BAKERRISK HYDROGEN QUALIFICATIONS AND EXPERTISE

Revision 1, Released October, 2025

Developed by:

Peter Diakow, CFEI
Murtaza Gandhi, P.E.
Jack Altwal, Ph.D.
Mikaela Dressendorfer

EXECUTIVE SUMMARY

Impact of Hydrogen

Hydrogen has been described as "the Swiss Army knife of zero carbon technologies" and is a key part of the clean energy transition.[1] Various governments and organizations have set hydrogen production and/or carbon neutral goals and according to the "2024 Global Hydrogen Review" the production of low-emission hydrogen has grown by 50% since 2021.[2] The US is aiming to produce 10 million metric tons (MMT) of hydrogen annually by 2030, a steppingstone towards the ultimate goal of 50 million metric tons annually by 2050.[1] Japan has set goals for producing 20 MMTs of hydrogen by 2050 and attracting $107.5 billion of hydrogen investments over the next 15 years. In 2020, the European Union unveiled the "hydrogen strategy for a climate-neutral Europe" that included 20 actions for Europe to carry out in the coming decades to carry out their clean energy transition. As the hydrogen supply chain grows, it is important to be aware of the hazards and risks inherent in handling hydrogen.

BakerRisk Hydrogen Services and Expertise

Noting that hydrogen specific studies were not tracked prior to 2020, Baker Engineering and Risk Consultants, Inc. (BakerRisk®) has engaged in over 200 hydrogen safety studies in just the past 5 years, including various research/test programs (see Section 5). Part of that commitment to hydrogen safety is leveraging expertise and industry partner relationships to help new entrants to the hydrogen industry manage the hazards and risks inevitably associated with handling hydrogen. In recognition for those efforts, BakerRisk was recently awarded the **inaugural Robert Zalosh Hydrogen Safety Excellence Award in the Organization category**. The award was recently established by the Center for Hydrogen Safety (CHS) to recognize organizations that have significantly contributed to the practice of hydrogen safety.

BakerRisk is engaged in a variety of hydrogen risk management services, most notably in the areas of Consequence and Risk-Based facility siting studies (FSS), also known as quantitative risk assessment (QRA), process hazards analysis (PHA), hazardous area classification (HAC), fire hazard analysis (FHA), incident investigation, and structural design. To support these services, BakerRisk has developed numerous in-house software packages that are continuously improved, based on the latest testing and research.

Expertise and Knowledge Sharing

BakerRisk is also committed to sharing its knowledge and expertise through involvement with safety organizations and codes/standards development. BakerRisk participates on numerous committees and works closely with the Compressed Gas Association (CGA), Center for Hydrogen Safety (CHS), the Hydrogen Safety Panel, and the renewable natural gas (RNG) coalition. BakerRisk is also a member of the Northwest Hydrogen Alliance, an industry group dedicated to developing the Northwest of England as the UK's primary hydrogen economy location; as well as the Green Hydrogen Association (GH2 India), which is dedicated to accelerating development of green hydrogen solutions in India.

---

1 A Deep Dive into Global Green Hydrogen Policy Incentives - Plug Power

2 International Energy Agency. *Global Hydrogen Review 2024*. Revised version, October 2024.

Our consultants also serve on technical committees of the National Fire protection Association (NFPA) and the American Petroleum Institute (API).

As process safety professionals, BakerRisk has background knowledge, industry experience, and insights to provide facilities and organizations with potentially life-saving knowledge. Over the years, we have contributed to over 20 books and guidelines for the Center of Chemical Process Safety (CCPS) as either a committee member or the lead author. BakerRisk continually shares our best practices and lessons learned in multiple Joint Industry Partnerships (JIPs) that we have established, serving as the lead for both the Explosion Research Cooperative (ERC) and the Ammonia & Fertilizers JIP.

BakerRisk also shares expertise with the industry through webinars (individually or in partnership with other organizations) and by presenting multiple papers at conferences each year or writing a multitude of articles for industry publications. In 2023, we published a 7-paper white paper series on a variety of hydrogen topics—the series is still available upon request. BakerRisk's one-day Hydrogen Training Course provides an overview of hydrogen production methods, transportation, and storage with a focus on key safety elements. The course includes workshop activity around hydrogen facility siting and safety systems, discussions of applicable hydrogen codes and best practices, and examples of past hydrogen incidents. Training is designed for a target audience of project managers, design/process engineers, and site health and safety advisors, but anyone involved in developing hydrogen projects and operations would benefit from the material covered.

This document summarizes BakerRisk's qualifications and expertise regarding hydrogen safety and highlights how we can support all segments of the hydrogen value chain in better assessment of the hazards and management of the associated risks.

For the Hydrogen Hubs

For companies and organizations that are part of the various U.S. hydrogen hubs (selected by the U.S. Department of Energy), BakerRisk can provide an end to end solution for any safety related needs. This collaboration with the producers, transport and end user companies, combined with our expertise in various facets of hydrogen safety, makes BakerRisk an ideal partner at any phase of the project. Early involvement with our team will help develop cost efficient safety strategies with fewer impacts on the overall project schedules. Our various experts are ready to provide any support to your project team as they lead the way in cutting edge hydrogen projects.

TABLE OF CONTENTS

1 BAKERRISK OVERVIEW 1
2 FACILITY SITING AND QUANTITATIVE RISK ASSESSMENTS 2
3 FIRE HAZARD AND MITIGATION ANALYSIS 3
4 FIRE AND GAS DETECTION ANALYSIS 4
5 TESTING 5
6 QUALITATIVE HAZARD IDENTIFICATION AND RISK ASSESSMENT 7
6.1 Process Hazard Analysis 7
6.2 Code Review 7
6.3 Hazardous Area Classification 8
7 HYDROGEN MATERIAL COMPATIBILITY 10
8 EXPERTISE AND KNOWLEDGE SHARING 11
8.1 Committee Memberships 13
8.2 Hydrogen White Paper Series 13
8.3 Hydrogen Safety Training 13
9 CLOSURE 14

LIST OF FIGURES

Figure 1. HACTool Data file Structure 9

APPENDICES

Appendix A. Qualifications A-1
Appendix B Facility Siting Study/Quantitative Risk Assessment Results Sample B-1

1 BAKERRISK OVERVIEW

BakerRisk is an employee-owned international risk management firm with over 175 engineers and scientists spread out across offices in the United States, Canada, the United Kingdom, Egypt, and the United Arab Emirates. Clients include companies from across the globe and in various sectors including oil and gas, petrochemical, renewable energy, specialty chemicals, manufacturing, aerospace, transportation, pharmaceutical, utilities, government and military. BakerRisk has been helping clients manage hazards and risks associated with hydrogen in "traditional" industries and applications (e.g., refining and ammonia-based fertilizer) for decades, but in 2020 BakerRisk began providing those same services to organizations with "non-traditional" hydrogen production schemes and/or applications, allowing BakerRisk to focus its tools and expertise specific to these new hydrogen production schemes and applications.

BakerRisk is engaged in a variety of hydrogen risk management services, most notably in the areas of:

- Consequence and Risk Modeling
- Fire Hazard and Mitigation Analysis
- Testing
- Qualitative Hazard Identification and Risk Assessment
- Structural Design
- Hazardous Area Classification
- Fire & Gas Detection
- Incident Investigation

BakerRisk has two test facilities that are supported by multidisciplinary testing teams capable of performing a variety of safety related tests.

The Wilfred E. Baker test facility covers 160 acres and is located 30 miles southeast of San Antonio. It boasts a 9,800 sq. ft high-bay test building, housing one of the world's largest and most fully featured Shock tube tests in the world. Additional test apparatuses available at Wilfred E. Baker include a dispersion and jet-fire test pad, vapor cloud explosion and flash fire test pads and a high-speed/high-pressure projectile and terminal ballistics research test pad.

The Box Canyon Test Facility (BCTF) covers 2,300-acres and is located approximately 100 miles west of San Antonio in Kinney County, Texas. The facility gets its name due to its unique topography and is home to the BakerRisk Deflagration Load Generator (DLG), supporting additional testing needs for research and litigation. Aside from the DLG, the BCTF is equipped with a high explosive testing range, vapor cloud explosion pad, and a custom hazard evaluation zone.

2 FACILITY SITING AND QUANTITATIVE RISK ASSESSMENTS

Facility Siting Studies (FSS) and Quantitative Risk Assessments (QRAs) are powerful tools used to quantitatively assess explosion, fire, and toxic (where appropriate) hazards and evaluate associated consequences and risks to onsite personnel and/or offsite population. BakerRisk emphasizes the value of FSS and QRA studies in ensuring the safe operation of hydrogen facilities, particularly hydrogen electrolyzer and liquefaction facilities While hydrogen is not inherently riskier than other fuels, its distinct properties present unique hazards and necessitate careful handling and a focus on risk management. Implementing FSS and QRA studies is essential for identifying and mitigating potential hazards in any hydrogen project or facility that incorporates hydrogen in its processes.

A key challenge in conducting consistent risk assessments across the hydrogen industry is the variability in methodologies, software, historical data sources, and presentation of results, as well as knowledge gaps about the physical phenomena taking place during a hydrogen release event. BakerRisk is a key contributor to addressing this challenge. BakerRisk has authored multiple books[3,4] on risk and consequence modeling and advocates for industry alignment on technical knowledge through organizations like the Center for Chemical Process Safety (CCPS) within the American Institute of Chemical Engineers (AIChE) and the National Fire Protection Association (NFPA) to minimize QRA result variability. BakerRisk also leverages its testing facilities to validate consequence analysis results (see Section 5).

BakerRisk utilizes its proprietary SafeSite$_{3G}$© and QRATool© software in FSS/QRA studies. BakerRisk's SafeSite$_{3G}$© computer code is used to calculate potential consequences of identified hazards for the facility. Pressure, temperature, maximum release size, and material composition are defined for release hazard scenarios. Discharge rates are calculated, and dispersion results are then predicted for a range of statistically significant release sizes and meteorological conditions.

Risk is modeled as predicted number of fatalities or probability of such fatalities, using the consequence analysis developed in SafeSite and occupancy data for onsite locations. Frequencies initiated by accidental releases are estimated using proprietary BakerRisk failure rates derived from industry-average failure rate data and source-specific equipment count and pipe length data. Frequency and consequence results are combined to define risk for each scenario. Since risk is additive, the overall risk posed by operation of the facility is calculated by adding the risk of each scenario assessed.

---

[3] *Guidelines for Siting and Layout of Facilities*, 2nd Edition. CCPS, March 2018. https://www.aiche.org/ccps/resources/publications/books/guidelines-siting-and-layout-facilities-2nd-edition

[4] *Guidelines for Evaluating Process Plant Buildings for External Explosions, Fires, and Toxic Releases*, 2nd Edition. CCPS, April 2012. https://www.aiche.org/resources/publications/books/guidelines-evaluating-process-plant-buildings-external-explosions-fires-and-toxic-releases-2nd

3 FIRE HAZARD AND MITIGATION ANALYSIS

As part of its fire protection services for hydrogen equipment and sites, BakerRisk uses Recommended Practice documents such as API 2001[5] and API 2218[6], along with CCPS[7] resources, and NFPA 30[8] which suggest that Fire Hazard Analyses (FHAs) be performed to mitigate fire damage from ignited flammable releases. Other standards, such as NFPA 1660[9], encourage that risk assessments are to be performed to develop tailored emergency pre-incident plans. NFPA 2[10] and NFPA 59A[11] allow performance-based designs, in whole or in-part, against hazards created by fire, explosion, and other hazardous conditions. A performance-based Fire Hazard and Mitigation Analysis (FHMA) methodology with a supplemental suite of tools can be applied to perform site-wide fire hazard evaluations to determine the capabilities of fixed protection and fire emergency response. Process unit, hydrogen generation/processing, loading/ unloading, and storage area fire hazards can be analyzed through this approach, which includes a field assessment with scenario-specific fire case workshops that incorporate a fire emergency response timeline, hydraulic firewater system performance, and fire brigade/ERT/off-site emergency response assets, training, and capabilities. The FHMA also helps facilities understand their maximum credible firewater demand for planning purposes. Mitigative solutions are offered for any identified gaps in protection or response.

BakerRisk has successfully applied FHMA studies at both existing locations and for greenfield design sites being constructed to manufacture hydrogen, ammonia, and related tank farm terminals storing, loading, and unloading these liquids. Third-party, multi-tenanted logistics sites where fire protection is dependent upon existing infrastructure are now called upon to protect compressed gas and/or cryogenic liquid fuels.

FHMA-style studies benefit from front-end hydraulic gradient testing on a site's firewater system to refine hydraulic model inputs, create higher-fidelity hydraulic models, increase confidence in results, and expose piping bottlenecks and other delivery system reliability concerns. Additional study integration including fire pump performance testing and in-depth pump asset reliability/operability reviews further enhance the value of FHMA-style studies to form a holistic foundation for assessing and improving a facility's readiness to respond-to and combat fires.

---

5 American Petroleum Institute (API) Recommended Practice 2001, "Fire Protection in Refineries"

6 American Petroleum Institute (API) Recommended Practice 2218, "Fireproofing Practices in Petroleum and Petrochemical Processing Plants"

7 Center for Chemical Process Safety (CCPS) book, *Guidelines for Fire Protection in Chemical, Petrochemical, and Hydrocarbon Processing Facilities*

8 2024 Edition, National Fire Protection Association (NFPA) 30, "Flammable and Combustible Liquids Code"

9 2024 Edition, National Fire Protection Association (NFPA) 1660, "Standard for Emergency, Continuity, and Crisis Management: Preparedness, Response, and Recovery"

10 2023 Edition, National Fire Protection Association (NFPA) 2, "Hydrogen Technologies Code"

11 2023 Edition, National Fire Protection Association (NFPA) 59A, "Standard for the Production, Storage, and Handling of Liquefied Natural Gas (LNG)"

FHMA-style studies are best-suited to the use of consequence and/or risk modeling to establish the radiant thermal heat flux contours for the fire cases or other fire scenarios that may be present throughout the facility, and can be used to perform other detailed fire protection studies such as Fireproofing Gap Analyses, Fire and Gas Detection Assessment/Optimization, the development of unit specific fire emergency pre-plans, and facilitating model-based simulations of process fires for tabletop training sessions for Emergency Response Team and Emergency Operations Center personnel.

FHMA and related fire protection studies can be used independently or in combination to assess facility fire emergency readiness and response capabilities, with proven value at both existing locations and projects under development. BakerRisk's involvement in FHMA-style studies helps produce consensus recommendations between the involved stakeholders and creates a prioritized action plan to assist clients in improving readiness at their facilities to the highest practicable level.

4 FIRE AND GAS DETECTION ANALYSIS

There are many theories on how to place detectors; too few detectors can be ineffective in providing early detection and too many detectors may result in spurious alarms and trips with reduced confidence in the system by the personnel who depend on it. Both situations can be detrimental to the purpose and may not provide an effective risk reduction strategy. Common practice allows experts to identify key locations for placing detectors, based on their experience. However, recent advancements in modeling have helped quantify the effectiveness of these systems, just as it has in calculating the consequences and overall risk at a facility.

Catching hydrogen releases with gas detectors depends on the surroundings from the potential leak scenarios. Hydrogen releases inside confined areas (such as buildings), increase likely accumulation of the hydrogen gas and the effectiveness of the detectors is higher. Typically CFD analysis is used for gas detector placement inside buildings by assessing the air flow within the building, the location of any venting areas, and potential release locations. Contrarily, hydrogen releases outside confined areas (such as within outdoor process units), are more challenging to detect because of the buoyancy of hydrogen. Detectors are typically placed fairly close to release locations in the path of the momentum of the hydrogen cloud or in areas where the gas can accumulate, such as pipe racks or heavily congested areas.

Hydrogen fire detection though IR detectors and/or IR cameras can be useful since hydrogen fires are unseen by the human eye. For fire detector placement typically a 'birds-eye' view of the potential release scenarios from multiple directions ensures releases are able to be captured. Attention to obstructions that would block the view of the fire detectors is extremely important, not just in initial placement but also during the life of the detector.

5 TESTING

For over 16 years, BakerRisk has utilized our internal test sites to carry out a wide array of hydrogen testing programs. Some of these were internal research efforts funded by BakerRisk. These research programs include lean hydrogen VCE tests to provide benchmark data for predicting deflagration to detonation transition (DDT) with unconfined lean hydrogen air clouds. These tests were performed with hydrogen and air mixtures that were from 16-22% hydrogen. A DDT was observed using 22% hydrogen in air[12].

BakerRisk has also performed additional VCE testing of very lean hydrogen-air mixtures to determine the lower concentration limit where hydrogen-air mixtures can produce damaging loads in an unconfined environment using a long, (96 ft) test rig. From this, BakerRisk has concluded that lean air-hydrogen mixtures, around 16% hydrogen, could result in DDT within industry scale congested volumes. This research also indicated that very lean hydrogen-air mixtures (<12% hydrogen) would not contribute to blast loads generated during a VCE. BakerRisk chose conservatism and used a lower explosion limit (LEL) of 10% hydrogen[13] for its facility siting studies.

In 2024, BakerRisk conducted an internal research project to test the deflagrations of lean hydrogen mixtures in the DLG. The tests included deflagration tests at 3 concentrations (vol%) of hydrogen in air: 9.9%, 13%, and 16.4%. BakerRisk has used results of that study to improve facility siting study blast models and approach for NFPA 68 analyses.

BakerRisk also conducted lab scale research into the effect of inert species on laminar burning velocity (LBV) of hydrogen and ethylene using both nitrogen and carbon dioxide. The results of that study were presented at the 2014 Mary Kay O'Connor Process Safety Conference at Texas A&M.

Explosion Research Cooperative Testing programs

BakerRisk also regularly carries out hydrogen testing programs at the behest of our industry partners primarily though the Explosion Research Cooperative (ERC). The ERC is a BakerRisk-organized Joint industry program (JIP) founded in 1993. It currently has 22 industry members who pool their funding to develop testing and research programs at BakerRisk to address industry concerns. Some of these studies are briefly described below.

Laminar burning velocity (LBV) is used as the reactivity index for the Baker-Strehlow-Tang (BST) vapor cloud explosion (VCE) blast load prediction model. In 2010, the ERC commissioned a testing program to

[12] J.K. Thomas, R.J. Duran, and M.L. Goodrich, "Deflagration to detonation transition in a lean hydrogen air unconfined vapor cloud explosion," Mary Kay O'Connor Process Safety International Symposium, College Station, TX, October 27, 2010.

[13] Malik, Darren & Lowry, W. & Vivanco, Elias & Thomas, J., (2023). Very lean hydrogen vapor cloud explosion testing. Process Safety Progress. 42. 10.1002/prs.12459.

measure the LBV of Hydrogen-Hydrocarbon mixtures. The study established limits of Le Chatelier's rule for the LBV of hydrogen-hydrocarbon mixtures and helped determine which fuel reactivity class can be used for any specific hydrocarbon-hydrogen mixture. A follow up study was done in 2012.

In 2022, BakerRisk conducted ISO container scale vented hydrogen/syngas deflagration testing. The tests were designed to explore the characteristics behind vented deflagrations involving hydrogen-rich syngas and pure hydrogen inside of a 20 ft. long Conex container with different confinement, congestion, and duration of fuel release. These results help BakerRisk and other ERC companies to learn more about NFPA 68 and to study these vented deflagrations.

BakerRisk also performed Hydrogen/methane VCE testing in 2023. That study investigated the VCE hazards associated with blending hydrogen into a natural gas transportation system. One consequence of this is that LBV increases, which increases the severity of VCEs. The study was performed using BakerRisk's deflagration load generator (DLG).

Industry partnerships

BakerRisk also collaborates individually with industry partners and Stakeholders on research and testing independent of the ERC. In partnership with Air Products, BakerRisk expanded on earlier work related to uncongested turbulent hydrogen jet explosions.[14,15] Those tests investigated the jet fires and blast loads produced by warm and cold hydrogen venting events and were used to validate JetEx and FLACS based dispersion/explosion models. In 2018, Daewoo Engineering & Construction Co. Ltd funded a testing program examining vented hydrogen deflagration to detonation transition (DDT). The tests aimed to support validation of a Computational Fluid Dynamics (CFD) analysis by performing partially confined vapor cloud explosions. Two tests were done using lean hydrogen mixtures. The first test (20% hydrogen) had an average peak overpressure of 8.6 psig (0.6 barg). The second test involved 22.5% hydrogen and had an average peak overpressure of 89 psig (6.1 bar).

Future testing programs

BakerRisk is continually performing and planning for new hydrogen testing programs including additional vapor cloud explosion testing of hydrogen-methane blends, ignition testing of large scale (>0.5 kg/s) hydrogen dispersions, testing to demonstrate detonation wave failure in sufficiently lean H_2-air mixtures, and hydrogen boiling liquid expanding vapor explosion (BLEVE) testing.

[14] D.Miller, C.D. Eastwood and J.K. Thomas, Hydrogen Jet Vapor Cloud Explosion: Test Data and Comparison with Predictions, 11th Global Congress on Process Safety, AIChE Annual Meeting, Austin, TX, 26-30 April 2015.

[15] S. Jallais, E. Vyazmina, D. Miller and J.K. Thomas. Hydrogen Jet Vapor Cloud Explosion: A Model for Predicting Blast Size and Application to Risk Assessment. 13th Global Congress on Process Safety, AIChE Annual Meeting, San Antonio, Texas, March 26-29, 2017.

6 STRUCTURES

7 QUALITATIVE HAZARD IDENTIFICATION AND RISK ASSESSMENT

7.1 PROCESS HAZARD ANALYSIS

BakerRisk has experience with various process hazard analysis (PHA) techniques, including Hazard identification (HAZID), What-if Analysis, Hazard & Operability (HAZOP) studies, Layer of Protection Analysis (LOPA), Bow-tie analysis, and failure mode and effect analysis (FMEA).

BakerRisk has performed PHAs for a variety of processes related to hydrogen generation, use and storage. These include gaseous hydrogen tube trailer systems, fuel cell modules, storage cylinders, and hydrogen electrolyzer, compression, and purification systems.

The scope of a PHA should include evaluating the process hazards that lead to catastrophic consequences and implementation of engineering and administrative controls applicable to that particular identified hazard and their applicability. Therefore, when performing PHAs, BakerRisk also considers incidents that occur on site, if any, and in industry for similar setup and consequences. When conducting PHAs, BakerRisk implements RAGAGEP and provides the client an assessment of applicable local regulations (including those required by local, municipal state or federal legislation) and applicable standards that constitute recommended industry best practices.

BakerRisk performs PHAs using a variety of third-party software including PHA-Pro® (Sphera), PHAWorks® (Primatech), and Leader™ (ABS Group). BakerRisk has also developed in-house PHA software: PHA-Tool©. PHA-Tool© is a comprehensive PHA suite computer code that supports the execution of various PHA methodologies including HAZID, What-If, HAZOP, and LOPA. The software also allows for Safety Integrity Level (SIL) selection using LOPA and SIL verification techniques.

7.2 CODE REVIEW

BakerRisk has performed multiple hydrogen design code reviews for proposed hydrogen installations at a number of different facilities, including several hydrogen tube trailer supply and vaporization/blending skids used for turbine supply, hydrogen electrolyzer production and tube trailer loading facilities and hydrogen blending facilities for use in natural gas blending. The code reviews in question involved assessing applicable local regulations (including those required by local, municipal state or federal legislation) to determine which industry standards were required for compliance, as well as identifying standards that constituted recommended industry practice, even where they were not required by legislation.

BakerRisk assessed the proposed designs (to the extent that they were known at the time of the code review) for compliance with identified standards and provided clients a summary of where they complied with regulations and where their design was non-compliant, along with an assessment of compliance with recommended standards. Additionally, where their initial design details did not have enough information to verify compliance, critical standards and practices, BakerRisk flagged the items so that the company could ensure compliance as their designs were more fully developed.

The exact standards and codes cited varied from site to site and project to project but typically included: International Building Code (IBC), International Fire Code (IFC), International Mechanical Code (IMC), International Fuel Gas Code (IFGC), NFPA 2, NFPA 55, CGA 5.5-5.7, ASME B31.12, and OSHA 29 CFR 1910.103.

7.3 HAZARDOUS AREA CLASSIFICATION

When it comes to Hazardous Area Classification (HAC), BakerRisk has worked on hundreds of HAC-related projects over the years in the chemical, petroleum, clean energy, and engineering-procurement-construction (EPC) industries that could also be applied to hydrogen production. Our staff has worked worldwide on projects that include LPG plants and terminals, **electrolyzer packages**, fuel cells, hydrogen tube trailer supplies, hydrogen compression and storage and chemical process plants. BakerRisk has actively participated in several API and NFPA committees and are part of the committees that produced the National Fire Protection Association (NFPA) standards 496, 497, 499, and are also well versed in applying API RP 500/505, IEC 60079-10-1 and IEC 60079-10-2. **In addition, we actively provide HAC support for clients with new installations and help to ensure existing equipment is suitable for the classified area in which the equipment is located.**

There are several nuances associated with hydrogen related HAC, primarily around applying NFPA 70 (National Electric Code), NFPA 497 (standard on HAC) and NFPA 2 (Hydrogen Technologies Code). This can cause discrepancies in how HAC is applied within various jurisdictions and applications. BakerRisk works with global clients on applying these standards and also how products manufactured and certified in various countries being imported into another country can meet the HAC requirements.

The BakerRisk patented, rule-based HACTool© software is an innovative approach to HAC – combining hands-on process evaluation using the appropriate NFPA, API, and IEC hazardous location classification guidelines as a foundation, with specific process material information aligned directly onto a facility plot plan. HACTool© allows import of existing site maps with complete use and calculation of HAC parameters such as the material group, auto-ignition temperatures for single or multi-component process stream applications, and other equipment data.

Documentation produced by the HACTool© includes 2-dimensional and 3-dimensional hazardous area classifications as well as tabularized summaries to address specific conditions, such as equipment GAP reports. The HACTool© approach provides a consistent base for a HAC and yields detailed drawings that were previously not cost-effective to manage. The creation of these detailed drawings permits the input data to be managed via HACTool© in a format that eases quality assurance checks, as well as the ability to quickly evaluate the effects of process and equipment changes.

The HACTool© data files formed by elements of the process include the plot plan, the flammable/ combustible materials making up the process streams, the process equipment addressed as potential sources of release, and the location of that process equipment in the process area, all of which could be applied to hydrogen production. These are assembled into a 5-tiered database contained within HACTool© as seen in Figure 1 below.

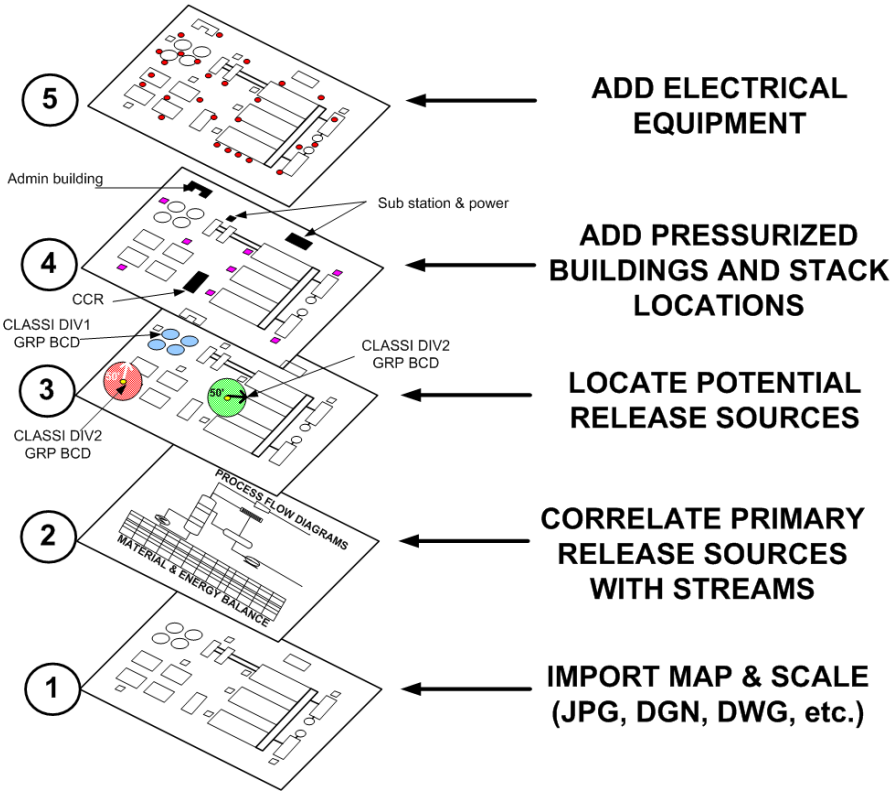


Figure 1. HACTool Data file Structure

8 HYDROGEN MATERIAL COMPATIBILITY

The BakerRisk Materials Engineering and Forensics Group is highly experienced with hydrogen-related mechanisms that can damage piping, vessels and equipment.

Failure Mechanisms

Structural materials exposed to monatomic hydrogen, hydrogen gas, or liquid hydrogen are at risk of several damage mechanisms specific to these environments.

- **Hydrogen embrittlement (HE)** involves the diffusion of monatomic hydrogen following welding, plating, or submerged cathodic protection. HE is a complex process that involves diffusion of hydrogen and concomitant reduction in fracture toughness near pre-existing microscopic defects, which can lead to sudden brittle fracture after an indeterminate time. High strength steels with ultimate tensile strength greater than 1200 MPa (~175 ksi) are especially susceptible but as a guideline the use of steel with strength higher than 790 MPa (150 ksi) should be avoided. This guideline is often expressed as an upper limit of 33 on the Rockwell C hardness scale (HRC).
- **Hydrogen Induced Cracking (HIC)** results from atomic hydrogen being absorbed by solid metals, then forming hydrogen gas from a corrosion process. This can occur during elevated-temperature thermal treatments and in service during electroplating, contact with maintenance chemicals, wet H_2S, corrosion reactions, cathodic protection, and operating in high-pressure hydrogen-containing environments.
- **High Temperature Hydrogen Attack (HTHA)** occurs in steels from ingress of hydrogen reacting with dissolved carbon and metal carbides, forming methane gas in the metal. Diffusion of hydrogen into steel at temperatures greater than 200°C (392°F).

These failure mechanisms each have telltale signs that can be identified by metallographic and fractographic examinations, and therefore require the use of scanning electron microscopes, optical microscopes and hardness testing equipment.

Of growing concern is the potential use existing pipeline networks to transport and distribute hydrogen for use as fuel. Such pipelines are typically made of steels that can be susceptible to hydrogen embrittlement (HE), especially at welds or bends where local hardness can exceed the limit of 22 HRC.

Selecting Compatible Materials

In general, industrial production, transport, and use of hydrogen demands the use of materials that can tolerate exposure to hydrogen-rich environments, since pipe or component failure that releases hydrogen could result in fire or explosion. Prevention and mitigation of hydrogen damage mechanisms require specific knowledge and application of ASTM standards (e.g., ASTM F1459, F1624, F2329 and A490) and industry recommended practices such as API 941 Nelson Curves.

Awareness is essential in developing the appropriate solutions for proper equipment inspection, damage mitigation, and failure prevention. For example, hydrogen can be present in a material from manufacturing or fabrication processes, such as in moist welding materials or in a humid welding environment. Service conditions can drive hydrogen into metal by corrosion reactions or through exposure to high pressure or partial pressure of hydrogen at specific temperature ranges. The susceptibility of a given material depends strongly on yield strength. One good indicator is a material's hardness, especially in the vicinity of welds where hardness in the heat-affect zone is of particular concern. The microstructure of the material may also influence the location of where the damage may occur. There are established levels of hardness, not to be exceeded, to avoid hydrogen damage. Susceptibility is also affected by residual stress and externally applied stress in the material. BakerRisk materials engineers are well versed knowledge of hydrogen damage mechanisms and industry recommended practices to mitigate or prevent hydrogen damage.

Specialized Equipment for Analysis

In the event of damage where hydrogen is suspected to have been causal or influential, BakerRisk's materials specialists employ state-of-the-art materials equipment in our 1,000-square-foot BakerRisk laboratory at the San Antonio offices. Materials are thoroughly and expertly characterized using digital optical and scanning electron microscopes, energy dispersive x-ray spectrometry, hardness testing, impact and tensile testing machines, plus a wide array of other state-of-the-art tools. The lab is divided into five functional areas: (1) optical microscopy (with Zeiss and Keyence digital optical microscope), (2) electron microscopy (with a Thermo Fisher Axia ChemiSEM scanning electron microscope), (3) chemical and metallographic sample preparation laboratory, (4) a mechanical workshop, and (5) a large general test room with generous open and flexible space that allows convenient access for staff and visitors.

In summary, understanding and preventing hydrogen damage mechanisms are among the most challenging materials engineering problems. BakerRisk Materials Engineering and Forensics Group specializes in forensic methods to diagnose the damage mechanisms in the event that failure has occurred, and the material selection for hydrogen service to mitigate and prevent failure in the first instance.

9 FORTRESS PROTECTIVE BUILDINGS

FORTRESS Protective Buildings, LLC (FORTRESS) was launched in 2020 with the aim of being the premier provider of buildings capable of protecting client personnel and critical equipment from high-hazard environments. BakerRisk was inspired to develop and design FORTRESS after recognizing a gap in available options for multi-hazard resistant buildings with a high degree of protection for building occupants. FORTRESS now offers multiple modular turnkey solutions for building protection add developed leveraging over three decades of experience in research, testing, process safety studies, and hundreds of incident investigations.

The FORTRESS MRB

FORTRESS's flagship product is the Multi-Hazard Resistant Building (MRB), an 8" precast reinforced concrete modular building with a flexible design and an interior that can be customized to meet individual client needs. The MRB was designed and constructed with one goal in mind: to provide clients with a building would be highly resilient, surviving catastrophic initiating events as well as the knock-on effects, to ensure building personnel have negligible exposure and go home safe, every day. It also underwent extensive testing at the BakerRisk test sites to ensure its performance exceeded design goals.

The MRB is capable of withstanding an 8 psi blast for long durations (>200 ms) and its precast concrete structure limits structural displacement and acceleration from blast waves. It also provides protection against fragments equivalent to that of a ¾" solid steel plate. The MRB exceeds requirements for toxic refuge with interior toxic shelter rooms and dual door airlock systems equipped with intelligent gas detection controls. In a world where climate change is increasing both the likelihood and severity of inclement weather, the MRB can also serve as a safe haven for many of these extreme weather events as it is ICC-500 compliant for a Category 5 hurricane and an F5 tornado. For locations where sheltering from natural disasters is a key design issue, FORTRESS meets the shelter requirements FEMA 320/361.

The FORTRESS MRB is a patented technology that was awarded the 2023 PCI Design Award Winner for innovative technology and has already been successfully deployed to various client sites throughout the United States.

The FORTRESS DEFENDER

The FORTRESS Defender is a 6" precast reinforced concrete single module building that provides similar multi-hazard protection to the FORTRESS MRB but with additional mobility and flexibility. With a 50+ year lifespan, the Defender's quick delivery, portability, and installation are ideal for projects with quicker turnarounds and tighter schedules.

The Defender was subjected to similar rigorous testing to the MRB at the BakerRisk test sites to ensure it met the highest standards of protection for people and critical equipment. It is rated for 5 psi blasts at 200 ms durations and, due to the weight, does not require anchoring to prevent sliding. It was designed to withstand long duration fires and was tested against gasoline and propane jet fires at pressure of up to 160 psi. The Defender provides the same extreme weather protections as the MRB and is ICC-500 compliant.

For the Hydrogen Industry

As the hydrogen industry continues to expand more corporations are exposed to Hydrogen's unique hazards, the FORTRESS MRB and Defender offer crucial protection to client personnel and critical equipment. The modular turnkey FORTRESS buildings have already been utilized in the oil and gas and low carbon industries, becoming industry standouts as control rooms and data centers, shelter-in-place (SIP) locations, and emergency response centers, remaining online even during incidents. Their high blast and

fire rating makes them ideal for serving an industry contending with hydrogen's wide flammability range and high fuel reactivity. FORTRESS's toxic hazard protections are also critical for hydrogen clients that produce or contain ammonia onsite. This protection may be augmented with the **FORTRESS Safe Haven,** designed to serve as the ultimate toxic mitigation with a leak tight building shell with <0.1 ACH, an interior safe room with <0.03 ACH, and capability to come fully equipped with a supplied breathing air system, SCBA escape respirators, and a highly effective fallback plan.

10 EXPERTISE AND KNOWLEDGE SHARING

As mentioned in preceding sections, BakerRisk has a team of engineers and scientists knowledgeable about key hydrogen hazards (including flammability, reactivity, and material compatibility), as well as team members familiar with common hydrogen regulatory programs and standards. To promote growth and understanding in hydrogen-related topics, that knowledge is shared through our training program, white paper series, and in hydrogen conference presentations.

10.1COMMITTEE MEMBERSHIPS

BakerRisk representatives serve on various technical committees, associations, and panels:

- The Compressed Gas Association (CGA)
- The Center for Hydrogen Safety (CHS)
- Green Hydrogen Association (GH2 India)
- Northeast Hydrogen Alliance (United Kingdom)
- The Hydrogen Safety Panel (HSP)
- API technical committees
- NFPA technical committee

10.2HYDROGEN WHITE PAPER SERIES

In 2023, BakerRisk compiled a series of seven white papers on Hydrogen that cover a variety of topics including hydrogen material compatibility hazards, performing hydrogen process hazard analyses, a future outlook into the hydrogen industry, and more.

The paper series is available to download, free of charge, from the BakerRisk website (https://www.bakerrisk.com/white-papers/the-complete-hydrogen-white-paper-series-1-7/). A follow-on webinar summarizing the white paper series: "Understanding Hydrogen Safety Challenges and Mitigation Strategies" also provides critical insights on safety and risk challenges relevant to hydrogen industries and potential mitigation strategies.

10.3HYDROGEN SAFETY TRAINING

BakerRisk also offers a 2 half-day course (8 hours total) to provide an overview of the hydrogen properties that drive its fire/explosion hazards as well as the unique material compatibility challenges it presents. This course includes workshop activities around hydrogen facility siting and safety systems, hazard

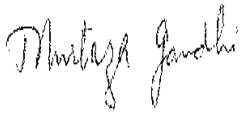
analysis, discussions of applicable hydrogen codes and best practices, and also presents examples of past hydrogen incidents. This training is designed for the target audience of project managers, design/process engineers, and site health and safety advisors, but anyone involved in developing hydrogen projects and operations is anticipated to benefit from the material covered and encouraged to attend. The following is a general scope list of items covered during the training. Note that training can be customizable to add/remove topics, upon request or interest.

- Introduction to hydrogen and its properties
- Hydrogen hazards and safety considerations
- Hydrogen material compatibility
- Hydrogen strategies and toolbox overview: utilizing studies to evaluate and assess hydrogen hazards such as,
    - Process Hazard Analysis (PHA)
    - Facility Siting Study/Quantitative Risk Assessment (FSS/QRA)
    - Hazardous Area Classification (HAC)
- Expectations of hydrogen under relevant standards and regulations (API, NFPA, ASME, etc.)
- Examples of hydrogen incidents and lessons learned
- Overview of hydrogen's outlook and future impacts

11 CLOSURE

We thank you for perusing this document and look forward to supporting you with your hydrogen-related projects. We encourage you to reach out should you have any questions or wish to discuss any of these matters further.

Peter Diakow: pdiakow@bakerrisk.com +1 (210) 721-7208
Murtaza Gandhi: mgandhi@bakerisk.com +1 (281) 404-6441



Peter Diakow
BakerRisk Hydrogen Lead
Senior II Consultant

Murtaza Gandhi, P.E.
Manager, Qualitative Risk & Sustainability
Principal Engineer

APPENDIX A. QUALIFICATIONS

BAKERRISK BRIEF HISTORY

Baker Engineering and Risk Consultants, Inc. (BakerRisk®) was founded in 1984 in San Antonio, Texas, by Dr. Wilfred. E. Baker following his retirement from the chemical industry. Then called Wilfred. E. Baker Engineering Inc (WBE), the company mission was to elevate industry standards, revolutionize explosion analysis, and redefine structural design. Thanks to the extensive expertise of its engineers and scientists, the company quickly developed a reputation as a globally recognized engineering consultancy firm.[16] In 2001, WBE merged with Energy & Chemical Risk Consultants (ECRC) to become BakerRisk. ECRC was well-established in the areas of insurance risk engineering and the merger allowed both companies to seamlessly broaden their expertise and breadth of services.

BakerRisk has also sought to increase our expertise and breadth of service through strategic acquisitions where possible. Since 2020, BakerRisk has been responsible for the update, maintenance, and dissemination of the Nelson Farrar Cost Index, one of the longest running cost indices for the oil and petrochemical industry. In December 2021, BakerRisk acquired Bryant-Lee Associates[17], a San Antonio, Texas-based materials science laboratory, to bolster our materials engineering consulting and testing services. Our fire protection and insurance risk engineering service capabilities were similarly increased with our late 2024 acquisition of Haines Fire and Risk Consulting (HFRC).

[16] https://www.bakerrisk.com/about-us/#who-we-are

[17] https://www.bakerrisk.com/news/bakerrisk-acquires-bryant-lee-associates-in-expansion-of-materials-engineering-and-testing/

APPENDIX B FACILITY SITING STUDY/QUANTITATIVE RISK ASSESSMENT RESULTS SAMPLE

This appendix shows a sample of some of the results generated by typical BakerRisk facility siting studies and quantitative risk assessments.

Typical outputs of a BakerRisk FSS and QRA include tables of location-specific societal risk, source-specific societal risk, and individual risk (as shown below in **Error! Reference source not found.** through **Error! Reference source not found.**) as well as composite consequence contour plots that are rotated for 16 wind directions (**Error! Reference source not found.** through **Error! Reference source not found.**). If a hydrogen project also involves an acute toxin (such as ammonia or carbon monoxide), toxic impacts would be similarly plotted and detailed.

BakerRisk FSS and QRA studies provide detailed explanations of building, location, and incident vulnerabilities, along with mitigation recommendations, such as enhancing building explosion resistance or implementing source risk mitigation strategies. These results should be evaluated against company or industry risk tolerance criteria. Given the high cost of post-construction mitigation, utilizing FSS and QRA tools early in the design process is crucial for identifying and implementing practical and cost-effective mitigation measures.

With the anticipated growth of hydrogen production, understanding the consequences and risks associated with a hydrogen facility are paramount. Employing FSS and QRA studies can enable the proper identification and mitigation of these risks optimally and cost-effectively.

Table B 1. Location Societal Risk

Building/Area	Building/Area Societal Risk (fatalities/year)				% of Total	
	Explosion	Flash Fire	Jet Fire	Total	Building/Area	Cumulative
Loading Station	**1.5E-4**	6.0E-8	2.8E-6	1.5E-4	36%	36%
Control Room	**1.3E-4**	9.2E-10		1.3E-4	31%	67%
Outdoor Area - Truck Loading		2.8E-5	**7.5E-5**	9.3E-5	22%	89%
Admin Building	**4.2E-5**	4.1E-10		4.2E-5	10%	98%
Outdoor Area - 1		**3.3E-6**	1.4E-6	4.6E-6	1%	99%
Outdoor Area - 2		**1.8E-6**	3.2E-7	2.1E-6	0.5%	100%
Totals	**3.2E-4**	**3.3E-5**	**7.9E-5**	**4.3E-4**		
	74%	**8%**	**18%**			

Table B 2. Source Societal Risk

Source	Source Societal Risk (fatalities/year)				% of Total	
	Explosion	Flash Fire	Jet Fire	Total	Source	Cumulative
H2Unit-18-Loading	**1.6E-4**	3.2E-5	7.7E-5	2.5E-4	60%	60%
H2Unit-03-H2Separator	**9.7E-5**	3.3E-10	7.6E-9	9.7E-5	23%	82%
H2Unit-04-H2Separator	**6.8E-5**	1.9E-10	4.6E-9	6.8E-5	16%	98%
Remaining Sources	**4.6E-6**	9.1E-7	2.1E-6	7.4E-6	2%	100%
Totals	**3.2E-4**	**3.3E-5**	**7.9E-5**	**4.3E-4**		
	74%	**8%**	**18%**			

Table B 3. Worker Individual Risk

Work Group	Worker Individual Risk (APoD)			
	Explosion	Flash Fire	Jet Fire	Total
Truck Driver	**1.4E-5**	2.7E-6	7.5E-6	2.3E-5
Operators	**1.4E-5**	5.7E-7	2.0E-7	1.5E-5
Lead Operator	**1.2E-5**	9.8E-11		1.2E-5
Admin	**8.8E-6**	8.7E-11		8.8E-6
Engineer	**8.8E-6**	8.7E-11		8.8E-6

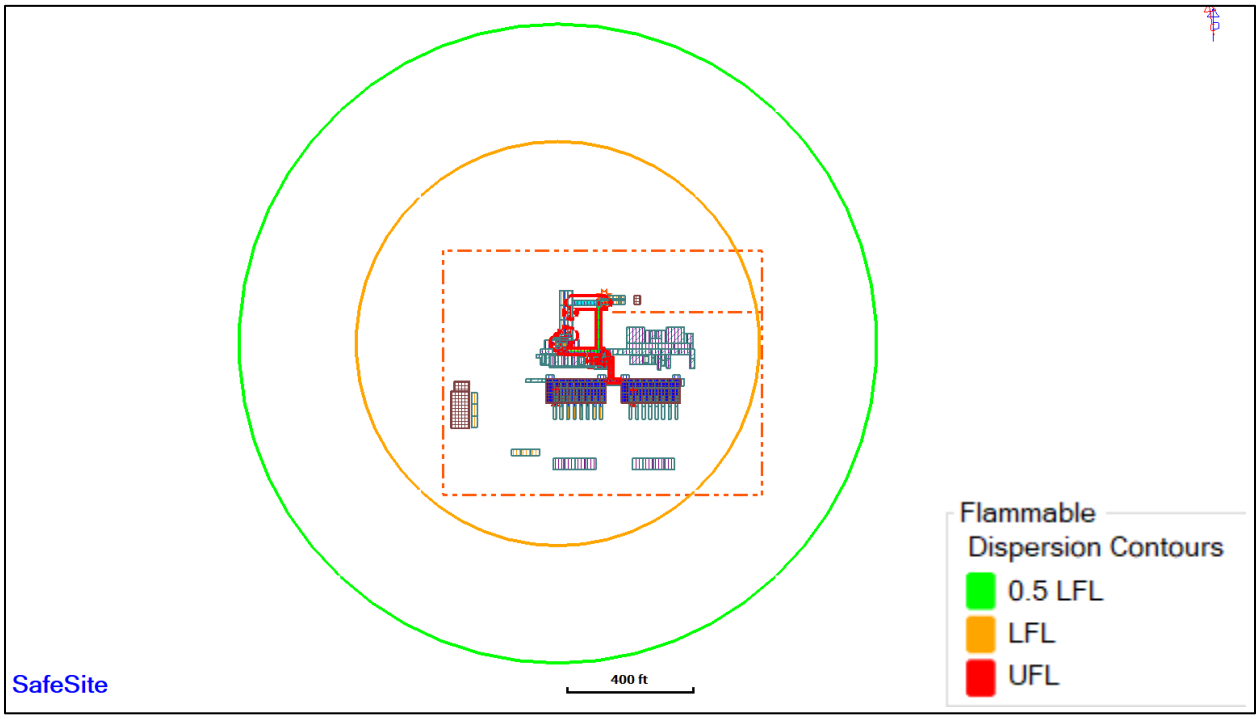


Figure B 1. Flammable Dispersion Contours for Full-Bore releases up to 6”

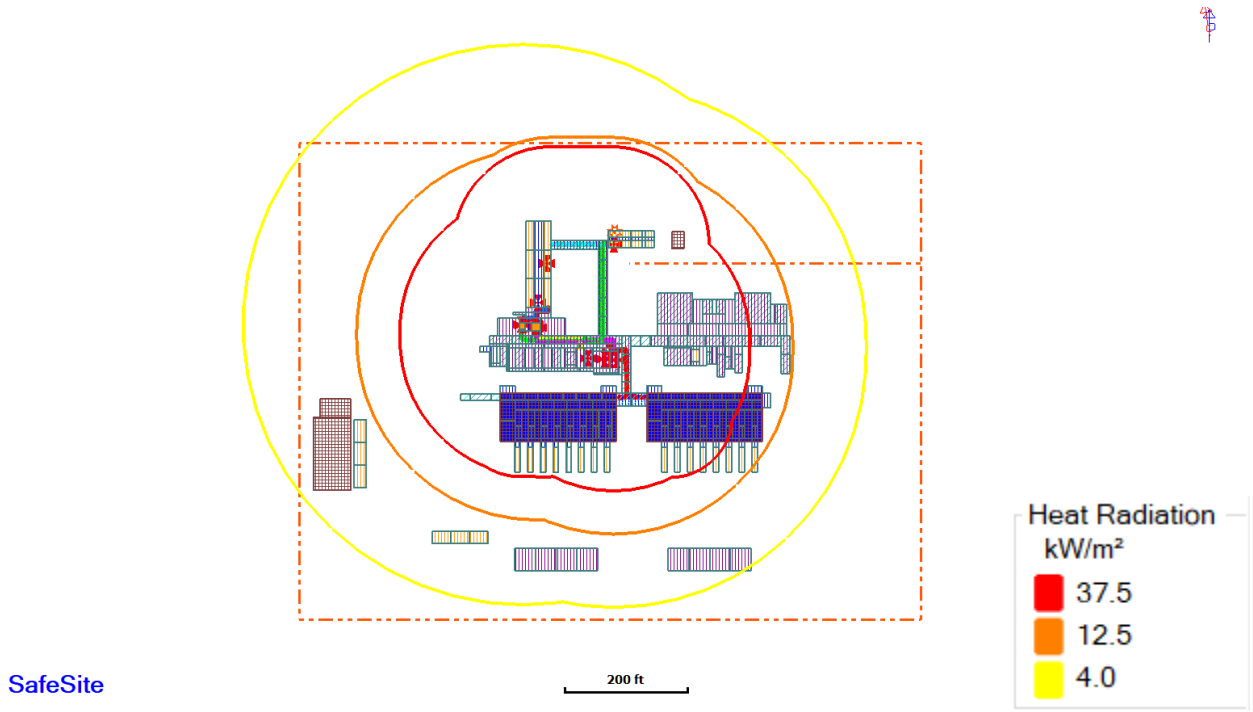


Figure B 2. Thermal Radiation Contours for Full-Bore releases up to 6”

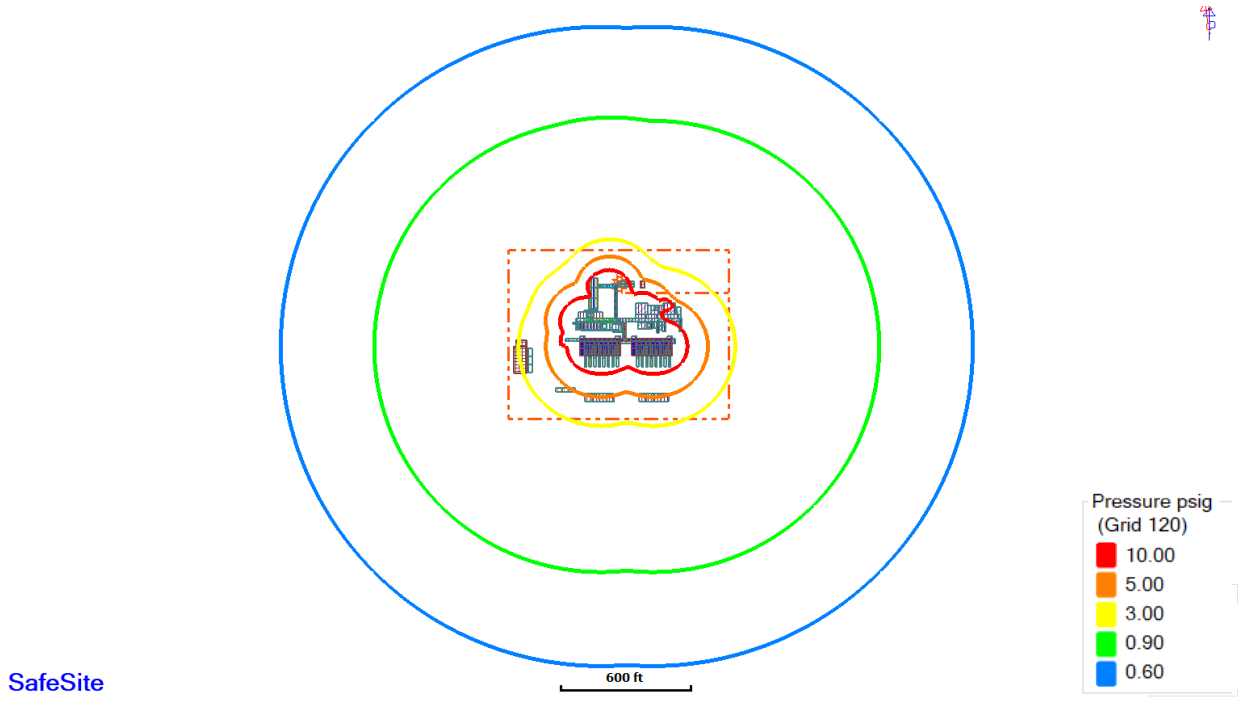


Figure B 3. Overpressure Contours for Full-Bore releases up to 6” *

*(*These results are limited to traditional DDT blast calculations)*

BAKERRISK

Better Risk Management Starts Here

BakerRisk.com

SERVICES

- Accident Investigation
- Functional and Electrical Safety
- Fire Protection and Insurance Risk
- Consequence and Risk Modeling
- Qualitative Hazard Identification and Risk Assessment
- Protective Structures
- Testing
- Low Carbon Energy

LOCATIONS

- San Antonio
- Chicago
- Houston
- Los Angeles
- Philadelphia
- Canada
- Egypt
- United Arab Emirates
- United Kingdom

BAKERRISK LEARNING CENTER

BAKERRISK LEARNING CENTER

By leveraging the expertise of our industry-leading instructors, BakerRisk provides insight into some of the most cutting-edge approaches to hazard evaluation for an unparalleled learning experience.