chicago Sun Times, May 1, 1995.

[128] Ann Kennedy, The Real Meaning of Community Service: The Economic and Financial Impact of the Oklahoma City Bombing, Oklahoma City National Memorial & Museum, http://www.oklahomacitynationalmemorial.org/uploads/documents/OKCNM_Economic%20and%20Financial%20Impact%20OCEE.pdf, accessed February 26, 2014.

Figure A-15. Damage to Alfred P. Murrah Building[129]

[129] Fox News, Oklahoma City Bombing, http://www.foxnews.com/topics/oklahoma-city-bombing.htm, accessed 3 March 2014.

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APPENDIX B. MODELING TOOLS

The Sandia National Laboratories (SNL) economic methodology described above uses a class of tools that can estimate economic impacts from a terrorist event involving a chemical facility. For example, if toxic chemicals are released at a chemical facility, the entire plant will likely shut down and the released chemical may disperse in a plume. This plume is likely to travel past the plant itself to the surrounding areas. Residential and commercial communities are likely to evacuate or shelter in place and businesses will temporarily close. The chemical plant itself will cease receiving input chemicals and shipping output chemicals, potentially affecting its suppliers and buyers. Decontamination crews will inspect and then clean the affected areas, and, once the area is considered safe, local activities will resume. Finally, the chemical plant will repair or replace the damaged processing units and resume production or the plant will halt production of the affected chemicals.

These physical disruptions will affect the local, regional, and national economies in many ways. First, businesses in the disruption area will largely cease conducting economic activity, reducing sales, employment, and income to workers. While some of these lost sales, for example, will return after the disruption, a fraction of them are permanently lost. Second, the cleanup efforts themselves will create business and employment for the cleanup companies, but these increases are likely small when compared with the broader business interruptions.

Third, the loss of the chemical plant's required input chemicals and produced output chemicals will impact the broader chemical supply chains in which it operates. As observed in historical case studies, the chemical plant would likely declare *force majeure (*a cessation of obligations by both parties to a contract), but then assist its customers in finding alternate sources of the affected chemicals. Chemical market prices may increase in the short run, while the overall set of chemical markets rationalizes supply and demand of all chemicals. If the disrupted chemical plant's output represents a large fraction of the market's chemical supply, the losses of chemical products could cascade to many other parts of the chemical supply chain; but if small, then there may only be a short and small increase in market prices. Finally, the replacement of the chemical plant's processing units will generate new investment, output, and employment.

Cleanup Costs

Following a chemical incident, steps must be taken to remediate or cleanup contaminated areas before people can reoccupy the affected area. Depending on the scale of the incident, the cleanup effort may be accomplished with local resources and capabilities or may require national-level resources and capabilities, as well as specific expertise. The time and cost of these resources and capabilities can vary significantly.

Costs incurred during the cleanup after a chemical incident can include debris removal, sampling to determine levels of toxicity, chemical-based decontamination, ventilation, destruction of contaminated materials, and many others. Costs are strongly dependent on the size of the area impacted, the infrastructure affected, and the type of incident: explosion, fire, or release.

SNL developed a comprehensive decision support tool for response and recovery activities following wide-area releases of Weapons of Mass Effect (WME). The tool is called the Prioritization Analysis Tool for All-Hazards/Analyzer for Wide-Area Restoration Effectiveness (PATH/AWARE). PATH/AWARE is a comprehensive tool that plans the sampling, waste disposal, decontamination, and clearance processes following a release. The tool uses decision logic to apply available resources to estimate the time and cost for recovery. The tool also has a prioritization module that facilitates the ranking of important infrastructures (e.g., hospitals, fire stations, police stations, etc.) based on recovery objectives (e.g., public health, emergency services, commerce, etc.). PATH/AWARE uses databases for infrastructure and building information to provide realistic situational awareness of an impacted area. PATH/AWARE was developed through funding from the U.S. Department of Homeland Security (DHS) and the U.S. Department of Defense and has been used extensively as a chemical and biological incident response tool.

PATH/AWARE began as a spreadsheet application in 2008 to provide analysis capabilities for a systems study for potential wide-area biological warfare agent releases as part of the Interagency Biological Restoration Demonstration (IBRD), funded by DHS and the Defense Threat Reduction Agency (DTRA). The tool was soon converted to a software application with a database engine and a mapping service to accommodate the complex nature of response and recovery operations. PATH/AWARE was used in a Simulation Experiment in 2010, which brought a number of stakeholders together from local, state, and federal agencies to use the tool in a variety of wide-area biological release scenarios. Upon completion of the IBRD program, DHS sponsored the Wide Area Recovery & Resiliency Program (WARRP). WARRP addressed chemical and radiological releases in addition to biological releases, and PATH/AWARE was updated to accommodate these additional types of hazards. Around the same time, DTRA began the Trans-Atlantic Collaborative Biological Resiliency Demonstration project, which focuses on wide-area biological releases outside the United States. DTRA is sponsoring the development of a web-based version of the PATH/AWARE tool, which should be completed during 2014. Table B-2 lists studies that employed PATH/AWARE.

Table B-2. Studies Using the PATH/AWARE Model

Year	Analysis	Publication
2008	Interagency Biological Restoration Demonstration (IBRD): to provide analysis capabilities for a systems study for potential wide-area biological warfare agent releases	Crockett, K. (2011)
2010	Simulation Experiment (SIMEX): local, state, and federal agencies to use the tool in some comprehensive wide-area biological release scenarios.	n/a
2012	Wide Area Recovery & Resiliency Program (WARRP): used to address wide-area biological releases and also chemical and radiological releases.	DHS (2012)
2012	Trans-Atlantic Collaborative Biological Resilience Demonstration (TaCBRD): "will demonstrate DoD's resilience to a wide-area biological event that affects civilian and military key infrastructure within the European Command (EUCOM) area of responsibility."	DTRA/SCC-WMD(RD-CB) (2011)

PATH/AWARE uses a Geographic Information System (GIS) representation (shapefile) of the impacted area, as shown in . PATH/AWARE GIS Representation of Chemical Release PATH/AWARE then draws upon the FEMA HAZUS model,[130] which provides detailed information on the number, type, and square footage of buildings affected by the chemical incident. Once the area impacted is defined, PATH/AWARE allows experts to select the resources and capabilities required for cleanup from a list of parameters. The set of parameters within each phase offered in PATH/AWARE were identified by experts as key to understanding cleanup cost and time, based on information gathered over many years. The phases include:

- *Resources:* The sampling capacity of people and teams collecting samples for the Screening, Characterization, and Clearance Phases is determined. Lab capacities for analyses are based on the number of samples that can be analyzed by domestic laboratories.
- *Screening:* A small number of samples are acquired to determine the areas for increased sample collection for the Characterization Phase.

[130] Federal Emergency Management Agency (FEMA), "HAZUS-MH 2.1," http://www.fema.gov/hazus, accessed November 8, 2013. The HAZUS dataset is fully integrated into the PATH/AWARE tool, which enables analysis of scenarios across the Nation.

- *Characterization:* Judgmental sampling[131] is used for characterizing areas to identify contaminated areas.
- *Waste:* These parameters define the approximate quantities of outdoor and indoor waste that require decontamination, sampling for waste classification, and then transport to a disposal facility. The waste module is patterned after the Environmental Protection Agency's (EPA) I-WASTE tool.[132] The metrics used in these calculations are based on defaults from the EPA tool.
- *Decontamination:* The best method of decontamination is determined based on the properties of the chemical released.
- *Clearance*: Statistical sampling[133] and judgmental sampling are both used on indoor areas to ensure safe re-entry to buildings and residences. Statistical sampling for residential space can be set for a certain confidence that a certain percent of the area is decontaminated: e.g., 95 percent confidence that at least 95 percent of the area is clean.

Figure B-1. PATH/AWARE GIS Representation of Chemical Release

[131] Judgmental sampling is non-statistical sampling where the location to sample is based partly on expert opinion; it is less time- and resource-intensive than statistic-based sampling.

[132] EPA, "Incident Waste Assessment & Tonnage Estimator (I-WASTE)," http://cfpub.epa.gov/si/si_public_file_download.cfm?p_download_id=508474, accessed November 8, 2013.

[133] Statistical sampling is random and systematic in order to provide specific confidence levels of clearance throughout the area of concern.

PATH/AWARE then uses unique algorithms to calculate cleanup time and costs based on the total area contaminated, the types of buildings impacted, and the total number of indoor square footage in need of decontamination. The total cleanup cost is broken into phases—characterization of contamination, waste removal, decontamination, and clearing buildings for re-entry—and the cleanup time is broken into a schedule of areas within the larger area of concern. PATH/AWARE provides a schedule of cleanup activities and the costs associated with each activity, as shown in Figure B-2 Cleanup Categories and Their Associated CostsThe total cleanup time is then used in REAcct for the assessment of losses due to business disruption.

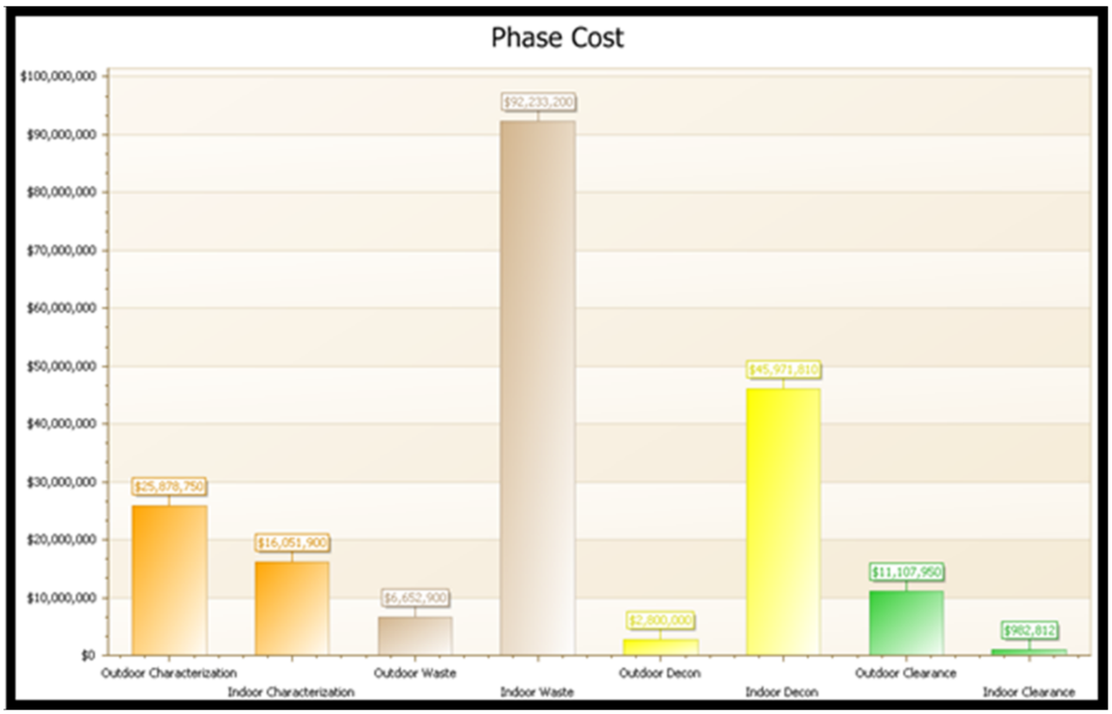

Figure B-2 Cleanup Categories and Their Associated Costs

Business Interruptions

One of the potential consequences of a chemical incident is the interruption of business activity near the incident. The temporary or permanent loss of business activity is a direct cause of economic impacts. Impacts to business activity can be measured as the effects to a single business, a collection of firms (e.g., a supply chain), a county, a state, a defined region, and the entire U.S. economy. Most of the economic impacts in the immediate aftermath of a business disruption are local and can be considered a microeconomic issue—local firms have immediate impacts on local economies. However, calculating the national, or macroeconomic, impact as a sum of the impacts to individual firms is extremely difficult.

For example, the loss of sales in one region could result in increased sales in another. Businesses may be interrupted to different degrees, depending on both the type of business and the type of incident. For example, businesses that provide goods and services onsite (e.g., stores) would likely be more severely impacted than those that provide services offsite, can operate remotely, or have multiple sites of operation. The latter types of businesses may be able to function at some level during cleanup. The key factor that determines the economic losses due to business interruption is the period of time over which business operations are impacted.

REAcct is a stand-alone software tool that incorporates geospatial computational tools, economic data, and input–output algorithms to estimate rapidly the economic impacts from business disruptions due to natural or manmade events.[134] REAcct was developed at SNL and has been used extensively for a variety of real and hypothetical disruption scenarios in support of DHS. Table B-3 lists studies that used the REAcct Model.

Table B-3. Studies Using the REAcct Model

Year	Analysis	Publication
2004-Present	All category 3 or above hurricanes with disruptions of less than one year.	NISAC[135] reports
2004-Present	All national-level exercises with disruptions of less than one year.	NISAC reports
2009	Potential impacts of New Madrid Seismic Zone on infrastructure and economy	DHS (2009a)
2009	Potential impacts of Hayward Earthquake Scenario on population, infrastructure, and economy	DHS (2009b)
2011	Potential impacts of Cascadia Earthquake and Tsunami	DHS (2011)
2012	NLE12: Potential impacts of water outage on WDC area	

[134] For a detailed explanation of REAcct see Vargas, V.N., and M.A. Ehlen, REAcct: a scenario analysis tool for rapidly estimating economic impacts of major natural and man-made hazards, E, 16 February 2013.
[135] NISAC (National Infrastructure Simulation and Analysis Center) is a modeling, simulation, and analysis program within the Department of Homeland Security (DHS) comprising personnel in the Washington, D.C. area, as well as from Sandia National Laboratories (SNL) and Los Alamos National Laboratory (LANL).

The total economic impact of a disruption scenario is divided into direct economic impacts, which are those that occur to firms directly impacted by the disrupting event, and indirect economic impacts, which are those that occur to firms impacted by the directly impacted firms. REAcct provides county-level economic impact estimates in terms of lost gross domestic product (GDP) and employment.

Given a particular disruption that affects the national economy, a subset of the overall economy will be directly affected. The impacts of a business interruption generally effects production, or output, more significantly than demand. For each day of economic disruption, affected industries lose economic output and income for its employees. The simplest means for estimating the direct loss is to sum up the loss at each firm. However, these firm-level data are not available and impacts must be estimated. The U.S. Bureau of Economic Analysis (BEA) provides economic production, or output, data by industry, according to the North American Industry Classification System (NAICS). The BEA also provides number of employees by industry, also by NAICS. Combining this information with county-level data on employment by industry from the U.S. Bureau of the Census provides an avenue for estimating impacts to the national economy and employment based on disruptions at the county level. The direct loss in a given industry is estimated as the product of the lost daily value added per worker nationally times the number of employees in that industry in the disrupted region times the number of days of economic disruption. Summing over industries and regions gives an estimate of direct economic impact:

$$= \sum_{r=1}^{R} \sum_{i=1}^{I} \frac{Y_i^{US}}{365 * E_i^{US}} * E_i^r * d_i^r$$

Multipliers are used to estimate indirect impacts. An output-driven multiplier (estimates the indirect impact on all industries of a particular industry changing its level of output) is used to directly estimate the total (i.e., direct plus indirect) impact of the output change. The Regional Input-Output Modeling System II (RIMS II) multipliers[136] from the BEA are the most current multiplier available with detailed regional earnings by industry data. If *m* is the output-driven multiplier for a direct loss of output in industry *i* and region *r*, then the total impact of a change in output can be expressed as:

$$= \sum_{r=1}^{R} \sum_{i=1}^{I} \frac{Y_i^{US}}{365 * E_i^{US}} * E_i^r * d_i^r * m_i^r$$

[136] U.S. Bureau of the Census, “Regional Input-Output Modeling System II (RIMS II),” October 23, 2004, retrieved from http://www.bea.gov/regional/pdf/rims/RIMSII_User_Guide.pdf on November 8, 2013.

Use of REAcct can be summarized in the following three steps:

Step 1: Define the Interruption Areas. As with PATH/AWARE, REAcct uses a GIS representation of the area of concern. The level of business interruption within this area may vary based on the potential hazards; therefore up to four zones with different levels of economic disruption may be defined. Each zone may also be assigned a different duration for the disruption. This duration is the amount of time it takes to remediate the area and restore functions – a value calculated using PATH/AWARE.

However, it was assumed that cleanup starts from the perimeter of the area and works its way toward the center, and that the rate of cleanup (the size of the crew conducting the cleanup) is constant over time. As a result, over time the area experiencing business interruption becomes smaller. In other words, businesses located furthest away from the chemical incident will reopen before those at the center of the incident. For each scenario the affected area decreased by 25 percent after each quarter of the calculated disruption time. For example, if PATH/AWARE calculated a cleanup time of 1 year, the entire 1-mile radius was assumed to be interrupted for the first quarter of the year. During the second quarter of the year, 75 percent of the area was assumed to be interrupted, the third quarter 50 percent of the area, and finally only the last 25 percent of the area was assumed to be interrupted for the entire year. Finally, the area impacted by business interruptions for onsite scenarios was assumed to include the entire chemical facility.

Step 2: Compile the Economic Data. The counties located within the area of concern are identified and data on annual county sales, income, value-added per worker, and days of impact are compiled. Data are compiled at the county level and then categorized by industry type according to NAICS codes.[137]

Step 3: Estimate Impacts and Report Results Direct GDP and income losses are calculated for the indicated disruption time by multiplying the GDP per worker-day, by industry, and the number of lost worker days. Summing this value across industries yields the total direct GDP lost.

[137] NAICS codes are used to classify businesses according to their economic activity. The numbering system uses a six-digit code in which the first two digits designate the largest business sector (e.g., utilities, construction, manufacturing, retail, educational services, health care and social assistance, etc.). There are 20 of these business sectors.

Indirect economic impacts are measured as losses in other industries and households through losses of input materials purchased and lost income (which affects spending across all industries).[138] Total impacts are estimated by multiplying the direct impacts by the RIMS II multipliers. Multipliers are used in economic-impact analysis to translate a dollar of direct economic impact into total economic impact. (Indirect impacts are estimated by subtracting direct impacts from total impacts.)

Facility Replacement

For onsite incidents at chemical facilities, the cost to rebuild the facility, replace equipment, and restore operations is considered to be in addition to general cleanup costs. As a result, replacement costs are incurred in addition to the economic consequences associated with remediation and business interruption costs. CFATS facilities, which represent 35 percent or more of domestic capacities, are required to report the estimated cost of replacement for the production units associated with a specific COI.

Costs associated with the replacement of other buildings and infrastructures damaged or destroyed in a chemical incident, onsite or off, are not included in the model. For example, the cost of replacing a building destroyed by an explosion is not included. These costs are generally relatively small, difficult to estimate, and typically covered by insurance.

Chemical Supply-chain Disruptions

While the operations at the facility are disrupted, the throughput of goods into (upstream) and out of (downstream) the facility may be severely reduced. As a result, the operations of businesses that supply the impacted facility as well as those that use the goods produced by the impacted facility may also be disrupted, thereby causing indirect economic impacts.

The economic impact of chemical supply-chain disruptions resulting from onsite chemical incidents were analyzed using the N-ABLE™ supply-chain model[139] in concert with SNL's extensive expertise in chemical supply-chain analysis. Table B-4 lists studies that used the N-ABLE™ model. In addition, the historical case studies in Section 4 address examples of large-scale chemical plant accidents that resulted in disruptions to a portion of domestic capacity of

[138] These income-related impacts to industry are often called induced impacts; total economic impacts are then computed as the sum of direct impacts to industries, indirect impacts to industries that supply to the directly affected firms, and induced impacts of lost income.

[139] Ehlen, M. A., Sun, A. C., Pepple, M. A., Eidson, E. D., and Jones, B. S. "Chemical Supply Chain Modeling for Analysis of Homeland Security Events," Computers & Chemical Engineering, Vol. 60, February 2014.

key chemicals. The N-ABLE™ supply-chain model was used to analyze hypothetical disruptions at a large chemical complex and a medium-sized chemical facility to estimate potential supply-chain impacts from worst-case and average-case scenarios.

Table B-4. Studies Using the N-ABLE™ Model

Year	Analysis	Publication
2005	Impacts on chlorine supply chain of WMD-related disruptions to chlorine rail transport.	Downes *et al* (2005)
2006	Multimodal transportation effects on U.S. milk & milk products supply chain.	Downes *et al* (2006)
2007	Comparative analysis of the impacts of Hurricane Katrina on the chlorine, food, and Goodyear Tire & Rubber Company supply chains.	Ehlen *et al* (2007a)
2007	The potential impacts of a pandemic influenza on the U.S. manufactured food supply chains.	Ehlen *et al* (1007b)
2010	Potential impacts of natural disasters on chemical supply chains	Ehlen *et al* (2010)
2011	Resilience of chemical supply chains to natural disasters	Vugrin *et al* (2011)
2012	Validation of simulated transportation shipments against Texas chemical shipments survey data.	Stamber *et al* (2013)

N-ABLE™ is an agent-based supply-chain model. N-ABLE™ simulations provide insight on when, where, and how portions of the economy outside the disruptive event might be impacted by the event. This includes the firms and commodities directly and indirectly impacted and the time required to return to normal operations. N-ABLE™ provides these estimates by conducting simulations based on detailed supply-chain models of individual firms, their markets, and their supporting infrastructure (e.g., transportation). The N-ABLE™ Chemical Supply-chain Model is designed to model the interactions of chemical production units, representing their purchasing, sales, and production decisions as economic agents in a cross-enterprise model of the Chemical Sector.

Modeling the flow of chemicals in large U.S. supply chains requires detailed data on chemical processes, production units, plants, and markets. Table B-5 outlines the data categories used to create chemical supply-chain models. N-ABLE™ uses detailed plant and production unit-level data, including company name, address, geo-location, chemical names, captive production, and annual capacities. The transportation infrastructure information includes rail and road segments as well as pipelines that transport the chemicals. The chemistry category refers to the process information that includes stoichiometry and production technologies. Chemistry data directs the flow of chemicals from one production unit to another in ways that are consistent with thermodynamics and stoichiometry. The end-use category refers to downstream product distributors and wholesalers that use the processed chemicals in other sectors of the economy. The economics category includes the number of employees and imports and exports needed to balance the flow of chemicals.

Table B-5. Chemical Supply-chain Data

Category	Detailed information
Plant information	Parent company, units, geo-location, chemicals, production capacities, captive production
Infrastructure	Transportation, port access, pipelines
Chemistry	Process, technologies, stoichiometry
End use	Wholesalers, geo-locations, quantities
Economics	Employees, imports, exports

The data[140] are first gathered and authenticated in a relational data management system before application to the chemical supply-chain simulation model. The data management system provides a single, consolidated source of chemical industry information that can be used for a wide variety of modeling and analysis at varying levels of granularity.

The N-ABLE™ Chemical Supply-chain Model allows experts to build a supply chain based on chemicals of interest to the problem being addressed. This same supply chain can then be perturbed using the same GIS-represented area of concern used in PATH/AWARE and REAcct, thereby allowing a comparison of baseline to disrupted conditions, which enables analysts to understand more complex market interactions. The N-ABLE™ supply-chain model is composed of three main submodels of enterprises, markets, and transportation. Each chemical plant in an

[140] The primary data sources include Directory of Chemical Producers obtained from IHS. Chemical process information is derived from a number of sources, including Chemical Economic Handbook (SRI Consulting, 2009c), Ullmann's Encyclopedia of Chemical Technologies (John Wiley & Sons, 2010), Kirk-Othmer Encyclopedia of Chemical Technology (John Wiley & Sons, 2007), and the open literature.

N-ABLE™ simulation is modeled as an enterprise that purchases, receives, and stores input chemicals in a warehouse and uses these input chemicals in one or more productions that are often connected in series or parallel to produce output chemicals that are then stored and ultimately sold in markets.

Each chemical plant can buy from or sell to other chemical plants using merchant markets that are characterized by a market map {g, r, m} that contains chemical g, market region r, and transportation mode m. For example, a particular buyer who is in charge of purchasing one chemical in one market using one or more transportation modes uses the set of market maps {g, r, {m}}. Such a buyer has access to all chemical sellers who sell the same chemical g in the same market r and have at least one mode m in common. For the model to function properly, at least one seller who has one of the {g, r, m} in the buyers set {g, r, {m}} is required. Given that chemical plants can buy and sell multiple chemicals in multiple markets and ship using multiple transportation modes, the full set of chemicals, markets, and transportation modes in the model is the union of the market maps of all buyers and sellers.

N-ABLE™ uses a variant of the traditional competitive model, in which many buyers and sellers compete in the market and no particular firm exerts significant market power (ability to control price and market share) over other selling and buying firms. Firms can compete with one another based on price and buyers can shop for lower-priced suppliers.

Once a seller is contacted for an order and completes that order, the chemical is transported using a particular mode of transportation: rail, road, water, and/or pipeline, as shown in Figure B-3. The transportation model consists of a large-scale, multi-modal and intermodal network, in which shipments can transfer from one mode to another at specific designated nodes. Shipping routes can and are altered due to disruptions in transportation infrastructure. The transportation model is composed of network graphs of North American rail and road transportation and U.S. and international water transportation;[141] shipping components that keep track of the fixed and variable costs of shipping by each transportation mode; and network algorithms to compute the shipping route of a particular shipment between a seller and buyer. Each of the transportation modes specified by a buyer or seller is meant to reflect the physical transportation capabilities of its plant. Shortest-path algorithms determine shipment routing on the transportation network, including during disruptive events.

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[141] Petersen, B.E. ,"CFS multi-modal network documentation," 2010, http://cta.ornl.gov/transnet/Cnetdoc.zip, accessed FebruaRY 1, 2012,

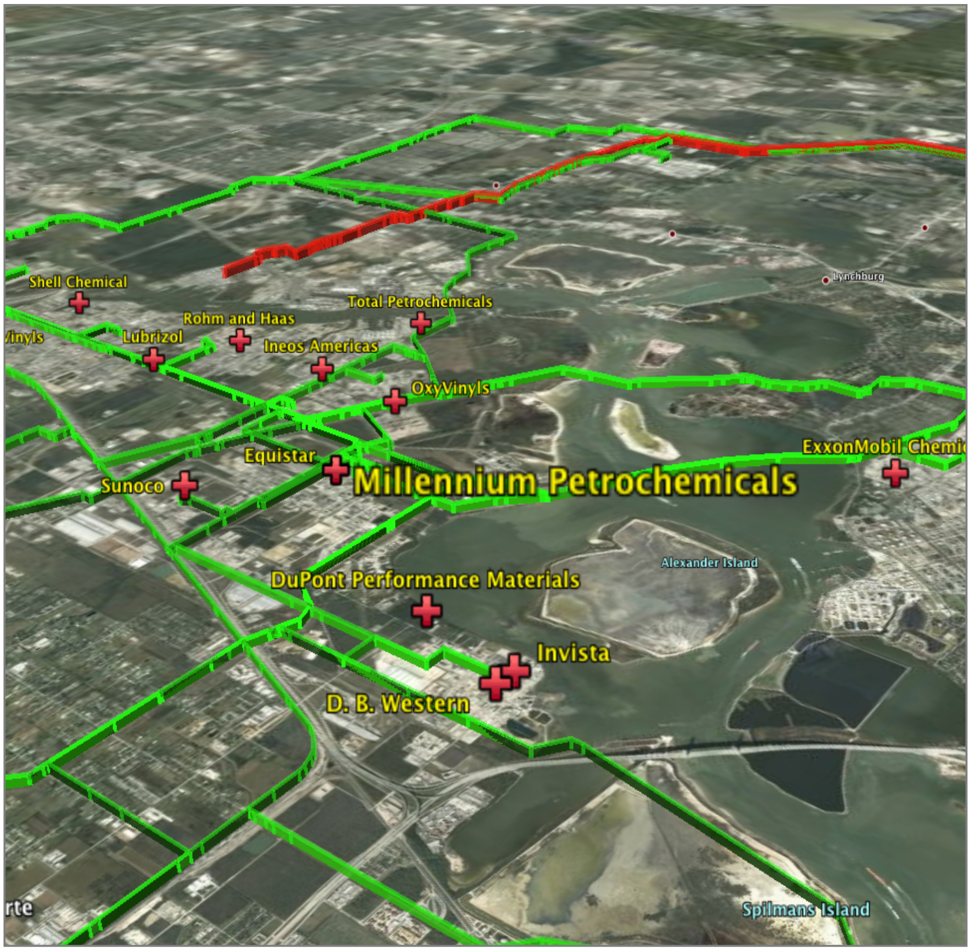

Figure B-3. N-ABLE™ Pipeline Network

The results of N-ABLE™ simulations of chemical supply chains and their disruption were validated through comparison with actual events. A model of the U.S. chlorine supply chain was validated against a prior analytical report[142] to compare modeled chlorine producers and consumers with chlorine industry operations during baseline and disrupted conditions. Simulations of impacts to the U.S. petrochemicals supply chain from Hurricane Dean were compared favorably against direct estimates of impacts from several chemical companies in the path of the hurricane.

National Macroeconomic Model

[142] Downes, P. S., Ehlen, M. A., Loose, V. W., Scholand, A. J., and Belasich, D. K., 2005, Estimating the economic impacts of infrastructure disruptions to the U.S. chlorine supply chain: Simulations using the NISAC Agent-Based Laboratory for Economics™ (N-ABLE™) (OUO), SAND2005-2031, Sandia National Laboratories, Albuquerque, NM.

The Oxford Economic Model, a macroeconomic model, is used to measure the impact of chemical incidents on the broader U.S. economy. The model itself estimates changes in production, consumption, trade, and prices for hundreds of economic sectors, using statistical macroeconomic relationships between economic production and consumption.[143] A national macroeconomic model is needed in the method because regional economic models tend to measure only short-term economic impact and are driven by regional spending, without specific consideration of the impact of this regional spending on the long-term national economy. The following sections describe how the macroeconomic model uses each of the constituent economic impacts to estimate the overall national economic impact of the disruption scenario.

Cleanup costs have long-run negative effects because they divert expenditures away from more economically beneficial goods and services, such as domestic manufactured goods.

The total amount of impact given by the REAcct model is assumed to be distributed over the number of quarters of the cleanup effort, with the peak amount coming in the first quarter, and each succeeding quarter reduced in a linear fashion until the end of the cleanup. A sum-of-years-digits accounting methodology is used to determine the actual quarterly impact figures. Initial estimates consider both direct and indirect economic impacts. This estimate assumes that both upstream and downstream industries in the surrounding region are adversely impacted by the loss of the directly impacted industries—i.e., the customers of the directly impacted industries are not able to find alternative suppliers, and the suppliers of the directly impacted industries are not able to find alternative customers.

Like cleanup costs, facility replacement costs are assumed to replace expenditures that would have gone into actual capital expansion, rather than replacement. In the Oxford Model, cleanup costs and facility replacement are modeled as losses of productive capacity to produce output (GDP). Statistically, macroeconomic reductions in such capacity result in losses of GDP over time. Business interruption-based losses are modeled as direct losses of GDP over time. These direct losses of GDP are distributed to both losses of consumption (75 percent) and investment (25 percent), based on reasonable estimates about the returns of GDP to labor and capital in affected sectors.

[143] The Oxford Model uses Keynesian theories for short-run demand effects and neoclassical production theories for long-run supply effects. For more details about the model, see Oxford (2012).

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ACRONYMS AND ABBREVIATIONS

ACRONYM	DEFINITION
9/11	The terrorist attacks in the United States on September 11, 2001
ACE	Agent-based computational economics
AEGL	Acute Exposure Guideline Level
ARCO	Atlantic Richfield Chemical Company
AWARE	Analyzer for Wide-Area Restoration Effectiveness
BART	Bay Area Rapid Transit
BEA	(U.S. Department of Commerce) Bureau of Economic Analysis
CFATS	Chemical Facility Anti-terrorism Standards
CGE	Computable general equilibrium
COI	Chemical of interest
CSAT	Chemical Security Assessment Tool
CSB	U.S. Chemical Safety and Hazard Investigation Board
CW	Chemical Weapon
CWP	Chemical Weapon Precursor
DHS	Department of Homeland Security
DTRA	Defense Threat Reduction Agency
EDC	El Dorado Chemical Company
EPA	Environmental Protection Agency
EXP	Explosives
FEMA	Federal Emergency Management Agency
FTEs	full-time employees
GDP	Gross domestic product
GIS	Geographical Information System
HDPE	High-density polyethylene
IBRD	Interagency Biological Restoration Demonstration
IDLH	Immediately dangerous to life or health
IEDP	Improvised Explosive Device Precursors
IO	Input-output
ISCD	Infrastructure Security Compliance Division
MTBE	Methyl tertiary butyl ether
MTs	million tons

ACRONYM	DEFINITION
N-ABLE™	NISAC Agent-Based Laboratory for Economics
NAICS	North American Industry Classification System
OSHA	U.S. Department of Labor's Occupational Safety and Health Administration
PATH	Prioritization Analysis Tool for All-Hazards
PH&S	Public health and safety
REAcct	Regional Economic Accounting tool
ppm	Parts per million
RDD	Radiological dispersal device
RIMS II	Regional Input-Output Modeling System II
SNL	Sandia National Laboratories
WARRP	Wide Area Recovery & Resiliency Program
WME	Weapons of Mass Effect

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