Report

FIRE PROTECTION EVALUATION REPORT

PERSPECTIVES ON TANK FARM FIRE ITC DEER PARK (TEXAS), MARCH 2019

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Abbreviations & Acronyms

API	American Petroleum Institute
CSB	United States Chemical Safety and Hazard Investigation Board
FM	Factory Mutual (currently FM Global)
HCFMO	Harris County Fire Marshal’s Office
ITC	Intercontinental Terminals Company, LLC
LPDS	Loss Prevention Data Sheet
NFPA	National Fire Protection Association
Pub	Publication
PSM	Process Safety Management
RP	Recommended Practice

Definitions

Below are definitions for terms that may not be familiar to most readers and are provided for clarity. The source of each definition is provided in brackets after each term.

Containment area – The space surrounded by structures, typically called dikes or berms, intended to contain hazardous liquids. [Modified from FM Global and NFPA definitions for dike]

Boil-Over – An event in the burning of certain oils in an open-top tank when, after a long period of quiescent burning, there is a sudden increase in fire intensity associated with expulsion of burning oil from the tank. [NFPA 30, *Flammable and Combustible Liquids Code*]

Fire Hydrant – A valved connection on a water supply system having one or more outlets and that is used to supply hose and fire department pumpers with water. [NFPA 24, *Standard for the Installation of Private Fire Service Mains and their Appurtenances*] See figures for common fire hydrant types (all courtesy Mueller Company).

Dry-Barrel Hydrant

Wet-Barrel Hydrant

Post (Dry-Barrel) Hydrant

Dry-Barrel Hydrant with Integral Monitor Mount

Firefighting Tactics

Offensive Firefighting – The mode of manual firefighting in which manual fire suppression activities are concentrated on reducing the size of a fire to accomplish extinguishment. [NFPA 600, *Standard on Facility Fire Brigades*]

Defensive Firefighting – The mode of manual fire control in which the only fire suppression activities taken are limited to those required to keep a fire from extending from one area to another. [NFPA 600, *Standard on Facility Fire Brigades*]

Monitor – A fixed master stream device, manually or remotely controlled, or both, capable of discharging large volumes of water or foam. [NFPA 1964, *Standard for Spray Nozzles and Appliances*] See figures below for common monitor types. (Photos courtesy of companies identified.)

Fixed Monitor (Yellow Piping) with Nozzle (Bronze)
[Sanco SpA]

Portable Monitor (Red Piping) with Nozzle (Black)
[Rosenbauer]

Fire Apparatus Mounted Monitor
with Large Capacity Nozzle
(S&H Products, Inc.)

Trailer Mounted Monitor
with Large Capacity Nozzle
(William Fire & Hazard Control

1.0 Introduction

At the request of the US Chemical Safety and Hazard Investigation Board (CSB), Jensen Hughes was requested to provide wide-ranging input and discussion related to the Intercontinental Terminals Company, LLC (ITC) tank farm fire events that occurred from Sunday, March 17, 2019, through Saturday, March 23, 2019.

The information presented in this document is a combination of general requests made in the contractual scope of work identified by the CSB, as well as those items identified during subsequent discussions between the CSB and Jensen Hughes.

This report is not intended to be an in-depth investigation or report of finding, but instead provides information to the CSB team for consideration alongside other data outside the purview of Jensen Hughes. The information contained herein is based upon information provided by CSB, contained in contemporaneous information obtained from public sources (such as press releases, ITC documents made public, etc), published as accounts or interpretation in recognized periodicals or obtained via similar sources. Information obtained by sources such as social media, accounts, or assemblages of information on personal or corporate websites, advertising or opinion-editorial (op-ed) writings and similar publications were treated as speculative or unsubstantiated unless sufficient confirmatory information was obtained from fact-based sources.

2.0 General Information

On the morning of March 17, 2019, a fire initiated at the Deer Park, Texas terminal owned and operated by ITC, specifically within the “First and Second 80’s” tank farm, which is located on the south side of the ITC site. Figure 1 provides an aerial view of the ITC Deer Park terminal prior to the fire (obtained via Google Earth Pro software), while Figure 2 provides a closeup of the “First and Second 80’s” tank farm where the fire occurred.

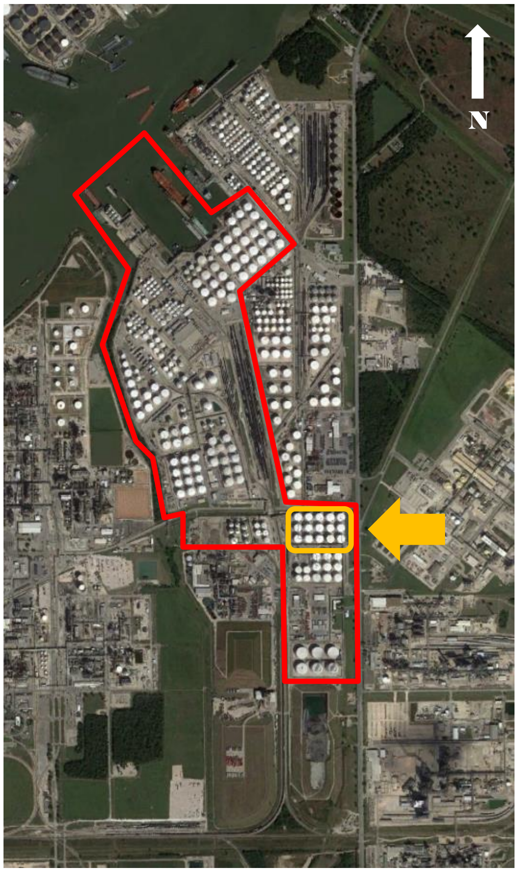

Figure 1: ITC Deer Park, Texas Facility with “First and Second 80’s” Tank Farm Highlighted (Imagery Date: October 28, 2017) [Source: Google Earth Pro]

Figure 2: “First and Second 80’s Tank Farm”
(Imagery Date: October 28, 2017) [Source: Google Earth Pro]
(Tank farm encircled in red. Area of suspected origin identified via blue cloud. Tank 80-8 highlighted in green.)

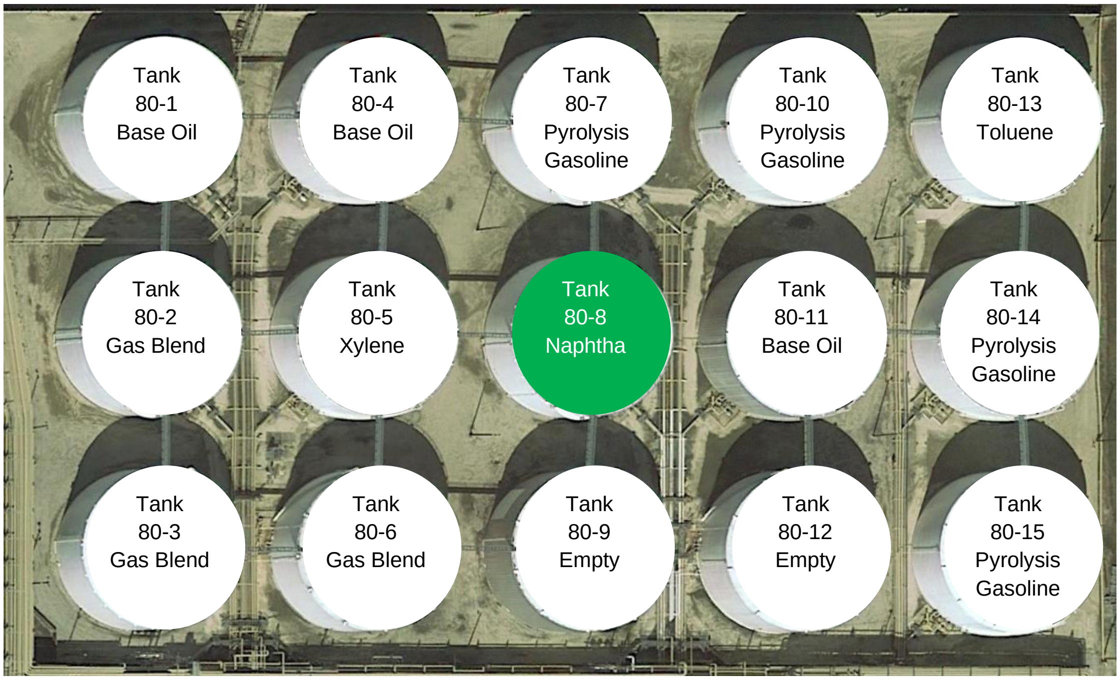

Figure 3: “First and Second 80’s Tank Farm” Tank Numbers and Contents at Time of Fire
(Imagery Date: October 28, 2017) [Source: Google Earth Pro, Contents from ITC Press Releases]
(Tank 80-8 highlighted in green.)

3.0 Facility and Tank Farm Development Information

Intercontinental Terminals Company (ITC) was founded as a division of Mitsui & Company (USA), Inc. on February 24, 1972. Over the next few years, acquisitions and leases were focused at the north portion of the site, primarily for the wharves, warehouses and support facilities located in that area. In 1974, approximately 135 acres south of Tidal Road, which were non-contiguous to the existing acquisitions to the north, were obtained from Rollins Environmental Services. Based on the description, this purchase appears to include the area of land where the “First and Second 80’s” tank farm was constructed. [ITC Deer Park History, 2020]

Construction and operating permits from the Texas Air Control Board for Tanks 80-1 through 80-12, are dated June 17, 1976 [Texas Air Control Board, 1976; 1977; 1978 and 1985]. Tank data plates recovered from post-fire debris show that Tank 80-8 was made in 1977 and suggest that construction of the tanks began soon after permits were issued. An aerial view of the facility from December 1978, shown in Figures 4 and 5 below, indicates Tanks 80-4 through 80-15 as being complete, as well as substantial completion of Tanks 80-1 through 80-3 [Google Earth, 2019]. Additionally, tanks to the south, Tanks 80-19 through 80-22, are identified to be under construction, and storage Spheres 25-1 through 25-4 and 50-1 are also constructed on the ITC property. Aerial photographs from December 1989 indicate Tanks 80-16 through 80-24 were complete, as was the Tank 160-series tank farm further south and the Sphere 36-series vessels to the west [Google Earth, 2019]. Aerial imagery from January 14, 1995, indicates Tank 80-34 and Tanks 60-1 through 60-3 were installed, effectively completing the current configuration of the site south of Tidal Road, as depicted in Figures 1 and 2 [Google Earth, 2019].

Tank 80-8 and its counterparts in the “First and Second 80’s” tank farm were 80,000 barrel capacity tanks, with a diameter of 110 feet and a height of 48 feet, based on the recovered data plate and documents provided by ITC Deer Park. With the exception of Tanks 80-9, 80-11 and 80-12, tanks in the farm were provided with an internal floating roof and an external cone roof. Tanks 80-9, 80-11 and 80-12 were provided only with a cone roof. [Texas Air Control Board, 1976a; ITC, 2019a]. At the time of the fire, Tanks 80-9 and 80-11 were provided with insulation, while the remainder are uninsulated. The insulation consisted of polyisocyanurate panels clad with aluminum jacket [ITC, 2019a].

The overall tank farm has approximate dimensions of 449 feet (north-south) by 732 feet (east-west) on the interior of the containment area, which was constructed at the same time as the tank farm based on the aerial photographs noted above. The surrounding containment wall is 4 feet in height.

Two tank farm manifolds (piping connections) are provided on the south side of the tank farm, external to the tank farm containment area and within its own containment system. One is located on the east side, approximately midway between Tanks 80-9 and 80-12. The other is located on the west, approximately midway between Tanks 80-3 and 80-6. The manifolds connect loading piping from other locations to piping systems serving the individual tanks (referred to as transverse piping). Transverse piping to Tanks 80-1 through 80-6 runs north-south between the Tank 80-1 through 80-3 group and the Tank 80-4 through 80-6 group. The transverse piping serving Tanks 80-7 through 80-12 runs north-south between the groups formed by Tanks 80-7 through 80-9 and Tanks 80-10 through 80-12. The transverse piping for Tanks 80-13 through 80-15 runs north-south between the Tank 80-10 through 80-12 group and Tank 80-13 through 80-15 group.

There are multiple configurations for how liquids can reach the transverse piping [ITC Drawings, various dates]. The primary method is via either, or in some cases both, of the manifolds identified above. However, there are several tanks, including Tank 80-8, that have delivery piping from nearby train or truck loading/unloading racks. Others have connections to additional manifolds, such as those in adjoining tank farms or at the dock facilities. For the purposes of this evaluation, the details of those connections are not as important as the fact that there are additional piping systems and processes present within the containment area. Since those piping systems may have liquid quantities ranging from full to residual, failure of the systems can add fuel to fires or can create pathways for fluid flow that might not be typically assumed within tank farms.

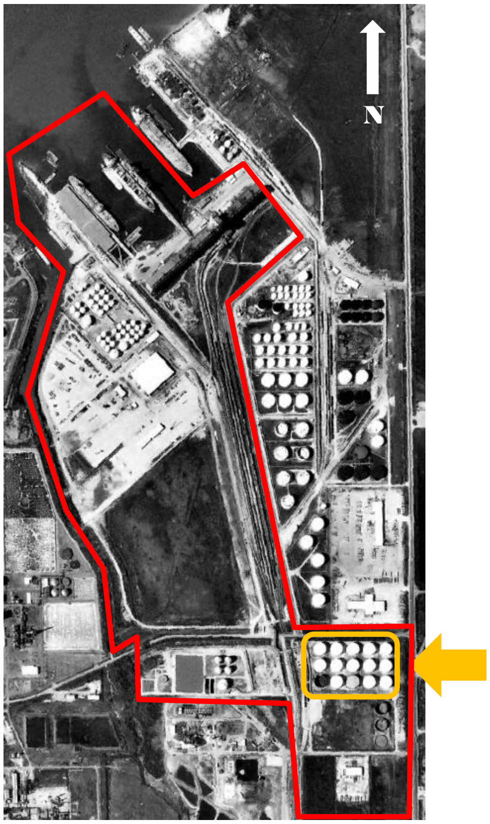

Figure 4: ITC Deer Park, Texas Facility with "First and Second 80's" Tank Farm Highlighted (Imagery Date: December 1978) [Source: Texas General Land Office via Google Earth Pro]

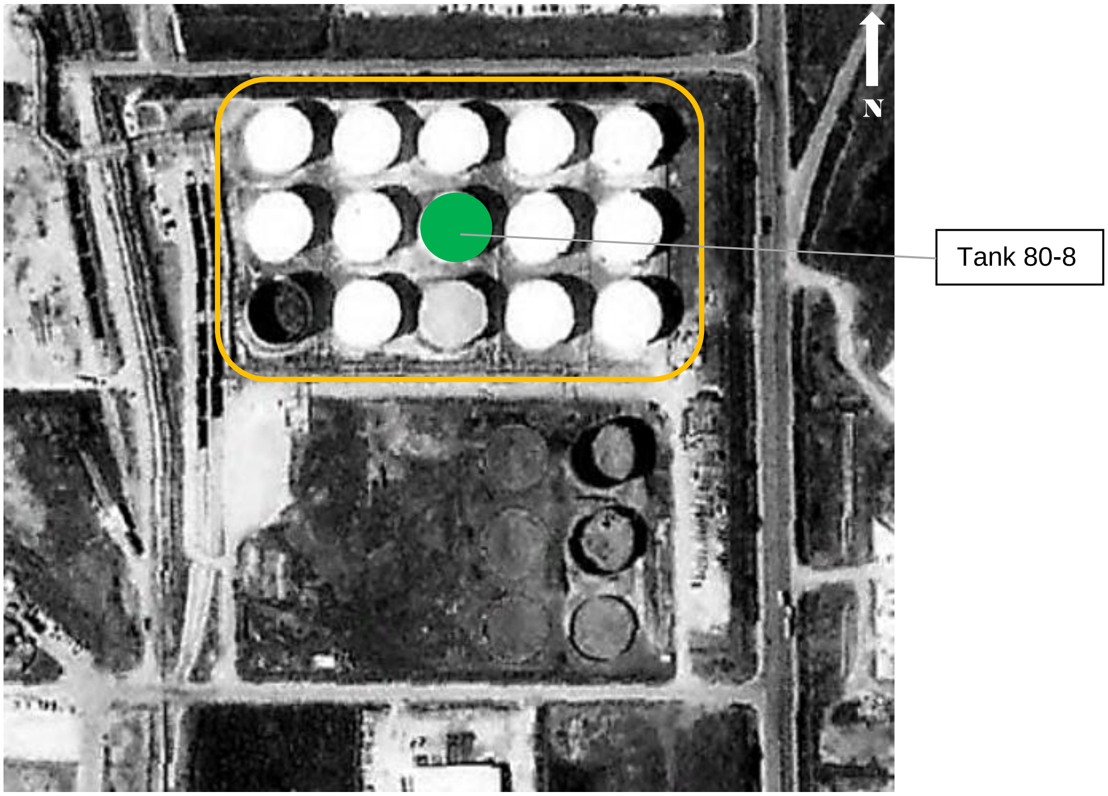

Figure 5: "First and Second 80's Tank Farm"
(Imagery Date: December 1978) [Source: Texas General Land Office via Google Earth Pro]
(Tank 80-8 highlighted in green.)

With the exception of Tanks 80-9, 80-11, 80-12 and 80-13, a pump system is provided at the base of the tank [ITC Drawings, various dates]. In general, the pump systems are either for filling/emptying of the tanks or to allow mixing within the tank. The Tank 80-8 system also allowed for blending of liquids delivered from various loading racks.

Drainage for chemicals within the tank farm is provided by a system of inlets placed between each of the fuel tank groups, with the piping between the outlets generally following the transverse piping described in the previous paragraph [ITC Drawings, various dates]. Three additional inlets are provided at the northwest area of the farm, with the piping running north-south to the west of the Tank 80-1 through 80-3 group. Each of the laterals are connected along the south of the farm, with east-west piping and eight inlets spaced across the area. The drainage connects to a similar system of piping for the tank farm to the south for the drainage piping transfers out of the area.

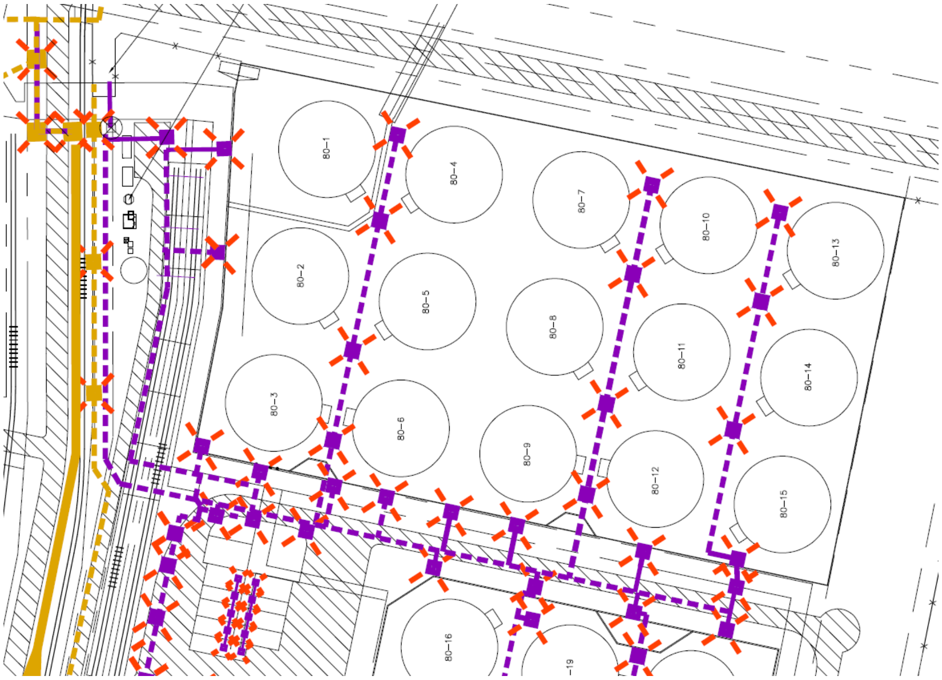

Figure 6: Drainage Arrangement
Purple Squares with Orange Arrows: Inlets; Purple Dotted Lines: Underground Piping
[Source: ITC Deer Park]

With respect to fire protection systems, there are multiple layers present [ITC Drawings, various dates; CSB Interview with ITC Vice President of Safety, Health, Environmental, Security, Regulatory Compliance and Operations (VP of Safety), 2019b]. Each of the tanks is provided with an installed foam fire suppression system, which is manually supplied and operated. The supply connections for the systems are located along the south containment wall, outside the containment wall. Hydrants and monitors (see definitions), the majority being combination units, are located around the perimeter of the tank farm. Additional monitors are provided between the Tank 80-1 through 80-3 and Tank 80-4 through 80-6 groups, with three monitors installed to spray water on surfaces that are otherwise difficult to access. A similar line is provided in the segment between the Tank 80-7 through 80-9 and Tank 80-10 through 80-12 groups. Water-spray systems were also installed on the tank farm manifold systems. These water-spray systems could also flow foam and required manual activation. The activation points for these systems is also on the exterior of the south containment wall. See Figure 7.

The fire systems and emergency response apparatus are supported by four fire pumps (numbered 1, 5, 6 and 7). All of the pumps are located at the north end of the facility, taking water from the ship channel. See Figure 8 for general location of all pumps.

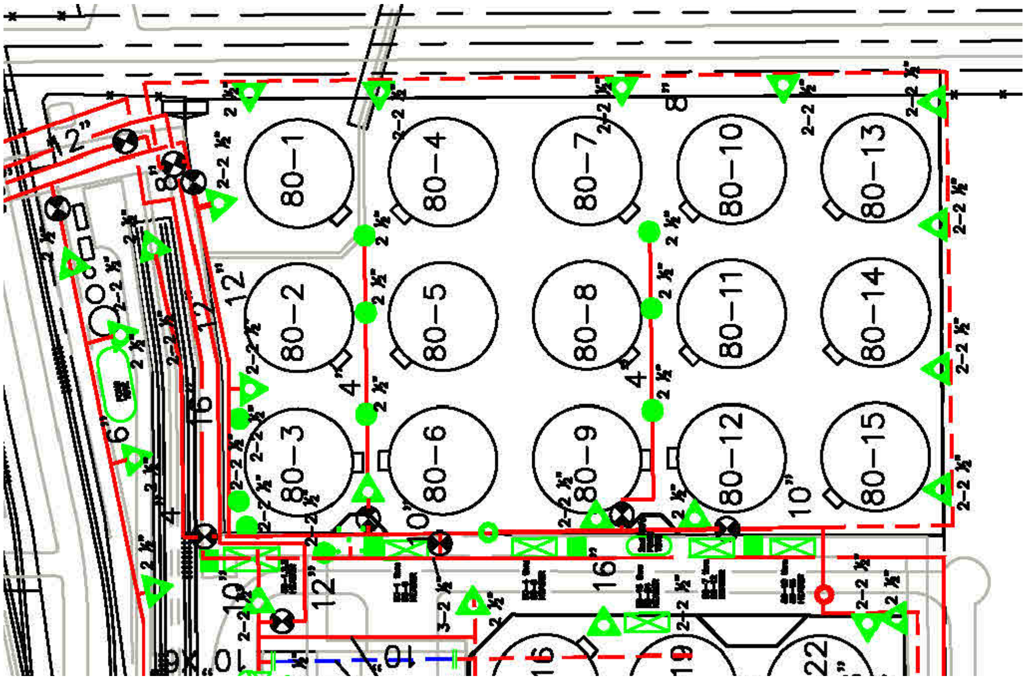

Figure 7: Fire Equipment Layout
Green Circles: Hydrants; Green Triangle with Circle: Hydrant with Monitor Attached; Green Rectangles and Ovals: Fixed Foam System Equipment; Red Lines: Water Piping
[Source: ITC Deer Park Facility Drawings]

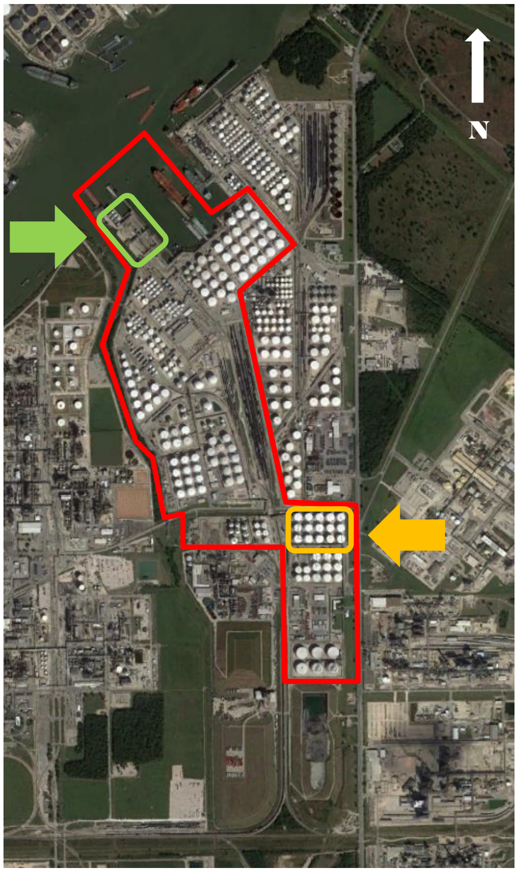

Figure 8: "First and Second 80's" Tank Farm (Yellow) and Location of Fire Pumps (Green) Highlighted
(Imagery Date: October 28, 2017) [Source: Google Earth Pro]

For vehicle-based emergency response, access is provided into the tank farm at the southeast corner, entering from a bump-out/turnaround in the road running south from the tank farm to that gate off Independence Parkway. Another access is provided at the northwest corner, allowing access from the area south of Tidal Road, near the rail loading equipment. Once inside the tank farm, there is available space for vehicles to access much of the area, except those areas described earlier where transverse piping, manifold equipment and drainage inlets are present.

4.0 General Approach to Tank Farm Fire Protection

To gain a better understanding of how the ITC "First and Second 80's" tank farm fire protection approach contributed to the March 2019 fire event, one must understand the various components to the approach and how they either overlap one another or become redundant to one another. As well, it is important to understand the underlying basis for the various recommended approaches.

In the broadest sense, the fire protection approach for a tank farm incorporates preventative, monitoring, mitigative and responsive elements. Each of the elements is intended to assist in controlling certain aspects of fire initiation and progression, with the overall goal of not having fires in the first place, keeping them small when possible and preventing large-scale spread of fire if those measures fail.

The approach to tank farm fire protection follows the general process safety model that has been in existence for over a century. It should be recognized that today's process safety methodology has much of its roots in the 1970s, with the rise of the Clean Air Act and Clean Water Act. However, similar approaches were used in the industry prior to that, generally dating to the mid- to late-1950s [American Insurance Association, 1968]. This approach is evident in the industry's most-often used fire protection standards for the design tank farms, documents such as NFPA 30, *Flammable and Combustible Liquids Code*; FM Global Loss Prevention Data Sheet (FM LPDS) 7-88, *Outdoor Ignitable Liquid Storage Tanks*; and American Petroleum Institute (API) Recommended Practice (RP) 2021, *Management of Atmospheric Tank Fires*.

Each of these industry standards and guidance documents describes the process safety approach to different degrees. For example, NFPA 30 provides the least amount of description, taking a very prescriptive approach and providing relatively minimal detail via supplementary information in annex and handbook text. On the opposite end of the spectrum, API RP 2021 provides significant explanation and detail for each of the elements for consideration, allowing operators to better assess which elements they would like to favor over others. FM LPDS 7-88 rests between these two documents, perhaps skewing closer to NFPA 30 than API RP 2021. FM LPDS 7-88 is ostensibly a prescriptive document, but provides supportive information for its recommendations that recognize a risk model that addresses issues not considered by NFPA 30.

There are, of course, other standards available around the world, ranging from locally or nationally developed codes to industry-specific insurance guidelines. It should be recognized, however, that the majority of these stem from a fairly limited set of source documents. For much of the first half of the 20th Century, the National Fire Protection Association worked closely with the various insurance agencies present during the period to develop many of their standards [NFPA History, 2020]. Among the most significant contributors in the field of flammable and combustible liquids was the Factory Mutual Insurance Companies, which is a primary predecessor to today's FM Global [FM Global History, 2020]. Those two entities, along with the National Board of Fire Underwriters (today's American Insurance Association), were intrinsic to the development of what would become NFPA 30 and continue to be key players in its current development.

The American Petroleum Institute (API), which was founded in 1919, began developing safety standards soon after its establishment as part of its relationship with the insurance industry [API History, 2020]. Industrial insurers had been pushing for standard safety practices to bring crude oil and chemical production into line with other business sectors, and the API worked with them accordingly. NFPA 30 had been first published in 1913, with assistance and input from the insurance and petroleum industry [Benedetti and Shapiro, 2018; NFPA 30, 2018]. From 1917 to 1957, it had been developed as an ordinance for adoption by local entities, but after 1957 it was developed into the standard that exists today. In the period that it was an ordinance, NFPA 30 relied heavily on the standards developed by API. Since 1957, the API was regularly involved in the development process for NFPA 30 and their documents continued to be referenced within the standard. When API RP 2021 was developed, the API obtained assistance from NFPA and various insurance agencies to ensure continuity of that relationship. It is no surprise, therefore, that API RP 2021 heavily references NFPA documents in its recommendations and justifications.

While NFPA 30, FM LPDS 7-88 and API RP 2021 diverge somewhat in their specific recommendations, based on their respective intents, the general framework is the same. Of particular note is that all of these standards are developed around probabilistically likely situations, as opposed to worst-case conditions. As such, a single fire location (for example, tank liquid surface, spill fire, etc) is assumed, and the size of fires, other than those on tank liquid surface, is based on industry-accepted failure probabilities (such as limited size openings in piping systems, failures of pump or valve packings, small areas of tanks corroding, etc) [Benedetti and Shapiro, 2018; API RP 2021, 2015].

The elements for tanks fire protection can be categorized as follows. Each of the industry standards and guidance documents noted contains a mix of these elements. However, it should be noted that the mix differs depending on the intent of the document (see Sections 5.1 through 5.4 for more information).

- Preventative measures
    - Materials and methods of construction – Aid in preventing loss of system containment. These focus on the tank itself, as well as piping and equipment that might be associated with or attached to the tank. Issues here include compatibility with fluids handled, corrosion conditions, integrity of joints, operation condition ratings (such as pressure, flow rate, temperature, etc) and reliability of equipment for pressure boundary conditions. Incorporated into these considerations are the resistance of items to environmental conditions, including loads from wind, precipitation, seismic, standing water and similar natural phenomena. Items such as insulation material are generally chosen with respect to ignition and flame spread resistance.
    - Ignition control – Aids in preventing ignition should a flammable liquid spill occur. This category includes electrical classification, static control, lightning protection and stray/induced voltage elimination. It can also include administrative controls such as those associated with smoking, hot work, hot surfaces (including on vehicles) and portable equipment.
    - Oxidant control approaches – In many cases, the vapors in the empty space between a liquid and a roof will be at concentrations above the upper flammable limit. In cases where the air-vapor mixture could be within the flammable range, the mixture can be augmented either with additional vapor so that the vapor concentration is raised above the upper flammable limit or with an inert gas, such as nitrogen or carbon dioxide, do that the available oxygen is reduced below the concentration needed for sustained flame development.
    - Process controls – With respect to fire protection, process controls are generally used to ensure system conditions remain within the design parameters for the piping, equipment, and tanks. Those parameters are generally pressure related, but they could also be related to temperature, flow rate, reaction time or other aspects. Process controls can be performed manually or via automatic control systems.
    - Precipitation drainage – Although nominally an environmental control, precipitation drainage is advantageous to fire prevention in that it aids in minimizing corrosion concerns and reducing excess forces on various items. It is also helpful in eliminating obstructions that might preclude performing needed corrective work in the area, such as standing water, ice development and presence of animals.

  - Mechanical damage control – Tanks, piping and equipment can be subject to mechanical damage for various reasons, with the most typical being vehicles. Engineered and administrative controls of various types can be employed, depending on what the expected hazards are.

- Monitoring measures

  - Process monitoring – Process monitoring tends to be a more passive approach to process controls. In these cases, the monitors may be the same as those for process controls, but rather than prompting an automatic or manual control they simply alert an operator to take some type of action. That action may or may not be pre-defined. Process monitoring could be as simple as visual observance during a process, or it could a sophisticated electronic system.

  - Adverse condition monitoring – Detection and alarm devices can be placed within the operating environment, either within the process/storage equipment or in the surrounding area, to detect conditions that represent releases in unexpected ways. This includes high- or low-pressure sensors, level sensors, leak detection, flammable vapor/gas detection and similar equipment.

  - Inspection, testing and maintenance – The administrative control of ongoing inspection, testing and maintenance is considered a monitoring measure because it validates integrity and functionality of systems and equipment. The program can identify individual issues with various items and can be used to track and trend multiple items to determine if a systemic issue exists.

- Mitigative measures

  - Facility siting – The location of a tank farm relative to its surroundings is considered a mitigative measure in that proper siting allow for reduced radiant exposure and impacts of other fire effects to other locations while emergency forces response. Within most standards, such locations specifically include structures on adjoining property, roadways adjoining the tank, important buildings on the same property and egress points both on and off the property. Other locations, such as other tank farms, rail lines, other operations on the same or adjoining properties and similar locations are addressed in a limited number of standards, but are often considered in evaluations.

  - Tank-to-tank spacing – Tank-to-tank spacing is similar to facility siting, but is intended to reduce radiant energy and other fire effects from one tank to another, even if within the same containment area. As well, the spacing is meant to address small spill fires or limited jet flames from pipe breaches. The tank spacing is also intended to allow space for emergency response operations.

  - Tank, piping and equipment design – Tanks are provided with vents of various types. In a passive mode, the vents allow vapor release, which aids in process control and mitigation of overpressure conditions. In a fire condition, venting of vapors is typically needed to avoid over-pressurization of the tank. Fluid overfill vents are also provided to ensure a tank cannot be filled with too much liquid. The design of piping and equipment often takes into account fire failure criteria, as well as providing pressure relief vents, elements that fail to a safe condition upon fire exposure or similar safety features.

  - Small spill control – Similar to precipitation control, elimination of small spills eliminates the immediate hazard posed by a flammable or combustible liquid, but also minimizes long term exposures to systems and equipment. This type of control can be localized, such as small containment walls (berms or dikes), and require manual intervention to correct or they may be a larger drainage system that removes spill to a collection or treatment system elsewhere.

  - Large spill control – Tank farms typically employ containment wall or barriers at the perimeter of the tank farm to control large spills. The containment is are typically sized to accommodate the largest tank within the containment plus certain amounts of precipitation. Where containment walls are impractical, a drainage and separate containment system might be used.

  - Vapor reduction systems – Some tank farms employ vapor reduction systems. Several common system types use firefighting foams or similar foams to coat the surface of a spill. Other materials are known to be used, depending on the fluid stored or used.

  - Active fire protection systems – A variety of fire protection systems can be installed within tank farms, including fixed foam systems for the tanks themselves, fixed exposure protection systems either on the tank or in the general vicinity of the tanks (via monitor nozzles, water spray systems, etc), fire detection systems that initiate process controls and equipment to support manual intervention. The type of fire protection equipment chosen for a given installation is generally chosen in balance with other preventative and mitigative measures (based on spread or exposure hazards to surrounding elements), as well as in consideration of responsive measures.

  - Passive fire protection systems – Passive fire protection includes both physical features that obstruct radiant energy or direct flame exposures, such as fire barriers or natural features (hillsides, for example) or physical separation that reduces those exposures to acceptable levels. The latter is most often used, with prescribed distances between tanks included in international standards.

  - Process controls – Process controls can be designed to aid in mitigating accidents by controlling fluid flow (such as eliminating delivery, venting to reduce pressure, moving of liquids to other vessels or tanks outside the accident area and other actions. Use of such controls can be manual or automated, but the methods vary considerably.

- Responsive measures

  - Active fire protection systems – Although the intent of active fire protection systems is typically to control fires and limit their spread, some events extend beyond the area of origin and require greater response. Installed fire systems will aid with these responses. Fire pumps, water supply systems, hydrants, monitors, fire department connections, foam connection points and other equipment fall into this category. It should be made clear, however, that the design of these systems must be considered in concert with the response agencies discussed below.

  - On-site emergency response agency – On-site emergency response consists of personnel and equipment dedicated to the site, often employed or directly contracted by the company that owns or operates the site. Personnel are trained in the hazards for the facility, with the apparatus and equipment matching the operations intended by the personnel. This can include any organized effort ranging from individuals that respond to small events such as spills or incipient fires to a dedicated organization such as a fire brigade or fire department.

  - Municipal emergency response agencies – Most tank farms are located in areas where a community fire and emergency response organization are present. This is typically some type of local fire department but can include more extensive services depending on the area. The experience and capabilities of such organizations, with respect to tank farm fires, varies considerably.

  - Mutual aid associations – In locations where multiple industrial facilities are located, shared resources through mutual aid associations is a common approach. These associations can combine any number of response agencies, and can include support from local industry, municipal response organizations, other governmental agencies (such as the US Coast Guard in areas with waterways) and established suppliers for materials and equipment. They may also involve non-traditional responders, such as heavy equipment operators, piping system operators and electrical system technicians and others. The experience and capabilities of the overall organization is highly dependent on that of each individual organization and the working relationships within the association.

  - Private emergency response contractors – Large industrial fires, particularly those that involve probabilistically unlikely events, can exceed the capabilities of the agencies identified above. There are a range of private companies, each with their own range of capabilities, that can be contracted to assist or take over the response. Some facilities will have such companies on an as-needed contract, while others will contract services when the need arises.

The extent to which each of these measures, particularly the responsive measures, is implemented varies among tank farms. The majority of the preventative, monitoring and mitigative measures are prescribed by industry standards, but some allow for judicious application. Features such as ignition controls, small- and large-spill control and materials and methods of construction have detailed recommendations that make them common approaches across industry. Features such as facility siting, passive fire protection systems, active fire protection systems and emergency response agencies are inter-related and the standards require such features at a generic level, but do not clearly define how such features must be implemented and how they should overlap. Detailed recommendations are available for some of those features once such systems are incorporated into a facility, such as NFPA standards for the design of fire suppression or fire detection systems. Similarly, there are few recommendations as to when an on-site emergency response agency should be provided, or what the capabilities of that agency should be, but there are national and local standards pertaining to personnel training, protective equipment, motorized apparatus, firefighting equipment, and other aspects of the agency once it is established.

The lack of prescriptive requirements for these aspects of tank farm fire protection often make it difficult for those unfamiliar with the balance of risks to determine how well a facility might be protected or how impactive a feature, or lack thereof, might be to an emergency situation. Even for those with a detailed familiarity with the various features and their risk implications, it is sometimes difficult to judge the impact a given feature may have overall. Because of that, within the context of this report, the opinions of potential lessons learned are based on the experience and opinions of the author, and it should be recognized those perspectives can be debated.

5.0 Engineering, Process Safety and Risk Management Considerations

Many aspects of the fire protection of tank farms are driven by regulatory requirements, such as adopted codes and standards within a local jurisdiction, national regulations for pollution control and laws regarding safety. Since at least the mid-1960s, local and/or state governments have had a direct hand in reviewing and permitting tank farms, both from a construction standpoint and a continued operation perspective.

As noted previously, available information from the tanks and original permits put tank construction between 1976 and 1978. If one accounts for typical industry timelines, obviously adjusted for the information technology methods of the mid-1970s, for civil engineering surveys, soil sampling for structural considerations, engineering and design, permit application and approval, procurement of tank construction services and scheduling and mobilization for construction, it is likely that engineering design would have occurred in the latter part of 1975 or the early portion of 1976.

An attempt was made to determine what agencies may have had a hand in reviewing and permitting the tank farm based on that assumption for the beginning date of facility design. Admittedly, this was a difficult undertaking given the length of time that has elapsed from original construction to the time of the fire. A request for original design plans and permitting information was made by the CSB, but ITC indicated that such information was not available. Therefore, information derived within this section is somewhat speculative and based on the data available.

It is clear, based on permits provided by ITC to CSB, that the Texas Air Control Board issued construction and operational permits for the "First and Second 80's" tank farm. What is unclear from a historical standpoint is what regulations, codes, standards, or other criteria were used as the foundation for the permits. The available histories of the Texas Air Control Board suggest the organization had a broader span of control during the 1970s than it has now, and could have had oversight of fire protection issues as part of its role as a regulator of pollution control concerns [TCEQ History, 2020]. However, legacy documents are unclear.

Other Texas state organizations that oversee crude oil and chemical operations, such as the Texas Railroad Commission, were found to not have oversight of the facility, as the extent of their responsibilities terminated at the site boundary.

Available information for the Harris County Fire Marshal's Office, which was established in 1974, and the Deer Park Volunteer Fire Department Fire Marshal's Office, which also appears to have been founded in the early 1970s, suggests that those organizations had not yet matured to a point of reviewing and permitting the industrial facilities within the jurisdiction [Zelade, 2011]. The Texas State Fire Marshal's Office was established as a standalone entity in 1975, but it existed as far back as 1910 under other the Commission of Insurance and its predecessors. Various histories suggest the State Fire Marshal's Office could have had review and permit authority, but no confirmation of this fact could be obtained.

At about the same time, national regulations were coming into play via the Occupational Safety and Health Administration. Code of Federal Regulations, Title 29, Part 1910 (29 CFR 1910) saw its first publication in 1974 and required compliance to NFPA 30 in its Subpart 106 series pertaining to flammable and combustible liquids [39 FR 9957]. Given this, there would have been a national regulatory obligation to utilize NFPA 30 and related codes and standards, regardless of the enforcement structure within the State of Texas. See Section 5.3 for more discussion on 29 CFR 1910 issues.

Outside the regulatory structure, but within the realm of good engineering and risk management practice, were a wide range of documents that could have informed the original design of the facility and supported continued operations. API RP 2021 has an original publication date of November 1974, but issues with printing delayed its public release until sometime in early 1975 [NFPA, 1975]. Therefore, it would have been newly available at approximately the time of design engineering for the site.

Although FM LPDS 7-88 wasn't published yet in its current form, the predecessor of FM Global did make its recommendations available via the *Handbook of Industrial Loss Prevention*, which had been published since 1959 and contained an entire section on flammable and combustible liquids storage [Factory Mutual, 1967]. Other documents, such as the *Hazard Survey of the Chemical and Allied Industries* pamphlet prepared by the American Insurance Association, first published in 1968, outlined the interactivity of process and fire safety [American Insurance Association, 1968]. The *Fire Protection Handbook*, published by NFPA, was also available and contained explanatory information to support NFPA 30 and general industry practices for fire protection in the process industry [NFPA, 1969]. These documents and others were available at the time of design and construction, and have continued to be available for emergency response and risk evaluation.

5.1 NFPA 30 CONSIDERATIONS

As noted above, the assumed approximate date for design is late 1975. The 1976 Edition of NFPA 30 wasn't approved until November of that year and was published in early 1977. Given that, the previous edition, 1973, would have been available for design and regulatory enforcement. That version of the standard was used to evaluate the original design. It should be noted, however, that the evaluation is limited to large-scope items, based on the available information, that could have influenced the fire event, and should not be considered an in-depth analysis of all aspects of the design.

Of obvious importance to the basic question of fire spread are spacing requirements (for example, from tank-to-tank, from tanks to adjoining buildings, from tanks to other process equipment, etc). It should be recognized from the outset that the spacing requirements in NFPA 30 are derived from the experience and data collected by committee members and the general industry. The following is taken from commentary in the *Flammable and Combustible Liquids Code Handbook* (2018 Edition) for Section 22.4.1 of NFPA 30 (2018 Edition) [Benedetti and Shapiro, 2018]:

> *The separation distances specified in the tables were developed through evaluation of storage tank fire incidents over the 70 or more years since this Code was first conceived. The minimum distances*

> *to adjoining property and between adjacent tanks…have occasionally been decreased over the years as the mechanism of fire spread has become better understood through experiment and experience.*

Although not clearly stated in this or other texts on the subject, an underlying assumption for the safe spacing of tanks is eventual emergency response and application of firefighting water or foam. As well, the spacing is meant to address radiant exposures from small ground fires that will be suppressed quickly by responders. Larger ground fires, particularly ones that expose adjoining tanks directly, are not assumed within the tank spacing requirements.

While the various texts recognize that fires may burn for some extended period, there is no stated objective that the proscribed spacings will definitively preclude ignition or damage of adjoining tanks or structures without some type of intervention. The premise that firefighting intervention will occur is based on the same loss records cited by the paragraph above, in that few of the incidents that are considered by the committee don't involve direct firefighting for the tank fire or exposure protection for surrounding structures. This is mentioned, though not explicitly stated, in the commentary in the *Flammable and Combustible Liquids Code Handbook* (2018 Edition) for Section 22.4.1 of NFPA 30 (2018 Edition):

> ***Protection.*** *In all three tank categories, distinction is made between the presence or absence of protection for exposures, as defined in 3.3.46 and explained in more detail in this commentary. The intent is that, if fire should occur in the tank, some fire-fighting capability will be available to prevent fire spread to the adjacent property. The fire in the tank is assumed to safely burn out, and no attempt will be made to extinguish it.*

NFPA 30 (1973 Edition), Section 2031 required aboveground tanks operating at near-atmospheric conditions to be constructed in accordance with any one of a number of industry standards, dependent on the type of tank and the fluid to be stored. Among the referenced standards are those from Underwriters Laboratories and the American Petroleum Institute. Without specific design specifications or drawings, one cannot be certain that the tanks were built to one of the noted standards, but given that similar requirements are present in NFPA 30 dating to the 1957 Edition and that the standards noted in Section 2031 had been published since at least the early 1960s, one could safety assume that compliance to basic construction was achieved. Those same standards include requirements for standard and emergency vents, which are called for in Sections 2140 and 2150. Those features are assumed to have been provided.

With respect to location and spacing, there are several applicable requirements. Section 2110 requires all aboveground vertical tanks containing stable flammable and combustible liquids (other than Class IIIB), operating below 2.5 psig and not containing liquids with boil-over characteristics, which would include all the tanks and permitted liquids in this tank farm, to comply with Table II-1 for spacing to property lines, for protection on neighboring lands, and to important buildings on the same property, for control of fire spread to a single owner's property. The required distance to a property line is one-half the tank diameter or 90 feet, whichever is less, for tanks with installed fire protection, and a full tank diameter for tanks without such a system. Input from ITC personnel suggests that the fire protection systems were present at installation of the tanks, so the protected tank requirements can be used. Therefore, the specified distance would have been 55 feet, based on tank diameters of 110 feet. For structures on the same property, the allowable distance is either one-sixth the diameter or 30 feet, whichever is less. Again, for a tank with a diameter of 110 ft, the allowable distance would be approximately 18.4 feet. As can be observed in Figures 1 through 4 above, these distances are easily met for the structures present at the time of installation.

For shell-to-shell spacing, Section 2121 would have been applicable. It identifies the required shell-to-shell spacing to be one-sixth the diameters of the two adjacent tanks. As with the above spacing, this criterion is based on tanks containing Class I through Class III liquids that are stable and not prone to boil-over and the tanks are operating at less than 2.5 psig. For this case, the required spacing would be one-sixth of 220 feet, which is approximately 36.7 ft. Measurements taken from available drawings and aerial photographs suggest distances between 35 and 37 ft. Therefore, it is assumed the tanks met their required spacing when installed.

Of note, however, is Section 2125, which stated “When tanks are in a diked [containment] area containing Class I or Class II liquids, or in the drainage path of Class I or Class II liquids, and are compacted in three or more rows or in an irregular pattern, greater spacing or other means may be required by the authority having jurisdiction to make inside tanks accessible for fire fighting purposes.” Additional spacing does not appear to have been provided in this case, but attempts to address the concern appear to have been made by providing firefighting monitor nozzles within selected areas. The nozzles would assist in providing cooling water to the tank faces that are otherwise obstructed when at the perimeter of the tank group. This would address the intent of the NFPA 30 requirement, although there is no clear information as to whether

Section 2170 identified requirements for containment. Containment walls are not specifically required, but they were the primary means employed for containment (and remain so today). Section 2172 identifies that the containment must be sized to accommodate the volume of the largest tank, with consideration of any other tanks or large equipment within the containment accounted for. The tanks are sized for 80,000 barrels, which equates to 3,360,000 gallons (assuming a barrel volume of 42 gallons) or 449,138 cubic feet. As noted earlier, the containment inner dimensions are approximately 449 feet by 732 feet, resulting in a horizontal area of 328,668 square feet. Each tank, assuming a 110 feet outer diameter, would occupy a horizontal area of 9,503 square feet. Subtracting the area of 14 of the tanks in the farm (since the failed tank is being considered) from the total area gives 195,626 square feet. Dividing 449,138 cubic feet (needed volume) by 195,626 square feet (available area) results in a needed depth of approximately 2.3 feet. The containment walls at the facility are 4 feet tall, providing ample additional volume for local precipitation, additional equipment, vehicle ramps and other items that might affect volume.

Section 2173 has additional requirements for the construction of containment walls that cannot be fully evaluated due to a lack of design drawings and potential modification over time. Other features, however, can be examined. Section 2173(g) required that subdivisions be provided for any containment containing two of more tanks. Those subdivisions could be drainage channels or intermediate containment walls. The drainage between the tanks within the containment area as described earlier (see latter paragraphs of Section 3.0) does not appear to conform with Section 2173(g)(2), which covers tanks in excess of 100,000 gallons and states:

> *(2) When storing normally stable flammable or combustible liquids in tanks not covered in sub-paragraph (1), one sub-division for each tank in excess of 100,000 gallons (2,500 bbls.) and one sub-division for each group of tanks (no tank exceeding 100,000 gallons capacity) having an aggregate capacity not exceeding 150,000 gallons (3,570 bbls.).*

The drainage as provided segregates the tank farm into groups of three tanks each, while Section 2173(g)(2) would have required the drainage to be provided such that each tank was separated from adjoining tanks. Section 2173 allows for the use of intermediate containment walls to either replace drainage or augment drainage, however no intermediate containment walls are provided. The sloping and draining across the entire tank area, evidenced by a general slope from the north to south direction and additional drains at the south side of the farm, may have been provided to offset the lack of inlets between tanks. In theory, the slope would move any spilled liquids away from the immediate tank of concern and transfer the liquids to the drainage system at the south side. As an alternative approach, the provided condition doesn’t satisfy the intent of the requirements in Section 2713(g)(2).

Section 6710 on fire control required the provision of small hose systems and fire extinguishers for initial fire control, but is relatively limited for large-scale fire control measures. The section, in its entirety, reads:

> *6710. Suitable fire-control devices, such as small hose or portable fire extinguishers, shall be available to locations where fires are likely to occur. Additional fire-control equipment may be required where a tank of more than 50,000 gallons individual capacity contains Class I liquids and where an unusual exposure hazard exists from surrounding property. Such additional fire-control equipment shall be sufficient to extinguish a fire in the largest tank. The design and amount of such equipment shall be in accordance with approved engineering standards.*

The spacing requirements noted above are for protected tanks, so it can be assumed that the tank-mounted foam fire suppression systems were installed at the time of tank design and construction. The provided monitors at the perimeter of the tank farm were a typical approach for manual tank fire suppression and exposure control. The intermediate line of monitor nozzles, installed within the tank farm as described earlier, are a somewhat unusual approach, in that they would require responders to enter the tank farm enclosure. They appear, however, to have been installed to, as a minimum, provide exposure protection for tank surfaces that would be inaccessible from the perimeter monitors. Providing monitors to achieve the general goal of tank cooling is common and accepted, but placing them between tanks and within the containment area is

In the 1973 Edition of NFPA 30, insulation on tanks was considered relative to vent sizing requirements, but was not included in tank separation distance requirements. There were no specific requirements regarding combustibility, flame spread or other fire-related characteristics, but Section 2157 did require insulation to remain in place during fire exposures, to not be dislodged by hose streams and to have a thermal conductance value of at least 4 British thermal units (Btu) per hour per square foot (Btu/hr-ft^2) if it were to be accounted for in certain ways for venting calculations.

There were no restrictions to performing firefighting operations within the containment area of tanks, though NFPA 30 discouraged it via general information in the Appendix. If such operations were present, they needed to be performed in accordance with other requirements in NFPA 30 (for handling, process, etc) and had to be controlled for ignition prevention and hazard exposure to the tanks.

Given the information above, the tank farm can be said to have been largely designed following the general parameters of the 1973 Edition of NFPA 30. However, there are some issues that complicate ground fire scenarios such as the one being evaluated herein. The overall drainage system is problematic in several ways.

One is that such drainage systems were not required to be designed for large-scale spills, and in this case resulted in the drains being inadequate to move liquids quickly from the area. Even if the system had been sized for such a large spill, the inlets were positioned along the same pathway as the transverse piping and the general slope of the tank farm overall would have moved the liquid toward pipeline systems, particularly the transverse piping racks and the manifolds at the south side. As a result, a “running fire” (i.e., one that tracked with the spill) would expose other tanks and piping before entering the drainage system. That appears to have been at least partially the case in this particular fire.

A second concern is that the movement of the fire toward the south, due to the drainage, prevented safe access to the fire system valves and foam connections located along that south wall. Those same safety reasons would be applicable to placing personnel at monitor nozzles or locating fire apparatus and personnel in this area.

That same slope likely also contributed to some of the initial tank exposures and can explain some of the fire progression. Burning liquids that were on the ground during the initial and subsequent releases would have followed the slopes toward the inlets to the east of Tank 80-8 and the general slope moving south toward Tanks 80-9 and 80-12, likely had some contribution to thermal exposure to those tanks as the liquid moved closer or past the tanks on their way toward drainage points. The southward movement would have continued as the drainage piping became overwhelmed, partially explaining the greater range of fire spread and damage on the south side of the tank farm than at the northern section.

With regard to subsequent changes in NFPA 30 since the time of design, the requirements for tank styles and material choices, construction standards, tank spacing (both shell-to-shell and to other locations), piping systems, and venting have not significantly changed in current editions. As well, the general requirements for drainage and containment have not changed considerably since that time, although there are some changes to the details of various components of the design. Placement of process equipment within the tank farm remains permissible, with newer editions (since the 2012 Edition) requiring a closer examination of such operations and their hazard exposure to the tanks.

On the whole, the tank farm could be configured largely similar to its original design if it were built more recently, if only NFPA 30 inputs are considered. It should also be noted that NFPA 30 does not retroactively apply (see Section 1.4 of more recent editions), so current requirements, even if they did diverge from the historic requirements, wouldn't have been applied to the tank farm as a matter of compliance to local codes. See the remainder of Section 5.0 for potential applicability of newer requirements under other compliance structures.

5.2 API RP 2021 CONSIDERATIONS

API RP 2021 is, as its title implies, a recommended practice. Like any code or standard, it does not on its own carry any legal authority unless specifically invoked by some law, regulation, or other legally-binding reference. Even if mentioned, any referencing legislation would have to adapt much of the language in API RP 2021 from "should" language to "shall" or "must" statements to require compliance.

At the time of design and construction of the ITC Deer Park "First and Second 80's" tank farm, it is unlikely that API RP 2021 was adopted by any jurisdictional authority having oversight of the facility. Although the document was released during the first quarter of 1975, the timing for adoption and implementation, which often takes three months to a year for most jurisdictions, would have overlapped the early design period of the facility. In such cases, engineering and development teams in all realms (i.e., industrial, commercial, residential, etc) typically request relief from the new standard, citing the cost and effort that has already been expended toward compliance to the existing regulations, codes and standards.

However, if one assumes the design team for the facility had the document available to them, its contents would be a bit of a conundrum in this particular case. API RP 2021 (known in its early versions as Publication 2021) couches its discussions on strategies, tactics and use of installed systems on the foundation that an established emergency response organization exists (either an onsite organization or a responding local fire department), the facility design is mature enough for that organization to evaluate against its capabilities (if the facility does not already exist) and a path forward for closing any gaps between response capabilities and facility design is established. At the time of construction of the tanks, it is not clear that an emergency response organization was in place or, if one was in place, that they were an integral part of the design of the facility as intended by API RP 2021.

Given these various perspectives, it would seem unlikely that API RP 2021 was implemented as part of the design effort for the "First and Second 80's" tank farm. The timing of the design and construction of the tank farm does not align well for the guidance document to have been adopted by the design team. Additionally, if it was taken up as design criteria, the timing of plant development and emergency response team founding and maturation also does not align well for obtaining detailed input for the design team.

Therefore, it would be more likely that the design team for the facility designed the fire protection based on existing industry practice of the day, and the emergency response team adapted to those conditions over time. See Chapter 6 on emergency response for more information.

5.3 WORKER SAFETY (29 CFR 1910) CONSIDERATIONS

When the "First and Second 80's" tank farm was constructed, 29 CFR 1910 was still a relatively new document. When the regulations were first published and became effective in 1974, they did not contain the requirements currently in 29 CFR 1910.119. Those requirements did not become part of the regulations until 1992 [57 FR 6403, 1992]. Therefore, the original installation and any pump or piping modifications made prior to May 26, 1992 (when the rule became effective), would not have been subject to the requirements [57 FR 6356]. After implementation of the rule, analysis of any modifications would likely have been assumed exempt from a process safety analysis based on the tank farm exception included in 29 CFR 1910.119(a)(1)(ii)(B).

The basic question, however, is whether or not the blending operations for Tank 80-8 constitutes a "process" that would be evaluated under the process safety management (PSM) standards. Means to fill and empty the tanks would, by necessity, seem to be included in the original scope of 29 CFR 1910.119(a)(1)(ii)(B). However, the introduction of blending and mixing operations for the tank does raise a question as to whether processing is performed within the tank farm.

The CSB asked exactly that question with regard to accidents in other facilities in its March 31, 2014, letter of comments and input to Occupational Safety and Health Administration (OSHA) Docket OSHA-2013-0020, which sought changes to the process safety management requirements in the same vein [CSB, 2014]. The extensive details of that letter will not be repeated here, but the CSB information provides ample reasoning to include blending and mixing in the scope of a process, and thus require application of PSM standards.

In its final decision, OSHA determined that tanks either connected directly to a process or involving a process are subject to the PSM guidance [OSHA 3903-03, 2017]. Hence, beginning in approximately mid-2016, the "First and Second 80's" tank farm would have been no longer exempt from the PSM process. While it could be argued that only Tank 80-8 would be subject to the PSM process since it is the only tank performing blending, a broader reading would include the entire tank farm because of the lack of segregation of Tank 80-8 from the remainder of the tank farm and the interplay of various scenarios. Based on available information, PSM analysis of the tank farm had not yet been performed by the time of the fire, although management of change and pre-startup safety review was performed under the broader ITC safety structure [CSB Interview with ITC VP of Safety, 2019a].

Subsequent to the March 2019 fire event, OSHA cited ITC Deer Park for violation of the Process Safety Management Standard (29 CFR 1910.119), confirming the applicability of PSM to Tank 80-8, as a minimum. Once the PSM process was started, the implementation of recognized and generally accepted good engineering practices (RAGAGEP) would have been expected [OSHA, 2016]. RAGAGEP in this case would have minimally included more recent editions of NFPA 30 and API RP 2021 (see Sections 5.1 and 5.2), as well as modern equipment considerations (see Section 5.6).

Separate from the process safety management aspect are changes in safety related to emergency responders, both in general industrial fire brigades, with 29 CFR 1910.156 being introduced in 1980, and hazardous materials responders, with 29 CFR 1910.120 being implemented in 1996. The impact of those conditions will be more fully evaluated in Section 6.0 of this report.

5.4 INSURANCE CONSIDERATIONS

When the tank farm was being constructed, industrial insurance companies had a strong hand in influencing design. The insurance business was influential in developing NFPA 30 (see Section 5.1 above), and many insurers would utilize NFPA 30 as the foundation for their own guidelines or framework for determining risk and rates for their insureds. In the 1950s and 1960s, process safety management approaches generally followed the insurance guidelines because it was those organizations that had developed the needed risk-based information accepted as input to PSM, such as probabilities of events, effectiveness of engineered systems and success of certain approaches.

In the late 1960s, organizations like Factory Mutual (today's FM Global), Factory Insurance Association (which later became Industrial Risk Insurers and today's AXA XL), American Insurance Association (which survives today) and others began making their risk-management approaches more public, in an attempt to influence industry to accept better practices through process safety management, as opposed to it being imposed through the insurance process. As one example, Factory Mutual updated its *Handbook of Industrial Loss Prevention*, which had been first published in 1959, to the second edition in 1967 [Factory Mutual, 1967]. The second edition greatly expands upon the original and provides several pages on tank farm installations. In the early- to mid-1970s, Factory Mutual began expanding the *Handbook* and its associated support documents into its Loss Prevention Data Sheet library that exists today. The *Handbook* chapters on flammable and combustible liquids would encompass a range of data sheets, with much of the large storage tank information landing in Loss Prevention Data Sheet (FM LPDS) 7-88, *Storage Tanks for Flammable and Combustible Liquids* [FM LPDS 7-88, 1976].

The approach to fire protection in the *Handbook* and the subsequent FM LPDS 7-88 focuses more on large fires that occur at ground level and expose the tanks. As a result, the FM approach leans more heavily on localized containment, smaller tank groups within a single containment, spacing that considers the edge of containment walls to exposed tanks and other structures and installed fire protection systems that can be operated reliably (and preferably automatically). Compared to NFPA 30, the FM approach better matches the multi-exposure concerns that arise for vessel or pipe failures, such as happened at the ITC Deer Park facility. It also tends to reflect the broader insurance approach that leans more on engineered controls as opposed to administrative controls and responses. It is for this reason that there is little to no discussion of emergency response or the recommended structure of emergency forces for tank farm fires contained in the *Handbook* and subsequent FM LPDS 7-88.

Tank farm fire protection standards in the insurance industry tend to range, depending on the rating and premium structure established by the particular insurance company, with NFPA 30 being the minimum expectation. Some companies, such as FM Global though its Loss Prevention Data Sheet program and AXA XL through its GAPS program, publish those standards for public use, while others hold them only for access by insureds and potential clients. Regardless of how companies make those standards available, it can be said that they represent improvements over NFPA 30 in many aspects regarding fire protection of tank farms. However, it must be clear that these standards tend to assume fundamentally different risk levels, from one another and from NFPA 30. Using historic versions of today's insurance-based tank farm standards, it is evident that the insurance standards were not implemented as part of the design. The "First and Second 80's" tank farm does not follow the containment and spacing requirements contained in the guidance included in contemporary standards from Factory Mutual, the Factory Insurance Association or the American Insurance Association. Since the standards from these three organization formed the backbone of the remainder of the industry, standards from other insurers were also assumed to have not been applied.

How an insurance company views the various aspects of tank farm fire protection and considers them in the framework of their protection, particularly for situations where the insurance company wasn't included in the original design, isn't always as clear as the above might appear [references withheld due to confidentiality]. As previously noted, some companies view tank farm protection methods as eventually requiring manual intervention, which would conflict with their general perspectives of not giving significant credit to manual or administrative controls. With that perspective, those companies will more likely write off the tank farm rather than analyze it in detail to determine a more likely loss. That appears to be the case in three recent insurance surveys provided by ITC Deer Park to the CSB, one each from 2015, 2017 and 2018. The 2015 assessment mentions the tank farm only in context of maximum foreseeable losses (which assumes little to no manual intervention) and indicates an assumption that the "emergency response personnel (both site PEO [Plant Emergency Organization] and public agencies) act in accordance with existing plans." The 2017 report provides significant focus on a different tank farm with regard to potential loss factors, but assumes any given tank farm to be completely lost, obviating any discussion on effectiveness of installed systems or emergency responders. The 2018 survey provides significantly more detail about the various systems and the emergency response team, but the information does not link the various aspects of fire protection and assumes a maximum loss of a tank farm.

The above information isn't meant to be critical of the insurance business and their varied approaches to tank farms, but is intended to highlight the variety of approaches taken and the information often available from insurance providers. Given that broad band of data, it is incumbent upon facility owners and managers, and more specifically their risk management leaders, to understand what is being assumed by insurers and what data is available from their organizations. In the case of ITC Deer Park, it is evident that the input from these two insurance surveys did not necessarily support site personnel in understanding the specific risks within the tank farms, only the potential loss from a large-scale fire in a single tank farm.

5.5 CORPORATE RISK MANAGEMENT CONSIDERATIONS

The term “corporate risk management” has gained much attention since the inclusion of process safety management in regulatory guidelines. But, in matter of fact, the concept is more than a century old. With respect to fire protection, it dates to fires in mills and other industrial facilities in the late-1800s and the formation of industrial insurance. For much of that history, the focus was mostly on financial loss prevention and business interruption. But since about the mid-1980s, other impacts such as environmental damage, company reputation loss, loss of community trust, damage to neighboring properties and other aspects have become important to the engineering of new facilities. Many petroleum and chemical facilities have developed their own corporate standards that address such issues, or at the very least discuss those issues in a general sense for guidance to design professionals and facilities operators.

In the author’s experience, however, applying those considerations on a retroactive basis isn’t as clear a path as when designing a new facility. NFPA 30, and much of the guidance that uses NFPA 30 as a foundation, does not incorporate these perspectives, as such issues are outside the general scope of the NFPA system. API RP 2021 and most insurance standards also do not consider such issues within their scope, although more recent trends in both API and the insurance business suggest they are moving in that direction. API RP 2021 and insurance standards can, however, be implemented via the PSM process.

Given this, there appears to be a gap between the risk-management needs of owners and/or operators of tank farms and the design and management standards available. Further, risk-based analysis documents, such as Thomas Barry’s *Risk-Informed, Performance-Based Industrial Fire Protection* and the well-respected *Lees’ Loss Prevention in the Process Industries*, can offer significant information in the preventative, monitoring and mitigative portions of a risk framework, but lack detail on the responsive aspects while also relying on those responses to complete the overall risk picture [Barry, 2002; Mannan, 2012].

Conversely, there is little information in industrial fire fighter training, textbooks, periodical articles or similar industry information that suggest emergency responders could have greater influence in aspects that greatly affect them, such as engineering of new facilities, process analysis of existing facility, repair and maintenance schedules, loss prevention framework development and corporate insurance procurement.

Although a detailed discussion with ITC Deer Park was not undertaken, the two interviews with the ITC Vice President of Safety, Health, Environmental, Security, Regulatory Compliance and Operations suggest involvement of personnel involved with emergency response in such activities, though it is unclear as to what extent or influence. Additionally, older facilities such as the “First and Second 80’s” tank farm would only benefit from such input if it were evaluated on the whole, as opposed to individual operations or areas (see Section 5.3).

5.6 EQUIPMENT CONSIDERATIONS

When the “First and Second 80’s” tank farm was constructed, there was little in the way of fire-tested equipment and what equipment was on the market couldn’t be assumed to conform to a single standardized test. Historically, standardized fire tests for petrochemical equipment were established in the early-1990s as a result of a combination of large fires dating from the late-1970s into the mid-1980s and the risk-based drive to prevent or mitigate large fires through engineered controls (see Sections 5.3, 5.4 and 5.5). Although some fire testing approaches were available as far back as the mid-1960s, many of those were proprietary to petrochemical corporations and not shared with the remainder of industry.

Since the establishment of standardized fire testing in the early-1990s and industry-available equipment in the mid- to late-1990s, the use of fire-tested equipment has become relatively common. Equipment now available to industry include items such as:

- Safety shut-off valves – Control valves (such as butterfly valves and gate valves) that are heat activated to shut or open, depending on the desired position under fire conditions.

- High-temperature gaskets and pipe seals – Non-combustible or fire-resistant materials are used to ensure the flexible/semi-flexible joints at pipe connections do not burn or melt, and thus leak, during a fire situation.
- High-temperature electrical enclosures or devices – Fire-tested electrical equipment or protective enclosures that may perform monitoring or control of systems.
- Non-combustible and fire-resistive insulations – These insulations can augment thermal protection of other fire-tested equipment or be used to protect equipment, piping or tanks that is not fire-tested.
- Structural fire protection – Fireproofing materials such as concrete, spray-applied fire resistive materials (SFRM), intumescent coatings and water-spray systems can aid in protecting steel, concrete, hangers/supports and other items to ensure systems remain in place.

In addition to fire-rated equipment, other process-safety equipment now considered beneficial to fire protection came into more regular use during the period from the mid-1980s to the late-1990s. One important one is remotely-operated valves. These valves can be controlled through a variety of means, including electric-motor drives, pneumatic and hydraulic systems. While the technology dates to the 1930s, their implementation prior to the mid-1980s was relatively minimal due to the cost of the controls infrastructure. In the mid-1980s, when the early forms of addressable point technology became both cost beneficial and reliable, the ability to utilize remotely-operated valves increased significantly. The same was true of all remotely-operated equipment, including pump and motor controls, fire monitor nozzles and equipment shut-downs.

More traditional equipment, such as check valves, were also given greater consideration for their safety aspects. In the time before the PSM process became the norm in the industry, the quantity of any given piece of equipment in a system was minimized whenever possible, to reduce long-term costs and improve overall system reliability. In current approaches, however, the increase in safety that such items might offer, such as reducing the potential for a tank to drain uncontrolled, is balanced against the other cost and operational concerns.

As noted, few of this equipment was available or cost-effective at the time the “First and Second 80’s” tank farm was constructed, and obviously was not included in the original design. In general, incorporation of any of the above technologies would need to be considered as modifications and upgrades occurred over time.

A detailed review of all the equipment within the tank farm was not undertaken, but it is relatively clear from the fire events that the tank farm would have benefitted from many of them. Items such as safety shut-off valves, check valves, remotely-operated valves, and high-temperature gasketing could have had a sizable impact on the fire conditions. Moving away from the polyisocyanurate insulation would have also been beneficial. Although there are “fire retardant” formulations of polyisocyanurate, they are typically only advantageous for temperatures up to about 350°F (177°C).

The primary method of identifying and implementing these changes would have been through the PSM process (see Section 5.3) but could also have been achieved through reviews by insurance companies (see Section 5.4) or corporate risk evaluations (see Section 5.5). In general, documents like NFPA 30, FM LPDS 7-88 and API RP 2021 do not dictate the use of specific technologies, instead preferring to include performance or functional requirements that can be achieved with these technologies.

5.7 PERSPECTIVES ON INSPECTION, TESTING AND MAINTENANCE

In general, inspection, testing and maintenance is a well-known and well-regarded aspect of both fire safety and process safety, in general. In the author’s experience, two overbearing issues tend to rise to the surface in evaluating emergency preparedness or in assessing lessons-learned in post-accident situations.

One is that fire systems are often not given the same level of attention as other process safety systems. There are varying reasons that have been expressed by facility management across a large band of industry, but those can be grouped in perspectives of fire systems being expensive to repair or replace, choices in resource management, focus toward production in particularly demanding times and a lack of understanding of the impacts of relatively minor changes in system capabilities. There is little available information to support any conclusions with regard to ITC Deer Park in particular, but events from the fire and information obtained afterward suggest some items to discuss.

For example, interviews performed by CSB and the Harris County Fire Marshal's Office both note fire water system pressure being less than necessary to support use of monitor nozzles in the early stages of the fire [HCFMO, 2019; CSB Interview with ITC VP of Safety, 2019a; CSB Interview with ITC VP of Safety, 2019b]. According to ITC, the monitor nozzles initially activated by those first on-scene were not designed to reach the area of the Tank 80-8 piping manifold. The units adjacent to Tank 80-8 that were designed to reach the tank's piping manifold had become unusable due to the fire exposure, which damaged the monitor nozzles, and thermal exposure concerns to responders. Attempts to use the monitor nozzles further away from the fire area resulted in water streams not reaching the area, since the available pressure at the utilized nozzles was not high enough to support the reach.

Based on the provided information, an investigation of the water supply issues at the time of the fire uncovered a concern. Data from monitoring sensors on the water supply system, provided from ITC to the CSB, indicate rises and falls in water supply pressure during the early fire period appeared somewhat unusual [ITC Information, 2019a]. Fire pump test data from site fire pumps suggest that several were underperforming with regard to pressure at the flow rates that would have likely been impacting the monitor nozzle system early in the fire [ITC Information, 2019a]. The performance curves provided suggest available pressures were between approximately 88% and 95% of those presented by the manufacturer's original operating curve. There is also some indication that during the early stages of the fire, the pressure maintenance (jockey) pumps associated with the fire water system may have been operating, prior to starting of the fire pumps and giving a false impression of low pressure from the fire pumps.

While NFPA 25, *Standard for the Inspection, Testing, and Maintenance of Water-Based Fire Protection Systems* allows for a 5% reduction from the manufacturer's original curve, it is not unusual in industrial settings to find reductions more in line with those found at ITC Deer Park [NFPA 25, 2017]. Such reductions are often accepted on the premise that they do not greatly impact the effectiveness of installed systems. Whether that premise is supported by engineering analysis or other data is inconsistent across the industry.

When significant reliance is placed on manual firefighting equipment, the subsequent pressure reduction at hose nozzles can affect the distance water can be projected. A survey of multiple manufacturers and nozzle types suggested a 10% reduction in nominal operating pressure can affect reach distances range by 5 to 15 ft. When a target is at the far edge of the nozzle's projection distance, as Tank 80-8 would have been since it is in the center of the tank farm and the nozzles used are at the periphery of the farm, the water arc might not reach the target, or at least may not reach all portions of the target and reduce the capability to extinguish fire or provide exposure protection. Similar concerns exist for foam production in tank fire suppression systems, spray patterns or foam/water density in spray systems and other aspects of firefighting equipment.

The other issue is that facility operators and emergency responders don't always understand the important aspects of tank farm design that impact fire safety, but those aspects aren't related to fire protection systems. Ground sloping, containment wall integrity, drainage effectiveness and integrity of electrical equipment are all important aspects of fire protection at tank farms, but often do not get the attention they deserve. An in-depth evaluation of the ITC Deer Park facility could not be undertaken due to a lack of original design plans, and a post-fire evaluation would have provided inconclusive results in many cases. However, the descriptions provided in interviews and videos available in the public realm raise questions as to whether the sloping and drainage systems were operating as designed or intended.

6.0 Fire Modeling Efforts

In an effort to better understand the fire spread mechanisms during the ITC Deer Park fire, Jensen Hughes was requested to model a portion of the fire and examine the thermal outputs against thermal exposure criteria generally accepted within the industry. That effort is documented in a separate report found in Appendix A of this document.

The ITC Deer Park fire represented two unusual conditions compared to fires that are typically modeled: namely fire issuing from vents on the sides of the tanks near the roofline, as opposed to fire issuing from the pool surface or roof structure, and a combined pool fire at ground level and tank fire. A literature review performed to support the modeling effort indicated that most fire modeling performed for tank farms assumes either a fire at ground level or a fire within a tank at the fuel surface, but not both occurring at the same time. Reviewed reports indicate model efforts generally assume either a full surface fire or a partial surface fire, depending on assumptions regarding the roof structure of the tank, but did not assume a concurrent pool fire at ground level. Those that assumed a pool fire at ground level varied in their assumptions as to fire size and shape, but did not assume a concurrent tank level fire. Jensen Hughes searched but were not able to find any publicly available modeling efforts that evaluated fire issuing from the tank vents.

To perform the task, an approach needed to be developed to approximate the vent fires at the top of the tank. Since this type of fire is not incorporated as a standard fire or approach within most industry-available models, hand calculations were performed to estimate the evaporation rate of the liquid within the tank, which in turn established predicted vapor flow at the vents. The flow at the vents was incorporated into the computer-based model as a means of establishing flame size and length. Hand calculations for flame characteristics and exposures to adjoining tanks were also performed to establish comparability with computer-based model output.

The results of the detailed fire modeling and hand calculations indicate that the Tank 80-8 rim fire alone did not provide enough heat to cause the fire to spread to adjacent tanks. An additional heat source, such as a large liquid pool fire at ground level, allowed the fire in Tank 80-8 to spread to the adjacent tanks. The exposures to adjoining tanks from the tank roof-level vent fires were lower than might be expected for a fire involving a fuel surface, as is anticipated by prescriptive codes such as NFPA 30, *Flammable and Combustible Liquids Code*, FM Loss Prevention Data Sheet (LPDS) 7-88, *Ignitable Liquid Storage Tanks*, and API Recommended Practice (RP) 2021, *Management of Atmospheric Storage Tank Fires*.

However, the ITC Deer Park fire model demonstrated that the synergistic effects of the tank fire and pool fire at ground level were sufficient to lead ignition at adjoining tanks. The results of the study indicate that the coupled impact of a tank fire and a liquid pool fire may need to be considered in evaluating the minimum safe separation distance of future installations and to evaluate existing installations, particularly older installations that predate the availability of safety features or equipment that aid in mitigating such conditions. Although a relatively limited pool fire was examined in this analysis, the combined impact of the pool and vent fires significantly raised the radiant exposure to adjoining tanks. Were the pool fire expanded in the model, as it did during the ITC Deer Park fire, igniting the contents of adjacent tanks from radiant heat exposure would be more likely.

In addition, the computational modeling showed that the fires exiting vertical pressure release vents on the side of the tank behaved significantly differently than a standard liquid tank fire, where the impact of wind on the thermal exposure was significantly less than has been documented in similar studies for other tank farms. In this study, the size and number of pressure release vents had a more significant impact on the predicted thermal exposure than the wind speed. Because this configuration is a trend within the tank storage industry, additional study appears to be necessary based on clearly different burning and radiant exposure mechanisms that have traditionally been incorporated into the above noted standards. The configuration also highlights the need for prescriptive codes to consider alternative fire configurations when recommending minimum safe distances.

Readers are directed to the fire modeling report found in Appendix A for more detailed information.

7.0 Firefighting Considerations

There is not a detailed description available of the firefighting operations performed at the ITC Deer Park fire. While a plethora of data was generated during the operation through incident command processes, responses by external organizations, news footage, weather data collection, environmental-monitoring data monitors and post-incident interviews, much of that information is contradictory or incomplete and does not necessarily lend itself to building a detailed timeline of the response. This situation is typical of large fire incidents due to the chaotic nature of the events. Despite that, there is sufficient information to evaluate the operations in a general sense and extract lessons from the event.

7.1 GENERAL INDUSTRY TANK FIREFIGHTING APPROACH

In general, it should be recognized that there is no international or national requirement specifically for owners and/or operators of tank farms to provide firefighting capabilities. The decision of whether to provide an on-site response organization is based on a combination of local laws, loss control approaches, availability of capable off-site resources and general fire safety considerations. If it is decided that an on-site response organization is to be instituted, then a wide variety of national regulations, local laws, international standards, and other guidance becomes applicable.

Also noteworthy is that tank fire response tactics are largely defensive in nature. As discussed in Section 5.0, the codes and standards generally available for tank farm design are founded on an assumption of a single, large fire event that is allowed to burn out while various measures are applied to reduce the potential for spread to other tanks [Benedetti and Shapiro, 2018]. The form and function of those assumed responses, however, are not well described in any of those documents. Further, industrial fire response organizations have been historically acknowledged in fire protection and loss prevention documents of various types, but very little supporting documentation exists outside of the industrial firefighting sector [Kelly et al, 2003].

As demonstration of this, dedicated industrial fire organizations have existed at petroleum and chemical industry facilities, including tank farms, since at least the 1930s [Kelly et al, 2003]. Their strategies and tactics have adapted over time, and they've been incorporated as crux elements of process safety and corporate risk management strategies since at least the mid-1960s. Schools specializing in industrial firefighting, such as the training program at Texas A&M University, have existed since at least the early-1960s, with some having their early stages founded in the mid-1950s. Information sharing among the industry was, and continues to be, the primary form of transferring those approaches, as opposed to dedicated schools, training academies or indoctrination programs that exist for structural firefighting and other response activities performed by pubic fire departments.

The period from the early days of industrial firefighting to the mid-1970s tended to allow for both defensive tactics, due to acceptance of the consequences by the public in general, and sometimes aggressive tactics, due to a general acceptance of injury and life loss among firefighters, responders and plant personnel [Kelly et al, 2003]. During that period, dedicated fire services did exist, but plants were often assisted greatly by non-response personnel that were either expected to respond by their site management or volunteered for the effort [American Insurance Association, 1968]. Since the mid-1970s, however, industrial emergency responders have been subject to greater control, which has eliminated the "all-in" strategy that underlies much of the pre-1980 loss data for tank farms [NFPA 600, 1986].

Concerns for industrial firefighters, and plant personnel in general, were part of the formation of the Occupational Safety and Health Administration in the early-1970s and closer inspection of fire concerns in the United States was the focus of the efforts of the National Commission on Fire Prevention and Control, which produced the *America Burning* report of 1972 [NCFPC, 1972]. Those two movements led to national regulations and a general movement toward improved protection for firefighters. A variety of fire protection organizations worked with federal organizations to address public-sector fire response organizations, but OSHA was able to regulate protections for industrial fire response organizations through existing structures, resulting in required protections via 29 CFR 1910.156 in 1980 [45 FR 60706, 1980]. Similar issues with emergency response to hazardous materials in the latter-1980s eventually resulted in the protections included in 29 CFR 1910.120 [61 FR 9227, 1996]. That worker-protection movement and eventual regulation emphasized the shift toward defensive and more cautious attack strategies and tactics within the industrial firefighting realm. As well, the regulations in 29 CFR 1910 preclude personnel that are not specifically trained and incorporated into the emergency response organization from responding in ways that would endanger them, effectively ending the "all-in" strategy of the past. In some cases, the risk of injury or death of plant personnel, as well as concerns over prosecution under federal regulation, has led many sites to reduce or eliminate their in-house response organizations.

Further influence on response organizations and their operations within tank farms comes from API and NFPA. The movement primarily driven by 29 CFR 1910.156 helped to quickly mature NFPA 600, *Standard on Facility Fire Brigades* from its predecessor (then titled as NFPA 27) [NFPA 600, 1981]. While it would take nearly a decade, more specific training and knowledge requirements for responders came in the form of NFPA 1081, *Standard for Facility Fire Brigade Member* in 2001 [NFPA 1081, 2001]. API RP 2001, through revisions starting in the 1991 edition and moving forward, included more details from industry experience and began incorporating incident command roles and plant functions (such as control room operators, process functions, etc) in their information on response [API Pub 2021, 1991; API RP 2021, 2015].

This history is important because the "First and Second 80's" tank farm design, as well as much of the basic assumptions of NFPA 30 and its derivatives, straddles those two eras. As previously discussed, the underlying presumption of an emergency response within a somewhat short but ill-defined response timeline tended to be more easily met in the mid-1970s and prior, given the "all-in" response approach that was present during that era. Since the mid-1970s, the "organization only" response approach has led to needs for more structured incident command, initial response protocols, call-in and call-back procedures, readiness procedures for equipment and apparatus and more. While these infrastructures definitely augment the response capabilities over the long duration of the response, there is often a longer initial response delay. Because of that, there are open questions as to whether the design standards for tank farms, as well as other industrial processes, have kept pace with the newer emergency response infrastructure and properly incorporate it into design or process safety efforts.

It should also be recognized that it has long been accepted that individual sites generally do not have sufficient capabilities to perform tank firefighting activities on their own [Factory Mutual, 1967; API RP 2021, 2015]. The three-tiered response structure described in Section 4.0 has been in place since approximately 1960. Prior to that date, large mutual aid pacts existed and were well utilized in large incidents. The founding of the Red Adair Company, Inc. in 1959 added the top tier of highly-specialized responders to the mix, with those organizations becoming a regular part of the response framework by the early-1970s. By the time the "First and Second 80's" tank farm was constructed, the framework was standardized within the industry, though as described in Section 5.0 incorporating that response capability into facility design and continued operations is a continuing issue.

7.2 GENERAL FIREFIGHTING INFORMATION

Note that the information contained herein is condensed from the overall fire timeline presented elsewhere, and is intended to provide some supporting information for the remainder of Section 6.0 of this report. The information contained in this section is not meant to be a complete timeline of emergency response into the fire area.

Information derived from interviews contained in other documents indicates that the initial response into the area was staffing of monitor nozzles (two or three are identified, depending on source), with ITC Deer Park emergency response team apparatus arriving on scene as the team was organized and a plan of attack formed [HCFMO, 2019]. The apparatus responded into the containment area at the northeast corner, positioning between Tanks 80-10 and 80-13 to achieve the best angle of attack on the ground fire at Tank 80-8 and the exposure to Tank 80-11 [CSB Interview with ITC VP of Safety, 2019b]. Interviews also suggest the location was chosen due to winds blowing from approximately the north/northeast.

By approximately noon on March 17, 2019, the ITC Deer Park emergency response team had activated their association with adjoining facilities and public emergency response agencies via the Channel Industries Mutual Aid (CIMA) group [CSB Factual Update, 2019]. As additional apparatus and personnel began to arrive during the afternoon of March 17, these additional resources were positioned within the containment area, predominantly on the east and north sides due to wind conditions and apparatus access availability [CSB Interview with ITC VP of Safety, 2019b]. By this time, fire had spread to Tank 80-11.

The installed monitors east of Tank 80-8 were damaged due to proximity of the fire and useful monitors at the south perimeter of the tank farm were exposed to smoke and direct flame, making them unsafe to use [CSB Interview with ITC VP of Safety, 2019b]. Monitors on the north side were noted to be ineffective by responders, due to low water supply pressure, and the use of those monitors was mostly abandoned by the time apparatus was in place. Remaining installed monitors around the perimeter would have been mostly incapable of supporting operations in the initial fire area for similar reasons.

During these initial hours, movement of personnel or apparatus to the southern part of the containment area quickly became a safety concern, either from large quantities of smoke due to wind direction or direct flame exposures as burning material moved in that direction [HCFMO, 2019; CSB Interview with ITC VP of Safety, 2019b]. Therefore, there was an inability to utilize the tank foam suppression systems, which are all manually supplied (no connected water supply) [CSB Interview with ITC VP of Safety, 2019b]. The inability to access the foam supply location augmented other considerations about tank fill height on Tank 80-8 specifically (see Section 7.3) in not operating the tank foam system early in the response.

Information provided by ITC Deer Park to CSB indicates that within the first hours of the response, the deployment included [Baker Botts, 2020b]:

- Personnel operating three fixed monitors (500 gpm rated nozzles)
- ITC Deer Park Fire Engine 3, employing 2,500 gpm rated engine-mounted monitor and deployed 1,250 gpm rated ground monitor
- ITC Deer Park Fire Engine 2, employing two monitors rated for 2,000 gpm each
- Personnel activating the deluge system for the west tank farm manifold (water spray system)
- Three CIMA quick attack vehicles, each with 2,000 gpm rated monitors
- One CIMA trailer-mounted monitor rated for 2,000 gpm
- Four CIMA 500 gpm rated ground monitors
- Two Port of Houston fire boats, rated for 5,000 gpm each (water supply only – no firefighting), pumping from the Houston Ship Channel
- Operation of all four ITC primary fire water pump (combined rated capacity of 13,500 gpm, estimated actual around 11,000 gpm based on testing records provided to CSB for some pumps), pumping from the Houston Ship Channel

Additional apparatus, equipment and personnel arrived during the first 24 hours of the event, but the exact timing and deployments are not clear from the available information.

Over the period from the afternoon of March 17 through the evening of March 18, the available information suggests that fairly typical response tactics were employed, albeit with greater numbers and quantities than if the event were a ground fire or tank fire alone. From limited video evidence, it is clear that foam application to burning surface fires (both in the tanks and on the ground) was being performed, as was exposure protection for tanks and piping systems and for responders on the ground. The latter is an often-employed technique to ensure safety of the personnel and response equipment.

The decision to contract US Fire Pump on the evening of March 18 would introduce additional personnel, equipment, and tactics to the operation by early morning on March 19 [CSB Factual Update, 2019]. The US Fire Pump team, according to interview information, brought additional personnel, which allowed relief of existing responders, and large-capacity, high-velocity monitor nozzles (specific makes and models could not be clearly determined from available information), which allowed for more effective deployment of foam. The US Fire Pump team, based on magazine articles that were published subsequent to the fire event, appears to have employed more aggressive tactics, as well, though the base information available for the fire event is not clear on those assertions [Riecher, 2019a; Riecher, 2019b].

7.3 GENERAL RESPONSE PERSPECTIVES

Overall, an examination of the data suggests a traditional emergency response to a tank farm, employing tactics that have become relatively well described in industry magazines, limited texts on industrial firefighting and the tactics taught at training schools. As noted above, providing a mix of exposure protection and direct fire suppression is the most commonly applied approach, and that approach was evident from the available information.

The ability to deploy foam fire suppression to the tanks was hindered over the duration of the fire due to safety concerns associated with response to the south side of the containment area. Although early deployment to the area and foam system activation might have been achievable, as was done for the water spray system on the west manifold, it is not clear that significant benefit would have been derived. Use of foam fire suppression systems on tanks assumes that a single tank is on fire and the goal is to suppress the fire until emergency forces can respond and to limit exposures to other tanks. While such systems often full extinguish fires, the base design assumption is reduction of hazard.

The decision to not deploy the foam suppression system on Tank 80-8 during the early fire stage would typically been seen as a point of debate. Interviews with the ITC VP of Safety revealed that the decision was made due to a combination of concerns, primarily based on fire and smoke conditions at the southern perimeter. As well, there was a concern that the tank had been filled to near capacity and the potential for subsequently overfilling the tank by applying foam [CSB Interview with ITC VP of Safety, 2019a; CSB Interview with ITC VP of Safety, 2019b]. The issue of wind direction and fire exposure is a common one and would likely have been a point of concern for any responder. The concern expressed by the ITC VP of Safety about tank capacity and overfilling might be challenged by some, however is certainly a valid safety concern. Spillage from the tank would have, at that point, exacerbated the fire and introduced an unknown fire spread element. Obviously, that decision had implications toward the actual timeline. Alternative assumptions about the performance of the system and impact on the timeline would be pure speculation, however. While one can easily assume some effectiveness based on past performance of such systems in general, the concerns about the fill height of the tank could just as easily translate to ineffective deployment of foam from the generator chambers inside the tank (due to partial or full submersion) or loss of foam through the overfill vent. In either case, ineffective suppression would still lead to extensive fire spread conditions, although such conditions may have been delayed.

Another point of discussion that might arise is whether or not more resources, or a different mix of resources, could have been added to the operation. A review of the initial response as noted above, additional resources included in incident command reports and noted apparatus or monitor locations identified in interviews suggests that the inability to introduce more resources was a combination of safety considerations, ability to access the fire between tanks, the inability to loft water from long distances outside the tank farm and fire conditions making advantageous locations inaccessible.

The tank farm is only accessible at points on the north and south, with the latter having been quickly compromised and eliminated as access for the majority of the response. The same is true for access to installed fire protection connections at the south. Initial apparatus setups quickly took up the most advantageous locations, which allowed hose streams to flow between tanks and onto exposed tank surfaces. But as more apparatus arrived and more monitors were placed, the area taken up by apparatus, hoses, trailers, ground monitors and other equipment, as well as the needed safe working space around each, precluded adding too many other resources. While space might have been available, the effectiveness of those resources would have been limited by the tank configuration and ability to access the fire. At some point, adding more apparatus would have also impacted the ability to retreat out of the tank farm should the incident challenge those positions. That action became necessary as the tank exposures led to fires in the tanks and the ground fire spread northward, forcing resources established within the containment area to pull back or to be abandoned [CSB Interview with ITC VP of Safety, 2019b; IFW, 2020].

The ability to place apparatus outside the containment area is also problematic. On the north side of the tank farm, between the north containment wall and Tidal Road, is a ditch that disallows apparatus from being set any closer than the south side of Tidal Road. That would necessitate foam streams to reach nearly 300 ft before being effective on the fire. While monitors on fire apparatus can reach those distances, foam or water will tend to disperse and become ineffective on a large fire such as this one, even when wind conditions are not considered. Therefore, use of apparatus at that location would actually have been harmful to the response, by utilizing available water flow and pressure to little advantage at the fire.

Similar conditions existed at the other perimeter locations for various reasons. On the east side, the plant road just to the east of the tank farm was the extraction point for those resources inside the containment area, and therefore could not be used until later in the fire, once resources within the containment area could no longer remain there. The next available spot would have been on Independence Parkway, putting the apparatus at distances 375 ft or more from the fire, and having existing resources in between them and the fire, for large portions of the response. Resources could locate there once the fire spread to tanks closer to the east side of the farm. On the west side, pipe racks and electrical equipment would have pushed resources to the west to allow for beneficial foam stream arcs. If foam or water streams are arced too high, they begin to break apart due to gravitational and velocity forces, thus making them ineffective. To achieve lower-angle arcs, apparatus would have had to set up closer to the railroad siding at the west side, putting the distance to fire at about 350 ft. The same condition exists at the south and would be problematic even if the location wasn't compromised by fire at that point. Further, movement south to achieve good foam stream angles would have put apparatus between tanks to the south (in the "Third 80's" tank farm), obstructing their view of the situation and placing them in further danger.

In most tank fire situations, the ability to obtain sufficient resources is a commonly cited issue. In this case, however, the main issues appear to have been available space for operations and the ability to deploy water/foam streams in an effective manner given the tank farm layout. A review of the number of apparatus, pumping capabilities, foam supplies and other aspects suggests that more than adequate resources were available at the outset of the operation. The limitations of available space and access appear to have impacted the ability of getting those resources into the tank farm and into advantageous positions.

As demonstration of that, the effectiveness of the US Fire Pump plan and execution appears to stem more from the use of newer, larger-capacity equipment and more directed efforts, as opposed to simply more personnel and apparatus [Riecher, 2019a; Riecher, 2019b]. The larger-capacity equipment gave the response team the ability to loft foam in extremely large quantities toward the core areas of individual fires, which the ITC and CIMA equipment could no longer reach. By attacking individual fire areas, including the ground fire, the team was able to extinguish tanks one-by-one and reduce the size of the ground fire. Also contributing to the extinguishment was a supply of an improved foam, brought by the US Fire Pump team, which was not yet commercially available.

7.4 RESOURCE AVAILABILITY

As noted in the previous section, there do not appear to be obvious concerns with resource availability for much of the response. From the information made available, sufficient apparatus, personnel, monitors, hose, foam, and other resources appear to be available for a fire of a more typical progression. The unique situation with this particular fire doesn't appear to have challenged the amount of resources as much as the ability to deploy them.

One issue that does stand out, however, relates to obtaining assistance from US Fire Pumps. Jensen Hughes was not privy to the contract timing and arrangement between ITC Deer Park and US Fire Pumps, but the information provided by CSB and that in the public realm indicates that no contract was in place at the time of the incident. As well, no contract or relationship beyond the local mutual aid agreements noted previously was in place, based on the available information. The resulting administrative delays and gathering of resources by US Fire Pumps hindered quickly bringing those resources to bear. Although third-party contractors like US Fire Pumps have been in existence for some time, advocacy for standing contracts or rapid implementation of contracts became standard practice in the mid- to late-1990s. The 2001 release of API 2021 (Fourth Edition) was the first to mention such arrangements [API RP 2021, 2001], with industry recognition of the need for those relationships based on fires that occurred during the two previous decades.

7.5 PRE-INCIDENT PLANNING

Limited pre-incident planning information was released by ITC Deer Park for review by the CSB. The information provided suggests typical information sheets for the tank farm, identification of initial apparatus and equipment for deployment, location of those resources, suggested number and placement of personnel and similar data. That information is augmented by knowledgeable personnel, which is evidenced from information in interviews and the immediate response tactics.

From the limited information available, there do not appear to be any lessons learned that would be specifically extracted from this event. There have been long-standing recommendations in the industry to transfer information from personnel onto response plans and to augment plans with more detailed information on engineered systems and their potential contributions or drawbacks to response. That recommendation would likely have had some benefit to this response, but how much of a contribution cannot be easily determined. As that lesson is not unique to this situation, it was not examined further. However, a need for reinforcement of that existing lesson is noted.

7.6 PRE-INCIDENT TRAINING AND DRILLS

Although requests were made to ITC Deer Park and CIMA for training information and records, that information was rebuffed. Therefore, there is little ability to judge whether or not the training developed by these organizations for tank farms reveals any lessons to be learned. Both acknowledged through responses to requests for information that they have robust training programs that align with industry standards. Given information contained in interviews and the relatively rapid deployment of resources during the initial phase of the response that training on the level asserted is likely. It is not clear from the event, however, that the training incorporated the various weather-related, slope/drainage and apparatus placement issues described herein. While “improved training” is an often-cited lesson learned from large industrial fires, this particular one emphasizes some of those in specific areas for training and drills, involving scenarios considered unlikely, incorporating worst-case conditions (for example, wind directions, access failures, etc), involving process or engineering personnel in the training/drill scenario development and delving deeper into “what if” questions during planning and drills (such as, What if we can’t access this area?, What if we lose this pump?, What if we need X-many apparatus in this area?).

8.0 Potential Lessons Learned

From the evaluation provided herein, it is clear that the ITC Deer Park fire represented a significant challenge to responding firefighting organizations. However, the examination of various aspects surrounding the tank farm, its operating conditions, the firefighting operations and potential exposure conditions suggests that specific underlying conditions contributed to the event in significant ways. From those considerations, potential lessons learned are suggested to the CSB for consideration for incorporation with lessons learned that may have been derived outside of the Jensen Hughes effort. The lessons learned provided herein are provided in no particular order, as their importance or effect will differ for each reader of the final CSB package of information.

1. Improved education on the baseline assumptions of tank farm fire protection design is needed. The investigation of the ITC Deer Park fire highlights that guidance documents available for tank farm design (such as NFPA 30, API 2021, FM LPDS 7-88, and others) assume specific scenarios that require emergency response. The ITC Deer Park fire demonstrated that operations within tank farms can lead to

fire scenarios not assumed by the implemented tank farm design standard. In this specific case, the NFPA 30 approach does not address the potential for the combination of a ground and tank fire. Over the long term, understanding the basis of the design standard can help better guide future management of change and emergency response.

2. Similarly, understanding of the design basis fire scenarios must be better understood for corporate risk management. The ITC Deer Park case demonstrates a disparity between risk profiles assumed by the original design, emergency responders, corporate risk managers and insurance companies. Better understanding of the underlying assumptions of the design standard would better inform the other parts of the risk and response structures.

3. Improved information sharing between engineering teams and emergency response agencies is needed. The initial design of the ITC Deer Park “First and Second 80’s” tank farm generally complied with NFPA 30 requirements at the time of construction, but deviated from that standard with respect to drainage, tank layout and number of tanks within the same containment area. Although not deviations, choices regarding fire system design (in this case, manual supply versus automatic supply) and placement of fire system connections also had an impact on response. It is not clear that emergency responders understood the impact of those decisions prior to the fire event.

4. Improved information sharing and involvement between technical teams and emergency responders is needed prior to making modifications to tank farms that could potentially impact response capabilities in the event of a fire. The configuration of the tank farms, and the operations therein and at the perimeter, had obviously changed from original construction to the time of the event. The impacts of expanding pipe racks, adding piping and pumps and changing access necessarily adapted response planning over time. The ITC Deer Park fire exhibited some of those impacts not just in the initiating event, but also in the ability to respond to the west and south sides of the facility.

5. Better recognition of the contribution and importance of systems other than fire suppression and detection systems to emergency response appears to be needed. The ITC Deer Park fire reinforced that systems such as mechanical piping, drainage systems and electrical systems are important to preventing and mitigating fire conditions, and that they can influence the growth and spread of fire and the ability to respond when they do not perform as intended.

6. Process safety management (PSM) requirements have changed, and tank farms should be examined in closer detail. As well, a wider cadre of personnel should be in included in that effort. Operations like the blending performed at Tank 80-8 has been clarified by OSHA to fall under PSM guidelines. However, consideration of implementing PSM even when such analysis may not be applicable (such as well simple filling/emptying is performed) would be beneficial. As well, including emergency responders, maintenance staff and field operators in such efforts would greatly enhance the efforts of more technically-oriented personnel.

7. Consideration of upgrading facilities with newer safety equipment is needed. A significant shift in the type and availability of safety equipment occurred from the late-1980s through today. Tank farms constructed prior to the mid-1990s, when such equipment became readily available, should be revisited to determine if such equipment could aid in avoiding coupled accident, such as this one at the ITC Deer Park tank farm. This effort is encouraged even if the PSM process is not implemented for a given tank farm.

8. Contracting for third-party fire response services should more closely examined by tank farm owners. Recent fire histories and guidance via API RP 2021 and other documents highlights the need for third-party response agencies, but the ITC Deer Park fire also emphasized the need to either have a standing relationship in place or the ability to quickly contract for such capabilities. Overall, such services should be viewed in the same light as oil spill removal organizations (OSROs), environmental contaminant responders and more traditional fire responders (that is, local emergency response teams and mutual aid associations).

9. Some of the long-standing issues and recommendations within the industrial fire response industry were re-emphasized by ITC Deer Park fire. While such issues were not examined in detail for this fire, the event stands as a reminder to facilities to address pre-incident planning, training, drills, and similar preparatory efforts. What the ITC Deer Park response may demonstrate is a greater need for more detailed training or drill efforts and a need to include events that are considered unlikely.

9.0 References

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- Fire Water System Drawings
- Fire Foam Use Data
- Fire Pump Operations Data
- Fire Pump Testing Reports
- Fire Water Data
- Incident Command Forms
- Insurance Survey/Loss Prevention Reports
- Management of Change Authorization Forms
- Piping and Instrument Diagrams
- Response Partners List
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- Update/Statement 2, March 17, 2019, 3:30 pm
- Update/Statement 3, March 17, 2019, 7:00 pm
- Update/Statement 4, March 18, 2019, 1:30 am
- Update/Statement 5, March 18, 2019, 5:30 am
- Update/Statement 6, March 18, 2019, 10:00 am
- Update/Statement 7, March 18, 2019, 3:00 pm
- Update/Statement 8, March 18, 2019, 10:00 pm
- Update/Statement 9, March 19, 2019, 2:30 am
- Update/Statement 10, March 19, 2019, 10:00 am
- Update/Statement 12, March 19, 2019, 9:45 pm

- Update/Statement 13, March 20, 2019, 4:00 am
- Update/Statement 21, March 24, 2019, 10:00 am
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Appendix A – Modeling Report

A-1.0 Introduction

At the request of the US Chemical Safety and Hazard Investigation Board (CSB), Jensen Hughes was requested to analyze the fire events which occurred from Sunday, March 17, 2019 through Saturday, March 23, 2019 at the Intercontinental Terminals Company, LLC (ITC) tank farm in Deer Park, Texas.

This report presents results from fire and heat transfer modeling of the tank-to-tank fire spread observed in the ITC fire. This report builds upon the observations documented in the previous Jensen Hughes report, “Perspectives on Tank Farm Fire – ITC Deer Park (Texas) Facility, March 2019” [1]. The report includes general information on the ITC fire, a review of the technical literature relating to tank farm fires, and a discussion of the fire modeling analysis performed in this work.

A-2.0 General Information

This section provides an overview of background information related to the tank farm, the progression of the fire during the incident, and computational fire modeling.

A-2.1. DEER PARK, TEXAS TANK FARM LAYOUT

Figure A-1 provides an aerial view of the ITC Deer Park terminal prior to the fire (obtained via Google Earth Pro software) [2]. Figure A-2 provides the contents of the tanks in the “First and Second 80’s” tank farm where the fire occurred. All tanks were filled with combustible liquids other than tanks 80-9 and 80-12, which were empty at the time of the incident. All tanks except 80-9, 80-11, and 80-12 were equipped with a floating roof to reduce the evaporation rate of fuel [3]. Each tank measured 110 feet in diameter and 48 feet in height, and was separated from adjacent tanks by approximately 36 feet [4]. The floating roof consisted of a 108 foot, 8.4 inch diameter pan (steel or aluminum) [4]. A schematic of the tank geometry and separation is shown in Figure A-3.

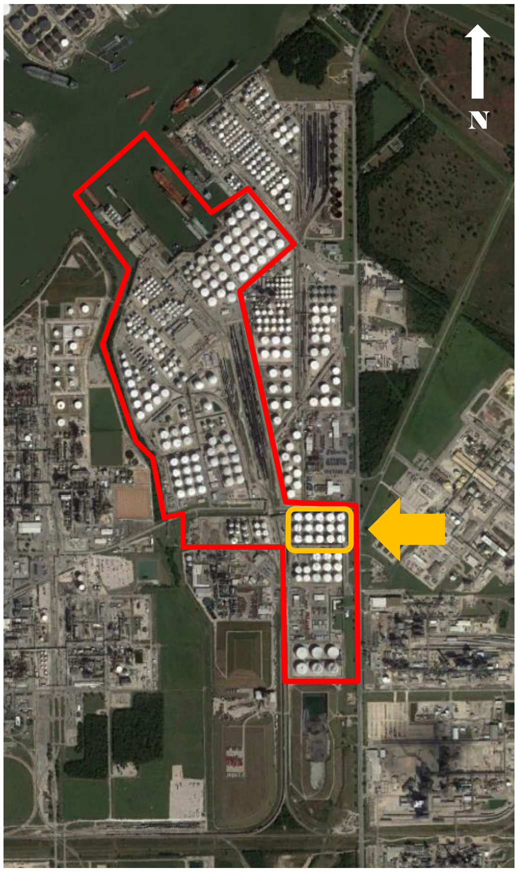


Figure A-1. ITC Deer Park, Texas Facility with “First and Second 80’s” Tank Farm Highlighted (Imagery Date: October 28, 2017) [2].

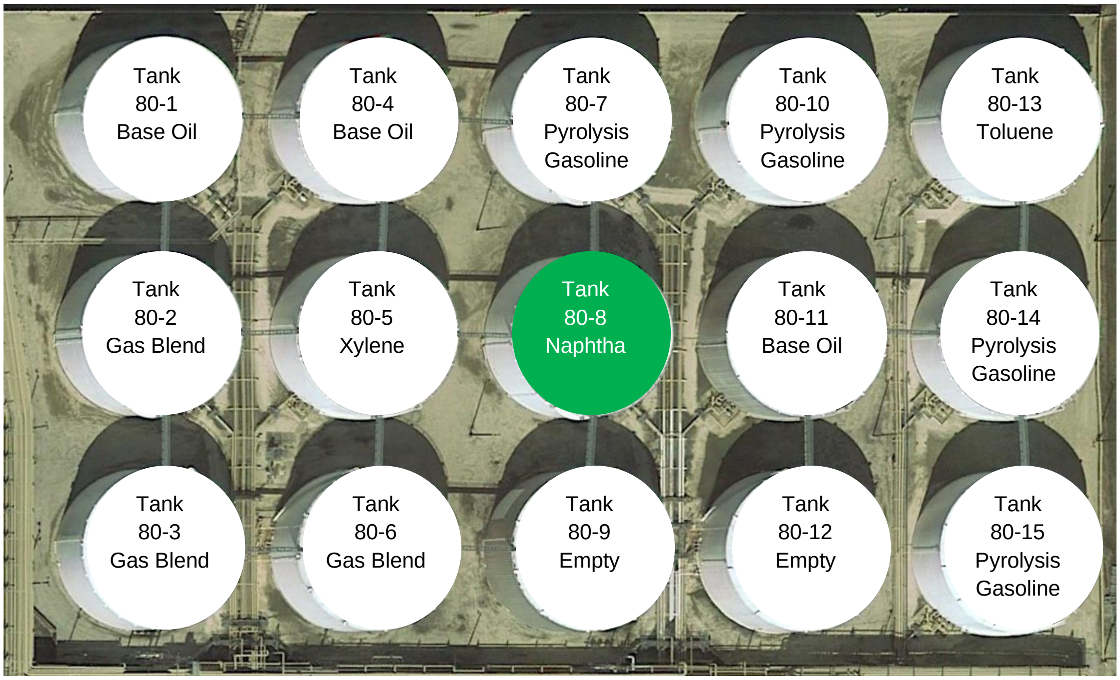
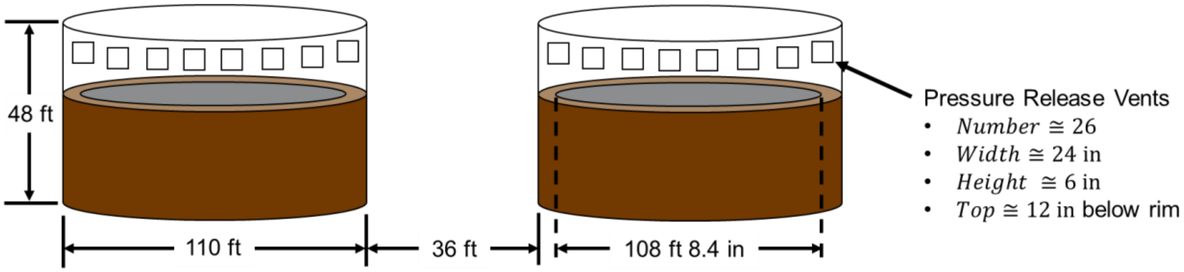


Figure A-2. "First and Second 80's Tank Farm" Tank Numbers and Contents at Time of Fire (Imagery Date: October 28, 2017) [2] (Contents from ITC Press Releases) [5] (Tank 80-8 highlighted in green).



- $Number \cong 26$
- $Width \cong 24$ in
- $Height \cong 6$ in
- $Top \cong 12$ in below rim

Figure A-3. Schematic of Tank 80-8 geometry and separation.

A-2.2. INCIDENT RESPONSE AND FIRE PROGRESSION

The incident response and fire progression for the ITC Deer Park established by the CSB team under separate cover was used to determine potential fire growth mechanisms. Of note is the length of time that Tank 80-5 took to ignite (approximately 7 hours after fire initiation) and the time indicated for subsequent ignitions (Tanks 80-2, 80-3, 80-6, 80-9 and 80-11 within 6.5 hours after ignition of Tank 80-5). Based on industry experience, this progression suggests radiant energy ignition of the tanks as opposed to direct exposure ignition.

A-2.3. ENVIRONMENT CONDITIONS

Figure A-4 and Figure A-5 show the wind conditions near the tank farm, taken from the weather station at Houston Ellington AFB (KEFD). The location of the weather station with respect to the tank farm is shown in Figure A-6. The weather station was located approximately 10 miles south-south-west of the tank farm.

Note the direction shown in Figure A-4 corresponds to the direction from which the wind was coming with respect to the tank farm. Figure A-4 shows the wind was initially coming from north-north-east during the day of 3/17/2019 but transitioned to south-south-east during the evening of 3/17/2019. During the morning of 3/18/2019 the wind transitioned to east-north-east for another day until it moved to a southerly direction in the evening of 03/19/2019. Figure A-5 shows the wind speed during the day generally ranged from 10-15 mph, with lower speeds of 0-5 mph in the evenings.

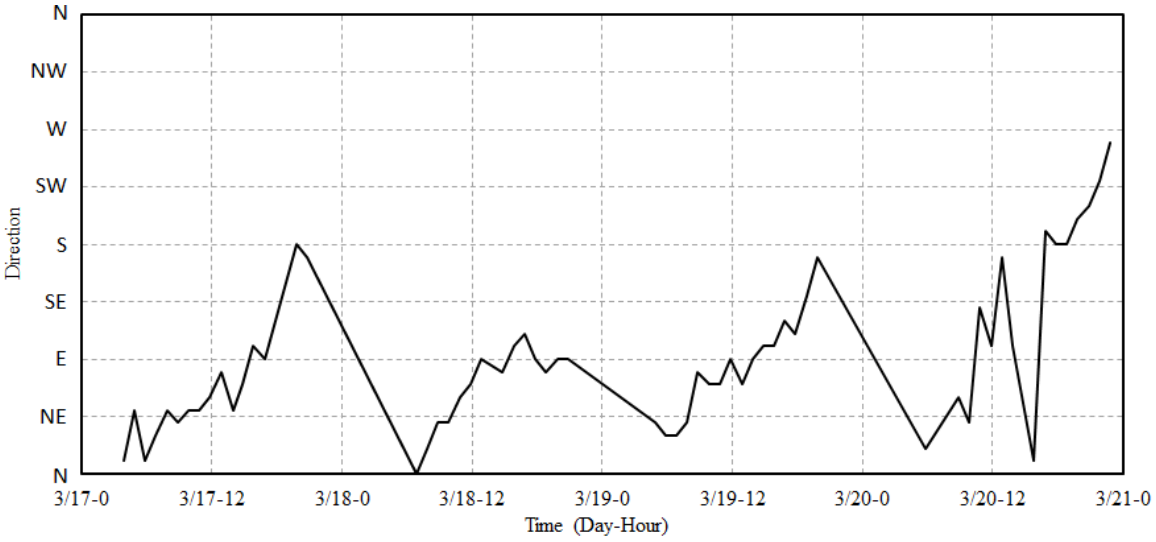


Figure A-4. Wind direction [Source: National Oceanic and Atmospheric Administration [6]].

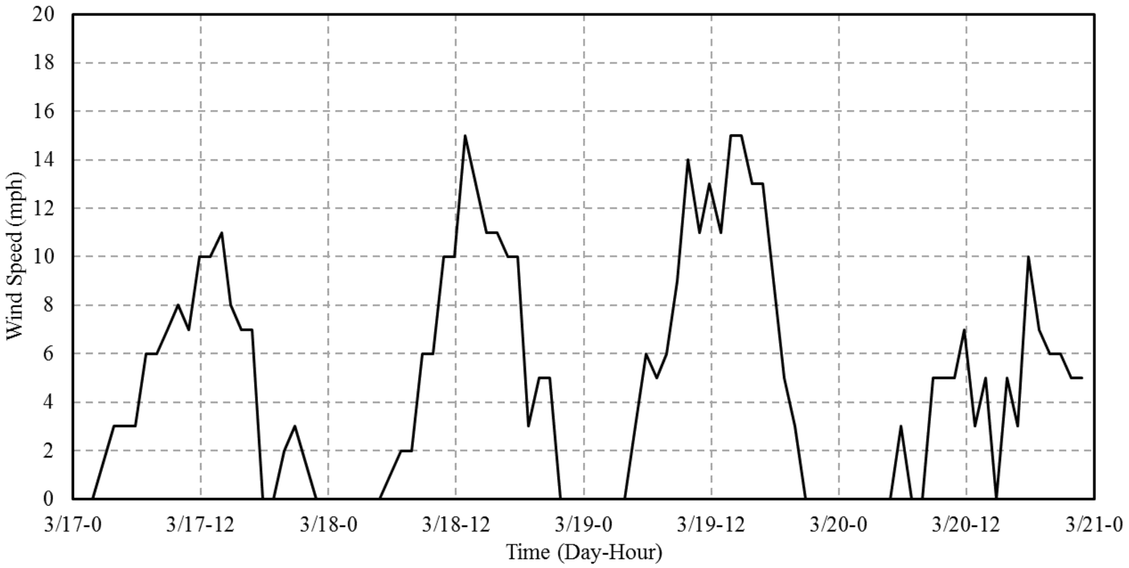


Figure A-5. Wind speed [Source: National Oceanic and Atmospheric Administration [6]].

A-3.0 Literature Review

Although the primary goal in tank farm fire protection is to avoid fires entirely, the secondary objective is to keep fires small to prevent large-scale fire spread and structural failure. One methodology which can be used to prevent large-scale fire spread is to increase separation distance between tanks to reduce the likelihood that a burning tank will ignite adjacent tanks. The minimum safe separation distance is defined as the distance where the heat transfer from one burning tank to an adjacent tank is insufficient to ignite the adjacent tank. The following subsections provide an overview of existing safe separation distance recommendations and analysis methodologies.

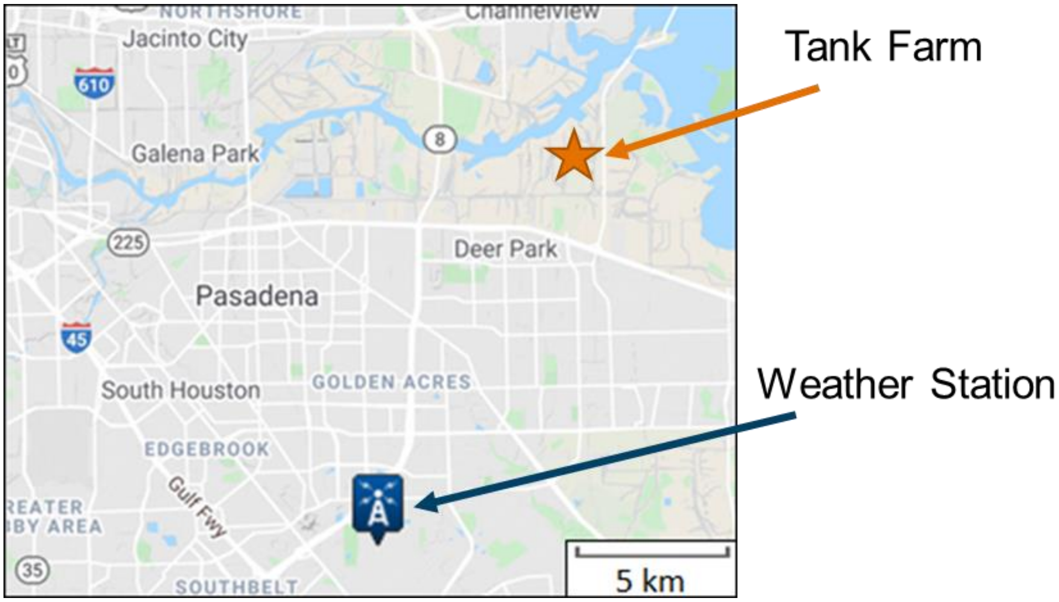


Figure A-6. Weather station location relative to tank farm [Source: Google maps [7]].

A-3.1. PRESCRIPTIVE CODES

Minimum safe separation distances are provided in several prescriptive codes such as *NFPA 30: Flammable and Combustible Liquids Code* [8], *FM Loss Prevention Data Sheet (LPDS) 7-88: Ignitable Liquid Storage Tanks* [9], and *API Pub 2021: Management of Atmospheric Storage Tank Fires* [10]. While the specific recommendations in NFPA 30, FM LPDS 7-88, and API Pub 2021 diverge somewhat, the general framework is the same. The following outlines a few key assumptions in these approaches.

- The safe distances are designed to address tank-to-tank fire spread events.
- The fire scenarios are based on probabilistically likely situations, as opposed to worst-case conditions.
- The size of fires are based on tank diameter, and industry-accepted failure probabilities (such as limited size openings in pipe systems) [11].
- Radiant exposures based on a single fire location (such as a tank liquid surface, or spill fire).
- Radiant exposures are estimated based on small scale experiments and data from historic tank-to-tank fire spread events.
- Radiant exposure thresholds vary significantly ranging, from 4.7 kW/m^2 (burns human skin after 30 s) [12], 7.0 kW/m2 (maximum tolerable value for firefighters in personal protective equipment) [12], to 8.0 kW/m^2 (limit to ignite an adjacent tank) [13].

While these codes provide conservative estimates for many scenarios, the specific scenarios observed in the fires at ITC did not align with several of these assumptions. These differences are outlined in Section 3.3.

A-3.2. PERFORMANCE-BASED ASSESSMENTS

The minimum safe separation distance is a function of the heat transfer from the flame (or radiant heat flux) as a function of distance and the critical radiant flux required to ignite an adjacent tank. Predicting the heat transfer in a tank farm fire is complex, requiring detailed information on the tank farm geometry, atmospheric boundary layer, liquid fuel evaporation, and combustion reactions. Researchers have developed several fire modeling approaches to predict the radiant heat transfer to adjacent tanks, each with varying levels of complexity of the physics.

Beyler provides an overview of hand calculation-based approaches used to predict heat transfer for large, open hydrocarbon fires in the SFPE handbook [14]. The Shokri and Beyler correlation provides an order of magnitude estimate of the radiative heat flux,

$$q'' = 15.4\left(\frac{L_c}{D}\right)^{-1.59} \tag{1}$$

where q'' is the heat flux, L_c is the length from the center of the pool, and D is the pool diameter [15]. Comparisons with experimental data show this approach reasonably reproduces the mean heat transfer observed in the experiments. However, the heat fluxes observed in the experiments have significant scatter which is not reproduced with this model (on the order of 10x lower, and 2x higher).

The point source model presented by Drysdale assumes the heat transfer from the flame is emitted by a single point at the center of the flame [16]. The heat flux is predicted using the equation,

$$q'' = \frac{\dot{Q}_r \cos\theta}{4\pi R_c^2} \tag{2}$$

where $\dot{Q}_r$ is the radiant energy released by the flame, θ is the angle between the normal to the target and the line of sight from the target to the center of the flame, and R_c is the distance from the center of the flame to the target. Similar to the Shokri and Beyler correlation, the point source method reasonably reproduces the mean heat transfer, but does not reproduce the scatter observed experimentally. Drysdale notes that the point source method is primarily applicable far from the fire, and a factor of 2 should be applied to any heat fluxes predicted to be less than 5 kW/m^2.

The two hand calculation approaches previously discussed were developed for diffusion flames under no wind conditions; however, Mudan has shown that wind tilting the flame towards an adjacent tank leads to higher exposures which are not captured in these approaches [17]. More detailed modeling approaches are needed to account for the impact of wind on the thermal exposure.

The simplest approach to account for the impact of wind is to modify the point source model based on empirically derived flame tilting data, such as in the approach presented by Sengupta [18]. In this approach, the extension of the flame is calculated using the dimensionless wind speed, and the flame tilt is calculated based on the ratio of the dimensionless wind speed and the maximum velocity within the fire plume. The new center of the flame is then used as the center in the point source model. While this approach provides reasonable estimates of the heat flux under different wind conditions, it inherits the same limitations as the standard point source model.

Mudan presented an alternative approach to predict the heat flux from a tilted pool fire based on view factor calculations from an inclined cylindrical source (representing a tilted flame) [17]. The flame extension and tilt are calculated using a similar approach to that presented by Sengupta. The inclined cylinder provides a more realistic representation of the flame shape than the point source model; however, this method has been shown to provide non-conservative estimates compared to experimental results [14].

The previously described approaches are all hand calculation-based methods. An alternative approach which has seen increased use in recent years is to use computational fluid dynamics (CFD) to predict the heat transfer from a flame to an adjacent tank. In a CFD fire model, the computational domain (including the fire, smoke, and surrounding environment) is discretized into small control volumes. Partial differential equations asserting conservation of mass, momentum, and energy are solved in each control volume to predict the development of the thermal flow field. The majority of the computational research to examine tank farm fires has been conducted using Fire Dynamics simulator (FDS) which is a CFD model developed by the National Institute of Standards and Technology (NIST). Zhou examined the impact of different wind configurations on the heat fluxes to an adjacent tank in a tank farm (diameter 80 m, height 22 m, separation 32 m) exposed to a crude oil fire [19]. Rengel et al. used FDS to recreate medium and large scale experiments of gasoline and diesel fuel tank fires [20]. Researchers have used other tools such as Ansys CFX [21], Ansys Fluent [22], FLACS [20].

While each of these approaches can provide estimates for many scenarios, the specific fire dynamics observed in the fires at ITC were different than a typical tank farm fire. This difference is outlined in Section 3.3.

A-3.3. ITC DEER PARK FIRE SCENARIO

Prescriptive and performance-based assessment of liquid tank fires are based on pool fire relationships. The mass evaporation rate of fuel in a pool fire is a function of the heat transfer to the surface and the latent heat of vaporization of the fuel. In a typical pool fire, the primary combustion reaction occurs directly above the liquid surface, as shown on the left in Figure A-7. The flame radiates heat to the surface which leads to an increased evaporation rate of the fuel. This feedback mechanism leads to a steady state evaporation rate where the heat flux from the flame is balanced by the latent and sensible heat losses from the surface. However, in the ITC fire the evaporated fuel was exiting the top of the tank through vertical pressure release vents, leading to a horizontal jet flame exiting the tank, as shown schematically in the right of Figure A-7. As a result, the heat transfer to the liquid surface is primarily due to heat transfer from hot gases in the vapor space above the floating roof in the tank rather than radiation from the flame. In addition, the tanks involved in the ITC fire were equipped with floating roofs designed to reduce the surface available for evaporation. Assuming the floating roofs function as intended, pool fire relationships based on the diameter of the tank will significantly overestimate the total heat release rate of the fire.

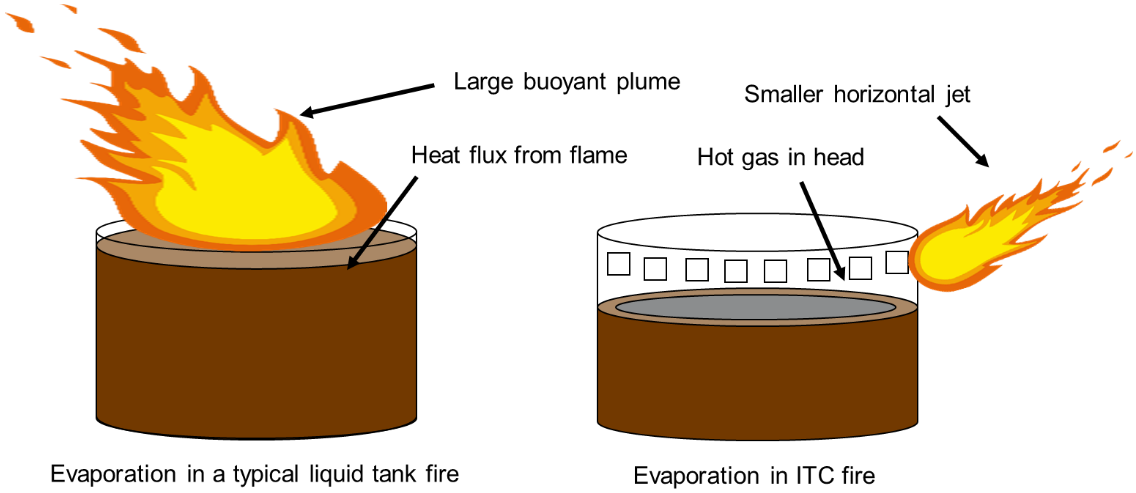


Figure A-7. Comparison of typical liquid fuel tank fire and ITC Deer Park, TX fire.

A-4.0 Fire Modeling

This work focused on modeling the fire dynamics observed in the ITC fire to better understand the tank-to-tank fire spread. The objectives of this analysis were the following:

1. Evaluate the tank-to-tank thermal exposure considering uncertainties in wind conditions, geometric configuration, fuel type, and fire size.
2. Evaluate the additive impact of pool fires at the grade level on tank exposure.
3. Evaluate the efficiency of tank spacing requirements in NFPA 30.

The fire modeling was conducted in three phases. The focus of each phase was the following:

1. Hand calculations to predict liquid evaporation rate in ITC Deer Park, TX configuration.
2. Hand calculations to predict thermal exposure (heat flux) versus distance in ITC Deer Park, TX configuration.
3. Detailed computational fluid dynamics (CFD) model to predict heat flux versus distance in ITC Deer Park, TX configuration.

A-4.1. HAND CALCULATIONS TO PREDICT LIQUID EVAPORATION RATE IN TANK

The focus of this phase of the analysis was to determine a realistic estimate of the fuel evaporation rate within the tank during the ITC fire. Several fundamental concepts related to this modeling effort are summarized below:

- The evaporation rate depends on the net rate of heat transfer and heat of vaporization of the fuel.
- The exposure heat transfer in the ITC fire is based primarily on the gas temperature in the head of the tank.
- Some of the incident radiation from the hot gas is transmitted through the surface of the fuel and absorbed through the depth of the fuel, based on the absorption coefficient of the liquid.
- Researchers have shown that the surface temperature of liquid fuels during steady burning is maintained at the boiling temperature of the liquid, as shown in Figure A-8.
- A hot zone can develop over time in a storage tank fire (especially in fires involved imperfect mixtures such as crude oil), where more of the fuel is at the boiling temperature, as shown in Figure A-9.

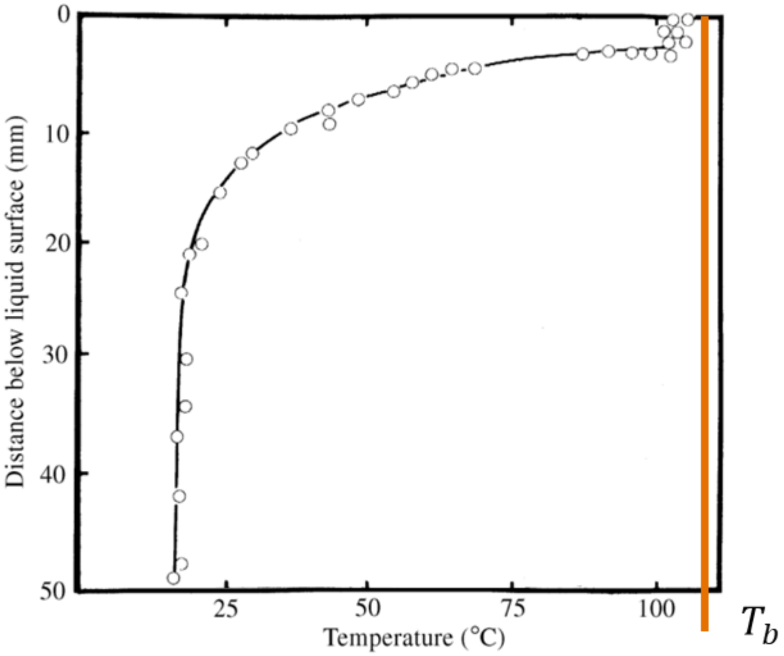


Figure A-8. Temperature distribution through the depth of a liquid pool fire during steady burning [23], [24].

After some period of transience, the liquid fuel will reach a steady burning period where the net energy being absorbed by the liquid equals the latent heat lost to evaporation. A one-dimensional heat transfer model was developed to predict the temperature distribution within the tank over time to understand the time required to reach this steady state.

The fundamental formulation of the model is based on the 1-D heat equation as formulated by Girgis et al. [25] for thermal stratification of stagnant lakes, where the radiant energy absorbed through the depth of the liquid is modeled as an internal generation term,

$$\frac{\partial T(z,t)}{\partial t} = \alpha \frac{\partial^2 T}{\partial z^2} + \frac{H(z,t)}{\rho c_p} \tag{3}$$

where T is the temperature of the liquid in the tank, z is the vertical position in the tank, t is time, α is the thermal diffusivity of the liquid, ρ is the density of the liquid, c_p is the specific heat capacity of the liquid, and H is the rate of heat generated per unit volume by internal absorption of radiation transmitted through the surface of the liquid. The internal absorption of radiation is calculated using the equation

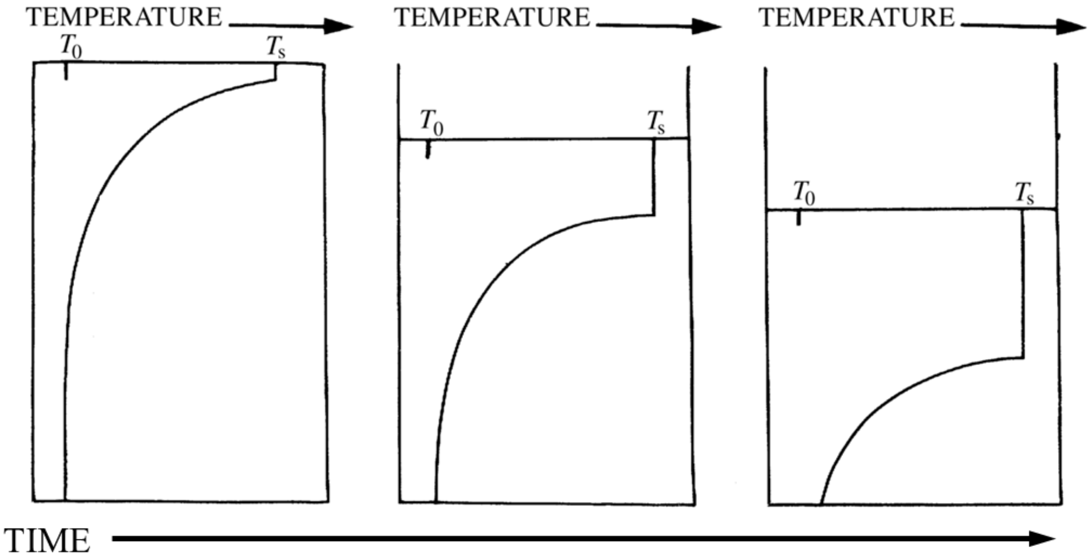


Figure A-9. Schematic showing the progression of a hot zone in a storage tank fire [24].

$$H(z,t) = \frac{\partial q''_{abs}}{\partial z} = q''_{inc}(t)(1-\beta)\kappa \exp(-\kappa z) \tag{4}$$

where q''_{inc} is the incident radiation on the surface, β is the fraction of energy absorbed at the surface, and κ is the absorption coefficient of the liquid. The incident radiation on the surface is calculated as

$$q''_{inc}(t) = \varepsilon_{gas}\sigma T_{gas}(t)^4 \tag{5}$$

where ε_{gas} is the gas emissivity (assumed to be 1.0 in this analysis), σ is the Stefan-Boltzmann constant, and T_{gas} is the gas temperature in the tank head in Kelvin. While the analytical formulation supports time-varying radiant exposure, a fixed value of gas temperature was used in this analysis. A mixed boundary condition was used at the surface of the liquid, defined as

$$\left(\frac{\partial T}{\partial z}\right)_{z=0} = \left[\beta q''_{inc}(t) + h\left(T_{gas}(t) - T(0,t)\right) - \varepsilon_l \sigma T(0,t)^4\right]\left(\rho c_p \alpha\right)^{-1} \tag{6}$$

where ε_l is the emissivity of the liquid surface (assumed to be 1.0 in this analysis). An adiabatic boundary condition was used at the bottom of the tank.

The assumptions made in the liquid tank model developed in this work are summarized below:

- The tank is large with a uniform exposure. Thus, there is an adiabatic boundary in the radial direction and the model only needs to calculate heat transfer in the vertical direction.
- The floating pontoon prevents evaporation of fuel, effectively reducing the exposed area.
- The tank is large relative to the evaporation of the fuel. Thus, the regression rate of the liquid surface can be neglected. This is believed to be reasonable based on the small fraction of liquid area not covered by the floating pontoon.
- The liquid fuel is stagnant. Thus, the convective motion of the fluid and the impact of eddy viscosity and turbulent diffusion can be neglected.
- The head of the tank is saturated with vaporized fuel. Thus, the evaporation rate of fuel is equal to the rate fuel leaves the tank.
- Incident radiation is partially absorbed at the surface ($\beta = 0.5$ in this analysis), and the remainder is absorbed through the depth of the fuel based on the absorption coefficient of the liquid.
- The maximum temperature the liquid can reach is its boiling temperature. Any energy absorbed by a control volume of liquid after reaching the boiling temperature goes to vaporizing fuel at the surface.

Equations 3-6 were solved numerically using an implicit finite difference scheme. A timestep of 0.01 s was used along with a grid size of 3 cm. The transient simulation was conducted for 2 hours of constant exposure with a head temperature 500 °C. Liquid properties in this analysis were based on petroleum-naphtha ($T_{boil} = 97.2℃$ [26], $L_v = 340\ kJ/kg$ [26]) which is representative of the liquid fuel in the initial tank involved in the ITC fire (Tank 80-8). Some properties were not available for petroleum-naphtha and n-heptane was used as a surrogate ($\kappa = 18.3\ atm^{-1}m^{-1}$ [27], $\Delta H_c = 44{,}400\ kJ/kg$ [28], $\rho = 688\ kg/m^3$ [28], $c_p = 2.2\ kJ/kg - ℃$ [28], $k = 0.14\ W/m - K$ [29]). Transient temperature profiles within a liquid tank of petroleum-naphtha exposed to a 500 °C head temperature are shown in Figure A-10, and the corresponding transient evaporation flux is shown in Figure A-11.

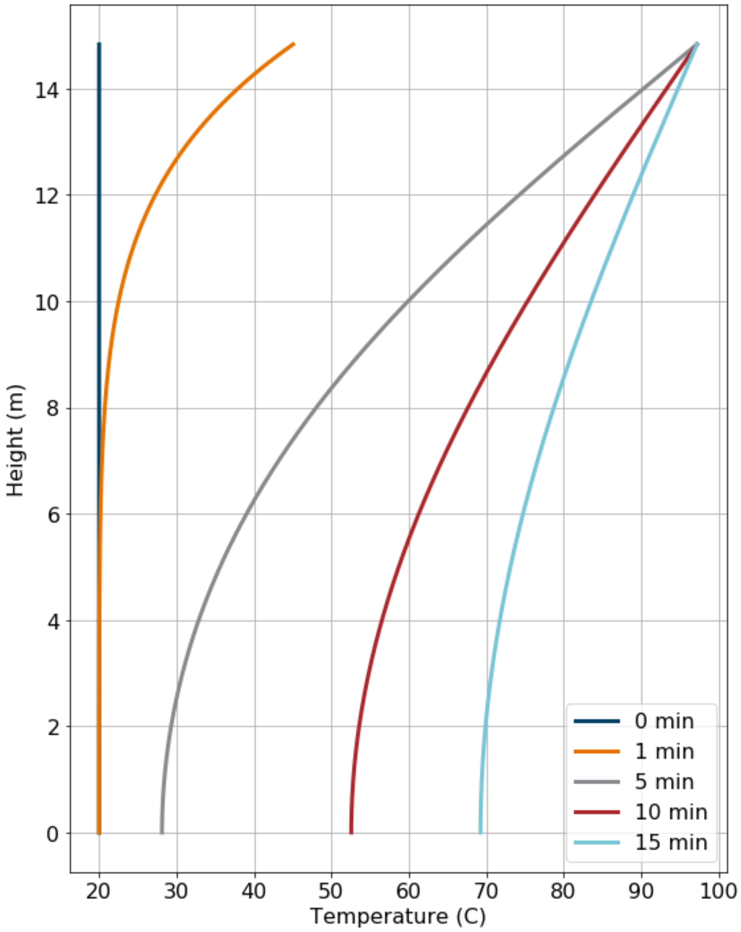


Figure A-10. Transient temperature profile in liquid tank of petroleum-naphtha exposed to 500 °C gas temperature.

Figure A-11 shows there is an initial spike in evaporation flux after 5 minutes of exposure, corresponding to the surface reaching the boiling temperature. The majority of the energy is absorbed at the surface due to the high absorption coefficient of the liquid, which results in the initial spike in evaporation flux nearly reaching the steady state value. The evaporation flux starts to rise after approximately 60 minutes of exposure as lower sections of the tank start to reach the boiling temperature. The time to reach the steady state evaporation flux is visualized in Figure A-12 by examining the time for the bottom of the tank to reach the boiling temperature. These results indicate that the liquid evaporation flux in the ITC fire likely reached a steady configuration within two hours of initiation.

The steady state evaporation flux was calculated for a range of head temperatures and fuel types and converted to a steady state heat release rate per unit of exposed area, as shown in Figure A-13. The corresponding total heat release rate of the tank based on an exposed area of 20.6 m^2 (221.7 ft^2) is shown in Figure A-14. A head temperature of 500 °C exposes the liquid to a similar heat flux as a flame above the surface (20 kW/m^2). These results indicate the total heat release rate for one tank in the ITC Deer Park, TX fire would be 63.22 MW for a

500 °C exposure. This yields a per vent heat release rate of 2.4 MW for 26 uniform vents. The flame length predicted based on a 2.4 MW fire (see phase 2 analysis, Eq. 7) agreed well with the flame extension observed in the ITC fire. These results were used as a baseline configuration for the analysis in the hand calculations and detailed CFD modeling.

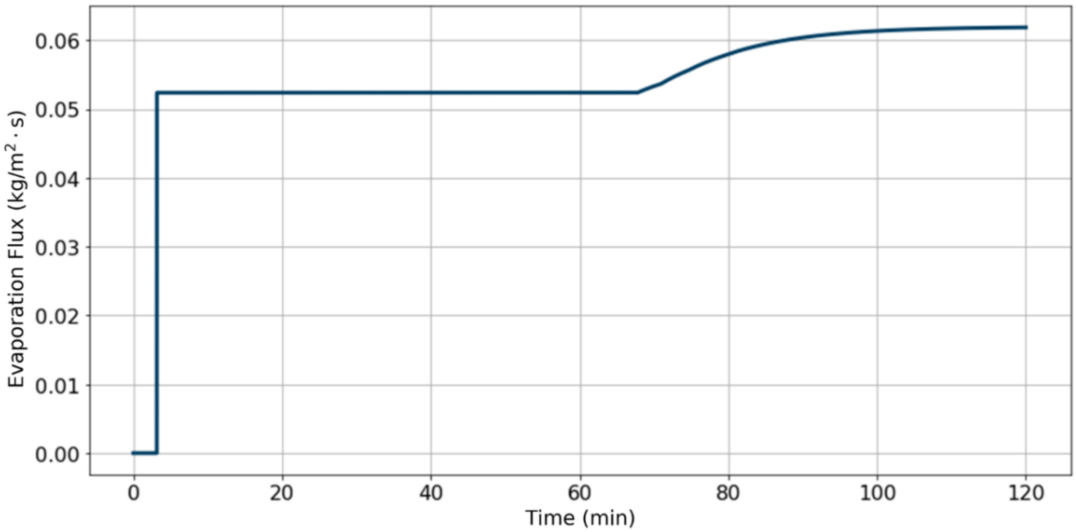


Figure A-11. Transient evaporation flux in liquid tank of petroleum-naphtha exposed to 500 °C gas.

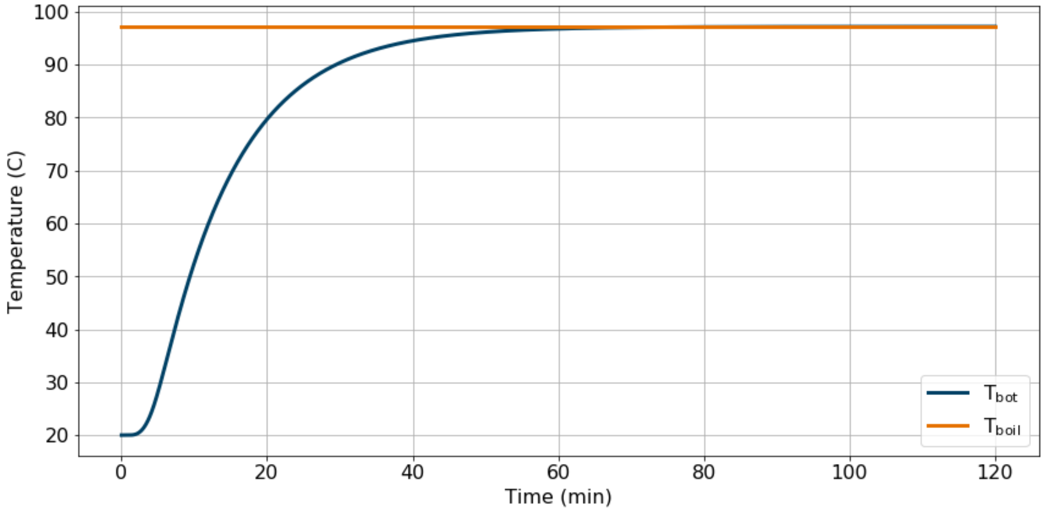


Figure A-12. Transient temperature at bottom of liquid tank of petroleum-naphtha exposed to 500 °C gas.

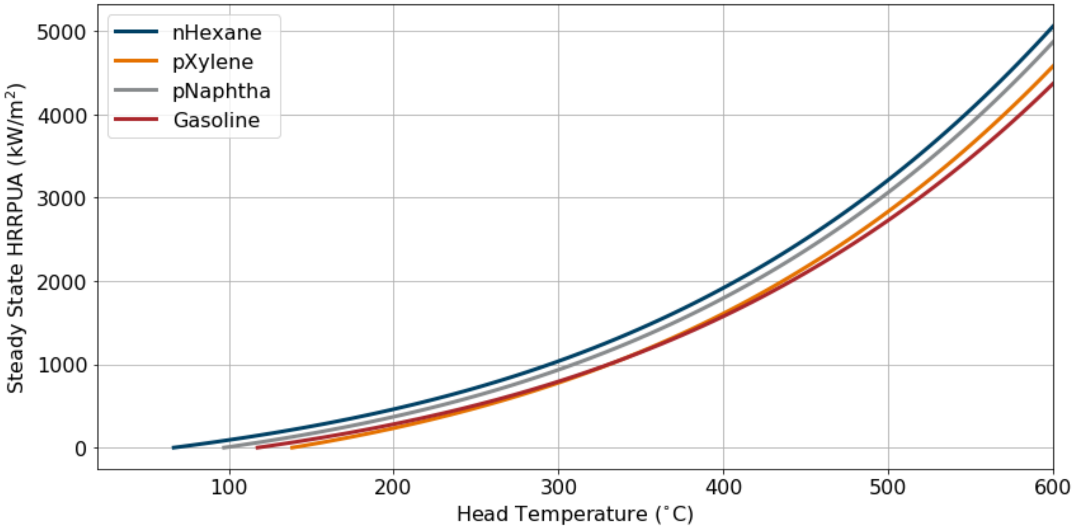


Figure A-13. Steady state heat release rate per unit exposed area versus head temperature for different fuels.

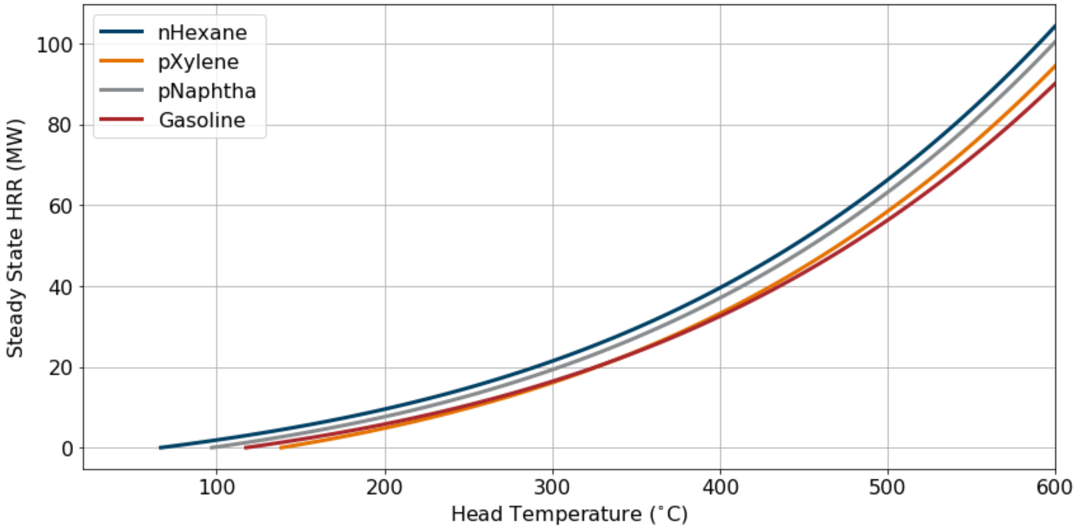


Figure A-14. Steady state total tank heat release rate versus head temperature for different fuels.

A-4.2. HAND CALCULATIONS TO PREDICT THERMAL EXPOSURE VERSUS DISTANCE

The focus of this phase of the analysis was to determine a realistic estimate of thermal exposure from the ITC fire with different separation distances using engineering hand calculations. Hand calculations were conducted using two models: the tilted point source [18], and the Mudan model [17]. The fundamental assumptions related to this modeling effort are summarized below:

- The evaporated fuel exits the side of the tank at several vent locations along the outer rim of the tank ($N_{vents} = 26$ in this analysis).
- The evaporated fuel is evenly distributed among the vents.
- The heat flux to the adjacent tank is a linear combination of the heat flux contribution from the fire at each vent.
- Tilting of the flame behaves similarly to a typical pool fire tilted by wind.
- Shortening of flame resulting from increased wind (due to increase in mixing near tank) neglected.

The tilted point source model was based on the modification presented by Sengupta [18] to incorporate the impact of wind. However, rather than placing the base of the fire at the center of the tank, the fire was split into N_{vents} sections, evenly distributed along the rim of the tank. A schematic of the representation is shown in Figure

A-15. Heat flux contributions from all vents in the front 180 degrees of the burning tank were considered in this analysis.

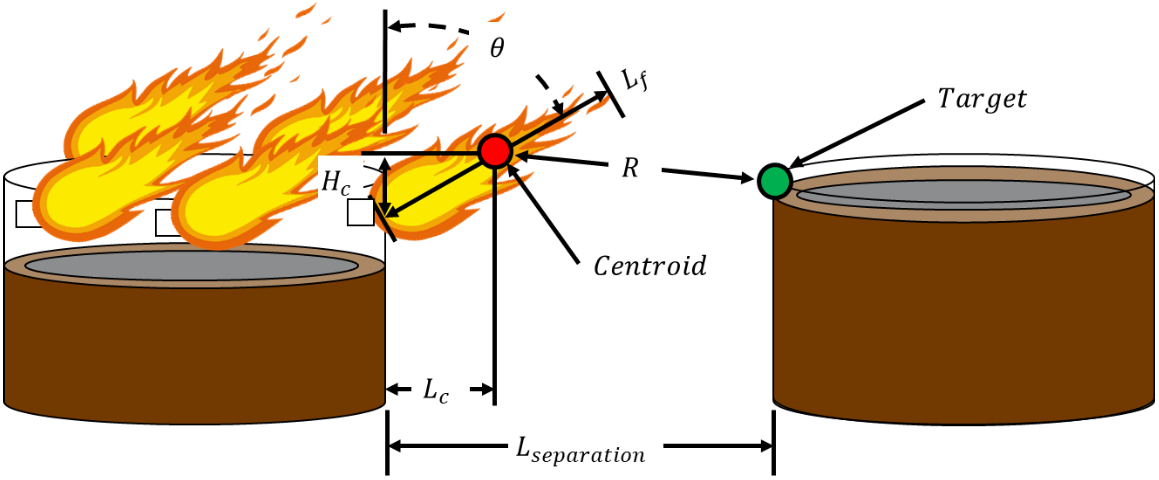


Figure A-15. Schematic representation of tilted point source hand calculation.

The flame length was calculated using Heskestad's correlation for flame length in a no wind configuration [30],

$$L_f = 0.235\dot{Q}_{vent}{}^{2/5} - 1.02D_{vent} \tag{7}$$

where L_f is the flame length, $\dot{Q}_{vent}$ is the per vent heat release rate, and D_{vent} is the equal area diameter of the vent. The height and width of the flame centroid was calculated using trigonometry,

$$H_c = \frac{L_f}{2}\cos(\theta) \tag{8}$$

$$L_c = \frac{L_f}{2}\sin(\theta) \tag{9}$$

where H_c is the height of the centroid, L_c is the length of the centroid, and θ is the flame tilt angle measured from vertical. The flame tilt angle was calculated using the Muñoz et al. correlation [31],

$$\theta = \begin{matrix} \cos^{-1}(0.96u^{*,-0.26}) & \text{for} & u^* \geq 1 \\ 0 & & u^* < 1 \end{matrix} \tag{10}$$

where u^* is non-dimensional velocity,

$$u^* = \frac{u_w}{u_c} = \frac{u_w}{(g\dot{m}''_{vent}D_{vent}/\rho_a)^{1/3}} \tag{11}$$

where u_w is the wind velocity, u_c is the fire plume velocity, g is the acceleration due to gravity, $\dot{m}''_{vent}$ is the mass burning rate at a single vent, and ρ_a is the ambient air density. The linear distance from the flame centroid to the target on the adjacent tank was calculated based on trigonometry,

$$R = [L^2 + H_c^2]^{1/2} \tag{12}$$

where R is the linear distance to the target on the adjacent tank, and L is the horizontal distance between the centroid and the target. The horizontal distance between the centroid and the target for a specific vent was calculated using trigonometry,

$$L = \left(\left[L_{separation} - L_c + D_{tank}(1 - 0.5\cos\psi)\right]^2 + [0.5D_{tank}\sin\psi]^2\right)^{1/2} \tag{13}$$

where D_{tank} is the diameter of the tank, and ψ is the angle of the vent off the centerline of the tank. The heat flux to the target is calculated using the point source model,

$$\dot{q}''_{gauge} = \frac{\chi_r \dot{Q}_{vent}}{4\pi R^2} \frac{L}{R} \tag{14}$$

where $\dot{q}''_{gauge}$ is the heat flux, and χ_r is the radiative fraction.

It is worth noting that χ_r in this context is not purely a property of the chemical reaction. By definition, it is the percentage of the total energy released by the fire which is transmitted to boundaries through radiation. For smaller fires typically observed in a laboratory setting, χ_r typically ranges from 0.3 to 0.4. However, the thick layer of soot generated in large pools absorbs a significant fraction of the radiant energy emitted by flames near the center of the pool, resulting in more of the energy being lost to the convective transport of the soot. Beyler presented a correlation to account for this phenomena [32],

$$\chi_r = 0.21 - 0.0034 D_{tank}. \tag{15}$$

Based on Eq. 15, $\chi_r = 0.1$ for the geometry examined in this work. However, this relationship is based on a large pool fire, and it is uncertain how valid this correlation is to the series of smaller fires on the rim observed in the ITC fire. For the hand calculations using this approach, a range of values for χ_r were considered to understand the impact of this parameter.

Heat fluxes with different separation distances and χ_r computed using the tilted point source model with a 10 mph wind speed are shown in Figure A-16. The safe separation distance threshold in this analysis is 8 kW/m^2 based on the heat flux required to ignite an adjacent tank. The heat fluxes predicted using the tilted point source model indicate that fire exiting the vents on Tank 80-8 would be well below the heat flux required to ignite an adjacent tank of 8 kW/m^2 regardless of the uncertainty in χ_r. Using Beyler's correlation for χ_r, the best estimate of the heat flux at the target position is 1.0 kW/m^2. Note, these results are prior to adding the recommended factor of safety multiplier of 2.0x.

The second hand calculation method conducted in this analysis used the method presented by Mudan [17]. In this approach, the point source is replaced with a titled cylinder. A schematic representation of the approach is shown in Figure A-17. The heat flux is calculated in this approach using the equation

$$\dot{q}'' = E F_{max} \tau \tag{16}$$

where E is the average emissive power at the flame surface, F_{max} is the view factor from the cylinder to the target, and τ is the transmissivity of the atmosphere. The average emissive power of the flame is given as the fractional average of the flame emissive power and smoke emissive power, by the equation

$$E = E_{max} \exp(-sD) + E_s[1 - \exp(-sD)] \tag{17}$$

where E_{max} is the equivalent blackbody emissive power (140 kW/m^2), s is the extinction coefficient (0.12 m^{-1}), E_s is the emissive power of smoke (20 kW/m^2), and D is the equivalent pool diameter. The equivalent pool diameter in Eq. 17 acts similar to χ_r in the point source model, effectively accounting for the fraction of energy which is lost due to convection of smoke. It is unclear whether basing the emissive power on D_{tank} or D_{vent} will provide a more realistic estimate due to the difference in fire dynamics. As the true emissive power is likely bounded between these two numbers, the analysis was performed both ways to provide a range of predicted values.

The view factor for the tilted cylinder was calculated using the equations presented by Beyler [14]. A more detailed discussion of the view factor calculation can be found in [14].

Beyler provides the atmospheric transmissivity as a function of relative humidity, ambient air temperature, and radiative path length [14], reproduced below in Figure A-18. A detailed discussion of the development of Figure A-18 can be found in [14]. Assuming the radiative path length is on the order of the tank separation (~11m) and a relative humidity of 40%, a value of 0.85 was used for τ in this analysis.

Heat fluxes with different separation distances and wind speeds computed using the tilted cylinder model assuming the effective diameter is the vent diameter and tank diameter are shown in Figure A-19 and Figure A-20, respectively. The heat fluxes predicted using the tilted cylinder model agree with the point source model, indicating that fire exiting the vents on Tank 80-8 would be well below the safe separation threshold of 8 kW/m^2

regardless of the uncertainty in the effective diameter. Using the vent diameter, the heat flux on the adjacent tank was predicted to be in the range from 3.0-3.5 kW/m^2 for different wind speeds. Using the tank diameter, the variation due to wind speed was negligible, with a predicted heat flux of 0.5 kW/m^2.

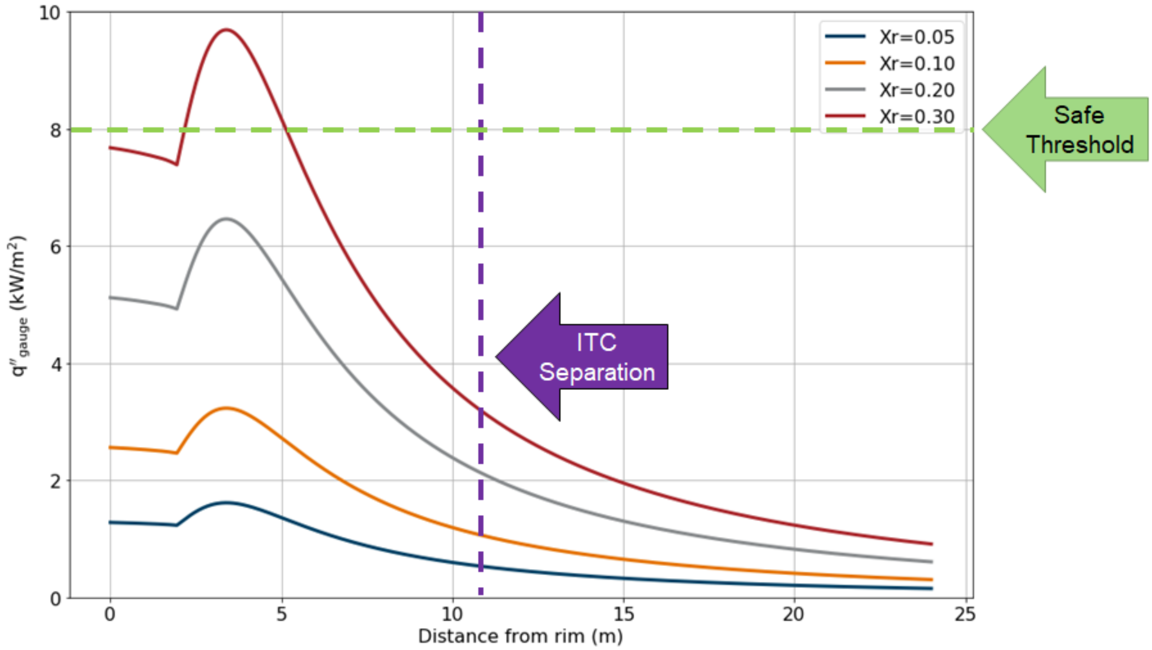


Figure A-16. Heat flux predictions using the titled point source model at different separation distances and χ_r.

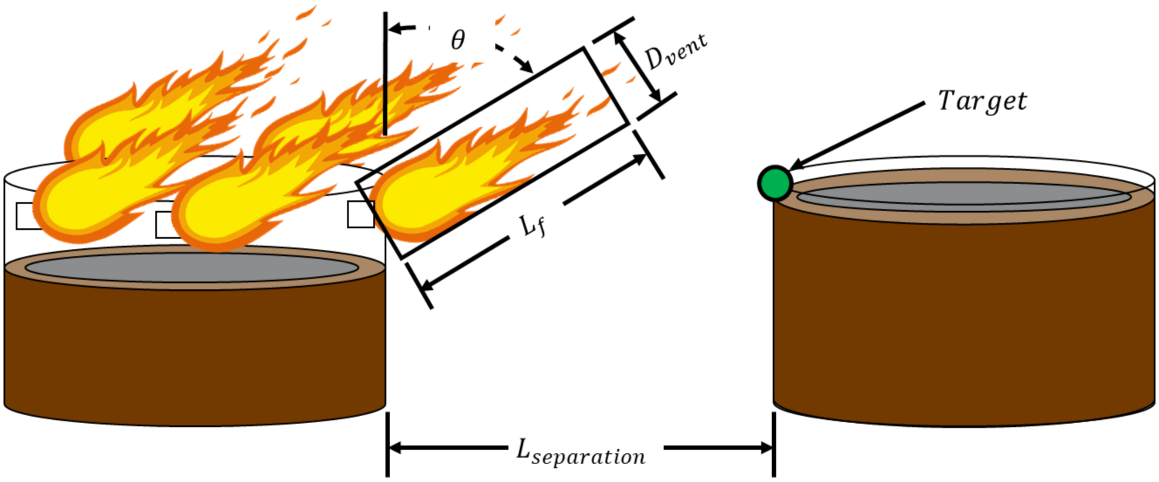


Figure A-17. Schematic representation of tilted cylinder hand calculation.

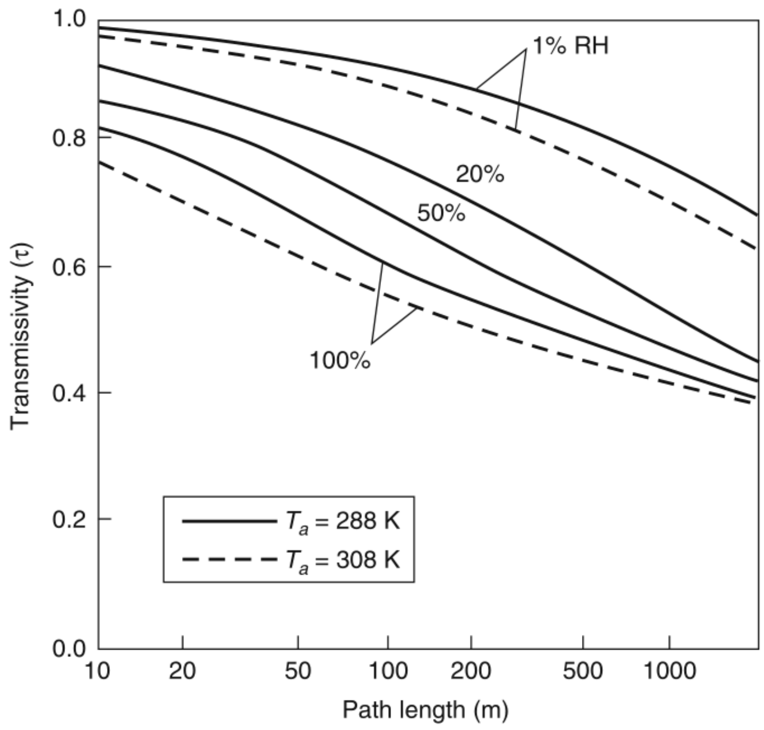


Figure A-18. Atmospheric transmissivity as a function of radiative path length, ambient air temperature, and relative humidity [14].

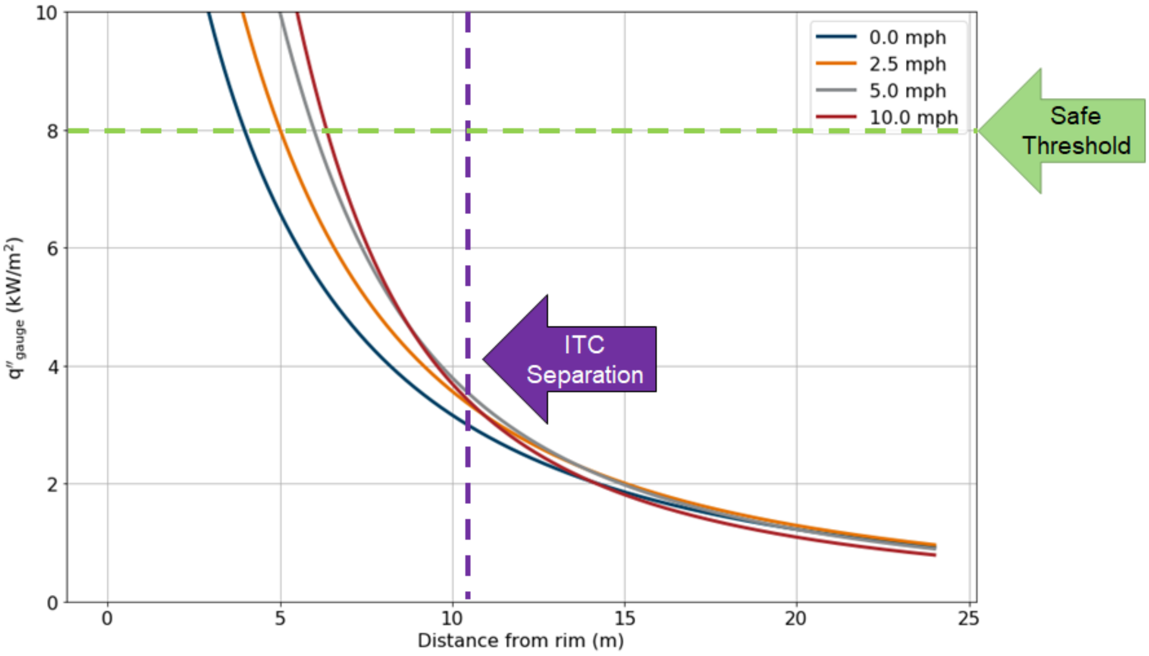


Figure A-19. Heat flux predictions using the titled cylinder model at different separation distances and wind speeds, assuming the effective diameter is the vent diameter.

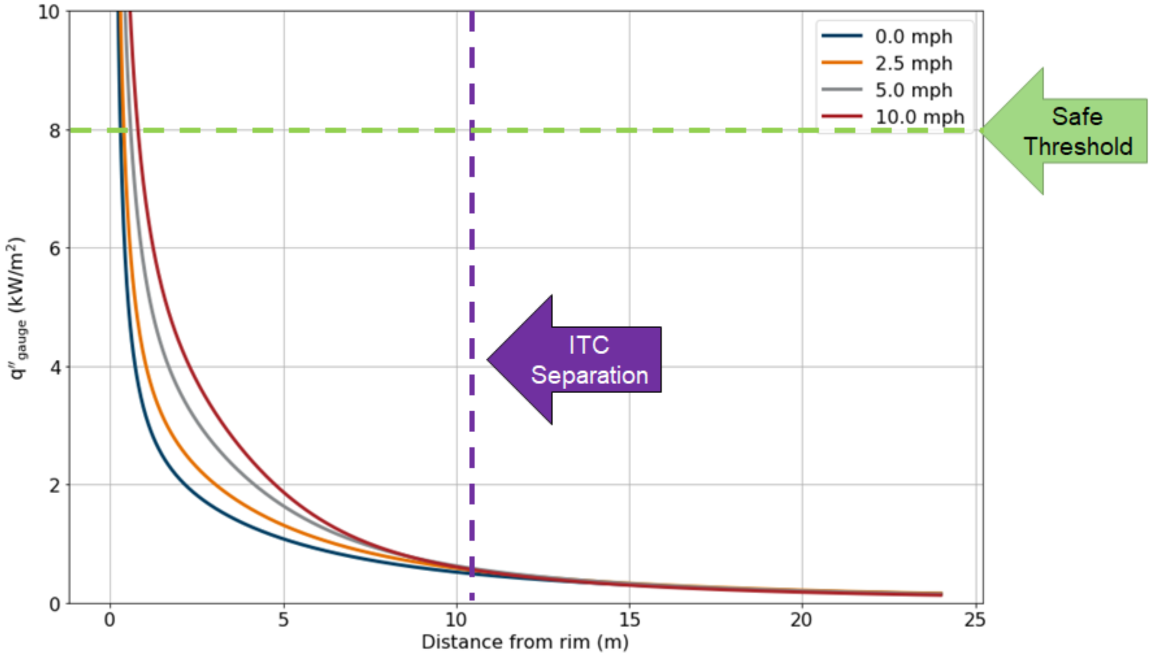


Figure A-20. Heat flux predictions using the titled cylinder model at different separation distances and wind speeds, assuming the effective diameter is the tank diameter.

A-4.3. DETAILED FIRE MODELING TO PREDICT THERMAL EXPOSURE

The focus of this phase of the analysis was to perform an assessment of the thermal exposure from the ITC fire using a highly resolved computational fluid dynamics (CFD) model to obtain a more realistic estimate of the exposure than can be achieved with engineering hand calculations. The simulations were conducted using Fire Dynamics Simulator (FDS, version 6.7.4) developed by the National Institute of Standards and Technology (NIST). The following sub-sections provide an overview of FDS, the specific fire scenarios modeled in this analysis, and a discussion of the model sensitivity and uncertainty.

OVERVIEW OF FIRE DYNAMICS SIMULATOR

Fire Dynamics Simulator (FDS) is a general purpose low-speed (Mach number < 0.3) computational fluid dynamics (CFD) software primarily designed to model buoyantly drive flows typical of diffusion flames [33], [34]. In an FDS simulation, the computational domain is divided into small (on the order of 10s of cm) control volumes (often called grid cells). By solving a set of partial differential equations asserting conservation of mass, momentum, and energy in each grid cell as well as a radiation transport equation, the software predicts the time-evolution of the gas temperature, velocities, and species concentrations in each grid cell as well as heat transfer to solid surfaces. FDS has an extensive validation basis in fire safety applications [35], and is considered the state-of-the-art in fire modeling for diffusion flames. An overview of the sub-models in FDS used in this analysis are summarized below.

Turbulence Model

Similar to other CFD software, FDS numerically solves the Navier-Stokes equations which are the set of partial differential equations for the transport of mass, momentum, and energy by a fluid acting as a continuum. In this context a continuum means that the fluid density is high enough that molecule-molecule interactions are not modeled by the equations outside of bulk physical quantities. Typically, FDS simulations are conducted using the large eddy simulation (LES) method. In this mode of operation, the grid cells are not small enough to fully resolve the diffusive fluxes of heat and mass on the grid. As a result, a subgrid model is needed to characterize the dissipation of energy from smaller eddies. The Deardorff subgrid turbulence model is the default turbulence model in FDS, which was selected due to the its agreement with full-scale experiments [33], [34]. This model was used in this analysis based on the strong validation basis in the FDS validation guide [36].

Radiation Transport

FDS solves an additional transport equation for gray gas radiation through an absorbing, emitting, but not scattering medium. The radiation transport equation is solved using a finite volume method similar to the convective transport equations. Each grid cell is discretized into a number of discrete radiation angles, with the total emission split among the different angles. The absorption along each angle is calculated based on the absorption coefficient in adjacent grid cells. The absorption coefficient is calculated based on species concentration and temperature using an external model, RadCal [37]. At the LES grid scales, the cell-averaged gas temperatures within the flaming regions are smeared due to the flame thickness (on the order of 0.1 cm) not being resolved. The fourth power dependence on temperature in the radiation emission leads to an underprediction in the radiant emission in the flaming regions. This underprediction is corrected using a corrective factor based on the reaction rate in a specific cell and a globally defined radiative fraction which is a property of the gas phase combustion reaction. The uncertainty in this correction is accounted for in the uncertainty assessment presented in the FDS validation guide [35].

Combustion Model

The combustion model used in this analysis was a single-step, mixing-controlled combustion. In this model, the reaction is assumed to occur infinitely fast, which means whenever gaseous fuel and oxygen are present in the same grid cell, they are assumed to react instantly until either the fuel is consumed or oxygen concentration in the cell reaches the lower flammability limit. The lower flammability limit is based on the limiting oxygen index concept discussed by Beyler [38]. FDS can be used to predict piloted and unpiloted ignition through the use of an autoignition temperature. Piloted ignition was used in this analysis.

Solid Boundaries

Solid boundaries in FDS are handled using a simple immersed boundary method. A subgrid model is needed to predict convection heat transfer since the boundary layer near the wall is not resolved. FDS contains a number of different correlations for computing the heat transfer coefficient to surfaces. The default approach used in FDS is to compute a natural and a forced convection heat transfer coefficient using flat plate heat transfer correlations where FDS picks the larger number of the two correlations. This model was used in this analysis.

Wind Model

The atmospheric boundary layer in this analysis was modeled using Monin-Obukhov similarity theory. Under this paradigm, the inlet wind profile is calculated based on a reference velocity and stability criterion. The wind profile with height is defined as

$$u_w(z) = \frac{u_*}{\kappa_c}\left[\ln\left(\frac{z}{z_0}\right) - \Psi\left(\frac{z}{L_o}\right)\right] \tag{18}$$

where $u_w(z)$ is the wind speed as a function of height, κ_c is the Von Kármán constant (0.41), z_0 is the aerodynamic roughness length (1.0 in this analysis, appropriate for suburbs, villages, and forests [39]), z is the height, u_* is the friction velocity, L_o is the Obukhov length, and Ψ is the similarity function [40],

$$\Psi\left(\frac{z}{L}\right) = \begin{cases} -5\dfrac{z}{L} & \text{for} \quad L \geq 0 \\ 2\ln\left[\dfrac{1+\zeta}{2}\right] + \ln\left[\dfrac{1+\zeta^2}{2}\right] - 2\tan^{-1}(\zeta) + \dfrac{\pi}{2} & \quad\quad\; L < 0 \end{cases} \tag{19}$$

$$\zeta = \left(1 - \frac{16z}{L}\right)^{1/4} \tag{20}$$

The friction velocity is calculated based on a specified reference velocity and reference height,

$$u_* = \frac{\kappa_c u_{ref}}{\ln\left(z_{ref}/z_0\right)} \tag{21}$$

where u_{ref} is the reference velocity, and z_{ref} is the reference height. In this analysis, u_{ref} was varied from 1.2 m/s (2.7 mph) to 6.7 m/s (15.0 mph) at a reference height of 10.0 m. The Obukhov length was fixed at 350 m in this analysis, corresponding to a buoyantly stable atmospheric boundary layer. The upstream wind profile was perturbed to trip a turbulent boundary layer by re-cycling the flow field downstream with a periodic boundary condition.

OVERVIEW OF BASELINE CONFIGURATION

The overall dimensions of the tank farm were approximately 137.2 m (450 ft) x 222.5 m (730 ft), consisting of three rows and five tanks of columns, as shown in Figure A-2. In this analysis, a three row x three column region centered on Tank 80-8 was included in the computational domain. It was decided to model a symmetric configuration so that the results could be used as general guidance to describe either westerly or northerly wind configurations.

The computational domain is visualized in Figure A-21. The overall computational domain was 460 m (1,509 ft) x 190 m (623 ft) x 80 m (262 ft). The tanks were centered on the shorter horizontal axis. The tanks were off-centered 90 m towards the windward boundary to allow the wind profile to more fully develop in the leeward direction prior to reaching the periodic boundary. Periodic boundary conditions were used on the vertical edges of the computational domain. A solid, adiabatic boundary condition was used on the bottom of the computational domain. A constant streamline boundary condition was used on the top of the computational domain.

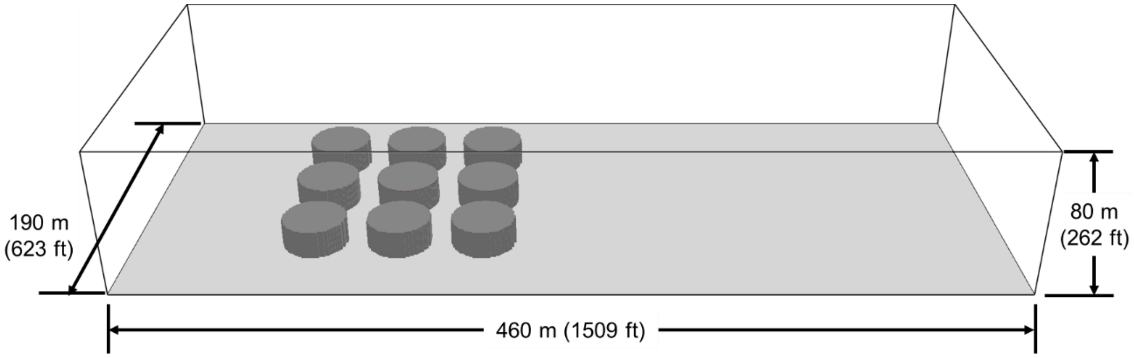


Figure A-21. Computational domain.

Using a fixed grid size across the entire computational domain was not feasible for this application (25 cm fixed grid would yield approximately 450 million grid cells). Hybrid meshing was used to reduce the number of grid cells, a visualization along the centerline of the domain is shown in Figure A-22. A grid size of 25 cm was used near the combustion reaction, encompassing the upper half of Tank 80-8 and the leeward tank and extending 5.0 m above the tanks (heights 8.0 m - 20.0 m). A grid size of 50 cm was used for a region extending 8.0 m beyond the finest mesh in all directions. A grid size of 100 cm was used for the rest of the computational domain, except the last 100 m at the leeward edge where a grid size of 200 cm was used. This meshing strategy resulted in approximately 10,185,000 grid cells. A sensitivity case which used 20 cm at the finest grid, and followed a similar hybrid strategy was simulated to verify this resolution was sufficient to achieve a grid independent solution. The mesh sensitivity configuration had approximately 20,029,000 grid cells.

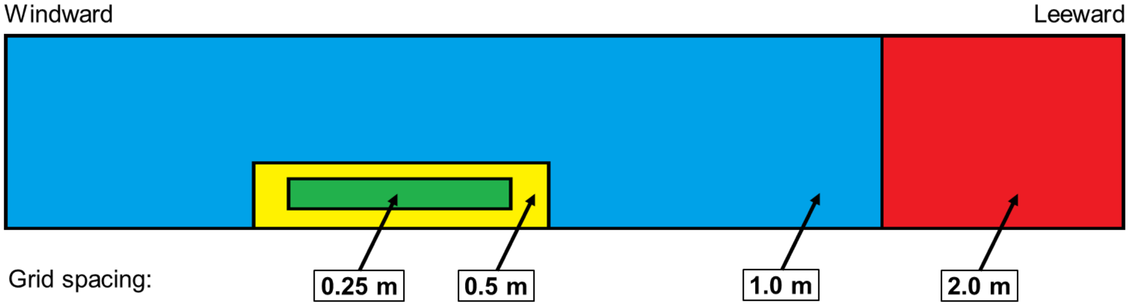


Figure A-22. Mesh resolution along centerline.

A total of 26 pressure release vents were applied at the top of the center tank, as shown in Figure A-23. The size of the vents was scaled to be 0.5 m (20 in) x 0.5 m (20 in) squares to align with the computational grid and provide four grid cells across the vent. The outlet temperature at the vent was fixed at 500 °C based on the interior head temperature. The total heat release rate for each vent was fixed at 2,431 kW (heat release rate per unit area = 9,725 kW/m^2) based on the liquid fuel evaporation rate found in the phase one analysis. The resulting overall heat release rate was 63.2 MW. The specified heat release rate was fixed throughout the entire simulation duration. A sensitivity case was simulated which included a 60 second lead in time for the wind flow field to initialize prior to ignition of the vents.

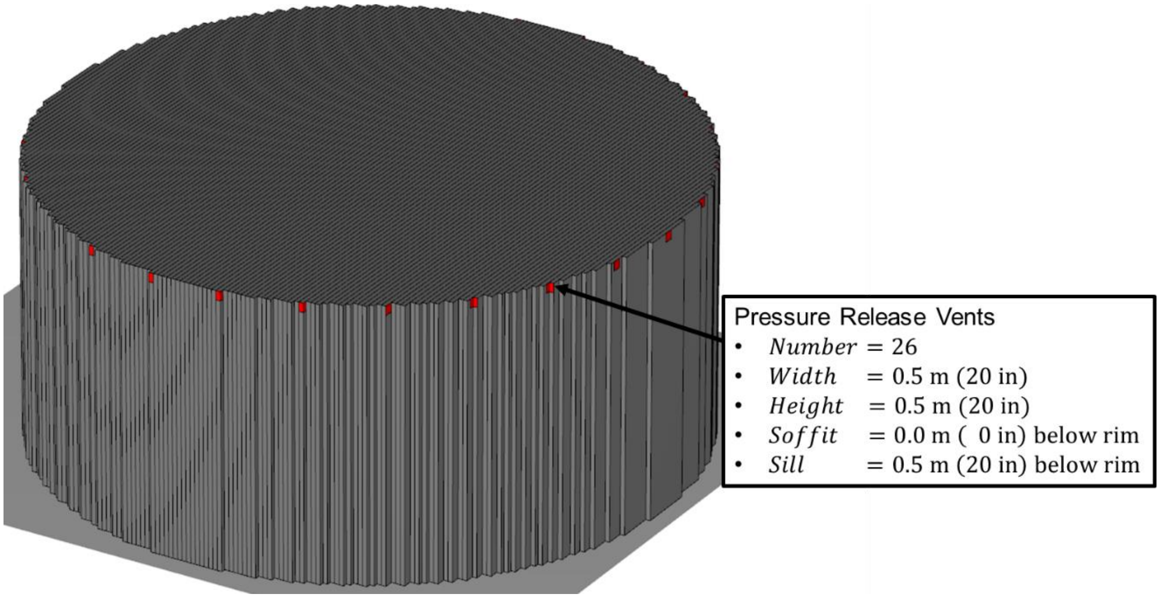


Figure A-23. Visualization of pressure release vents on Tank 80-8.

The gas phase combustion reaction was based on petroleum-naphtha ($C_{10}H_8$), with a normalized chemical formula of $CH_{0.8}$, soot yield of 0.175 (g/g), carbon monoxide yield of 0.065 (g/g), heat of combustion of 39,000 kJ/kg, and radiative fraction of 0.4256 [28]. The resolution on the radiation transport equation was increased to 360 angles from the FDS default of 100 based on the size of the computational domain. Two sensitivity cases were simulated with 180 and 540 angles to verify this resolution was sufficient.

Ambient conditions in the model represented a relative humidity of 40%, gas temperature of 20°C. The baseline configuration used a 10 m wind speed of 2.2 m/s (5 mph). Each simulation was run for 300 seconds of fire exposure to allow quasi steady state conditions to develop. The thermal exposure from the adjacent tank to the leeward tank was quantified using a gauge heat flux. The heat flux gauge had a fixed emissivity of 1.0 and temperature of 20°C.

Each simulation was run on a linux cluster on Amazon Web Service (AWS). All cases used 48 central processing units (CPUs) with 48 message passing interface (MPI) processes, except the fine grid sensitivity case which used 96 CPUs with 96 MPI processes. Computational time varied across the models, but was typically on the order of 5-6 days. Computational time for the fine grid sensitivity case was 8 days.

The transient development of the fire and smoke from the fire in Tank 80-8 is visualized in Figure A-24. The smoke profile generally stabilized after 180 seconds of exposure. The time-resolved thermal exposure at the peak location and the center on the windward side of the adjacent tank is shown in Figure A-25. These results show that the thermal exposure stabilizes to a quasi-steady state after approximately 60 seconds, although there is variability in the instantaneous thermal exposure (standard deviation from 60-300 seconds was 0.09 kW/m^2). The maximum time-averaged thermal exposure observed on the adjacent tank was 1.34 kW/m^2, occurring approximately 1 m (3.3 ft) below the rim of the tank. The spatial distribution of the time-averaged thermal exposure on the windward side of the adjacent tank is visualized in Figure A-26.

OVERVIEW OF UNCERTAINTY

It is important to understand the impact of uncertainty on the thermal exposure predictions made using the detailed CFD model. There are two main sources of uncertainty relevant to the analysis: Input parameter uncertainty, and Model uncertainty. The overall uncertainty in a CFD prediction is the combination of the input parameter uncertainty and model uncertainty.

Input parameter uncertainty is associated with factors that must be known about a scenario and provided to the model to make predictions. Some example input parameters in this analysis include the wind conditions, heat release rate of the fire, and details regarding the chemical reaction. In developing the baseline model of the ITC fire, we specified each of these parameters to the best of our ability based on available information. However, it is important to understand the impact of uncertainty in these estimates on the thermal exposure predicted by the model. One way to quantify this impact is to run additional simulations where the uncertain input parameters are varied and compare the results with the baseline simulation. Several additional simulations were conducted in this analysis to understand the impact of uncertainties in the wind conditions, fuel source, pressure release vent geometry, numerical discretization, and radiation transport on the predicted thermal exposure.

Model uncertainty on the other hand, is the potential error in model predictions when all the input parameters are well understood. This type of uncertainty is typically quantified by recreating carefully controlled experiments with the modeling software and comparing the predictions to the measurements. The FDS validation guide provides an extensive suite of experiments which have been gathered from the literature and reproduced using the software. The resulting model predictions are routinely compared with the experimental measurements to identify statistical bias and uncertainty in the predictions of specific quantities by FDS.

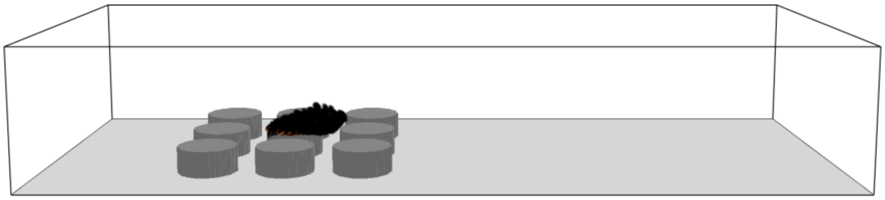
In this context, the bias represents the mean tendency of the model to over or under predict a specific quantity. Correcting for the model bias provides a best estimate of the true value. It is important to note that, by definition, the majority of simulations will agree well with experiments after correcting for the bias. However, there will always be some degree of scatter about the true value (outlier experiments which were not well predicted). The model uncertainty represents this degree of scatter about the true value.

The model bias and uncertainty in FDS is expressed in terms of a Gaussian distribution with a mean and sigma defined as,

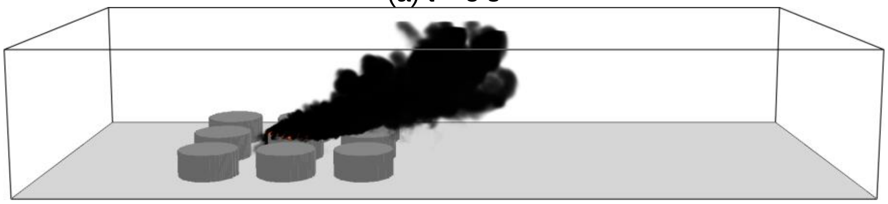
$$\mu = \frac{M}{\delta} \tag{22}$$

$$\sigma = \sigma_M^2 \left(\frac{M}{\delta}\right)^2 \tag{23}$$

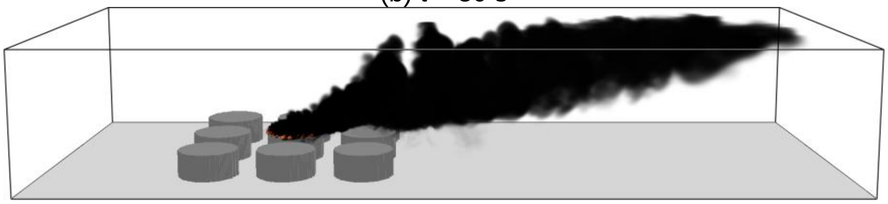
where M is the model predicted value, μ is the center of the distribution after correcting for the model bias, δ, σ is the standard deviation of the distribution, and σ_M is the model uncertainty. The FDS validation guide quantifies δ and σ_M for thermal exposure predictions to a target using FDS 6.7.4 is as 0.88 and 0.39, respectively.



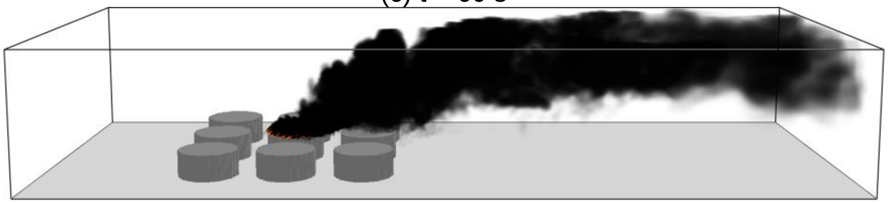
(a) t = 5 s



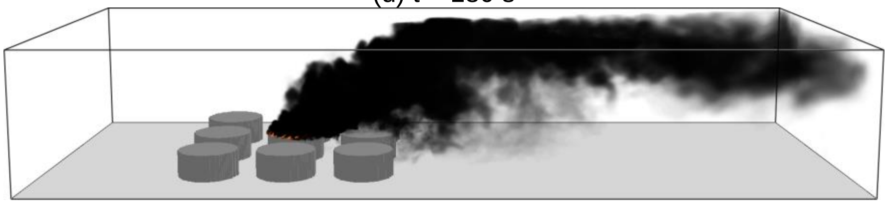
(b) t = 30 s



(c) t = 60 s



(d) t = 180 s



(e) t = 300 s

Figure A-24. Visualization of fire and smoke development in baseline model configuration.

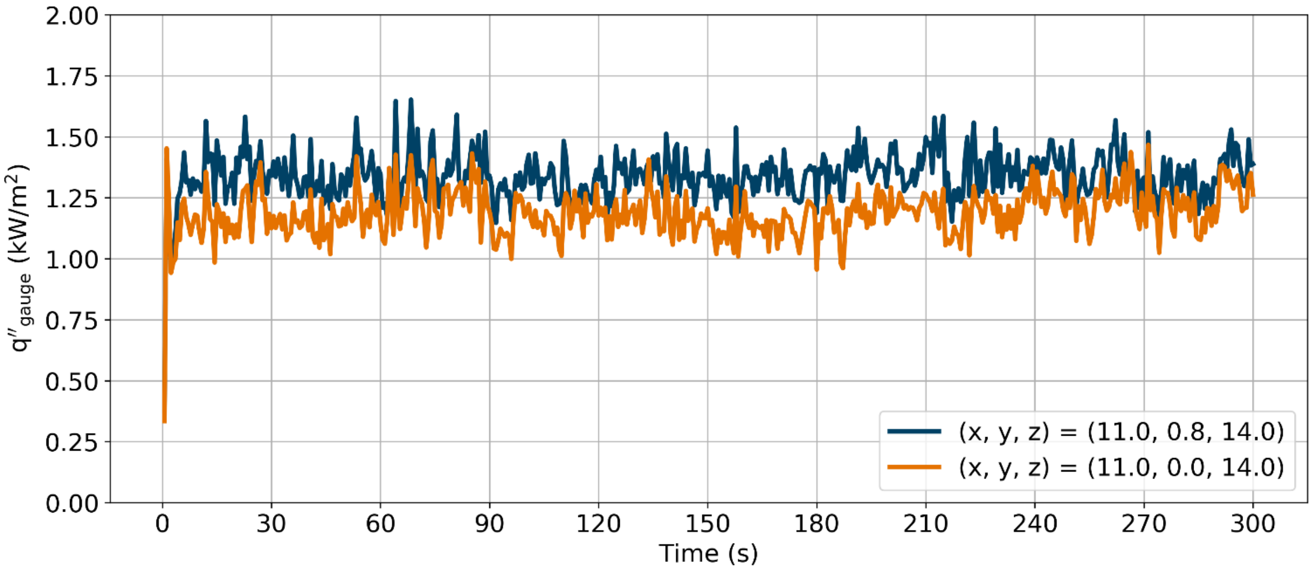


Figure A-25. Time resolved thermal exposure at peak location (blue) and at center of tank (orange) on windward side of adjacent tank.

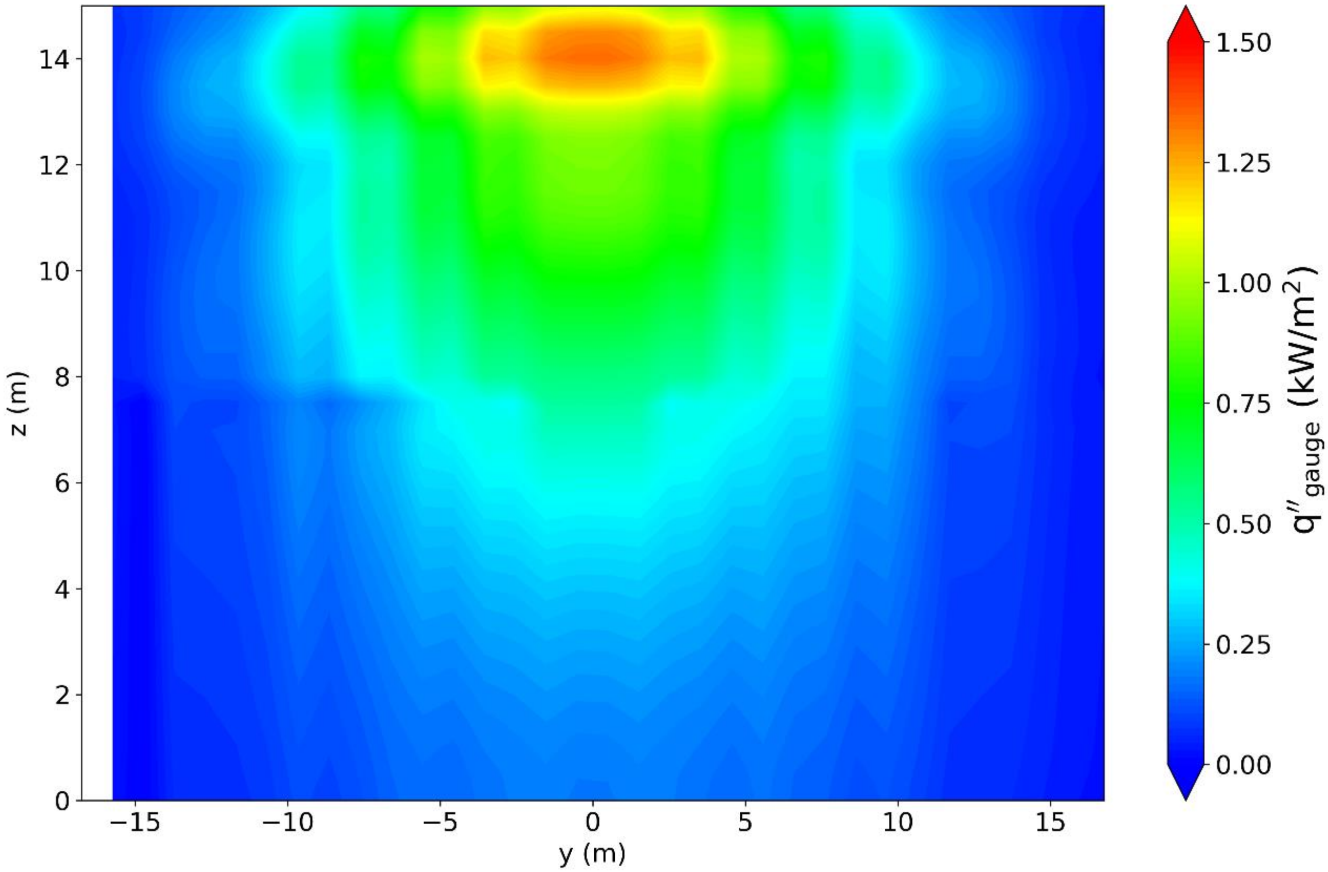


Figure A-26. Quasi steady state thermal exposure on windward side of adjacent tank.

This information is usually presented in terms of a probability density function (PDF) or cumulative distribution function (CDF), as shown for the peak thermal exposure on the windward wall of the adjacent tank in the baseline simulation in Figure A-27. The PDF shows the probability that the true thermal exposure is a specific value. The PDF in Figure A-27 shows that after accounting for the bias in the model, the actual best estimate of the thermal exposure is 12% higher at 1.52 kW/m^2 the raw model prediction of 1.34 kW/m^2. The CDF shows the probability that the true thermal exposure does not exceed a given value. This representation is often used in a risk assessment context where there is a need to design to a higher confidence, such as a 97.5th percentile (two standard deviations higher than the mean). For this higher degree of confidence in design, a thermal exposure of 2.23 kW/m^2 would be used. Considering our safe separation threshold of 8 kW/m^2, there is approximately a 1 in 1 quadrillion chance (10^{15}) that the model uncertainty would be sufficient to account for ignition of the second tank. Since a second tank did ignite, this implies that there is either significant uncertainty in the model inputs, or an additional heat source (such as a pool fire) which contributed to the ignition.

OVERVIEW OF SENSITIVITY ASSESSMENTS

Additional permutations of the baseline configuration were simulated to examine the sensitivity of the thermal exposure predictions to the grid discretization, simulation initialization, and the radiative path length.

Table A-1 summarizes the statistical differences between each sensitivity case and the baseline model configuration.

In CFD simulations it is important to verify that the grid resolution is resolved enough such that the solution is not dependent on the grid spacing. Figure A-28 compares the quasi steady state thermal exposure on the adjacent tank using the baseline mesh configuration (minimum grid size of 25 cm) and a more resolved mesh configuration (minimum grid size of 20 cm). These results indicate the spatial resolution in the baseline configuration is sufficient for this application, with the difference in peak exposure 1.5% and a root mean square error (RMSE) of 0.023 kW/m^2.

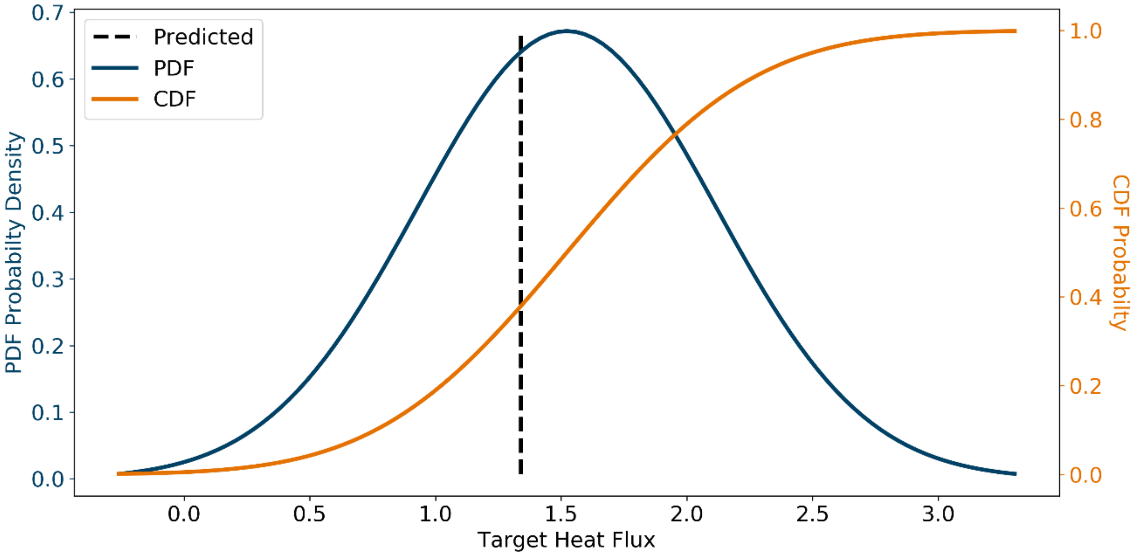


Figure A-27. Uncertainty in peak thermal exposure on windward wall of adjacent tank in baseline FDS model.

Table A-1. Statistical comparison of sensitivity cases. (*) denotes the model predictions were scaled by a factor of 2 prior to comparison with the baseline.

Scenario	$\bar{q}''_{gauge,max}$ (kW/m^2)	$RMSE$ (kW/m^2)
Baseline	1.34	-
Grid Independence ($\Delta = 20$ cm)	1.36	0.023
Initialization (60 seconds with wind without fire)	1.32	0.006
Radiation Angles (Coarse - 180 angles)	1.46	0.060
Radiation Angles (Fine - 540 angles)	1.27	0.021
Radiation Path Length (Larger – 1.0 m)	2.75	0.552
*Radiation Path Length (Larger – 1.0 m)	1.37	0.086

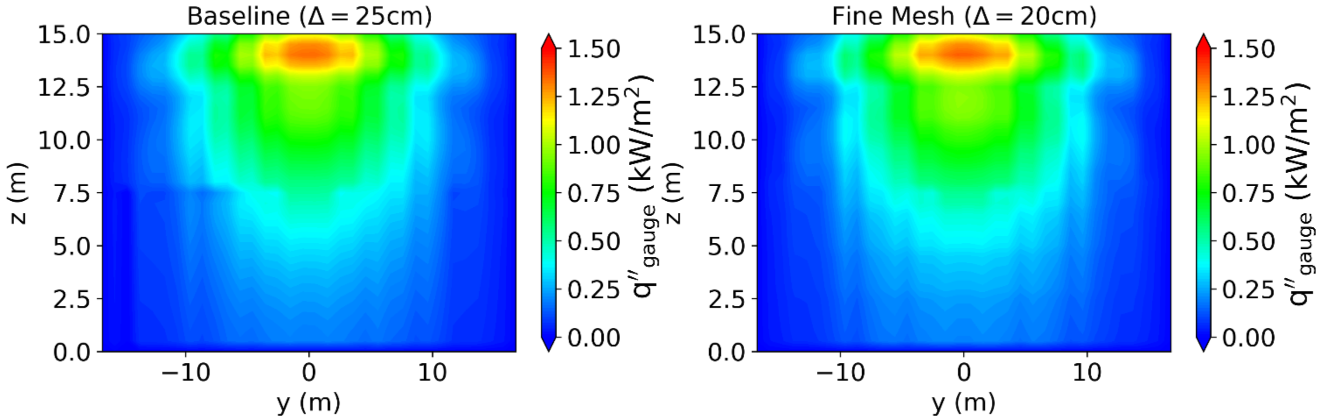


Figure A-28. Sensitivity assessment of grid resolution on quasi steady state thermal exposure on adjacent tank.

By default, FDS uses a fairly coarse discretization of the unit sphere in the radiation transport equation (100 angles). While this is sufficient for many applications in smaller domains, more angles are needed in this application due to the large spacing between tanks. Figure A-29 compares the quasi steady state thermal exposure on the adjacent tank using the baseline radiation angles used in this analysis (360) with less angles (180) and more angles (540) to verify the convergence of the angular discretization. These sensitivity results show that the peak thermal exposure decreases with more radiation angles due to the same amount of energy being distributed into more rays. This results in a less extreme peak, but a smoother distribution in radiant intensity across the tank. These results indicate the angular discretization in the baseline configuration is sufficient for this application, with the difference in peak exposure 5.2% and a RMSE of 0.021 kW/m^2 when compared with the 540 angles configuration.

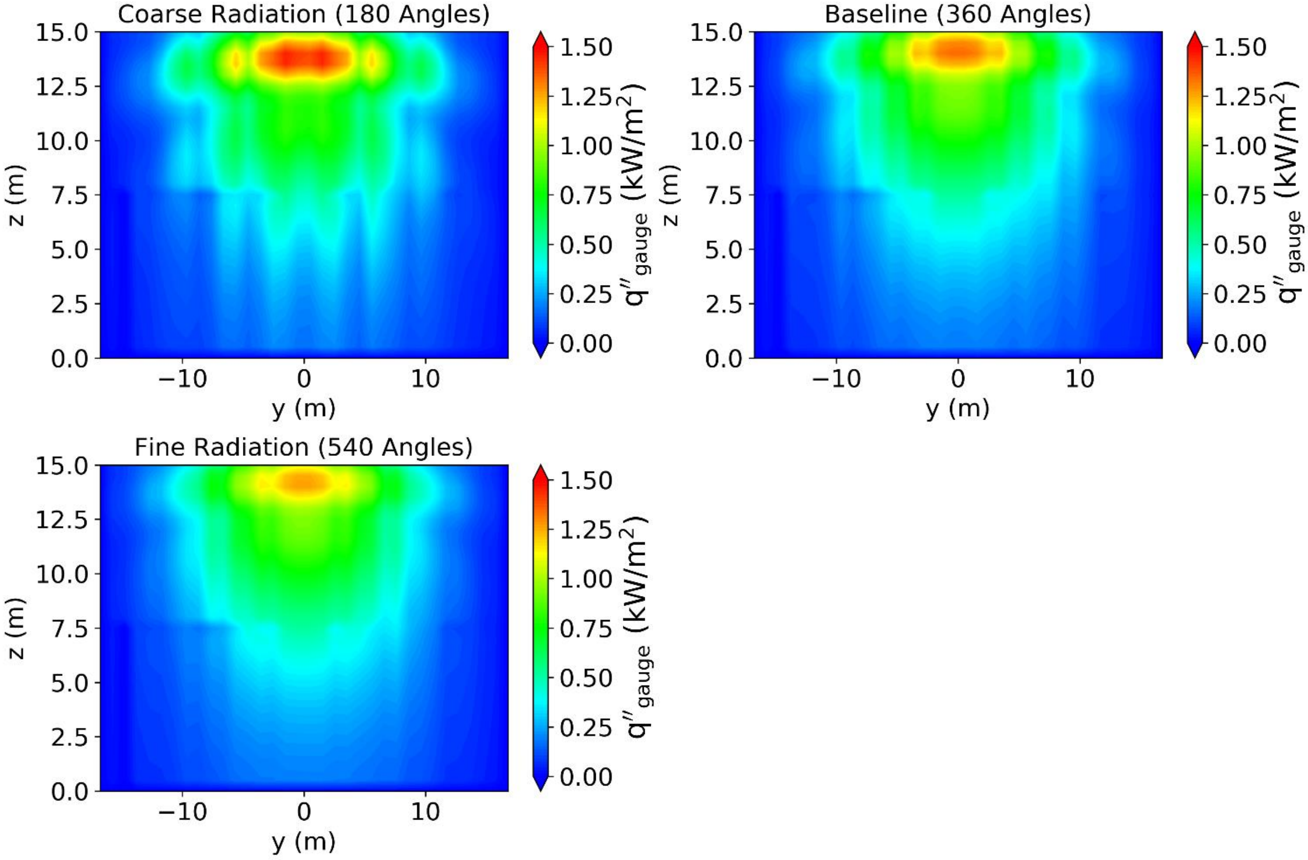


Figure A-29. Sensitivity assessment of radiation angles on quasi steady state thermal exposure on adjacent tank.

Figure A-30 compares the quasi steady state thermal exposure on the adjacent tank using the baseline configuration with no wind initialization (steady burning from t = 0 seconds) with that of a simulation with the wind field initialized for 60 seconds prior to ignition. These results indicate that the quasi steady state thermal exposure is independent of the wind initialization, with the difference in peak exposure 1.5% and a RMSE of 0.006 kW/m^2.

One of the key parameters in the radiation transport equation is the absorption coefficient in the gas phase. FDS computes the absorption coefficient using an external software, RADCAL [37]. The absorption coefficient in RADCAL is calculated based on the species concentrations, gas temperature, and radiative path length. The path length is used to compute the path mean absorption coefficient. Essentially, this term represents the difference in radiant intensity emitted by a uniform gas layer of thickness equal to the radiative path length and that of a black body at the effective temperature of flame radiation. The default path length used in FDS is 0.1 m

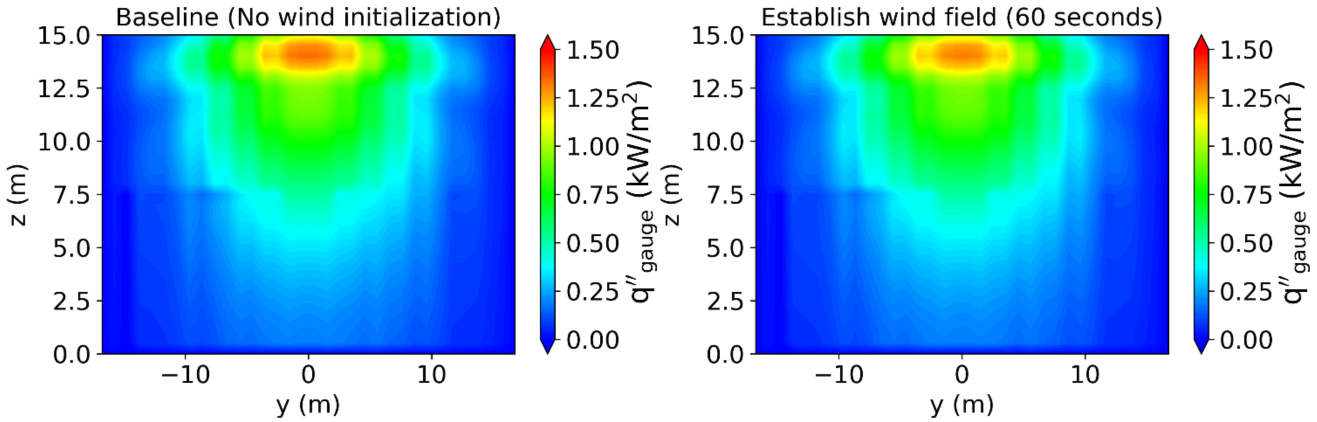


Figure A-30. Sensitivity assessment of wind initialization on quasi steady state thermal exposure on adjacent tank.

which is used in the FDS Validation guide. However, this path length may be larger in the ITC fire scenario due to the high separation distance between tanks. A sensitivity case was simulated with the path length increased by a factor of 10x (path length of 1.0 m) to better understand the impact of the default path length on the ITC fire simulations.

Error! Reference source not found. compares the quasi steady state thermal exposure on the adjacent tank using the baseline configuration. The top row of the figure shows the direct comparison between the two numerical simulations. The peak exposure is approximately 2x higher in the increased path length simulation over the baseline case (2.75 kW/m^2 versus 1.34 kW/m^2). In the bottom row, the predicted thermal exposures from the larger radiative path length case were linearly scaled by a factor of 2. The bottom row shows the general profile is in agreement, with the difference in peak exposure after scaling 2.2% and the RMSE 0.086 kW/m^2. These results indicate that uncertainty in the radiative path length could result in the baseline model predictions under predicting the thermal exposure by a factor of 2. Unfortunately, there is not a strong experimental basis to use in selecting the radiative path length which makes it difficult to determine which is a more accurate representation of the fire scenario. For this analysis, it was decided to proceed with the default 0.1 m radiative path length based on the quantified uncertainty in the FDS validation guide. However, the uncertainty in radiative path length is further discussed in the context of overall uncertainty in the discussion section.

OVERVIEW OF ADDITIONAL SCENARIOS

Additional permutations of the baseline configuration were simulated to examine the sensitivity of the thermal exposure predictions to different modeling inputs. These studies considered the impact of wind speed, changes in the pressure release vents, increases in fuel evaporation rate, and uncertainty in combustion radiative fraction. An additional scenario was simulated with the addition of a pool fire at the base of the model. The simulation matrix summarizing the permutations is shown in

.

Results from simulations with five different wind speeds are compared in Table A-3 and Figure A-31. In general, the maximum thermal exposure was not highly sensitive to the wind speed in the model, varying by approximately ±5% from the baseline case. However, the spatial variation in thermal exposure varied more significantly, as is seen in the increase in the root mean square difference (RMSD) from the baseline configuration. This difference was particularly prevalent in the 6.7 m/s (15.0 mph) wind configuration. Figure A-31 shows that the increase in RMSD corresponds to an increase in the thermal exposure at the edges and bottom of the tank. In addition, the peak region is shifted down approximately 1.0 m (3.3 ft).

Results from simulations with four different vent configurations are compared in Table A-4 and Figure A-32. This assessment was done by varying either the vent area or total number of vents. The maximum thermal exposure

Table A-2. Model input sensitivity study simulation matrix.

Scenario	Wind Speed [m/s (mph)]	Heat Release Rate [MW]	Radiative Fraction, χ_r	Number of Vents	Vent Width [cm (in)]	Vent Height [cm (in)]
Baseline	2.2 (5.0)	63.2	0.43	26	50 (19.7)	50 (19.7)
Fuel source, 25% more volatile,	2.2 (5.0)	79.0	0.43	26	50 (19.7)	50 (19.7)
Fuel source, 50% more volatile	2.2 (5.0)	94.8	0.43	26	50 (19.7)	50 (19.7)
Fuel source, 10% higher χ_r	2.2 (5.0)	63.2	0.53	26	50 (19.7)	50 (19.7)
Fuel source, additional pool fire	2.2 (5.0)	136.0	0.43	26	50 (19.7)	50 (19.7)
Vents, fewer	2.2 (5.0)	63.2	0.43	19	50 (19.7)	50 (19.7)
Vents, larger	2.2 (5.0)	63.2	0.43	26	75 (19.7)	50 (19.7)
Vents, smaller	2.2 (5.0)	63.2	0.43	26	75 (19.7)	25 (19.7)
Wind, None	0.0 (0.0)	63.2	0.43	26	50 (19.7)	50 (19.7)
Wind, 2.7 mph	1.2 (2.7)	63.2	0.43	26	50 (19.7)	50 (19.7)
Wind, 10.0 mph	4.5 (10)	63.2	0.43	26	50 (19.7)	50 (19.7)
Wind, 15.0 mph	6.7 (15)	63.2	0.43	26	50 (19.7)	50 (19.7)

Table A-3. Statistical comparison of wind sensitivity.

Scenario	$\bar{q}''_{gauge,max}\ (kW/m^2)$	$RMSD\ (kW/m^2)$
Wind, 0.0 m/s (0 mph)	1.25	0.084
Wind, 1.2 m/s (2.7 mph)	1.36	0.028
Wind, 2.2 m/s (5.0 mph)	1.34	-
Wind, 4.5 m/s (10.0 mph)	1.22	0.080
Wind, 6.7 m/s (15.0 mph)	1.31	0.199

increased in both the smaller vents and fewer vents scenarios, and decreased with the larger vents when compared to the baseline configuration. The largest change was observed in the smaller vent configuration where the peak thermal exposure increased by close 60%. The RMSD was significantly higher for the smaller and fewer vents scenarios than the larger vent scenario. Figure A-32 shows that the increase in RMSD corresponded primarily to an increase in size of the peak exposure region, rather than increases at the edges and bottom of the tank as seen in the 6.7 m/s (15.0 mph) wind configuration. The height of the peak exposure was not impacted by changing the vent configuration.

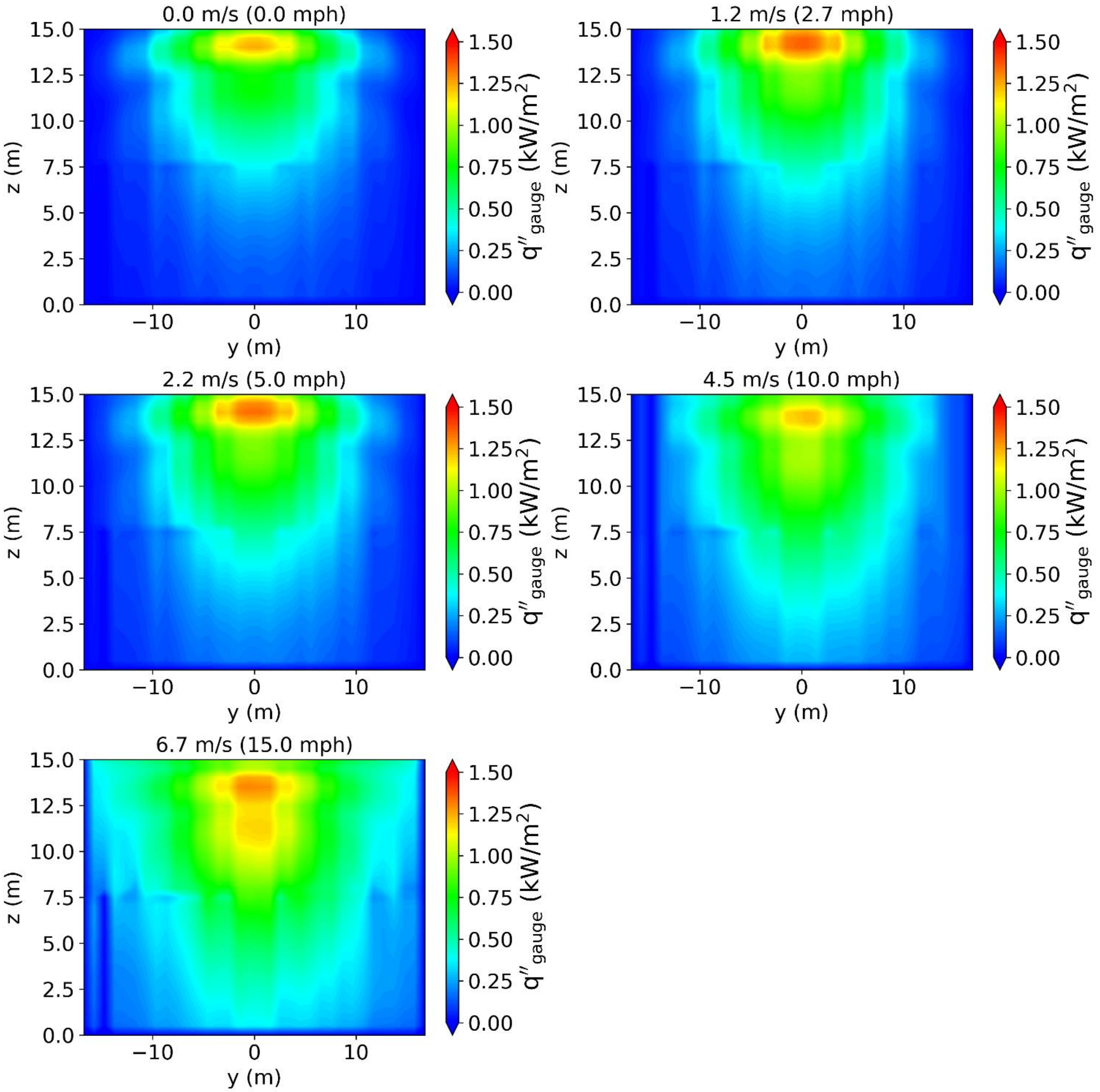


Figure A-31. Sensitivity assessment of wind speed on quasi steady state thermal exposure on adjacent tank.

Table A-4. Statistical comparison of vent sensitivity.

Scenario	$\bar{q}''_{gauge,max}$ (kW/m^2)	$RMSD$ (kW/m^2)
Baseline (26 vents – 0.50 m wide x 0.50 m tall)	1.34	-
Vents, fewer (19 vents – 0.50 m wide x 0.50 m tall)	1.63	0.110
Vents, larger (26 vents – 0.75 m wide x 0.50 m tall)	1.26	0.034
Vents, smaller (26 vents – 0.75 m wide x 0.25 m tall)	2.14	0.253

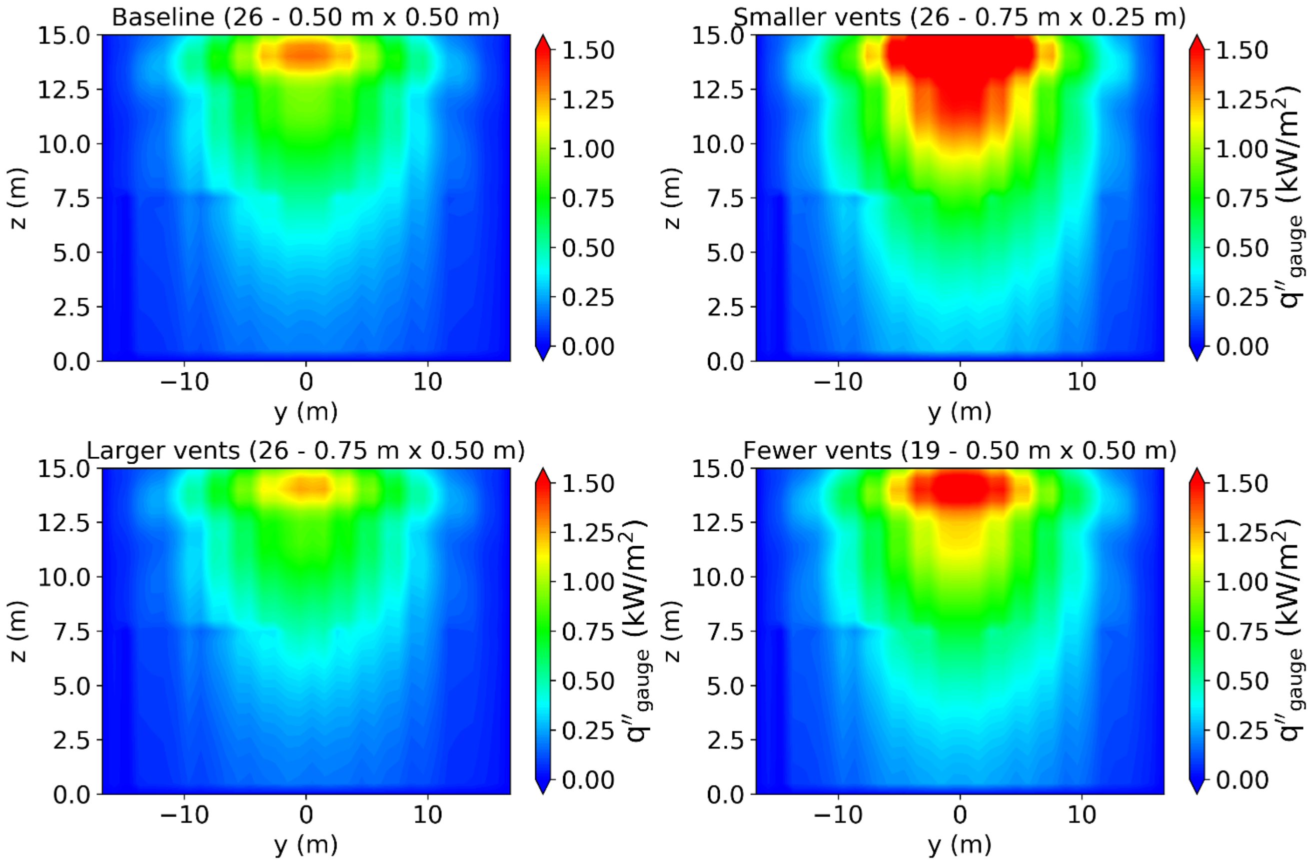


Figure A-32. Sensitivity assessment of vent configuration on quasi steady state thermal exposure on adjacent tank.

Four additional models were simulated to examine the impact of the fuel configuration on the predicted thermal exposures. In two scenarios, the overall heat release rate of the tank was increased by 25% and 50%, respectively. In another scenario the gas phase radiative fraction was increased by 10%. A large pool fire was added in the fourth scenario. The size and position of the pool fire was estimated based on aerial imagery from the ITC fire. The flames from the pool were observed to reach beyond the top of the tank (estimated at 15.0 m), and the base of the pool covered approximately one half of the separation distance between tanks (5.5 m). The heat release rate of the pool was estimated to be 72.9 MW using these observations by inverting Heskestad's flame height correlation, see Eq. 7 for reference. The center of the pool was placed at the corner of the projected square which inscribes the circle of the bottom of the tank, as shown in Figure A-33. The pool was specified as a square burner with a side length of 5 m so that the vent would directly align with the computational grid. The side length was selected based on an equal area diameter of 5.6 m. The mesh in the pool fire simulations extended the 25 cm grid to the bottom of the computational domain, and 5 m beyond the pool.

Results from the fuel configuration simulations are compared with the baseline thermal exposures in **Error! Reference source not found.**, Figure A-34, and Figure A-35. The maximum thermal exposure increased in each of the fuel configuration simulations relative to the baseline configuration. The 25% and 50% increase in heat release rate resulted in the peak exposure increasing by 22%, and 44%, respectively. The 10% increase in radiative fraction resulted in a 19% increase in the thermal exposure. However, the most significant impact was the addition of the pool fire, which increased the peak thermal exposure by 304%. Increasing the heat release rate and the radiative fraction increased the peak exposure area, but did not significantly increase the thermal exposure near the edges or bottom of the tank. In addition, the peak exposure location was not impacted by changing the heat release rate or radiative fraction. The addition of the pool fire significantly changed the profile of the thermal exposure. The heating on the adjacent tank was asymmetric, with the side closer to the pool experiencing heat fluxes 2-4x higher than the further side. In addition, the peak location occurred approximately 2.5 m above the ground, rather than 1.0 m below the rim of the tank.

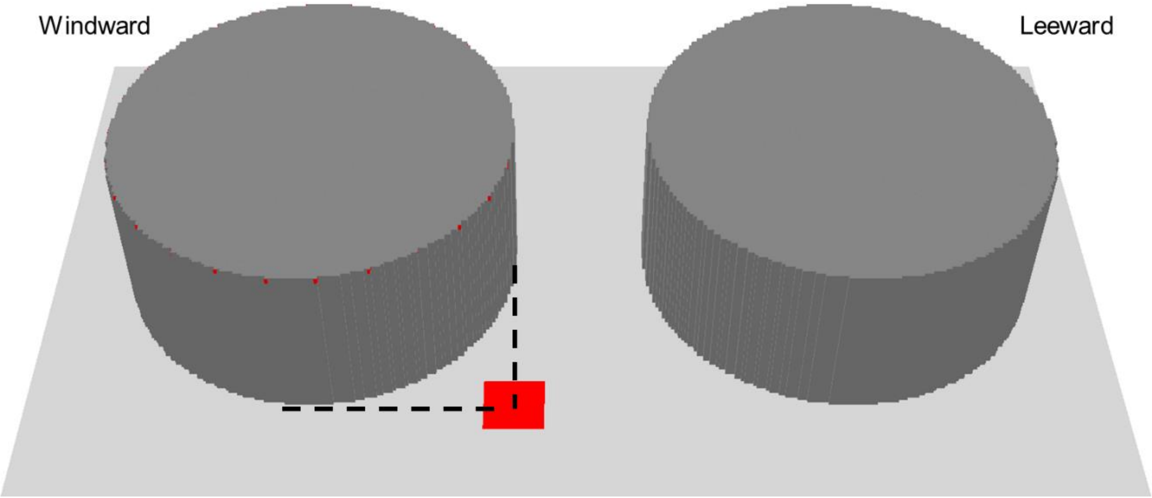


Figure A-33. Location of pool fire.

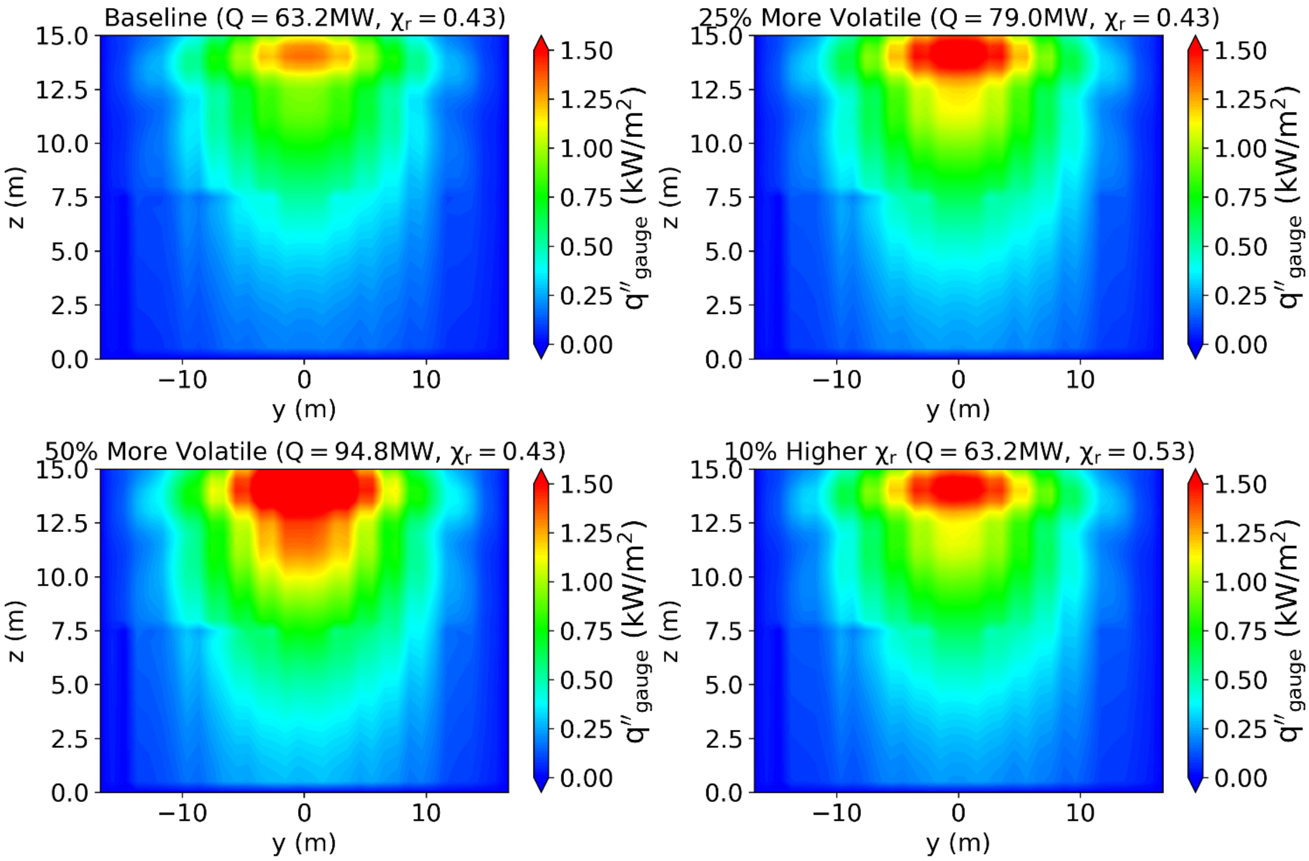


Figure A-34. Sensitivity assessment of fuel configuration on quasi steady state thermal exposure on adjacent tank.

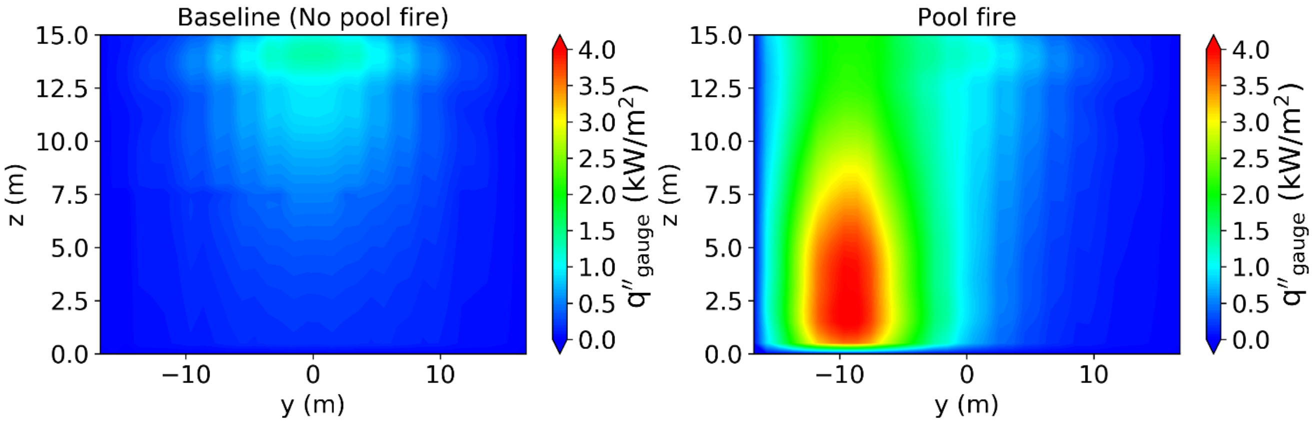


Figure A-35. Comparison of heat flux on adjacent tank with and without the addition of a pool fire.

A-4.4. DISCUSSION

Fire and smoke visualization of the baseline FDS simulation is compared with aerial imagery obtained during the ITC fire in Figure A-36. Qualitatively, the flame length and soot density agree well.

(a) Aerial imagery of ITC fire

(b) Fire and smoke visualization of CFD predictions

Figure A-36. Fire and smoke from aerial imagery compared with model predictions.

The heat flux versus distance from the baseline CFD model along the centerline is shown in Figure A-37. Figure A-37 shows that after the first 4 m of separation distance, the heat flux on the adjacent tank does not vary significantly with height.

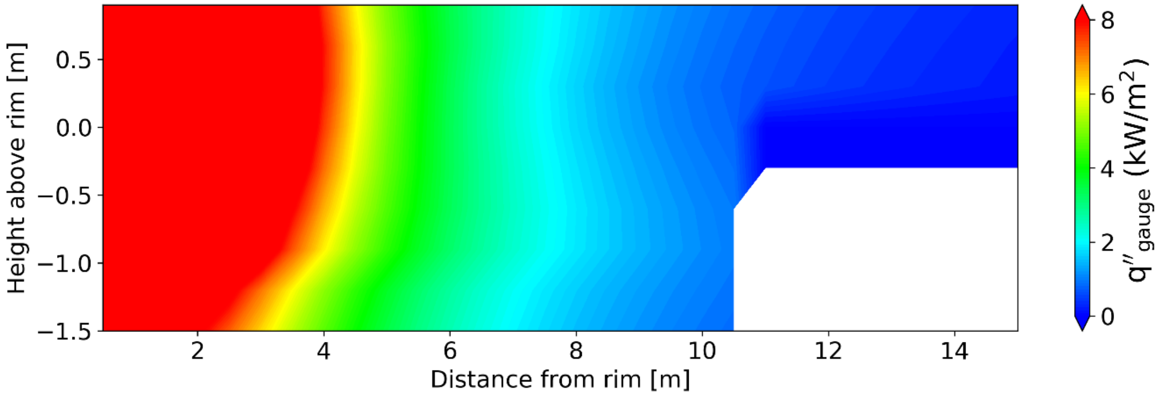


Figure A-37. Heat flux versus distance from rim from baseline CFD model.

The CFD thermal exposure predictions are compared with the hand calculation approaches in Figure A-38. Note that the tilted point source model was calculated using a radiative fraction of 0.10, based on the tank diameter correlation in Eq. 15. Note that the curve corresponding to the FDS maximum was calculated in post-processing by scaling the centerline measurements by the maximum observed off-center on the windward side of the tank. The results indicate that both hand calculation methods underpredict the thermal exposure to the adjacent tank compared with the detailed CFD model.

Recall that a large source of uncertainty in the tilted point source model is the unknown value of the radiative fraction to use. Radiative fraction in the point source model is an effective property which is a function of both the reaction and the geometry. However, radiative fraction in the CFD model is purely a property of the reaction. If we consider the entire computational domain as a control volume, an effective radiative fraction which accounts for the impact of the geometry in addition to that of the reaction can be calculated from the CFD predictions by comparing the ratio of energy leaving the control volume due to radiation to the heat released by the fire. The effective radiative fraction calculated from the baseline FDS simulation and the pathlength sensitivity simulation are shown in Figure A-39. The effective radiative fractions were found to be 0.06, and 0.08, respectively, which generally agree with the values recommended by Beyler.

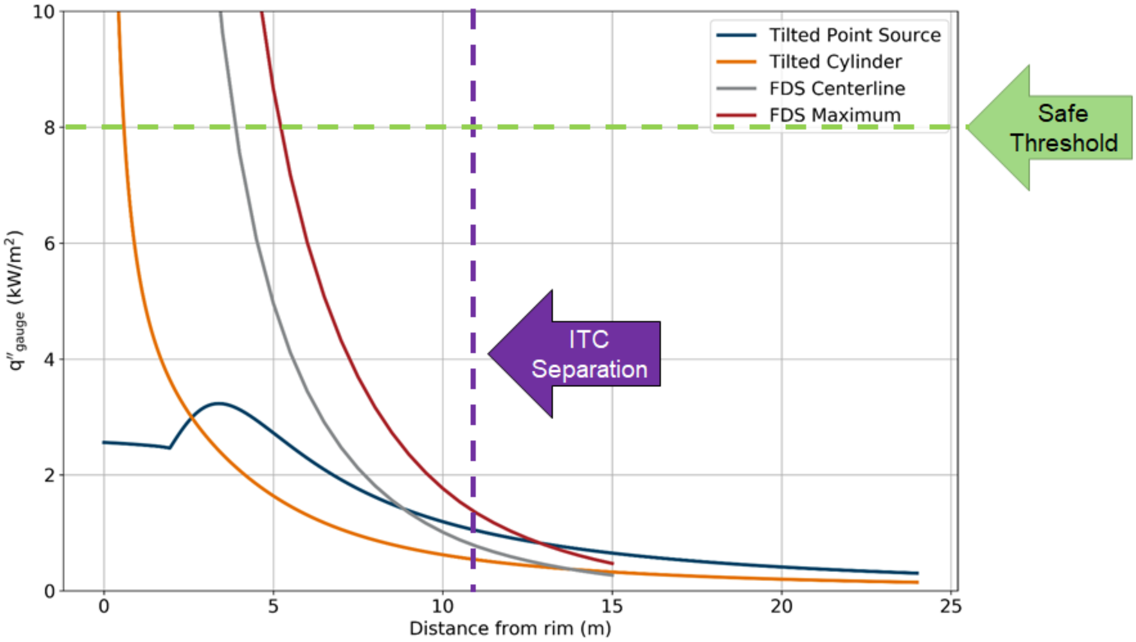


Figure A-38. Comparison of thermal exposure predictions using each approach.

The thermal exposure predictions after accounting for the model uncertainty for each case are summarized in Table A-5. Accounting for the uncertainty in FDS, the true thermal exposures could be a factor of 2x higher than those predicted by the model. This agrees with the variation observed in the path length sensitivity model. After accounting for the uncertainty in the modeling predictions, the model predicted thermal exposures in all scenarios without the pool fire are still below the industry accepted critical heat flux required to ignite an adjacent tank of 8 kW/m^2. However, after accounting for the uncertainties, there is a 15% chance the thermal exposure from the pool fire scenario could exceed the critical heat flux threshold. However, this does not account for the model input uncertainty in estimating the size and location of the pool fire. The pool fire in this analysis was 72.8 MW based on the observed flame heights; however, if the pool fire were actually larger, the chance to ignite the adjacent tank would increase.

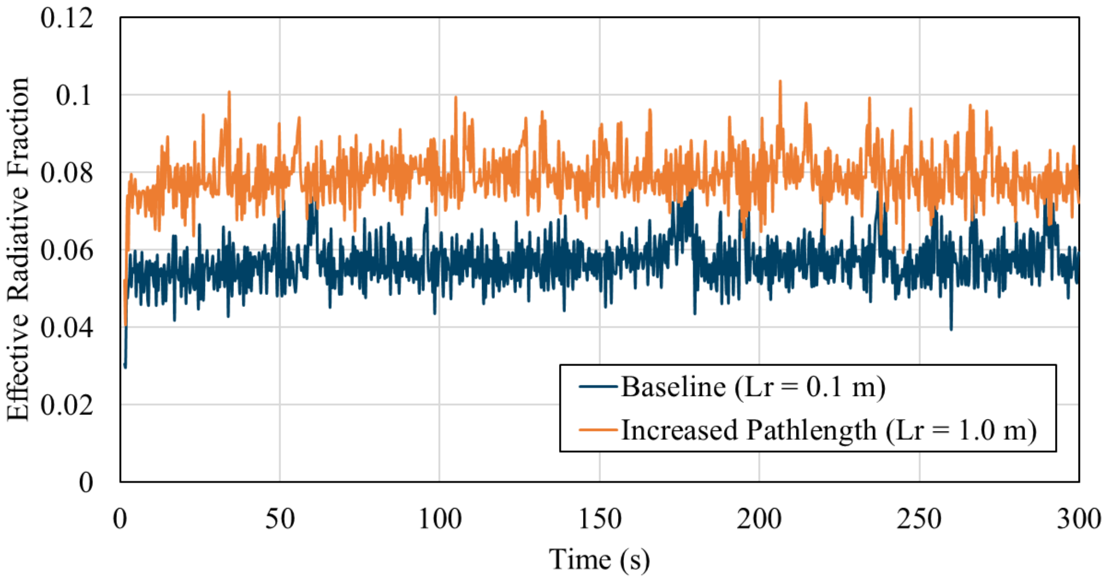


Figure A-39. Effective radiative fraction calculated from the baseline and pathlength sensitivity FDS simulations.

Table A-5. Statistical assessment of CFD predictions after correcting for model bias and uncertainty.

Scenario	$\bar{q}''_{gauge,max}\ (kW/m^2)$				
	Raw	50.0th Percentile	84.1th Percentile	97.5th Percentile	99.9th Percentile
Baseline	1.34	1.52	1.88	2.23	2.58
Fuel source, 25% more volatile,	1.64	1.86	2.39	2.92	3.45
Fuel source, 50% more volatile	1.93	2.19	2.92	3.66	4.39
Fuel source, 10% higher χ_r	1.60	1.82	2.32	2.82	3.33
Fuel source, additional pool fire	4.07	4.63	7.88	11.1	14.4
Vents, fewer	1.63	1.85	2.37	2.90	3.42
Vents, larger	1.26	1.43	1.74	2.06	2.37
Vents, smaller	2.14	2.43	3.33	4.23	5.1
Wind, None	1.25	1.42	1.73	2.03	2.34
Wind, 2.7 mph	1.36	1.55	1.91	2.27	2.64
Wind, 10.0 mph	1.22	1.39	1.68	1.97	2.26
Wind, 15.0 mph	1.31	1.49	1.83	2.16	2.50

A-5.0 Fire Modeling Conclusions

The results of the hand calculations and detailed fire modeling indicate that it is highly unlikely that the fire in Tank 80-8 would have resulted in ignition of fuels in the adjacent tanks without the contribution of an additional significant heat source, such as a large liquid pool fire on the ground. Existing prescriptive codes such as *NFPA 30: Flammable and Combustible Liquids Code* [8], *FM Loss Prevention Data Sheet (LPDS) 7-88: Ignitable Liquid Storage Tanks* [9], and *API Pub 2021: Management of Atmospheric Storage Tank Fires* [10] are based on industry experience and the contribution from a single fire source (in example, either a liquid pool or an adjacent tank).

The results of this study indicate that the coupled impact of a tank fire and a liquid pool fire may need to be considered in evaluating the minimum safe separation distance, particularly in older installations that predate the availability of safety features or equipment that aid in mitigating such conditions. Although a relatively limited pool fire was examined in this analysis, the combined impact of the pool and vent fires significantly raised the radiant exposure to adjoining tanks. If the pool fire expanded, as was the case with the ITC fire, igniting the contents of adjacent tanks from radiant heat exposure would be more likely.

In addition, the computational modeling showed that the fires exiting vertical pressure release vents on the side of the tank behaved significantly differently than a standard liquid tank fire, where the impact of wind on the thermal exposure was significantly less than has been documented in similar studies for other tank farms. In this study, the size and number of pressure release vents had a more significant impact on the predicted thermal exposure than the wind speed. Because this configuration is a trend within the tank storage industry, additional study appears to be necessary based on clearly different burning and radiant exposure mechanisms that have traditionally been incorporated into the above noted standards. The configuration also highlights the need for prescriptive codes to consider alternative fire configurations when recommending minimum safe distances.

These conclusions are incorporated into Section 6.0 of the body of this report.

A-6.0 Appendix References

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