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BayoTech Risk and Modeling Support of NM Gas Site

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EXECUTIVE SUMMARY

The BayoTech hydrogen generation system has been evaluated in terms of safety considerations at the NM Gas site. The consequence of a leak in different components in the system was evaluated in terms of plume dispersion and overpressure. Additionally, the likelihood of a leak scenario for different hydrogen components was identified. The worst-case plume dispersion cases, full-bore leaks, resulted in relatively large plumes. However, these cases were noted to be far less likely than the partial break cases that were evaluated. The partial break cases resulted in nearly negligible plume lengths. Similarly, the overpressure analysis of the full-bore break scenarios resulted in much larger overpressures than the partial break cases (which resulted in negligible overpressure at the lot line).

There were several cases evaluated in the analysis that represented leak scenarios from both hydrogen and natural gas sources. Generally, the natural gas leak scenarios resulted in a smaller horizontal impact than that of hydrogen leaks. The worst-case consequence from a hydrogen leak resulted from the compressors, storage pods, or dispensing system. To consider the safety features that may isolate the leak, the consequence was evaluated at different times after the leak event to show the reduction of pressure. After 2 seconds, the plume dispersion from this event is contained within the perimeter of the site.

The worst-case consequences show that the plume may disperse to adjacent facilities and to the street. When considering both likelihood and consequence, the risk may be considered low because the maximum frequency of a full-bore leak from any component within the hydrogen compound is 8.2 E-5/yr. This means that a full-bore leak is expected to occur less than once every 10,000 years. The risk can be further reduced by implementing mitigative countermeasures, such as CMU walls along the sides of the equipment compound. This would reduce the overall consequence of the worst-case dispersion scenarios (horizontal impact of plume).

In terms of siting and safety analysis, the NFPA 2 code was used to provide a high-level evaluation of the current site plan. The most limiting equipment in terms of set-back distance are the compressors/storage units because of the high-pressure hydrogen. The site layout was evaluated for an acceptable location for the compression/storage unit based on NFPA 2 set-back distances. It is important to note that the NFPA 2 set-back distances consider both likelihood and consequence. This is important because the worst-case results evaluated herein also represent the least likely leak scenario. Other site-specific considerations were evaluated, including the parking shade structure with photovoltaic cells and refueling vehicles. These issues were dispositioned and determined to not present a safety risk.

1. BACKGROUND

This white paper describes the work performed by Sandia National Laboratories in the New Mexico Small Business Agreement with BayoTech. BayoTech is a hydrogen generation and distribution company that is located in Albuquerque, NM. Their goal is to distribute hydrogen via their hydrogen systems which utilize the core design that was developed by Sandia. However, because the hydrogen economy is in its nascency, the safety and operation of the generating systems require independent validation. Additionally, in their pursuit of permitting at various locations around the nation, they require fire protection engineering support in discussions with local fire marshals and neighboring industrial entities. Sandia National Laboratories has subject matter expertise in hydrogen risk modeling of consequence (overpressure and dispersion) as well as fire protection engineering. Throughout this project, Sandia has worked with BayoTech to provide our expertise in these subject areas to facilitate the market entry of their hydrogen generation project to address the dire need for decarbonization due to climate change. The general approach of the support by Sandia is outlined and the location specific evaluation for New Mexico Gas Co. is contained in within this report.

2. CODE REQUIREMENTS AND NM GAS SITE PLAN

In hydrogen generation, it is important to authorities having jurisdiction to show compliance with codes regulating the hydrogen generation, storage, and dispensing unit of the system. Specific to hydrogen generation, the codes used in the design of the BayoTech system include:

- NFPA 2, Hydrogen Technologies Code – 2020 Edition
- ISO 16110:2007 Hydrogen generators using fuel processing technologies – Part 1: Safety
- NFPA 70, National Electrical Code
- NFPA 79, Electrical Standard for Industrial Machinery, 2018 Edition
- UL 121201 Nonincendive Electrical Equipment for Use in Class I and II, Division 2 and Class III, Divisions 1 and 2 Hazardous (Classified) Locations
- ASME B31.3 (Process Piping)
- ASME Boiler and Pressure Vessel Code

In addition to the hydrogen generation codes, there are many additional design specifications for which the BayoTech system is in compliance:

- SAE J2719, Hydrogen Fuel Quality for Fuel Cell Vehicles – March 2020
- ASTM International Designation D1193-06, Standard Specification for Reagent Water, Reapproved 2018
- NFPA 86, Standard for Ovens and Furnaces, 2019 Standard
- NFPA 497, Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas
- NACE MR0103-2015/ISO 17945-2015, Petroleum, petrochemical, and natural gas industries - Metallic materials resistant to sulfide stress cracking in corrosive petroleum refining environments
- NEMA, National Electrical Manufacturer's Association
- API 520 Part I, 10th Edition & API 520 Part II, 7th Edition, Sizing, Selection, and Installation of Pressure-Relieving Devices in Refineries, October 2020
- API Standard 521, 7th Edition, Pressure-relieving and Depressuriing Systems, June 2020
- CSA/ANSI FC5, Hydrogen Generators Using Fuel Processing Technologies - Part 1: Safety, March 2021
- PIP Process Industry Practices, Latest Editions

Note that the adherence of the BayoTech hydrogen generation system to the above codes and standards was not evaluated herein.

Sandia staff has subject matter expertise in NFPA 2 as well as communicating code requirements to fire marshals and authorities having jurisdiction. The relevant sections of NFPA 2 include Chapter 4: General Fire Safety Requirements, Chapter 6: General Hydrogen Requirements, Chapter 7: Gaseous Hydrogen, and Chapter 10: Vehicle Fueling Facilities.

There are several components in the BayoTech hydrogen generation system that may require analysis. These components contain hydrogen, natural gas, and syngas at varying pressures and pipe sizes. Table 1 shows a high-level summary of the components of interest with differing gases and physical characteristics. Note that the elemental composition of the different gas mixtures is defined in Table 3.

Table 1: Leak Cases for NM Gas Co. Safety Evaluation

Gas	Source	Pressure	Pipe Size (Nominal ID)
Natural Gas	Meter Assembly	~ 60 psig	3”
Natural Gas	Feed gas booster compressor discharge, desulfurization	~ 175 psig	1 ½”
Natural Gas D+H20 mix	Reaction section	~ 150 psig	2”
Syngas	Reaction section	~ 145 psig	3”
Syngas	PSA booster compressors	~ 180 psig	2”
Tail Gas	PSA to furnace burner	~ 2 psig	3”
H2 product	PSA	~ 160 psig	1 ½”
H2 product	Compressors, storage pods or dispensing system	~ 7500 psig	¾”

As shown, the compressors and storage pods yield the highest-pressure hydrogen components in the system. Therefore, the set-back distances due to the storage system will be limiting for the entire system. In NFPA 2, there are different recommended set-back distances for bulk outdoor compressed hydrogen systems to different exposure groups. Exposure group 1 generally has the largest set-back distances. This group includes lot lines, air intakes, operable openings in buildings and structures, and ignition sources such as open flames and welding. Exposure Group 2 includes exposed persons other than those servicing the system and parked cars. This group generally has smaller set-back distances than Group 1. Exposure Group 3 has the least restrictive set-back distances and includes the following:

- Buildings of non-combustible non-fire-rated construction
- Buildings of combustible construction
- Flammable gas storage systems above or below ground, hazardous materials storage systems above or below ground
- Heavy timber, coal, or other slow-burning combustible solids
- Ordinary combustibles, including fast-burning solids such as ordinary lumber, excelsior, paper, or combustible waste and vegetation other than that found in maintained landscaped areas
- Unopenable openings in building and structures
- Encroachment by overhead utilities (horizontal distance from the vertical plane below the nearest overhead electrical wire of building service)
- Piping containing other hazardous materials
- Flammable gas metering and regulating stations such as natural gas or propane.

Per the compressor/storage pressure (~7,500 psig) and line size (0.75”), the set-back distances from NFPA 2, Table 7.3.2.3.1.1, for exposure groups 1, 2, and 3, are 55.5 ft, 36 ft, and 27.5 ft, respectively [1]. Based on the utility plan and site layout for the BayoTech system at the NM Gas site, the area for which compressed hydrogen can be stored has been estimated. Figure 1 shows the utility plan with the various set-back distances and the area in which compressed hydrogen at ~7,500 psig can be stored (in purple). As shown, the area is within the current planned layout. Note that the relative distances shown below are only rough estimates based on the utility plan dimensions. The orange and blue lines are being measured from the different exposure groups in proximity to the hydrogen system. The purple rectangle represents where on the site that the compressor can be located per the NFPA set-back distances. The blue lines are measured from the site boundary and the orange line is measured from a nearby parking lot. Although there is a gas line present, the Exposure Group 3 set-back distance is not applicable since it is part of the BayoTech system. Based on this review, the current design is in compliance with the NFPA 2 mandatory set-back distances.

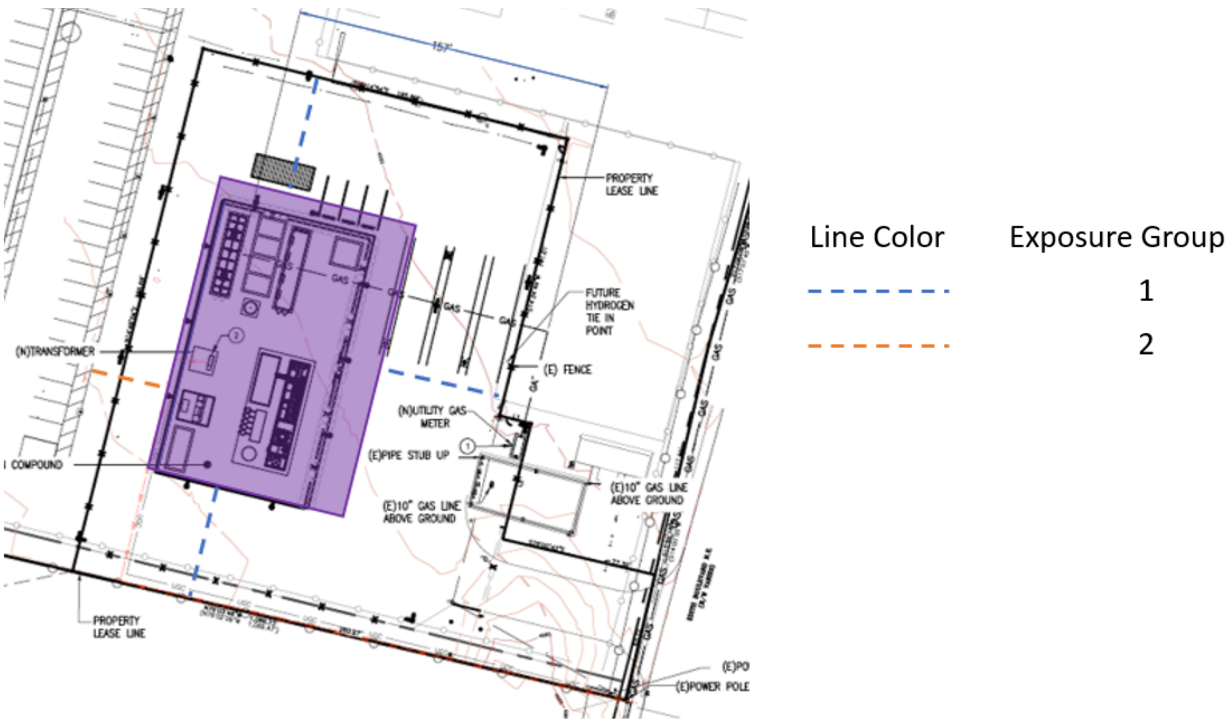


Figure 1: Storage Area for Compressed Hydrogen at NM Gas Site

3. CONSEQUENCE EVALUATION

An important aspect in permitting a hydrogen generation system is evaluating the risk that the system imposes on the public and neighboring entities. Specifically, the extent of the potential consequence of a postulated incident is of great interest to local fire marshals and authorities having jurisdiction. Additionally, knowing the extent of a potential consequence is important for the company producing the hydrogen generation system so that they can incorporate the necessary safety protocols into the system. Sandia performed a consequence evaluation for the BayoTech hydrogen generation system for their use in safety, protection, regulation, and permitting decision making. A consequence evaluation includes scenario identification, consequence modeling for multiple values of interest, and site-specific considerations.

3.1. Scenario Identification

Sandia staff worked with the BayoTech team to evaluate the system and identify the most relevant event scenarios for consequence evaluation. When identifying scenarios, it is important to consider the likelihood of occurrence of a situation. Although regulators and authorities having jurisdiction are generally interested in the worst-case scenario, it is important to consider likelihood when evaluating these scenarios because it puts the extent of consequence in perspective. A good example of the importance of likelihood is in airline travel. The consequence of an airline travel accident would most likely be very severe. However, travel by air is a well-accepted mode of transportation because the likelihood of an accident is very low. Without considering the likelihood component, airline travel would be most-likely viewed as too risky. Sandia has expertise in evaluating the likelihood of a leak scenario in a hydrogen system by using historical data in similar industries (e.g., natural gas) and applying Bayesian statistics to incorporate the limited hydrogen leak data. Utilizing this expertise, Sandia was able to identify scenarios that represented the worst-case consequence/low-likelihood as well as those that were low-consequence/high-likelihood.

The process to identify scenarios for evaluation involves evaluating the system piping and instrumentation diagrams to identify the system parameters (e.g., pipe size, temperature, pressure) of the pipes within the system that are of interest. The BayoTech system utilizes steam methane reforming to generate the hydrogen. The input into the system is steam and natural gas while the primary output is hydrogen, with secondary emission of flue gas from the reaction furnace (CO_2 rich). Within the system, the water is purified and heated to steam while the natural gas is desulfurized (sweetened) and heated as well. The steam and natural gas are reacted over a proprietary catalyst at high temperature in the steam methane reformer and converted to syngas (a mixture of CO, H_2, steam, CO_2, and unreacted methane). These products go through a water gas shifter in which the CO is converted to CO_2, along with the H_2 and steam. Finally, these products are fed through a purification step which uses pressure-swing adsorption to separate the H_2 from the other components. Through discussions with BayoTech, it was decided that the consequence of both hydrogen carrying components and natural gas components were of interest in the evaluation. Therefore, the system parameters for these pipes were identified (see Table 1).

The scenarios in Table 1 can include an evaluation of the worst-case full-bore leak scenario as well as a partial-bore leak (0.01% total leak area). The partial-bore leak was included to emphasize the importance of likelihood, since it is the most-likely scenario. Note that a specific leak frequency assessment was not addressed as part of this work. However, the results of a previous analysis of leak frequency of hydrogen components are included below in Table 2 [2]. As shown in the table, the difference between the mean leak frequency varies by component and relative leak size. The relative leak size is the ratio of the leak area to the total flow area of a component. For example, the mean leak frequency of a 0.01% relative leak size is 4 orders of magnitude more likely than a full-bore 100% relative leak size for a compressor (1.0E-01/yr compared to 3.2E-05/yr). However, a comparison of the same relative leak sizes for a pipe or a hose are on the order of a single order of magnitude difference. Comparing the mean frequency of a given relative leak size across different components, it is shown that there is a large variation in the likelihood of a 0.01% relative leak size break (ranging from 1.0E-01 to 1.6E-06). The variation in likelihood for a mean full-bore leak is less, with the largest mean frequency magnitude for any component of a full-bore break being 8.2E-05/yr. This means that a full-bore leak is expected to occur less than once every 10,000 yrs. The consequence results of full-bore leaks are included for additional information on the worst-case scenario; however, the overall likelihood of this event is generally far less than that of a partial-bore leak.

Table 2: Hydrogen Component Leak Frequencies (yr^{-1})

Component	Leak Size	Generic Leak Frequencies				Hydrogen Leak Frequencies			
		Mean	5th	Median	95th	Mean	5th	Median	95th
Compressor	0.0001	6.0E+00	2.5E-01	2.2E+00	1.9E+01	1.0E-01	5.9E-02	1.0E-01	1.6E-01
	0.001	1.8E-01	2.1E-02	1.1E-01	5.4E-01	1.9E-02	6.8E-03	1.7E-02	3.8E-02
	0.01	9.2E-03	1.0E-03	5.2E-03	2.7E-02	6.3E-03	1.2E-03	4.6E-03	1.7E-02
	0.1	3.4E-04	8.2E-05	2.6E-04	8.0E-04	2.0E-04	4.6E-05	1.5E-04	4.9E-04
	1	3.3E-05	1.7E-06	1.2E-05	9.3E-05	3.2E-05	2.0E-06	1.5E-05	1.0E-04
Cylinder	0.0001	1.5E+00	6.6E-02	6.6E-01	5.3E+00	1.6E-06	3.5E-07	1.4E-06	3.4E-06
	0.001	3.4E-02	3.4E-03	2.0E-02	1.0E-01	1.3E-06	3.7E-07	1.2E-06	2.8E-06
	0.01	8.4E-04	1.6E-04	6.4E-04	2.1E-03	9.0E-07	2.6E-07	7.9E-07	1.9E-06
	0.1	2.5E-05	6.6E-06	1.9E-05	5.9E-05	5.2E-07	1.6E-07	4.5E-07	1.1E-06
	1	7.6E-07	1.9E-07	6.1E-07	1.8E-06	2.7E-07	8.1E-08	2.3E-07	6.0E-07
Filter	0.0001	6.9E-02	3.4E-04	5.3E-03	8.4E-02	NA	NA	NA	NA
	0.001	1.4E-02	6.2E-04	5.1E-03	4.1E-02	NA	NA	NA	NA
	0.01	1.6E-02	6.0E-04	4.8E-03	3.9E-02	NA	NA	NA	NA
	0.1	6.1E-03	1.4E-03	4.6E-03	1.5E-02	NA	NA	NA	NA
	1	6.4E-03	1.2E-03	4.4E-03	1.6E-02	NA	NA	NA	NA
Flange	0.0001	6.5E-02	1.7E-03	2.0E-02	2.3E-01	NA	NA	NA	NA

Component	Leak	Generic Leak Frequencies				Hydrogen Leak Frequencies			
	0.001	4.3E-03	3.4E-04	2.2E-03	1.4E-02	NA	NA	NA	NA
	0.01	3.5E-03	8.4E-06	2.4E-04	7.0E-03	NA	NA	NA	NA
	0.1	3.5E-05	8.3E-06	2.7E-05	8.6E-05	NA	NA	NA	NA
	1	1.9E-05	1.9E-07	2.9E-06	4.6E-05	NA	NA	NA	NA
Hose	0.0001	2.8E+01	1.6E+00	1.3E+01	9.4E+01	6.1E-04	2.9E-04	5.8E-04	1.0E-03
	0.001	2.2E+00	2.9E-01	1.4E+00	6.4E+00	2.2E-04	6.6E-05	2.0E-04	4.5E-04
	0.01	2.1E-01	4.3E-02	1.6E-01	5.2E-01	1.8E-04	5.3E-05	1.6E-04	3.8E-04
	0.1	2.2E-02	6.0E-03	1.7E-02	5.3E-02	1.7E-04	5.1E-05	1.5E-04	3.4E-04
	1	5.6E-03	1.9E-04	2.0E-03	1.8E-02	8.2E-05	9.6E-06	6.2E-05	2.2E-04
Joint	0.0001	1.3E+00	7.0E-02	5.3E-01	4.6E+00	3.6E-05	2.3E-05	3.5E-05	5.1E-05
	0.001	1.7E-01	2.1E-02	1.0E-01	5.2E-01	5.4E-06	8.4E-07	4.7E-06	1.2E-05
	0.01	3.3E-02	4.2E-03	1.8E-02	9.3E-02	8.5E-06	2.9E-06	7.9E-06	1.6E-05
	0.1	4.1E-03	1.3E-03	3.5E-03	8.6E-03	8.3E-06	2.4E-06	7.5E-06	1.7E-05
	1	8.2E-04	2.3E-04	6.3E-04	1.9E-03	7.2E-06	1.8E-06	6.4E-06	1.5E-05
Pipe	0.0001	5.9E-04	7.1E-05	3.6E-04	1.8E-03	9.5E-06	2.1E-06	8.0E-06	2.2E-05
	0.001	8.6E-05	1.7E-05	6.2E-05	2.2E-04	4.5E-06	1.1E-06	3.7E-06	1.1E-05
	0.01	3.5E-05	9.1E-07	1.1E-05	1.3E-04	1.7E-06	9.9E-08	9.6E-07	5.9E-06
	0.1	4.7E-06	2.3E-07	1.9E-06	1.6E-05	8.4E-07	5.8E-08	4.6E-07	2.9E-06
	1	3.7E-06	1.0E-08	3.2E-07	1.0E-05	5.3E-07	5.5E-09	1.5E-07	2.3E-06
Pump	0.0001	3.9E-02	2.4E-03	1.8E-02	1.3E-01	NA	NA	NA	NA
	0.001	6.5E-03	8.5E-04	4.2E-03	1.9E-02	NA	NA	NA	NA
	0.01	2.5E-03	9.9E-05	9.5E-04	8.3E-03	NA	NA	NA	NA
	0.1	2.8E-04	7.2E-05	2.1E-04	6.7E-04	NA	NA	NA	NA
	1	1.2E-04	5.4E-06	4.9E-05	4.1E-04	NA	NA	NA	NA
Valve	0.0001	2.0E-02	2.2E-03	1.2E-02	6.4E-02	2.9E-03	1.9E-03	2.9E-03	4.2E-03
	0.001	2.8E-03	5.0E-04	1.9E-03	7.5E-03	6.3E-04	2.7E-04	5.9E-04	1.1E-03
	0.01	1.2E-03	2.6E-05	3.1E-04	4.0E-03	8.5E-05	6.6E-06	5.4E-05	2.7E-04
	0.1	6.4E-05	1.8E-05	5.3E-05	1.5E-04	3.0E-05	8.7E-06	2.5E-05	6.7E-05
	1	2.6E-05	8.3E-07	8.5E-06	9.1E-05	1.1E-05	4.7E-07	4.8E-06	4.2E-05

3.2. Consequence modeling

There are two different consequence metrics evaluated herein, the extent of plume dispersion and overpressure resulting from detonation.

3.2.1. *Plume Dispersion*

Modeling of the identified scenarios was performed utilizing Sandia internal hydrogen risk models for overpressure and dispersion of hydrogen as well as the publicly accessible HyRAM+ toolkit. Note that HyRAM+ can evaluate the consequence of a hydrogen or methane leak, although cannot yet evaluate blended gas. Therefore, select scenarios were identified and evaluated with either pure hydrogen or pure methane (which is used as a surrogate for natural gas). Additionally, when calculating dispersion, HyRAM+ assumes steady state conditions when calculating the plume length of a given leak (infinite fuel supply, constant pressure, etc.). This assumption generally leads to conservative results in terms of dispersion consequence, especially when considering safety features that may isolate the leak. There are safety features in the BayoTech system that can isolate the compressor if a leak occurs. This means that the total mass of hydrogen that can be released is limited to the filled storage tank. To account for this, the blowdown phase of the tank was modeled in HyRAM+ to determine the pressure in the tank as a function of time for the compressor/storage full-bore leak scenario. The plume was then modeled using the pressure at discrete times after the release to show how quickly the plume length dissipates. Note, the detailed blowdown calculations are included in Appendix A.

With these considerations, the leak cases from Table 1 were used to identify scenarios for evaluation using the HyRAM+ toolkit. Table 3 shows the scenarios for which plume dispersion was modeled. Note that there were three cases not modeled from Table 1. Case 3, the natural gas/H_20 mixture in the reaction section, was not modeled because the gas composition was approximately 80% H_20 and less than 20% natural gas. Case 6, tail gas from the PSA to the burner, was not modeled because the low pressure of ~5 psig. Additionally, Case 7, H_2 in the PSA, was not modeled because it is bounded by Cases 4 and 5. In addition, it the following assumptions were made in the plume dispersion simulations:

- The natural gas temperature for the leak cases is the battery limit supply temperature during summer (90 °F)
- The hydrogen temperature for the leak cases is 120 °F (from Block Flow Diagram (BFD) of Steam Methane Reforming (SMR) system)
- The ambient temperature is 60 °F
- The atmospheric pressure is 12.08 psi (at Albuquerque, NM elevation)
- The release coefficient for each leak case is conservatively set to 1 (no further reduction in leak size)
- For blowdown calculations, it was assumed that the tank size is 325 liters.
- In HyRAM+, the blowdown calculation cannot incorporate modified ambient pressure (default is ~14.7 psi)

Table 3: Consequence Evaluation Cases for NM Gas Site Analysis

Case #	Gas	Source	Pressure	Pipe Size	Gas Composition (mole %)							Assumptions
					H_2	CH_4	C_2H_6	CO	CO_2	N_2	H_2O	
1a	Natural Gas	Meter Assembly	~ 60 psig	3"		96.30%	2.90%		0.20%	0.60%		100% Methane, full-bore leak (3")
1b												100% Methane, partial leak (0.03")
2a	Natural Gas	Feed gas booster compressor discharge, desulfurization	~ 175 psig	1 ½"		96.30%	2.90%		0.20%	0.60%		100% Methane, full-bore leak (1.5")
2b												100% Methane, partial leak (0.015")
3	NG+H_20 mix	Reaction section	~ 150 psig	2"		16.84%	0.51%		0.04%	0.11%	82.51%	Not Modeled, mostly H_20
4a	Syngas	Reaction section	~ 145 psig	3"	43.93%	1.16%		4.88%	7.45%	0.08%	42.50%	100% H_2, full-bore leak (3")
4b												100% H_2, partial leak (0.03")
5a	Syngas	PSA booster compressors	~ 180 psig	2"	78.03%	1.87%		0.28%	19.42%	0.13%	0.27%	100% H_2, full-bore leak (2")
5b												100% H_2, partial leak (0.02")

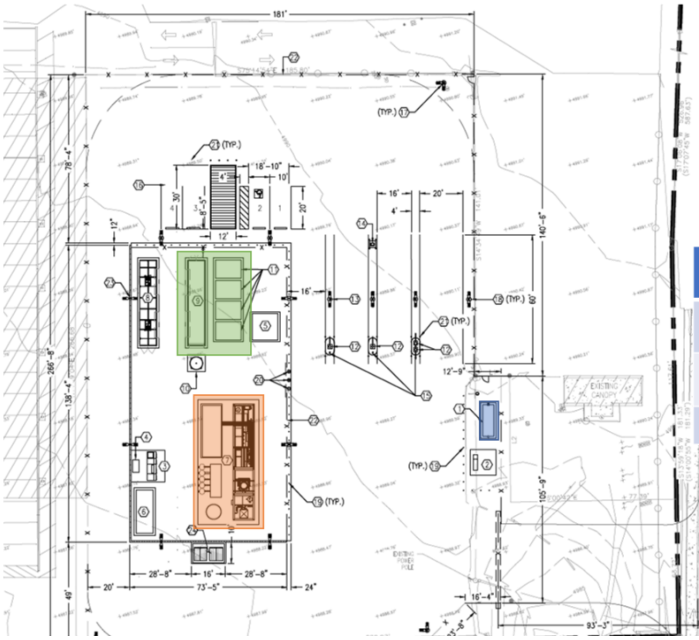
Case #	Gas	Source	Pressure	Pipe Size	Gas Composition (mole %)							Assumptions
					H_2	CH_4	C_2H_6	CO	CO_2	N_2	H_2O	
6	Tail Gas	PSA to furnace burner	~ 2 psig	3”	42.77%	4.88%		0.74%	50.68%	0.33%	0.59%	Not Modeled, much lower pressure than other cases
7	H_2 product	PSA	~ 160 psig	1 ½”	100.0%							Not Modeled, bounded by Case 5
8a	H_2 product	Compressors, storage pods or dispensing system	~ 7500 psig	¾”	100.0%							100% H_2, full-bore leak (0.75"), @ 0s
8b			~ 2161 psig									100% H_2, full-bore leak (0.75"), @ 1s
8c			~ 783 psig									100% H_2, full-bore leak (0.75"), @ 2s
8d			~ 7500 psig									100% H_2, partial leak (0.0075")

Table 4 shows the plume dispersion results evaluated for the NM Gas site. Note that the worst-case full-bore leak results yield relatively large dispersion plumes for each case. However, these leak scenarios are much less likely than the partial bore leaks, which have very small dispersion zones. The blowdown analysis was conducted for Case 8 and the dispersion at discrete pressures/times after the leak were evaluated. As shown, within two seconds of the leak occurring, the distance to the LFL for hydrogen is reduced by nearly 1/3. Note, the set-back distances discussed in Section 2 take into account likelihood and consequence of potential leak scenarios. This consequence analysis is provided herein is meant to provide additional detail for the worst-case leak scenarios that are possible in the BayoTech system at the NM Gas site location. The detailed output of the plume dispersion consequence modeling for the NM Gas site is contained in Appendix A.

Table 4: Plume Dispersion Results

Case #	Pressure	Pipe Size	Assumptions	Plume Length at LFL (ft)
1a	~ 60 psig	3"	100% Methane, full-bore leak (4")	~ 59
1b			100% Methane, partial leak (0.04")	~ 1
2a	~ 175 psig	1 ½"	100% Methane, full-bore leak (1.5")	~ 48
2b			100% Methane, partial leak (0.015")	~ 1
4a	~ 145 psig	3"	100% H_2, full-bore leak (3")	~ 213
4b			100% H_2, partial leak (0.03")	~ 2
5a	~ 180 psig	2"	100% H_2, full-bore leak (2")	~ 154
5b			100% H_2, partial leak (0.02")	~ 2
8a	~ 7500 psig	¾"	100% H_2, full-bore leak (0.75") @ 0s	~ 328
8b	~ 2161 psig		100% H_2, full-bore leak (0.75") @ 1s	~ 187
8c	~ 783 psig		100% H_2, full-bore leak (0.75") @ 2s	~ 115
8d	~ 7500 psig		100% H_2, partial leak (0.0075")	~ 3

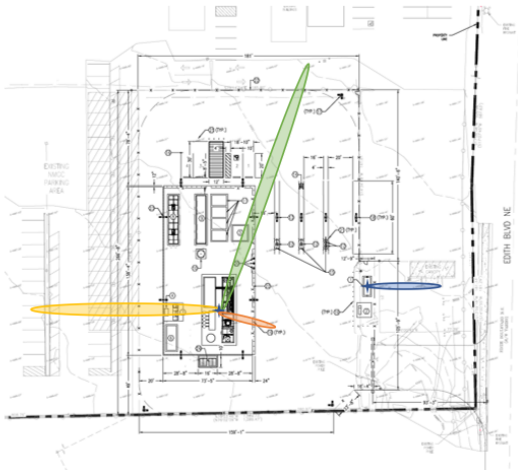
It is important to note that these plume lengths are postulated at a horizontal release for all cases. A leak can occur around the entire circumference of a pipe, so any leak occurring off of the horizontal line would result in a smaller horizontal footprint (i.e., if the leak was oriented in the vertical direction, the plume would have a negligible horizontal footprint). However, the horizontal release cases are the most conservative and show the worst extent of dispersion in the event of a leak. Figure 2 shows the maximum horizontal dispersion of cases 1b, 4b, 5b, and 8d with relation to the currently planned site layout. The length of the 2b plume is bounded by 4b and 5b, and is therefore not shown on the figure. The dispersion in these cases is shown as a continuous perimeter around the relevant equipment. Note that the "b" series cases represent the most likely leak scenario (e.g., partial leak). As shown in the figure, the affected area for these leaks is fairly minimal and does not affect adjacent equipment or targets.



Case #	Source Pressure	Description	Plume Length	Color
1b	60 psig	Partial leak (0.03”) (Methane)	1 ft	Blue
4b/5b	170/180 psig	Partial leak (0.03”/0.02”) (H_2)	2 ft	Orange
8d	7,500 psig	Partial leak (0.0075”) (H_2)	3 ft	Green

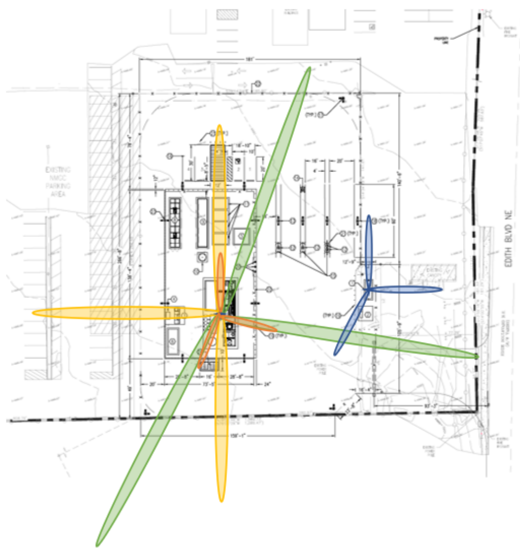
Figure 2: Case 1b, 4b, 5b, and 8d Plume Dispersion on Site Layout

Figure 3, Figure 4, and Figure 5 show the Case 1a, 2a, 4a, and 5a plumes overlaid on the site layout plan. Figure 3 shows a single plume for each case in a random direction in this figure to illustrate the extent of dispersion. Figure 4 shows 3 potential release scenarios for each case in random directions as well. Figure 5 shows the “zone of influence” that captures the extent of plume release for all horizontal directions. It is important to consider that a single plume will only impact a portion of this total zone of influence, as illustrated in Figure 3 and Figure 4. These figures illustrate that there is a potential for case 4a and 5a to impact targets beyond the western, southern, and northern property lines. However, it is important to consider likelihood when evaluating these cases. The maximum frequency of a full-bore break from any component is 8.2E-05/yr (see Section 3.1). The probability of the release being completely horizontal further reduces the likelihood of the worst-case horizontal impact. Therefore, based on the low probability of these full-bore rupture events, it is unlikely that additional mitigative measures are necessary for these events to reduce impact. These cases are included to provide information on worst-case scenarios, noting that their risk impact is low.



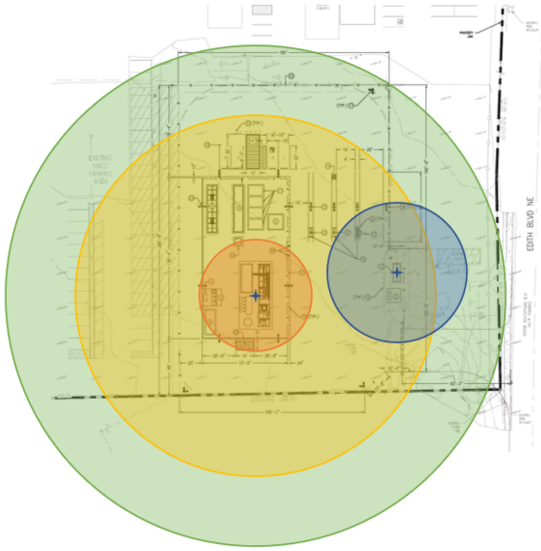
Case #	Source Pressure	Description	Plume Length	Color
1a	60 psig	Full-bore leak (3”) (Methane)	59 ft	Blue
2a	175 psig	Full-bore leak (1.5”) (Methane)	48 ft	Orange
4a	170 psig	Full-bore leak (3”) (H_2)	213 ft	Green
5a	180 psig	Full-bore leak (2”) (H_2)	154 ft	Yellow

Figure 3: Case 1a, 2a, 4a, and 5a Plume Dispersion on Site Layout (single plume)



Case #	Source Pressure	Description	Plume Length	Color
1a	60 psig	Full-bore leak (3”) (Methane)	59 ft	Blue
2a	175 psig	Full-bore leak (1.5”) (Methane)	48 ft	Orange
4a	170 psig	Full-bore leak (3”) (H_2)	213 ft	Green
5a	180 psig	Full-bore leak (2”) (H_2)	154 ft	Yellow

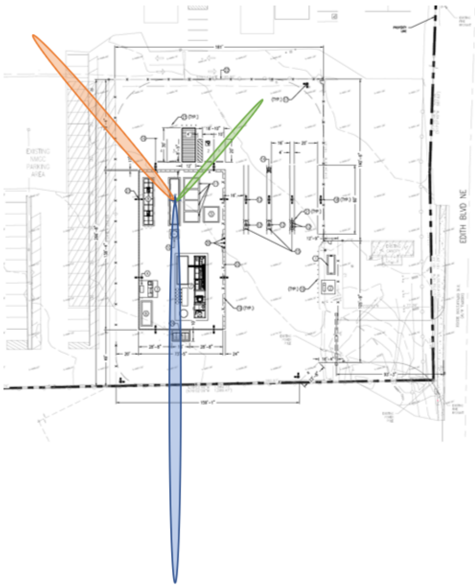
Figure 4: Case 1a, 2a, 4a, and 5a Plume Dispersion on Site Layout (multiple plumes)



Case #	Source Pressure	Description	Plume Length	Color
1a	60 psig	Full-bore leak (3”) (Methane)	59 ft	Blue
2a	175 psig	Full-bore leak (1.5”) (Methane)	48 ft	Orange
4a	170 psig	Full-bore leak (3”) (H_2)	213 ft	Green
5a	180 psig	Full-bore leak (2”) (H_2)	154 ft	Yellow

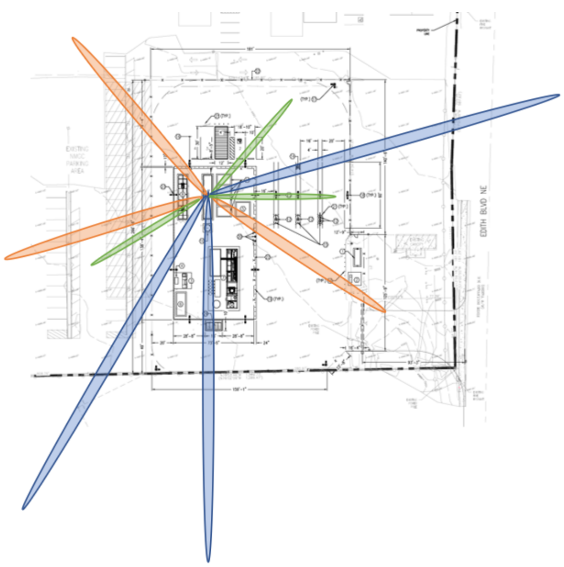
Figure 5: Case 1a, 2a, 4a, and 5a Plume Dispersion on Site Layout (zone of influence)

Similarly, Figure 6, Figure 7, and Figure 8 show the Case 8a, 8b, 5c plumes overlaid on the site layout plan. Figure 6 shows a single plume for each case in a random direction in this figure to illustrate the extent of dispersion. Figure 7 shows 3 potential release scenarios for each case in random directions as well. Figure 8 shows the “zone of influence” that captures the extent of plume release for all horizontal directions. As with the previous figures, it is important to consider that a single plume will only impact a portion of this total zone of influence. These figures illustrate that there is a potential for case 8a to impact targets beyond the western, eastern, southern, and northern property lines. Case 8b, which represents the reduced plume length after 1 second of the leak event, is contained within the eastern property line, but still extends beyond the other property lines. Case 8c, which represents the reduced plume length after 2 seconds of the leak event, is contained within the property lines. The same considerations for likelihood need to be consider for this case as well. Similarly, based on the low probability of these full-bore rupture events, it is unlikely that additional mitigative measures are necessary for these events to reduce impact. These cases are also included to provide information on worst-case scenarios, noting that their risk impact is low.



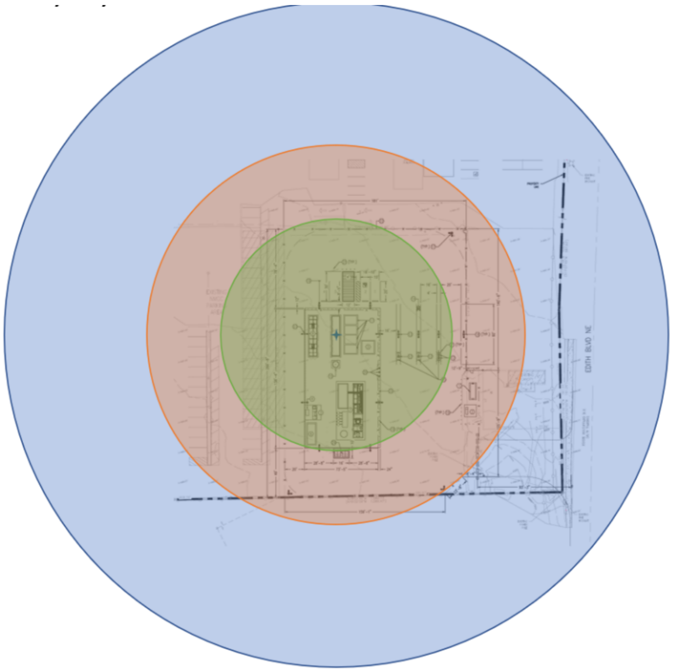
Case #	Source Pressure	Description	Plume Length	Color
8a	7,500 psig	Full-bore leak (0.75”) @ 0 s	328 ft	Blue
8b	2,161 psig	Full-bore leak (0.75”) @ 1 s	187 ft	Orange
8c	783 psig	Full-bore leak (0.75”) @ 2 s	115 ft	Green

Figure 6: Case 8a, 8b, and 8c Plume Dispersion on Site Layout (single plume)



Case #	Source Pressure	Description	Plume Length	Color
8a	7,500 psig	Full-bore leak (0.75”) @ 0 s	328 ft	Blue
8b	2,161 psig	Full-bore leak (0.75”) @ 1 s	187 ft	Orange
8c	783 psig	Full-bore leak (0.75”) @ 2 s	115 ft	Green

Figure 7: Case 8a, 8b, and 8c Plume Dispersion on Site Layout (multiple plumes)



Case #	Source Pressure	Description	Plume Length	Color
8a	7,500 psig	Full-bore leak (0.75") @ 0 s	328 ft	Blue
8b	2,161 psig	Full-bore leak (0.75") @ 1 s	187 ft	Orange
8c	783 psig	Full-bore leak (0.75") @ 2 s	115 ft	Green

Figure 8: Case 8a, 8b, and 8c Plume Dispersion on Site Layout (zone of influence)

It is noted that CMU walls are being considered in the current design along two to three sides of the equipment compound as a mitigation countermeasure. This type of countermeasure would impact the inertial force of plume dispersion and limit the horizontal impact. Although the most-likely leak scenario (partial leak) would not necessitate this countermeasure, it would mitigate a worst-case leak scenario. Based on potential targets, the CMU walls may be chosen on the north, south, and eastern sides of the equipment compound. This would potentially reduce exposure to the NM Gas buildings to the north, the PNM building to the south, and the street to the east. A parking lot is located to the west of the equipment compound.

3.2.2. Overpressure

Internal hydrogen risk models were used to evaluate the overpressure generated from the detonation of a plume resulting for the worst-case leak scenarios. This was performed at discrete distances of interest to determine if the overpressure consequence was of concern to the public or neighboring entities. Note that the internal risk models can only evaluate the overpressure resulting from detonation of a hydrogen leak. Therefore, only cases 4, 5, and 8 were evaluated for potential overpressure consequences.

Table 5 shows the overpressure results for select cases. Note the overpressure is documented at the discrete Exposure Group 1 set-back distance of 55.5 ft. This is the minimum distance at which the compressed hydrogen can be located with relation to the lot lines. Therefore, this table gives an estimate of the maximum expected overpressure at the lot line at the NM Gas site. As shown, the largest overpressure is seen for Case 8a at 1.5 psi at 55.5 ft. Each of the partial break scenarios (0.01% of total leak area) result in a negligible overpressure at the lot line distance of 55.5 ft. See Table 6 for FEMA damage approximations due to overpressure for reference. Similar to plume dispersion, the most likely cases ("b" series) result in negligible overpressure at the site boundary for all cases.

Note that the detailed output of the overpressure consequence modeling for the NM Gas site is contained in Appendix A.

Table 5: Overpressure Results

Case #	Pressure	Pipe Size	Assumptions	Overpressure at 55.5 ft (psi)
4a	~ 170 psig	3”	100% H2, full-bore leak (3")	~ 0.6
4b			100% H2, partial leak (0.03")	~ 0
5a	~ 180 psig	2”	100% H2, full-bore leak (2")	~ 0.4
5b			100% H2, partial leak (0.02")	~ 0
8a	~ 7542 psig	¾”	100% H2, full-bore leak (0.75") @ 0s	~ 1.5
8b	~ 2161 psig		100% H2, full-bore leak (0.75") @ 1s	~ 0.6
8c	~ 783 psig		100% H2, full-bore leak (0.75") @ 2s	~ 0.2
8d	~ 7542 psig		100% H2, partial leak (0.0075")	~ 0

3.3. Target Impact

Another important aspect of consequence evaluation is the impact that the consequence will have on select targets. This is especially important when considering overpressure. To provide information on this topic, the FEMA damage approximations to structures as a function of overpressure were identified. These damage approximations allow authorities having jurisdiction to make qualitative comparisons to targets surrounding the hydrogen system to determine what time of damage is expected. Table 6 shows the FEMA Damage Approximations [3]. As shown in the table, typical window glass breakage can occur at relatively low incident overpressures, while serious damage to steel or concrete structures requires significantly more incident overpressures.

Table 6: FEMA Damage Approximations

Damage	Incident Overpressure (psi)
Typical window glass breakage	0.15-0.22
Minor Damage to some buildings	0.5-1.1
Panels of sheet metal buckled	1.1-1.8
Failure of concrete block walls	1.8-2.9
Collapse of wood framed buildings	Over 5.0
Serious damage to steel framed buildings	4-7
Severe damage to reinforced concrete structures	6-9
Probable total destruction of most buildings	10-12

3.4. Site-specific Considerations

There are two site-specific considerations in terms of ignition sources that were evaluated herein. The first is the potential for the parking shade structure with photovoltaic cells to cause an adverse reaction to a potential hydrogen leak. The other consideration is the potential for refueling trucks to provide an ignition source to leaked hydrogen.

3.4.1. Hydrogen Leak in Close Proximity to a Photovoltaic System

There is a potential safety concern in locating a hydrogen generation facility in close proximity to a photovoltaic (PV) system. If a leak were to occur in the hydrogen generation facility, leaked hydrogen may come in contact with the PV cells and lead to an ignition event. This is because the photovoltaic cells are potentially at a high enough temperature to cause autoignition. This has been examined herein through discussion with Sandia National Laboratory (SNL) Subject Matter Experts (SMEs). In addition to safety implications, hydrogen rolling over the PV system may cause performance issues including potential-induced degradation (PID) and corrosion. These non-ignition effects have also been examined.

Previous studies have shown that PV surface temperatures are generally under 100 °C. Maximum surface temperatures of PV cells can reach around 65 °C [4], while a study conducted by SNL at a specific site in Arizona documented a maximum surface temperature of 58 °C [5]. Note that the SNL study was conducted on 600 V PV systems, and some new systems may operate up to 1500 V, which would increase the surface temperature of the solar panels. Additionally, although the surface temperature of the panels is fairly low, the SNL SME noted inverters/transformers in the PV system may get up to temperatures around 150 °C. Additionally, arc faults could occur in inverters/transformers, which would create an ignition source to exposed hydrogen.

Although there is a range of hydrogen auto-ignition temperature given in literature, the lower end of the range is 500 °C [6]. Therefore, the magnitude of the temperatures presented by the PV system would not lead to an additional ignition hazard due to a hydrogen leak from the hydrogen generation system. Additionally, the low likelihood of a leak occurring simultaneously with an arc in the PV system would exclude the scenario from being evaluated in a standard risk analysis.

As far as non-ignition effects of a hydrogen leak interacting with the PV system, there doesn't seem to be an apparent safety hazard. PID and corrosion are potential effects of gases that may interact with PV cells. For instance, oxygen with appreciable amounts of salt may cause PID, which would turn the glass yellow and could decrease the performance of the cells. However, hydrogen rolling over the solar panels would not cause this type of issue. The most likely effect that hydrogen may cause on the PV system is excess condensation on the surface, possibly leading to corrosion. However, since solar panels are rated to be outdoors and exposed to the elements, this is not likely a concern. Non-ignition effects of a hydrogen leak in close proximity to a PV system is likely not a safety hazard.

3.4.2. Vehicle Ignition Source

NFPA 2 (Hydrogen Technologies Code) Section 10.2.3 states that vehicles shall not be considered a source of ignition with respect to the requirements of this chapter (design, construction, and installation of GH2 systems to be utilized for vehicle fueling) [1]. Similarly, NFPA 52 (Vehicular Natural Gas Fuel Systems Code) Section 11.3.1.4.1 states that vehicles shall not be considered a source of ignition with respect to the provisions of the chapter (general CNG fueling system requirements) [7]. Therefore, vehicles do not need to be evaluated as a potential ignition source. However, it should be noted that there are set-back distances for parked cars that are discussed in Section 2.

3.5. Risk discussion

The results of the consequence analysis performed herein are supplementary to an overall risk assessment. It should be noted that the codes that the system and layout adhere to (see Section 2) should be the primary source of safety assurance. This analysis was performed to explore worst-case scenarios and site-specific considerations. The results can inform potential additional safety mitigations to reduce overall risk. The CMC walls are an example of a potential countermeasure that can reduce the horizontal impact of worst-case plume dispersion events. However, it is important to consider likelihood when evaluating the overall risk of the compound. The most-likely leak scenarios were also evaluated that show the impact of these events with regard to dispersion or overpressure is negligible. In absence of a quantitative risk analysis, this analysis can provide valuable insight to regulators and authorities having jurisdiction of the potential safety hazards of the compound.

4. CONCLUSION

Sandia National Laboratories and BayoTech have evaluated several topics of interest in the small business agreement. Sandia has provided subject matter expertise in consequence evaluation and fire protection engineering for the NM Gas site analysis. In consequence evaluation, Sandia has engaged BayoTech in identifying scenarios, modeling consequences, and evaluating the impact on given targets. Although the worst-case plume dispersion cases resulted in relatively large plumes, these cases were noted to be far less likely than the partial break cases that were evaluated. The partial break cases resulted in nearly negligible plume lengths. Similarly, the overpressure analysis of the full-bore break scenarios resulted in much larger overpressures than the partial break cases (which resulted in negligible overpressure at the lot line).

There were several cases evaluated in the analysis that represented leak scenarios from both hydrogen and natural gas sources. Generally, the natural gas leak scenarios resulted in a smaller horizontal impact than that of hydrogen leaks. The worst-case consequence from a hydrogen leak resulted from the compressors, storage pods, or dispensing system. To consider the safety features that may isolate the leak, the consequence was evaluated at different times after the leak event to show the reduction of pressure. After 2 seconds, the plume dispersion from this event is contained within the perimeter of the site.

The worst-case consequences show that the plume may disperse to adjacent facilities and to the street. When considering both likelihood and consequence, the risk may be considered low because the maximum frequency of a full-bore leak from any component within the hydrogen compound is 8.2 E-5/yr. The risk can be further reduced by implementing mitigative countermeasures, such as CMU walls along the sides of the equipment compound. This would reduce the overall consequence of the worst-case dispersion scenarios (horizontal impact of plume).

In terms of siting and safety analysis, the NFPA 2 code was used to provide a high-level evaluation of the current site plan. The most limiting equipment in terms of set-back distance are the compressors/storage units because of the high-pressure hydrogen. The site layout was evaluated for an acceptable location for the compression/storage unit based on NFPA 2 set-back distances. It is important to note that the NFPA 2 set-back distances consider both likelihood and consequence. This is important because the worst-case results evaluated herein also represent the least likely leak scenario. Other site-specific considerations were evaluated, including the parking shade structure with photovoltaic cells and refueling vehicles. These issues were dispositioned and determined to not present a safety risk.

It should be noted that a quantitative risk analysis was not conducted herein. The results of the consequence analysis are supplementary to an overall risk assessment. The codes that the system and layout adhere to (see Section 2) should be the primary source of safety assurance. This analysis was performed to explore worst-case scenarios and site-specific considerations. The results can inform potential additional safety mitigations to reduce overall risk. A quantitative risk analysis may be beneficial to perform in the future to provide additional insight into the overall risk of the facility. Additionally, only two discrete relative leak sizes were evaluated. Other relative leak sizes, such as a 0.1% or 1% of total area leak, could be modeled. Note that the NFPA 2 set-back distances were calculated based on a 1% total area leak.

REFERENCES

[1] NFPA 2, "Hydrogen Technologies Code," 2020.

[2] A. Glover, A. Baird and D. Brooks, "SAND2020-10828 - Final Report on Hydrogen Plant Hazards and Risk Analysis Supporting Hydrogen Plant Siting near Nuclear Power Plants," October 2020.

[3] FEMA, "Explosive Blast 4," [Online]. Available: https://www.fema.gov/pdf/plan/prevent/rms/428/fema428_ch4.pdf. [Accessed 4 October 2021].

[4] EnergySage, "How hot do solar panels get? Effect of temperature on solar performance," 15 July 2020. [Online]. Available: https://news.energysage.com/solar-panel-temperature-overheating/.

[5] K. M. Armijo, "Performance Impact of Solar Gain on Photovoltaic Inverters and Utility-Scale Nergy Generation Systems".

[6] The Engineering ToolBox, "Fuels and Chemicals - Autoignition Temperatures," [Online]. Available: https://www.engineeringtoolbox.com/fuels-ignition-temperatures-d_171.html. [Accessed 16 February 2022].

[7] NFPA 52, "Vehicular Natural Gas Fuel Systems Code," 2019.

[8] S. Dorofeev and C. Bauwens, "Quantifying the potential Consequences of a Detonation in a Hydrogen Jet Release".

APPENDIX A. DETAILED MODELING RESULTS

This appendix contains the work done specifically for the NM Gas site safety evaluation.

A.1. Consequence Modeling

Two parameters of interest were quantified through consequence modeling: the extent of hydrogen dispersion and overpressure from detonation of the hydrogen plume.

A.1.1. Dispersion

As discussed previously, the dispersion was modeled in HyRAM+ version 4.0. Also, for Case 8, the blowdown from a tank containing hydrogen was calculated to achieve more realistic results. This is because HyRAM assumes steady state conditions when calculating the hydrogen plume length of a given leak (e.g., infinite hydrogen supply, constant pressure, etc.). This assumption generally leads to conservative results in terms of plume length, especially when considering safety features that may isolate the leak. These safety features may isolate the compressor if a leak occurs, leaving the leak supply of hydrogen from a potentially filled storage tank. To reduce the conservatism of the plume length calculations, the blowdown phase of the tank was modeled in HyRAM to determine the pressure in the tank as a function of time. The dispersion was then modeled using the pressure at discrete times after the release to show how quickly the plume length dissipates.

A.1.1.1. Case 1

The HyRAM inputs for dispersion analysis of Case 1a (full bore leak) are shown in Figure A-1.

Variable	Value	Unit
X lower limit	0	Meter
X upper limit	20	Meter
Y lower limit	-5	Meter
Y upper limit	5	Meter
Contours (mole fraction)	0.044	...
Ambient pressure	12.08	Psi
Ambient temperature	60	Fahrenheit
Orifice diameter	3	Inch
Orifice discharge coefficient	1	...
Angle of jet	0	Radians
Fluid pressure (absolute)	72.08	Psi
Fluid temperature	90	Fahrenheit

Figure A-1: Case 1a HyRAM Plume Dispersion Inputs

The resulting plume calculated from the inputs are shown in Figure A-2. As shown, the maximum horizontal distance of the postulated methane plume is around 24 meters (79 ft).

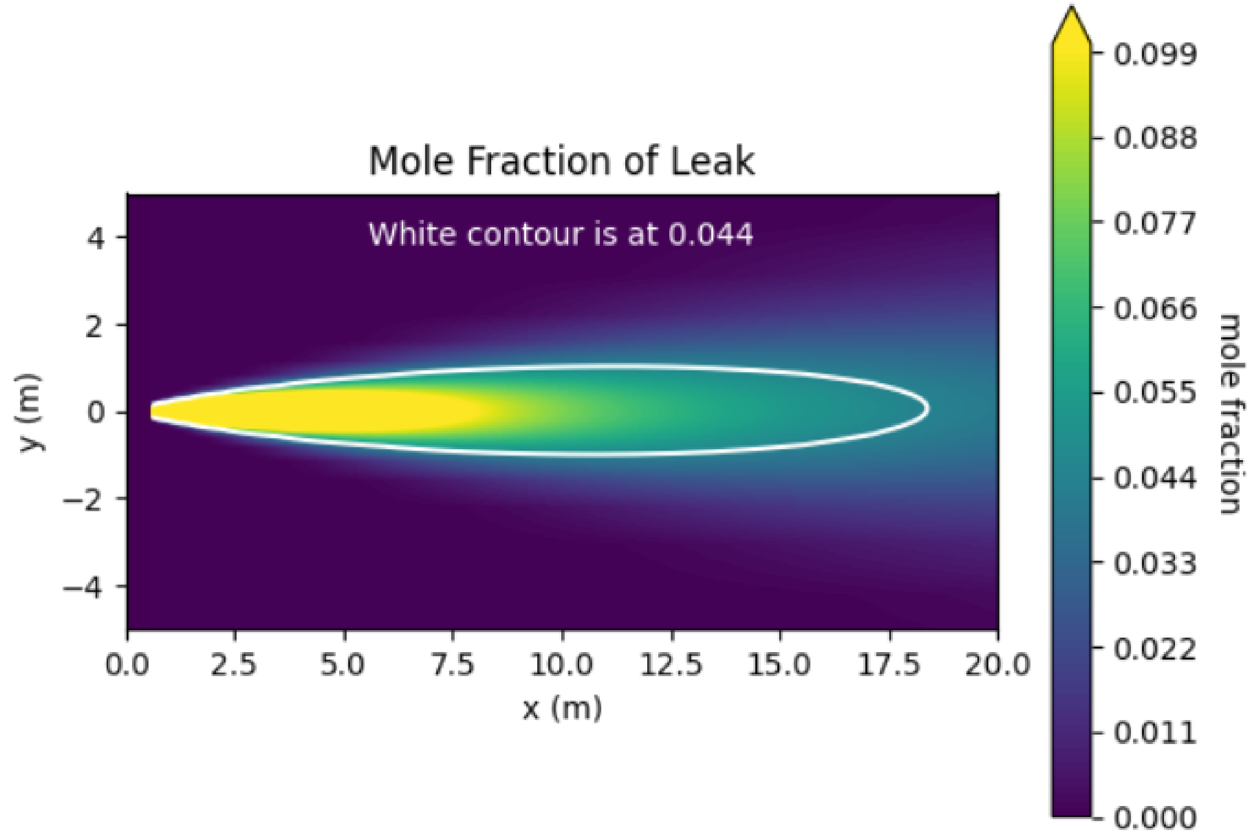


Figure A-2: Case 1a HyRAM Plume Dispersion Results

The HyRAM inputs for dispersion analysis of Case 1b (partial bore leak, 0.01% area) are shown in Figure A-3.

Variable	Value	Unit
X lower limit	0	Meter
X upper limit	0.5	Meter
Y lower limit	-0.5	Meter
Y upper limit	0.5	Meter
Contours (mole fraction)	0.044	...
Ambient pressure	12.08	Psi
Ambient temperature	60	Fahrenheit
Orifice diameter	0.03	Inch
Orifice discharge coefficient	1	...
Angle of jet	0	Radians
Fluid pressure (absolute)	72.08	Psi
Fluid temperature	90	Fahrenheit

Figure A-3: Case 1b HyRAM Plume Dispersion Inputs

The resulting plume calculated from the inputs are shown in Figure A-4. As shown, the maximum horizontal distance of the postulated methane plume is around 0.2 meters (1 ft).

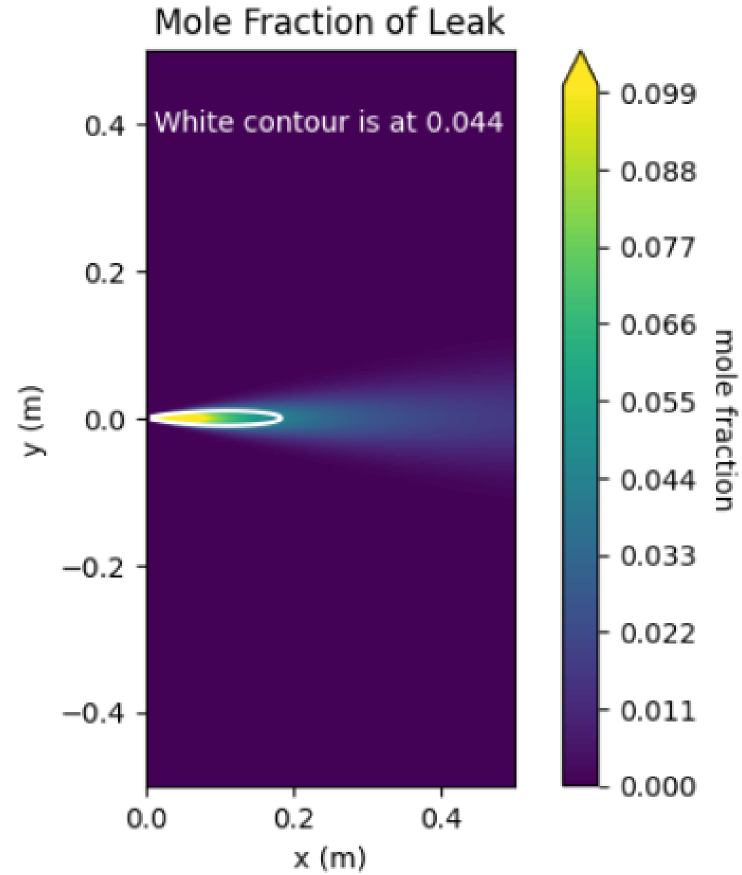


Figure A-4: Case 1b HyRAM Plume Dispersion Results

A.1.1.2. Case 2

The HyRAM inputs for dispersion analysis of Case 2a (full bore leak) are shown in Figure A-5.

Variable	Value	Unit
X lower limit	0	Meter
X upper limit	15	Meter
Y lower limit	-2	Meter
Y upper limit	2	Meter
Contours (mole fraction)	0.044	...
Ambient pressure	12.08	Psi
Ambient temperature	60	Fahrenheit
Orifice diameter	1.5	Inch
Orifice discharge coefficient	1	...
Angle of jet	0	Radians
Fluid pressure (absolute)	187.08	Psi
Fluid temperature	90	Fahrenheit

Figure A-5: Case 2a HyRAM Plume Dispersion Inputs

The resulting plume calculated from the inputs are shown in Figure A-6. As shown, the maximum horizontal distance of the postulated methane plume is around 14.5 meters (48 ft).

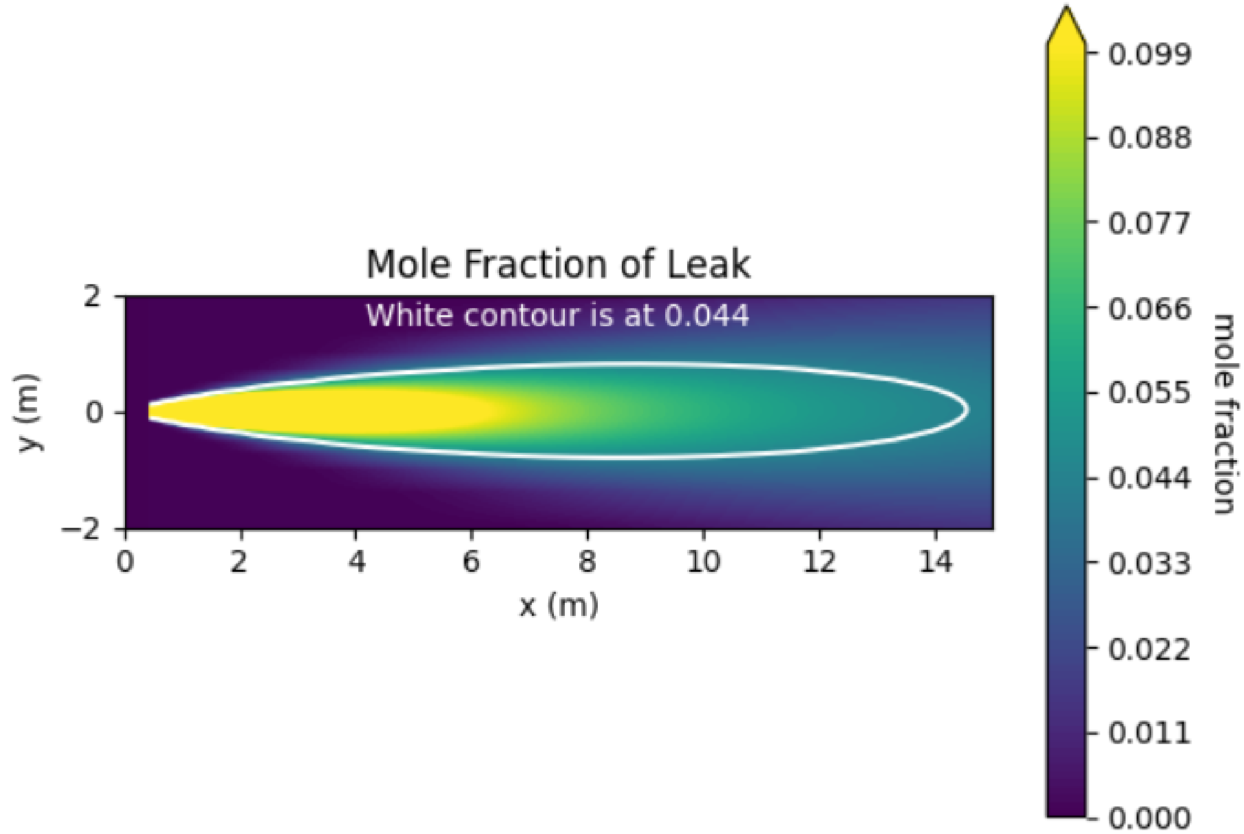


Figure A-6: Case 2a HyRAM Plume Dispersion Results

The HyRAM inputs for dispersion analysis of Case 2b (partial bore leak, 0.01% area) are shown in Figure A-7.

Variable	Value	Unit
X lower limit	0	Meter
X upper limit	0.5	Meter
Y lower limit	-0.5	Meter
Y upper limit	0.5	Meter
Contours (mole fraction)	0.044	...
Ambient pressure	12.08	Psi
Ambient temperature	60	Fahrenheit
Orifice diameter	0.015	Inch
Orifice discharge coefficient	1	...
Angle of jet	0	Radians
Fluid pressure (absolute)	187.08	Psi
Fluid temperature	90	Fahrenheit

Figure A-7: Case 2b HyRAM Plume Dispersion Inputs

The resulting plume calculated from the inputs are shown in Figure A-8. As shown, the maximum horizontal distance of the postulated methane plume is around 0.2 meters (1 ft).

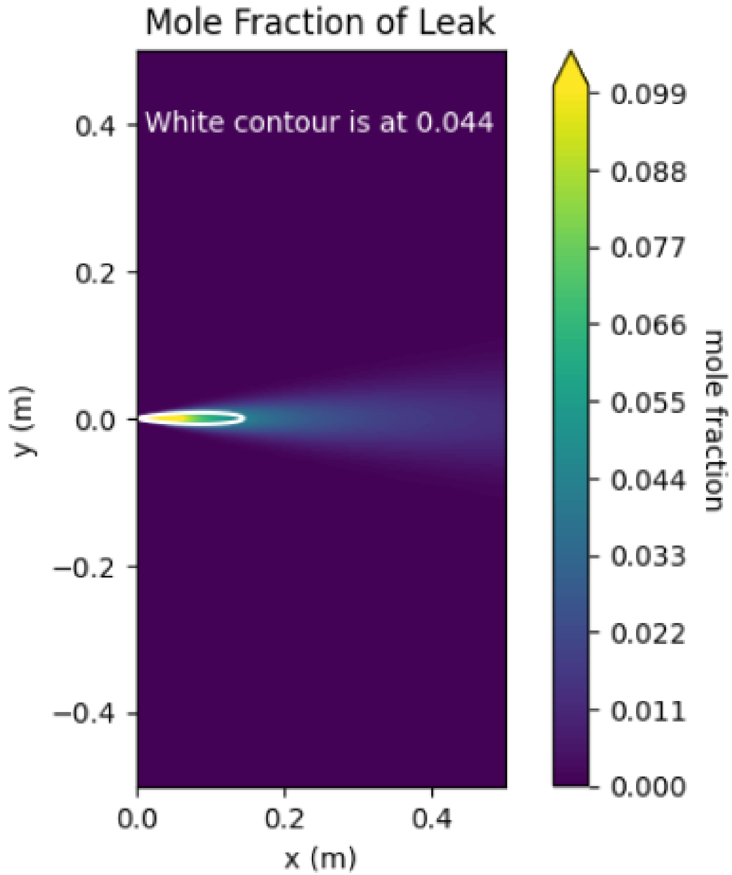


Figure A-8: Case 2b HyRAM Plume Dispersion Results

A.1.1.3. Case 4

HyRAM was used to model hydrogen dispersion for Case 4a. The HyRAM inputs are shown in Figure A-9.

Variable	Value	Unit
X lower limit	0	Meter
X upper limit	70	Meter
Y lower limit	-10	Meter
Y upper limit	10	Meter
Contours (mole fraction)	0.04	...
Ambient pressure	12.08	Psi
Ambient temperature	60	Fahrenheit
Orifice diameter	3	Inch
Orifice discharge coefficient	1	...
Angle of jet	0	Radians
Fluid pressure (absolute)	157.08	Psi
Fluid temperature	120	Fahrenheit

Figure A-9: Case 4a HyRAM Plume Dispersion Inputs

The resulting plume calculated from the inputs is shown in Figure A-10. As shown, the maximum horizontal distance of the postulated hydrogen plume is around 65 meters (213 ft).

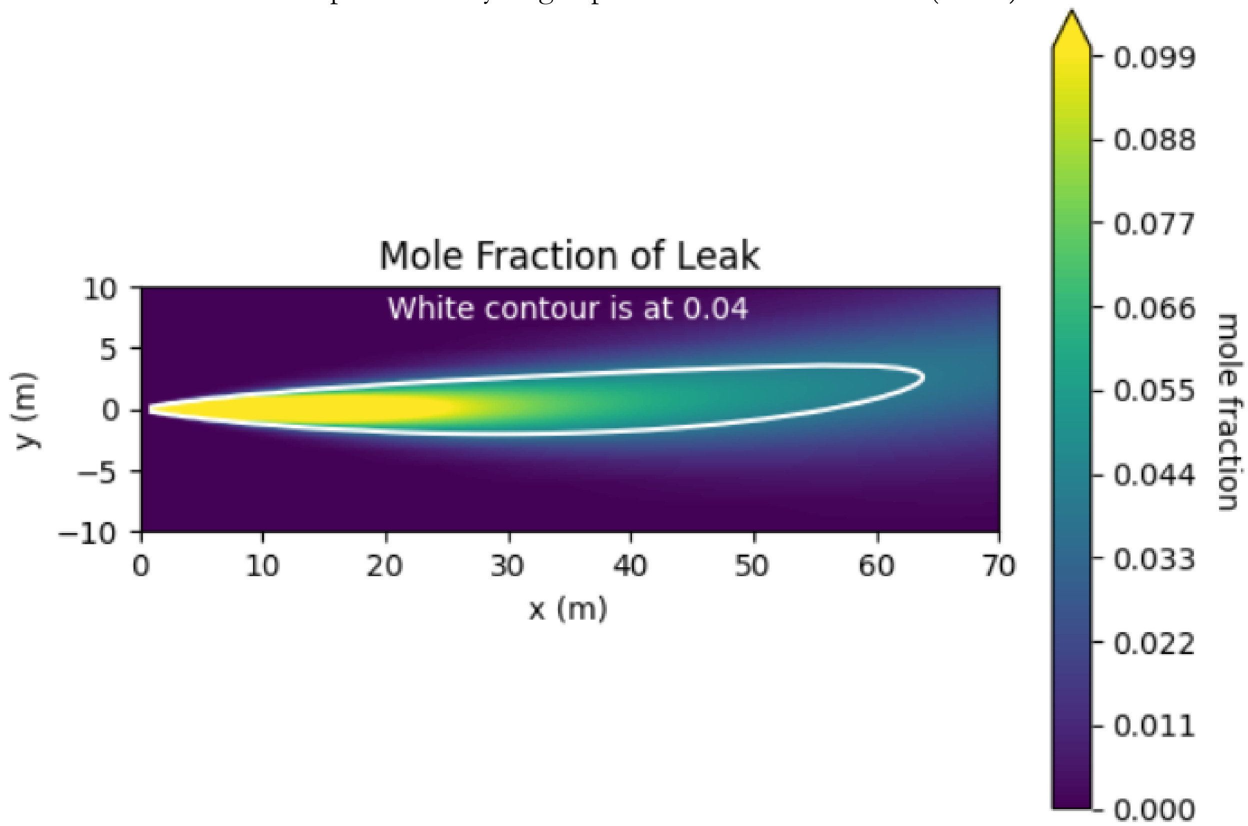


Figure A-10: Case 4a HyRAM Plume Dispersion Results

The HyRAM inputs for dispersion analysis of Case 4b (partial bore leak, 0.01% area) are shown in Figure A-11.

Variable	Value	Unit
X lower limit	0	Meter
X upper limit	1	Meter
Y lower limit	-0.5	Meter
Y upper limit	0.5	Meter
Contours (mole fraction)	0.04	...
Ambient pressure	12.08	Psi
Ambient temperature	60	Fahrenheit
Orifice diameter	0.03	Inch
Orifice discharge coefficient	1	...
Angle of jet	0	Radians
Fluid pressure (absolute)	157.08	Psi
Fluid temperature	120	Fahrenheit

Figure A-11: Case 4b HyRAM Plume Dispersion Inputs

The resulting plume calculated from the inputs are shown in Figure A-12. As shown, the maximum horizontal distance of the postulated hydrogen plume is around 0.7 meters (2 ft).

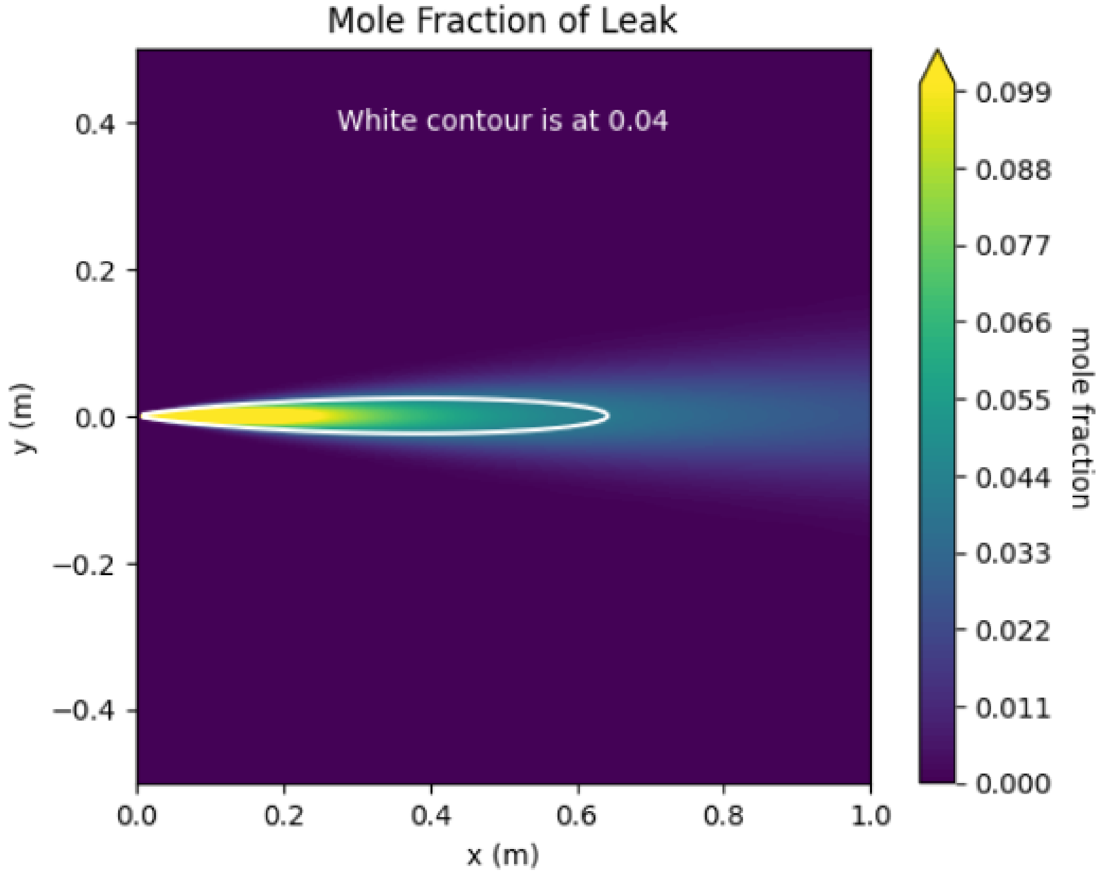


Figure A-12: Case 4b HyRAM Plume Dispersion Results

A.1.1.4. Case 5

HyRAM was used to model hydrogen dispersion for Case 5a (full bore leak). The HyRAM inputs are shown in Figure A-13.

Variable	Value	Unit
X lower limit	0	Meter
X upper limit	50	Meter
Y lower limit	-10	Meter
Y upper limit	10	Meter
Contours (mole fraction)	0.04	...
Ambient pressure	12.08	Psi
Ambient temperature	60	Fahrenheit
Orifice diameter	2	Inch
Orifice discharge coefficient	1	...
Angle of jet	0	Radians
Fluid pressure (absolute)	192.08	Psi
Fluid temperature	120	Fahrenheit

Figure A-13: Case 5a HyRAM Plume Dispersion Inputs

The resulting plume calculated from the inputs are shown in Figure A-14. As shown, the maximum horizontal distance of the postulated hydrogen plume is around 45 meters (148 ft).

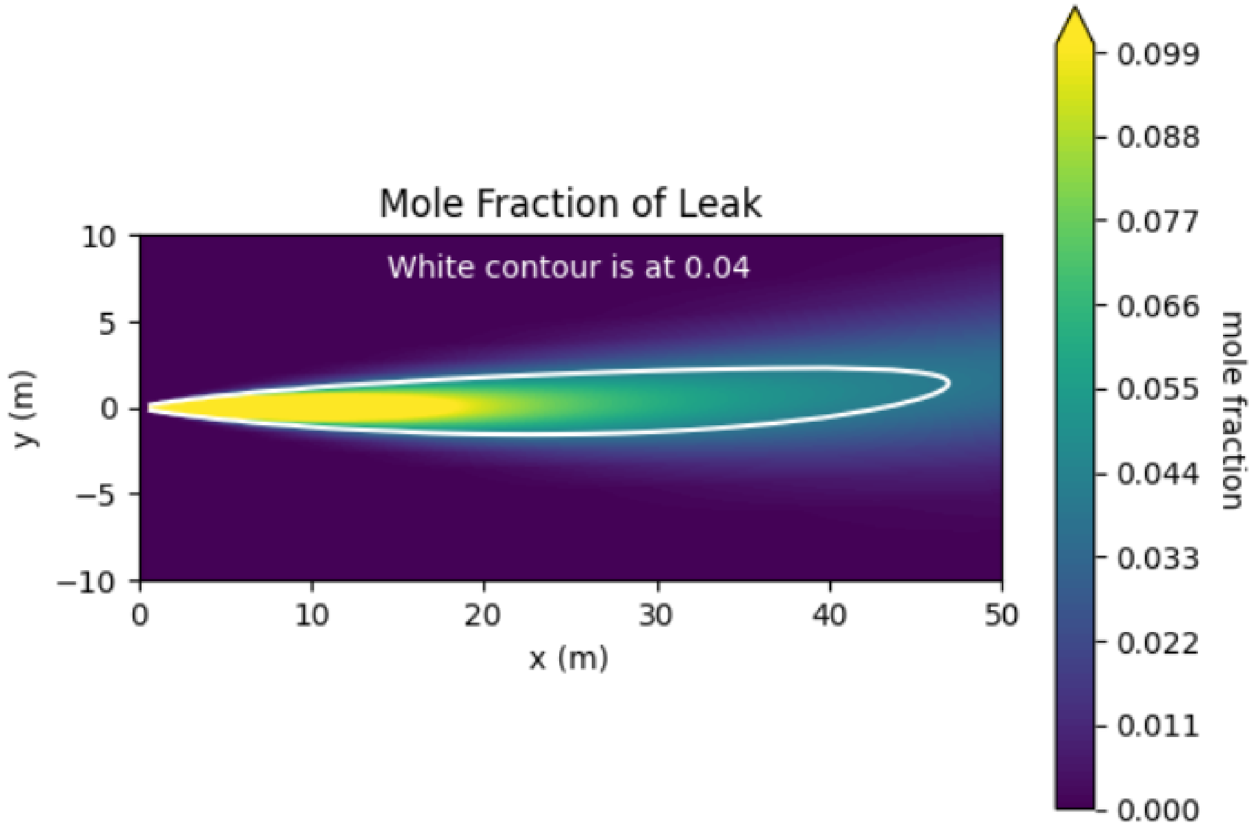


Figure A-14: Case 5a HyRAM Plume Dispersion Results

The HyRAM inputs for dispersion analysis of Case 5b (partial bore leak, 0.01% area) are shown in Figure A-15.

Variable	Value	Unit
X lower limit	0	Meter
X upper limit	0.5	Meter
Y lower limit	-0.5	Meter
Y upper limit	0.5	Meter
Contours (mole fraction)	0.04	...
Ambient pressure	12.08	Psi
Ambient temperature	60	Fahrenheit
Orifice diameter	0.02	Inch
Orifice discharge coefficient	1	...
Angle of jet	0	Radians
Fluid pressure (absolute)	192.08	Psi
Fluid temperature	120	Fahrenheit

Figure A-15: Case 5b HyRAM Plume Dispersion Inputs

The resulting plume calculated from the inputs are shown in Figure A-16. As shown, the maximum horizontal distance of the postulated hydrogen plume is around 0.5 meters (2 ft).

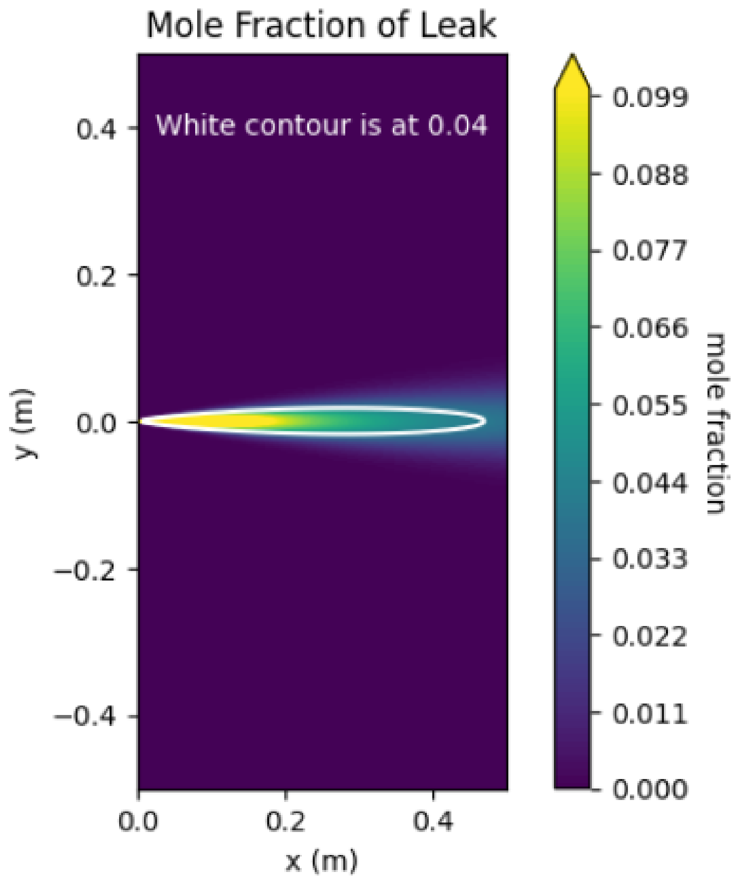


Figure A-16: Case 5b HyRAM Plume Dispersion Results

A.1.1.5. Case 8

Case 8 was identified as a potentially limiting leak scenario, therefore, the blowdown calculations described previously were evaluated for this case. Figure A-17 shows the inputs for HyRAM to calculate the pressure as a function of time during blowdown.

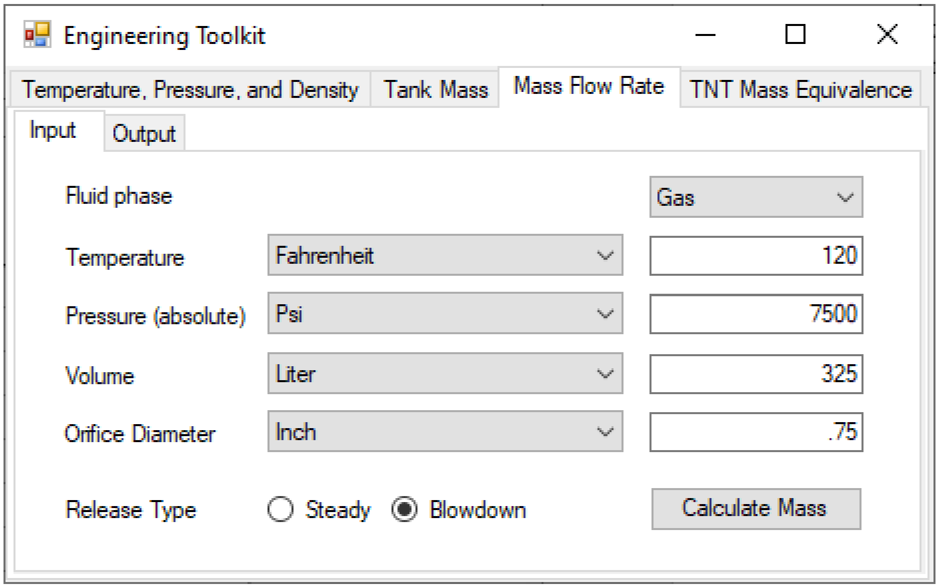


Figure A-17: Case 8 Blowdown Calculation Inputs

Figure A-18 shows the resulting time-dependent pressure calculation. As shown in the figure, the pressure drops fairly rapidly after the initial leak. The discrete pressure at 1 second is ~150 bar (2176 psia) and the discrete pressure at 2 seconds is ~55 bar (798 psia).

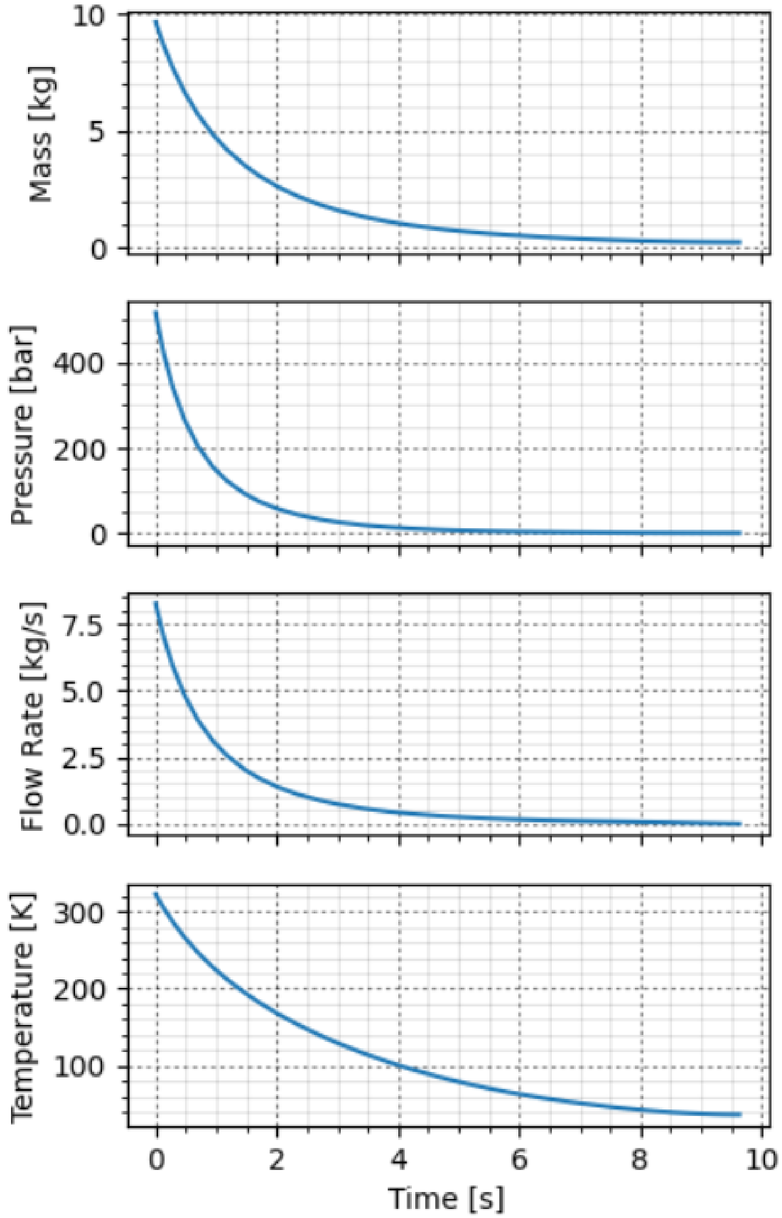


Figure A-18: Case 8 Blowdown Calculation Results

HyRAM was used to model hydrogen dispersion for Case 8a (full bore leak, t=0s). The HyRAM inputs are shown in Figure A-19.

Variable	Value	Unit
X lower limit	0	Meter
X upper limit	100	Meter
Y lower limit	-10	Meter
Y upper limit	10	Meter
Contours (mole fraction)	0.04	...
Ambient pressure	12.08	Psi
Ambient temperature	60	Fahrenheit
Orifice diameter	0.75	Inch
Orifice discharge coefficient	1	...
Angle of jet	0	Radians
Fluid pressure (absolute)	7512.08	Psi
Fluid temperature	120	Fahrenheit

Figure A-19: Case 8a HyRAM Plume Dispersion Inputs

The resulting plume calculated from the inputs are shown in Figure A-20. As shown, the maximum horizontal distance of the postulated hydrogen plume is around 92 meters (302 ft).

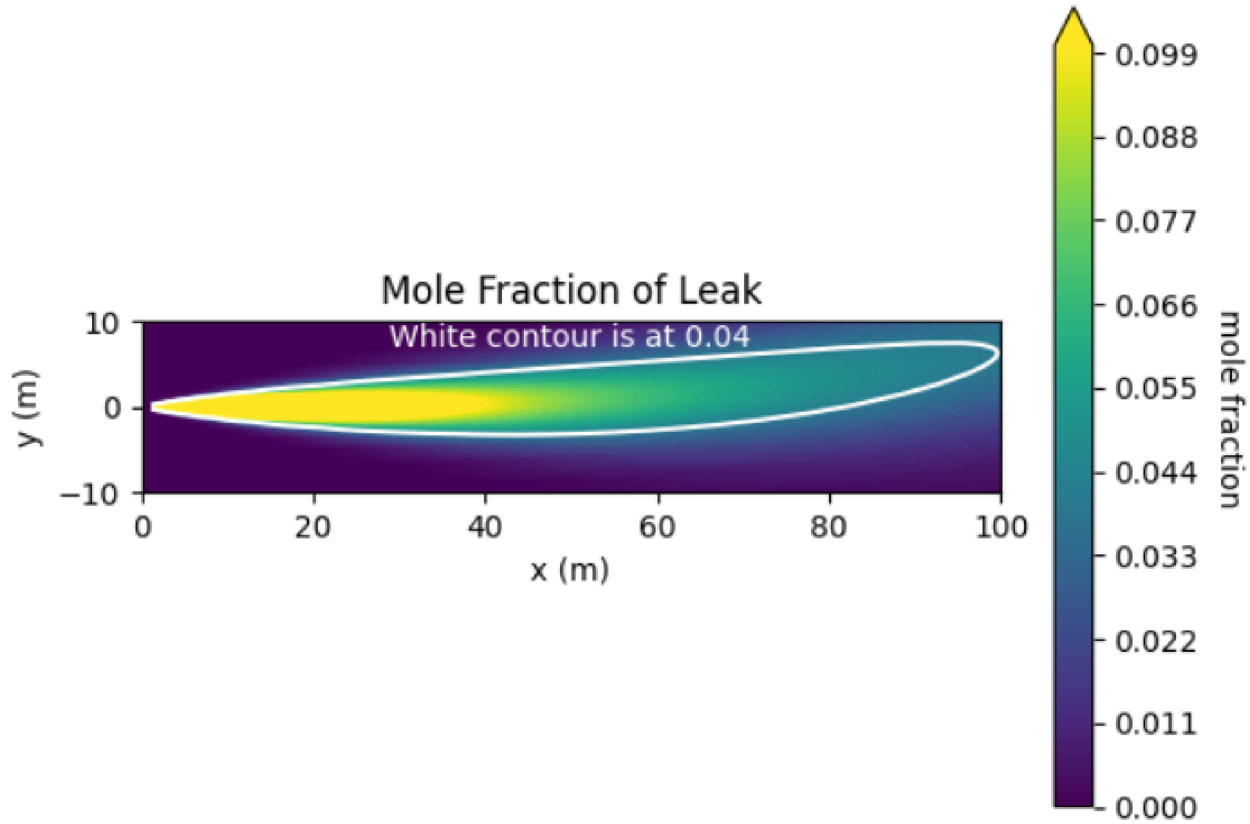


Figure A-20: Case 8a HyRAM Plume Dispersion Results

HyRAM was used to model hydrogen dispersion for Case 8b (full bore leak, t=1s). The HyRAM inputs are shown in Figure A-21.

Variable	Value	Unit
X lower limit	0	Meter
X upper limit	60	Meter
Y lower limit	-10	Meter
Y upper limit	10	Meter
Contours (mole fraction)	0.04	...
Ambient pressure	12.08	Psi
Ambient temperature	60	Fahrenheit
Orifice diameter	0.75	Inch
Orifice discharge coefficient	1	...
Angle of jet	0	Radians
Fluid pressure (absolute)	2176	Psi
Fluid temperature	120	Fahrenheit

Figure A-21: Case 8b HyRAM Plume Dispersion Inputs

The resulting plume calculated from the inputs are shown in Figure A-22. As shown, the maximum horizontal distance of the postulated hydrogen plume is around 52 meters (171 ft).

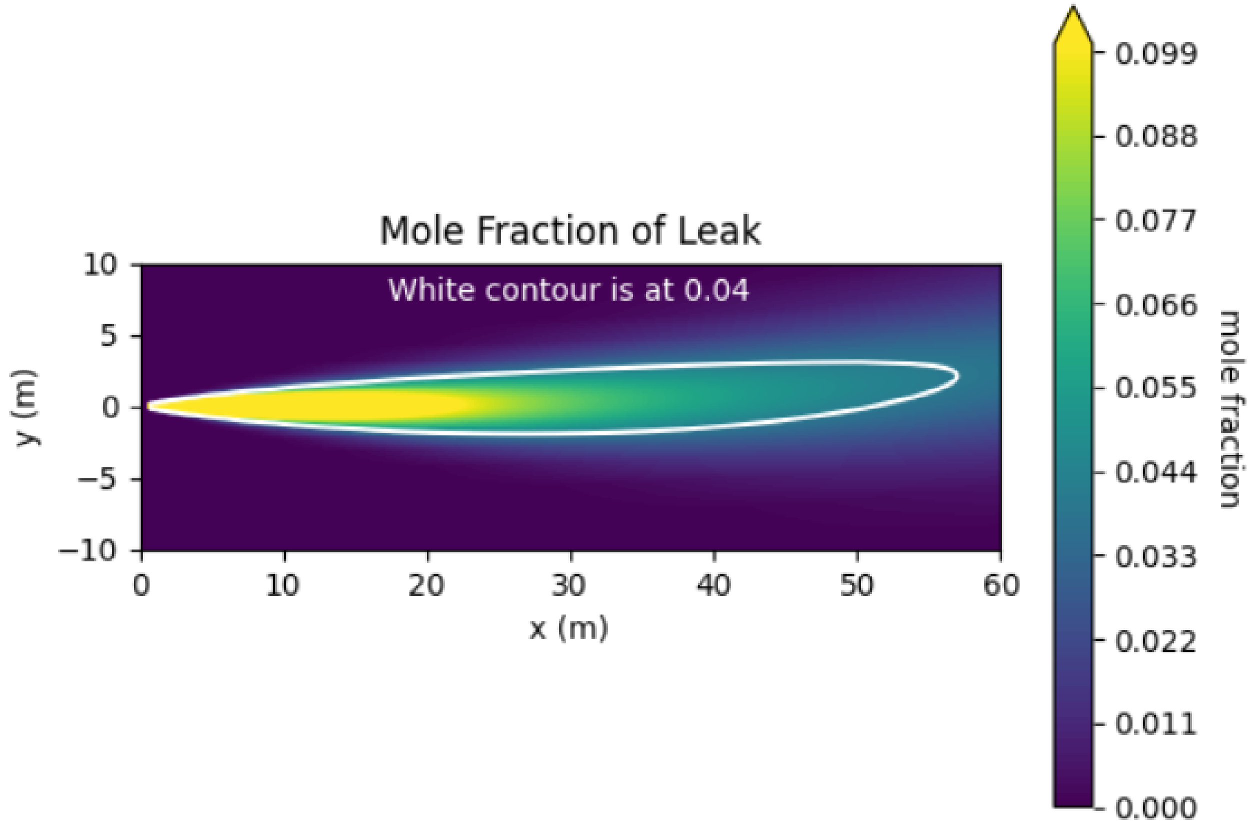


Figure A-22: Case 8b HyRAM Plume Dispersion Results

HyRAM was used to model hydrogen dispersion for Case 8c (full bore leak, t=2s). The HyRAM inputs are shown in Figure A-23.

Variable	Value	Unit
X lower limit	0	Meter
X upper limit	40	Meter
Y lower limit	-10	Meter
Y upper limit	10	Meter
Contours (mole fraction)	0.04	...
Ambient pressure	12.08	Psi
Ambient temperature	60	Fahrenheit
Orifice diameter	0.75	Inch
Orifice discharge coefficient	1	...
Angle of jet	0	Radians
Fluid pressure (absolute)	798	Psi
Fluid temperature	120	Fahrenheit

Figure A-23: Case 8c HyRAM Plume Dispersion Inputs

The resulting plume calculated from the inputs are shown in Figure A-24. As shown, the maximum horizontal distance of the postulated hydrogen plume is around 33 meters (108 ft).

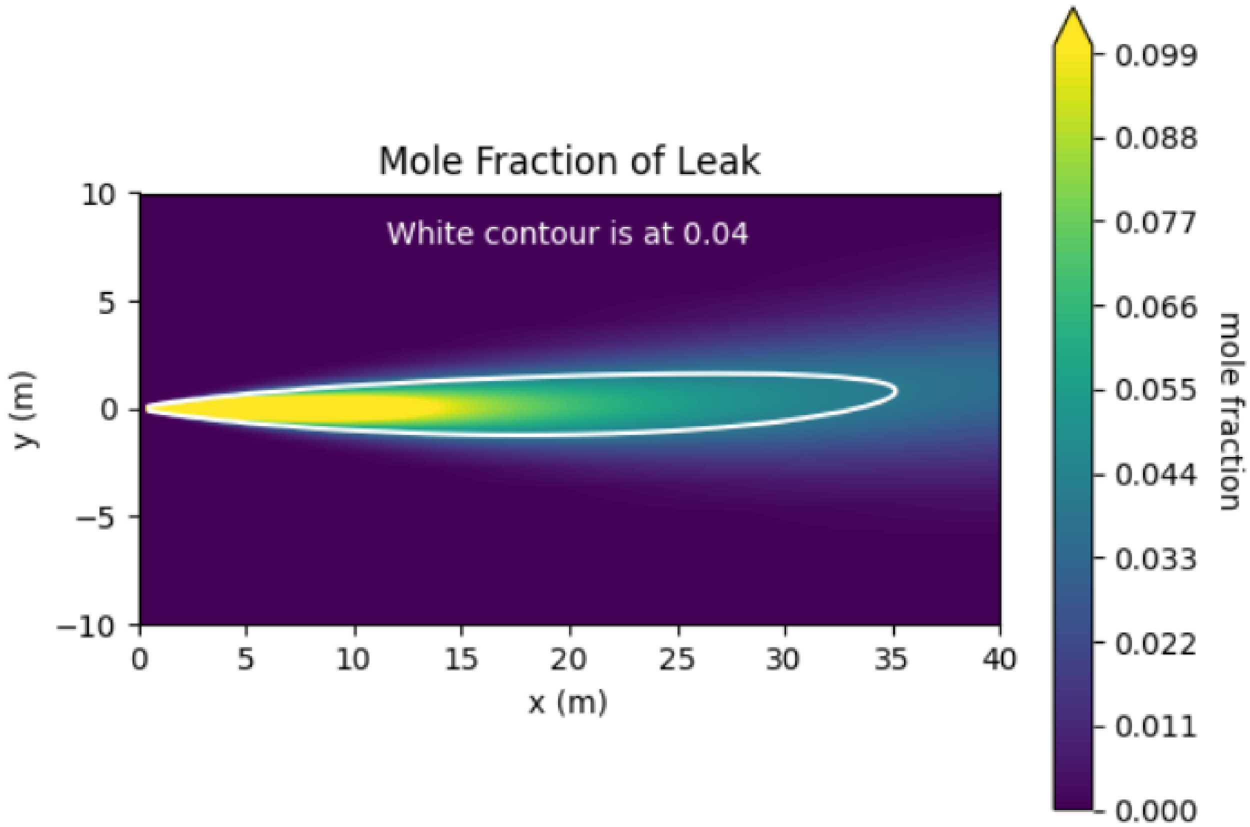


Figure A-24: Case 8c HyRAM Plume Dispersion Results

HyRAM was used to model hydrogen dispersion for Case 8d (partial bore leak, 0.01% area). The HyRAM inputs are shown in Figure A-25.

Variable	Value	Unit
X lower limit	0	Meter
X upper limit	1.5	Meter
Y lower limit	-0.5	Meter
Y upper limit	0.5	Meter
Contours (mole fraction)	0.04	...
Ambient pressure	12.08	Psi
Ambient temperature	60	Fahrenheit
Orifice diameter	0.0075	Inch
Orifice discharge coefficient	1	...
Angle of jet	0	Radians
Fluid pressure (absolute)	7512.08	Psi
Fluid temperature	120	Fahrenheit

Figure A-25: Case 8d HyRAM Plume Dispersion Inputs

The resulting plume calculated from the inputs are shown in Figure A-26. As shown, the maximum horizontal distance of the postulated hydrogen plume is around 1 meters (3 ft).

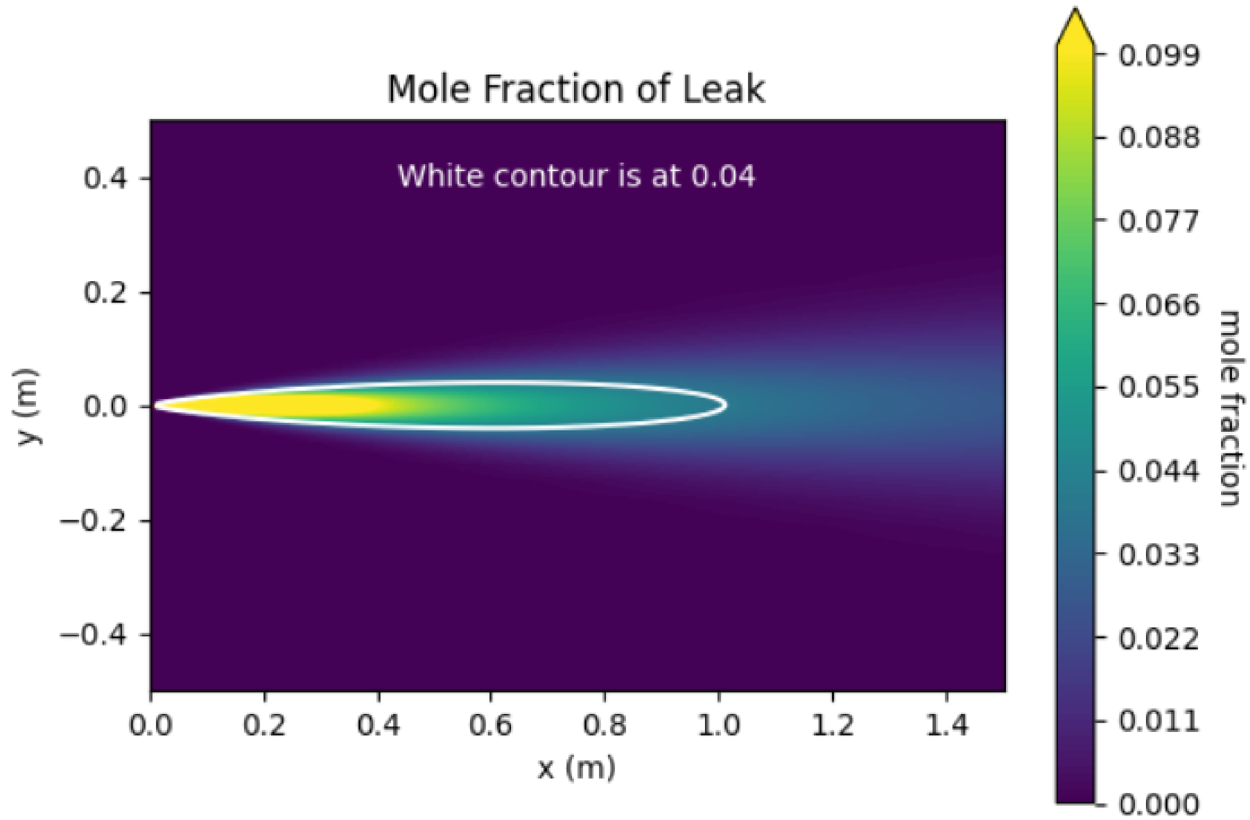


Figure A-26: Case 8d HyRAM Plume Dispersion Results

A.1.2. Overpressure

A leak in the system could release an unconfined high-pressure hydrogen jet with the potential to damage surrounding structures. The flammable jet released from the leak could result in a detonation, which would expose nearby targets to potentially damaging overpressure. However, due to the strong concentration gradients in the hydrogen jet, the detonable region of the plume is reduced when compared to the total amount of fuel within the flammability range. Detonations are inherently unstable and depend on critical dimensions and the concentration gradient of the hydrogen jet, which determines if a propagating detonation can be supported. The limits of the hydrogen concentration in the jet to support detonation reduce the portion of the flammable plume that is available as fuel. The overpressure released through detonation of the large cloud can be calculated from the detonable region [8].

The overpressure was evaluated using this method for hydrogen leak scenarios only (Cases 4, 5, and 8). Additionally, each of the discrete times/pressures from the blowdown calculation for Case 8 were evaluated to show how quickly the overpressure would be reduced. Note that Sandia internal hydrogen risk models for overpressure of hydrogen were used for these calculations.

A.1.2.1. Case 4

Figure A-27 shows the detonable region calculations for Case 4a (full bore leak).

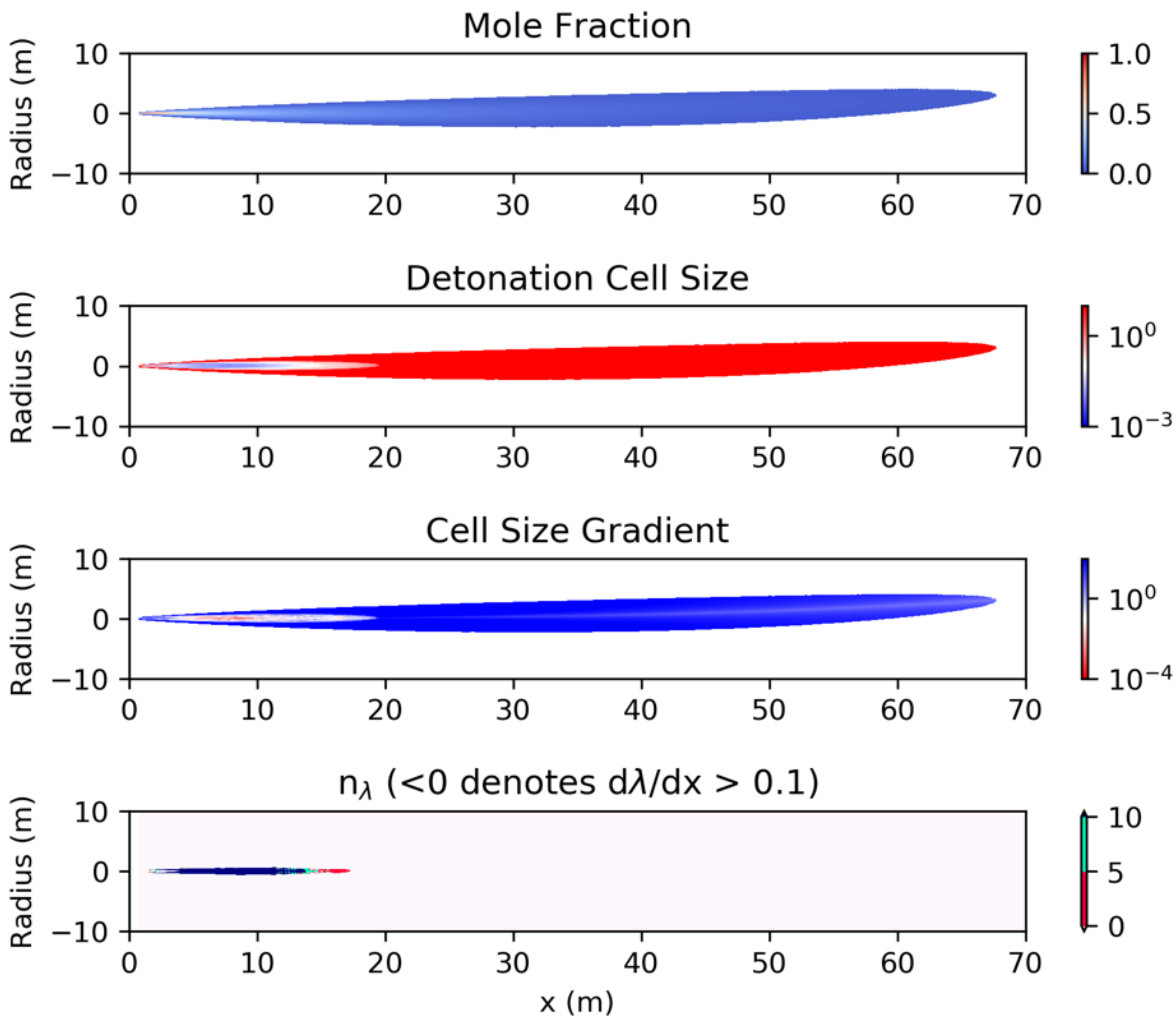


Figure A-27: Case 4a Detonable Region Calculations

Figure A-28 shows the resulting overpressure from the detonable region calculated previously. A dashed line is placed horizontally at 1 psi. The overpressure is shown to drop below 1 psi at around 45 ft from the leak location. The discrete overpressure at 73 ft from the center of the detonable region is 0.52 psi.

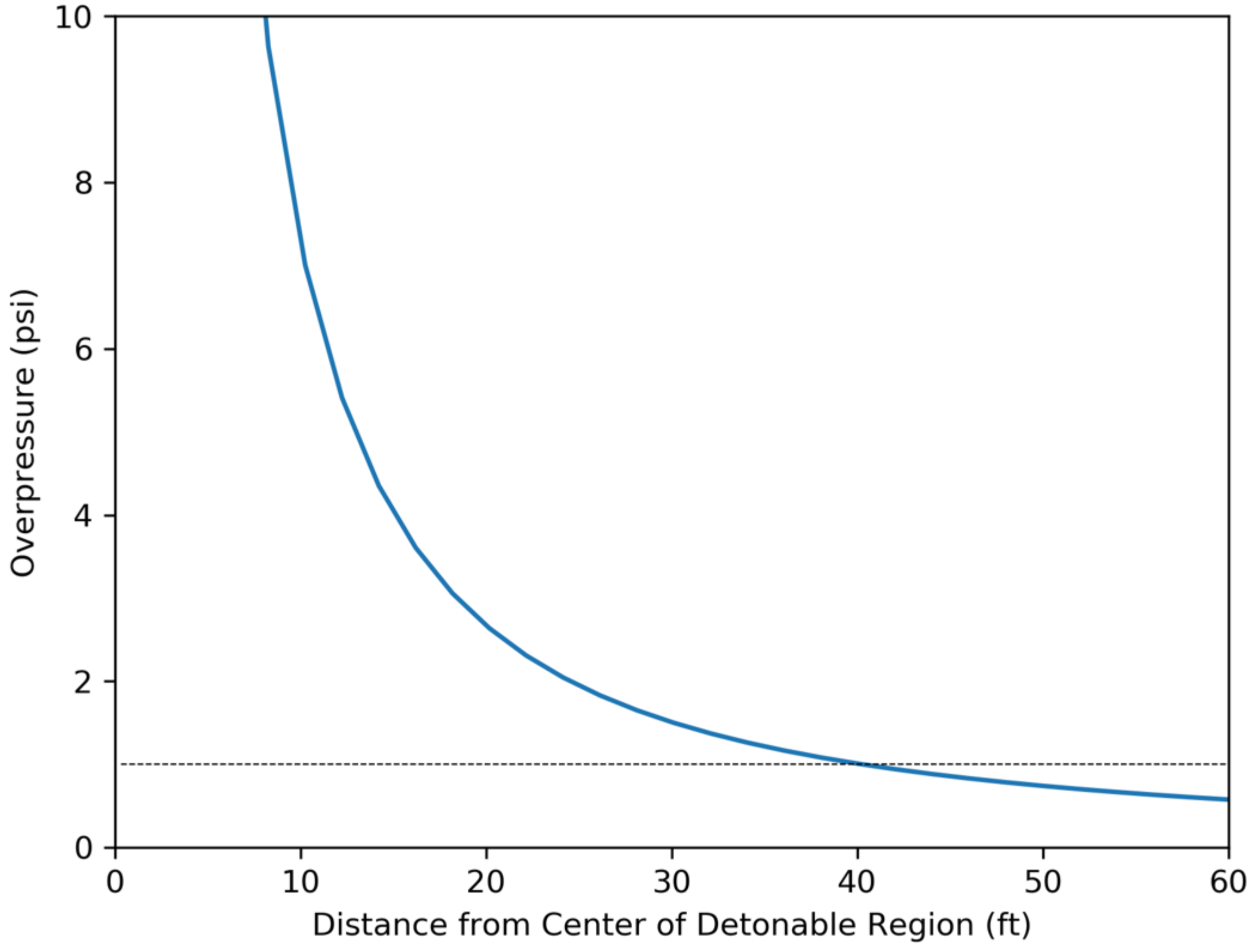


Figure A-28: Case 4a Overpressure Calculation

Figure A-29 shows the detonable region calculations for Case 4b (partial bore leak).

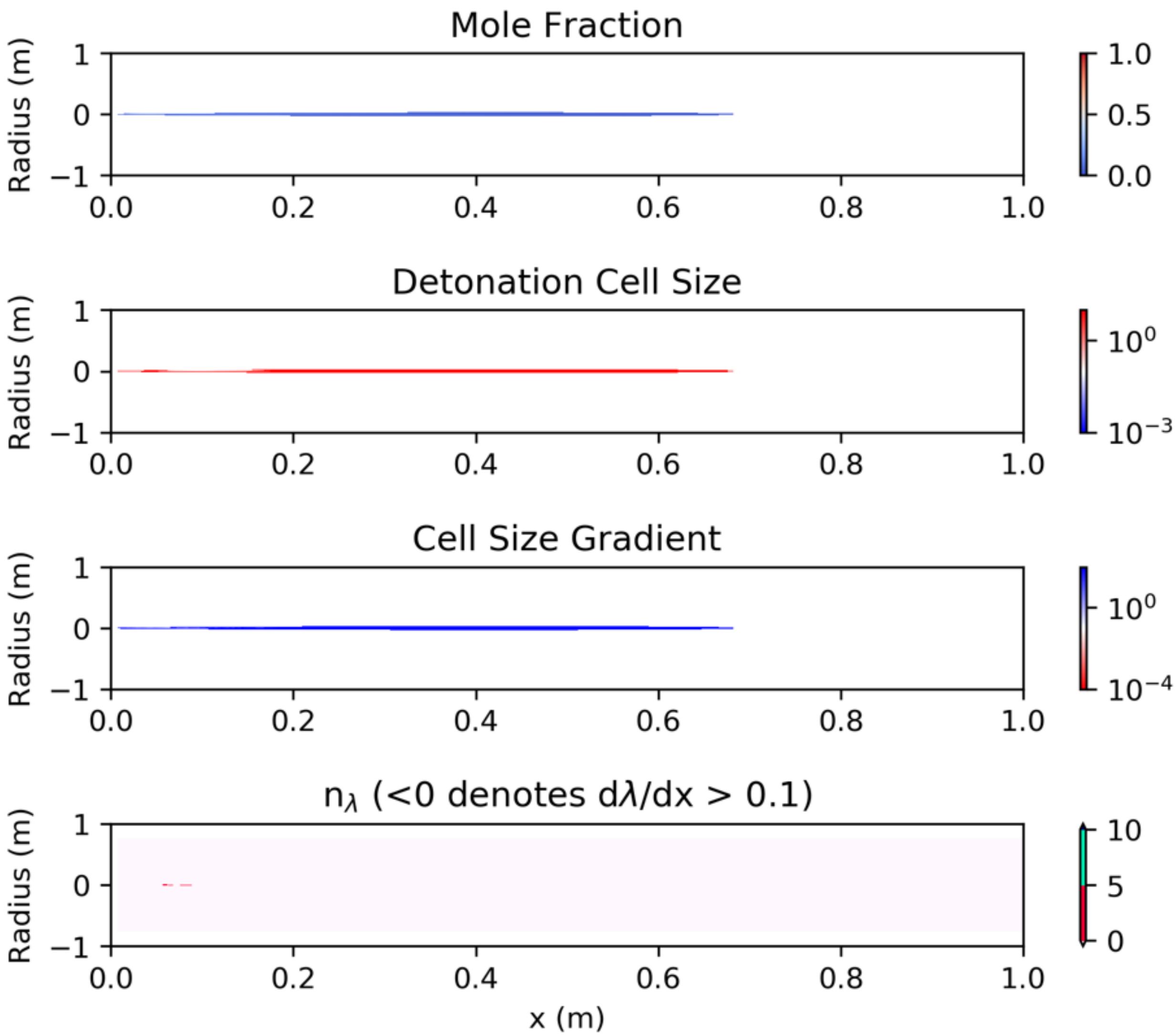


Figure A-29: Case 4b Detonable Region Calculations

Figure A-30 shows the resulting overpressure from the detonable region calculated previously. This case results in a negligible overpressure calculation.

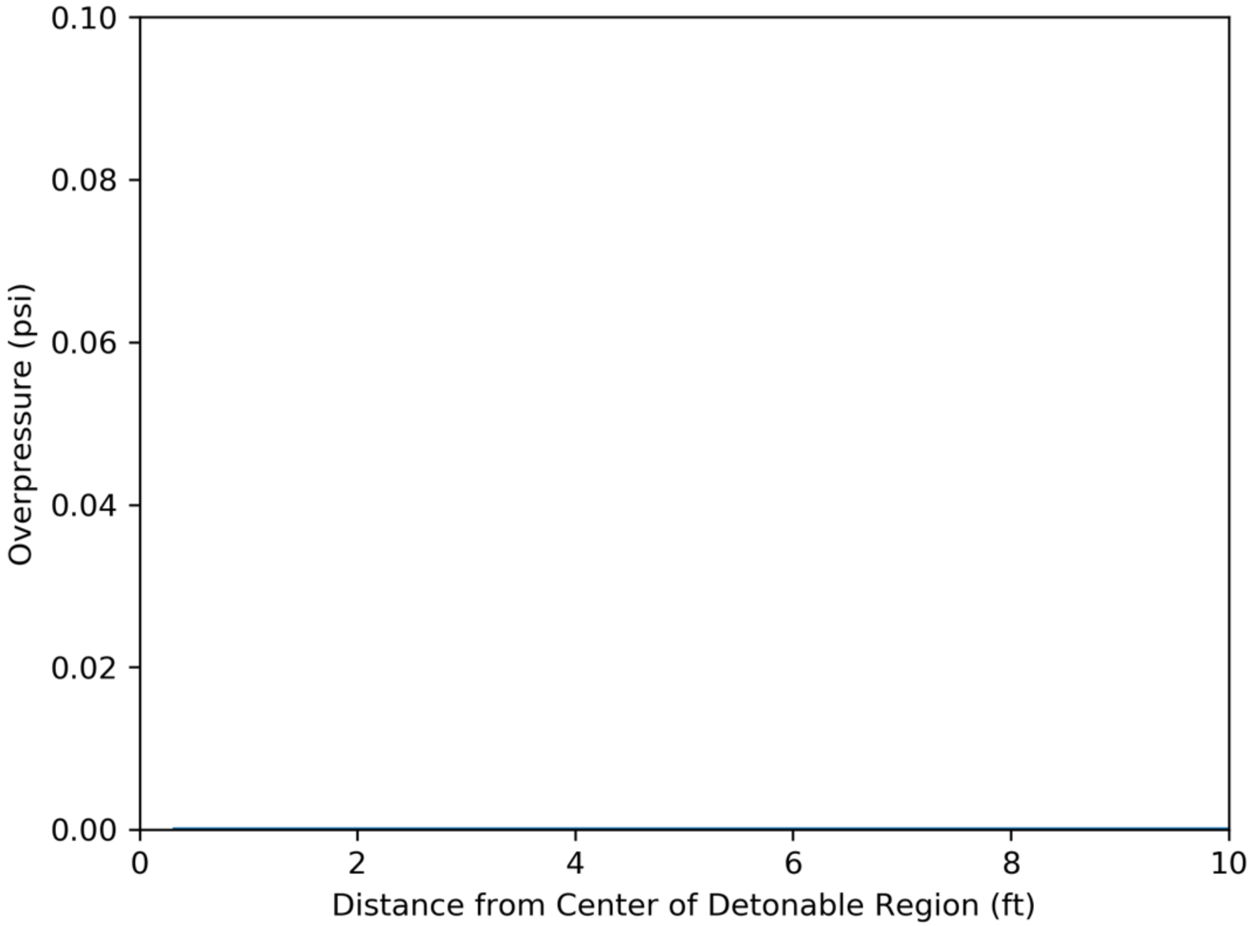


Figure A-30: Case 4b Overpressure Calculation

A.1.2.2. Case 5

Figure A-31 shows the detonable region calculations for Case 5a (full bore leak).

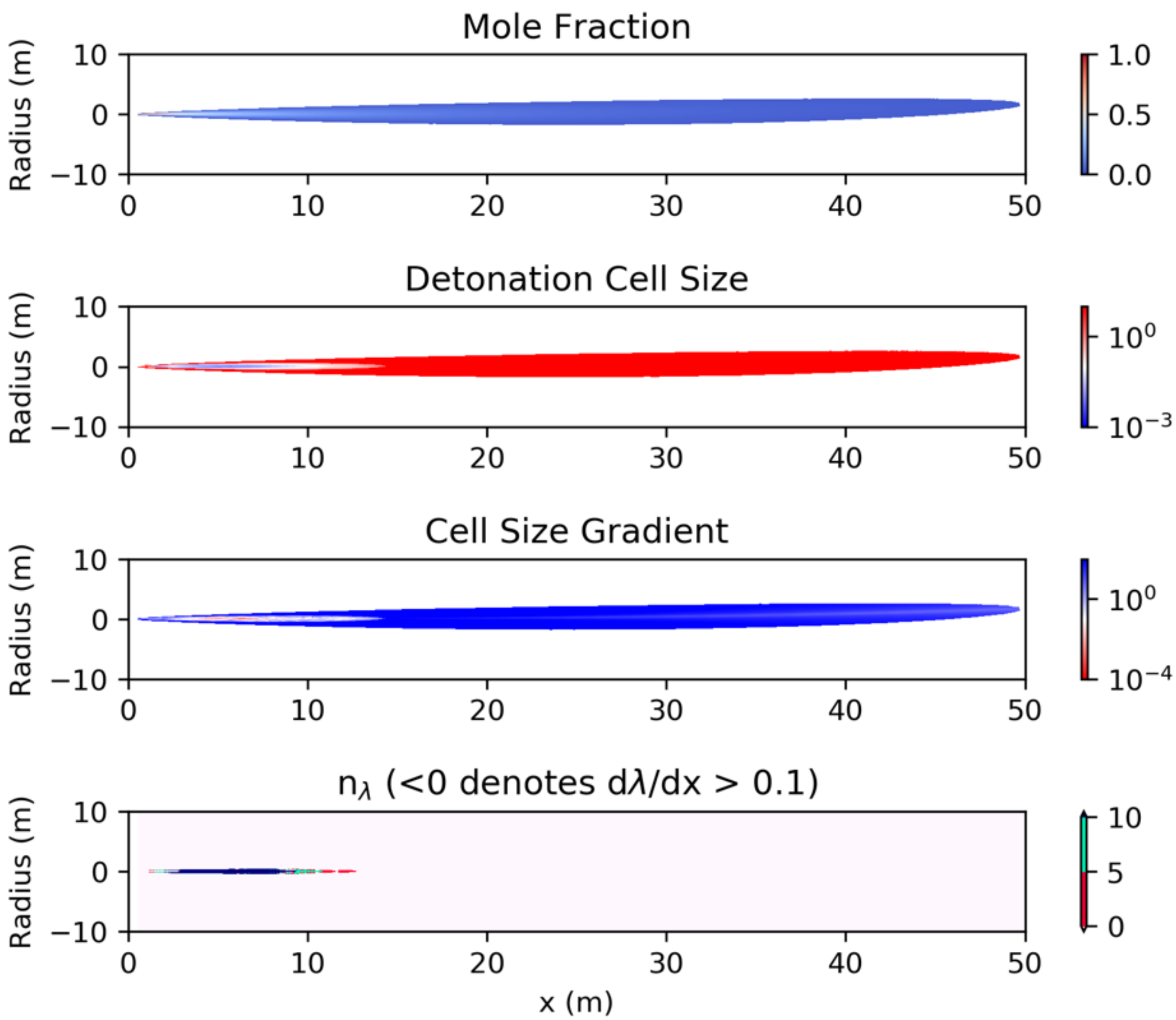


Figure A-31: Case 5a Detonable Region Calculations

Figure A-32 shows the resulting overpressure from the detonable region calculated previously. A dashed line is placed horizontally at 1 psi. The overpressure is shown to drop below 1 psi at around 30 ft from the leak location. The discrete overpressure at 73 ft from the center of the detonable region is 0.28 psi.

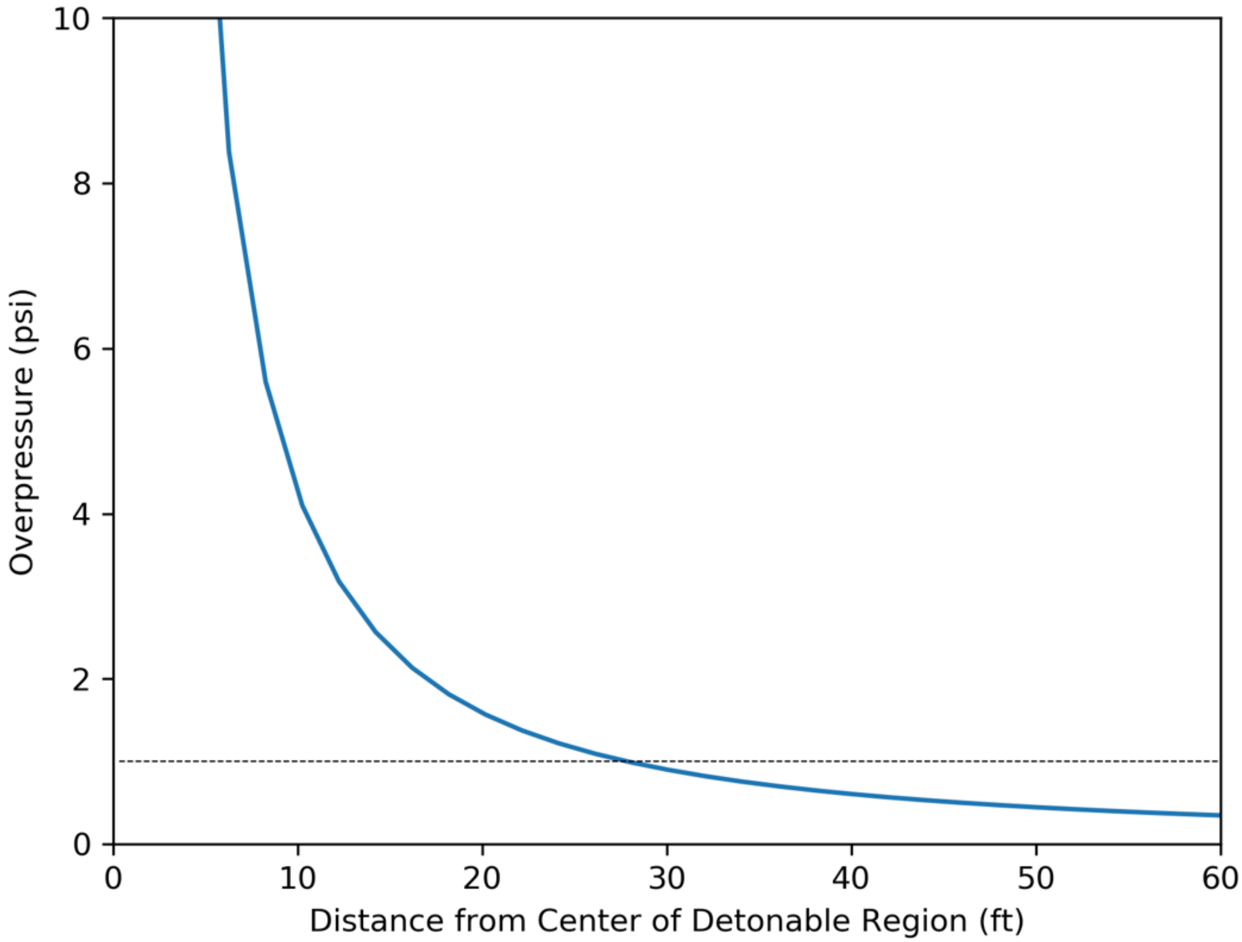


Figure A-32: Case 5a Overpressure Calculation

Figure A-33 shows the detonable region calculations for Case 5b (partial bore leak).

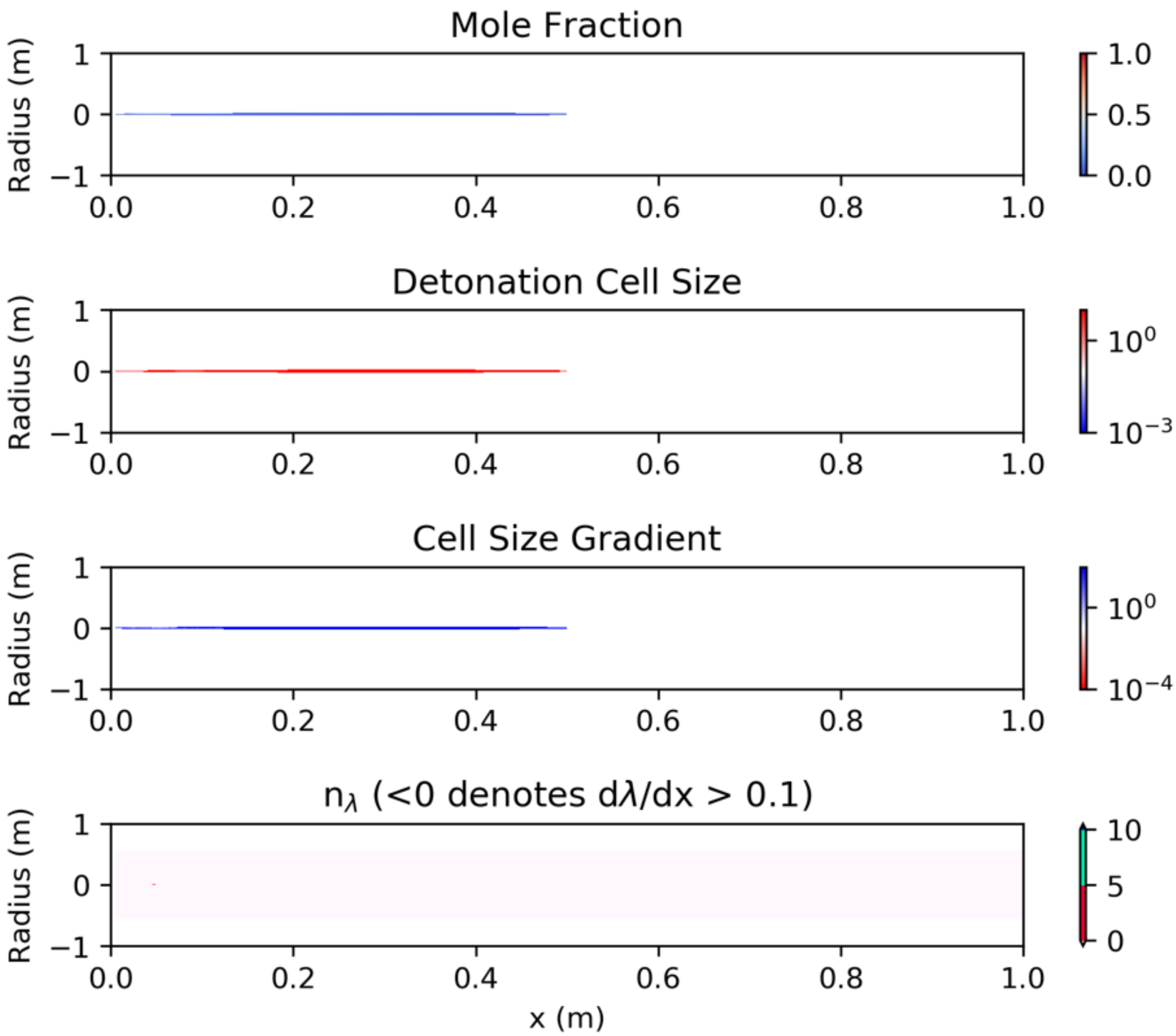


Figure A-33: Case 5b Detonable Region Calculations

Figure A-34 shows the resulting overpressure from the detonable region calculated previously. This case results in a negligible overpressure calculation.

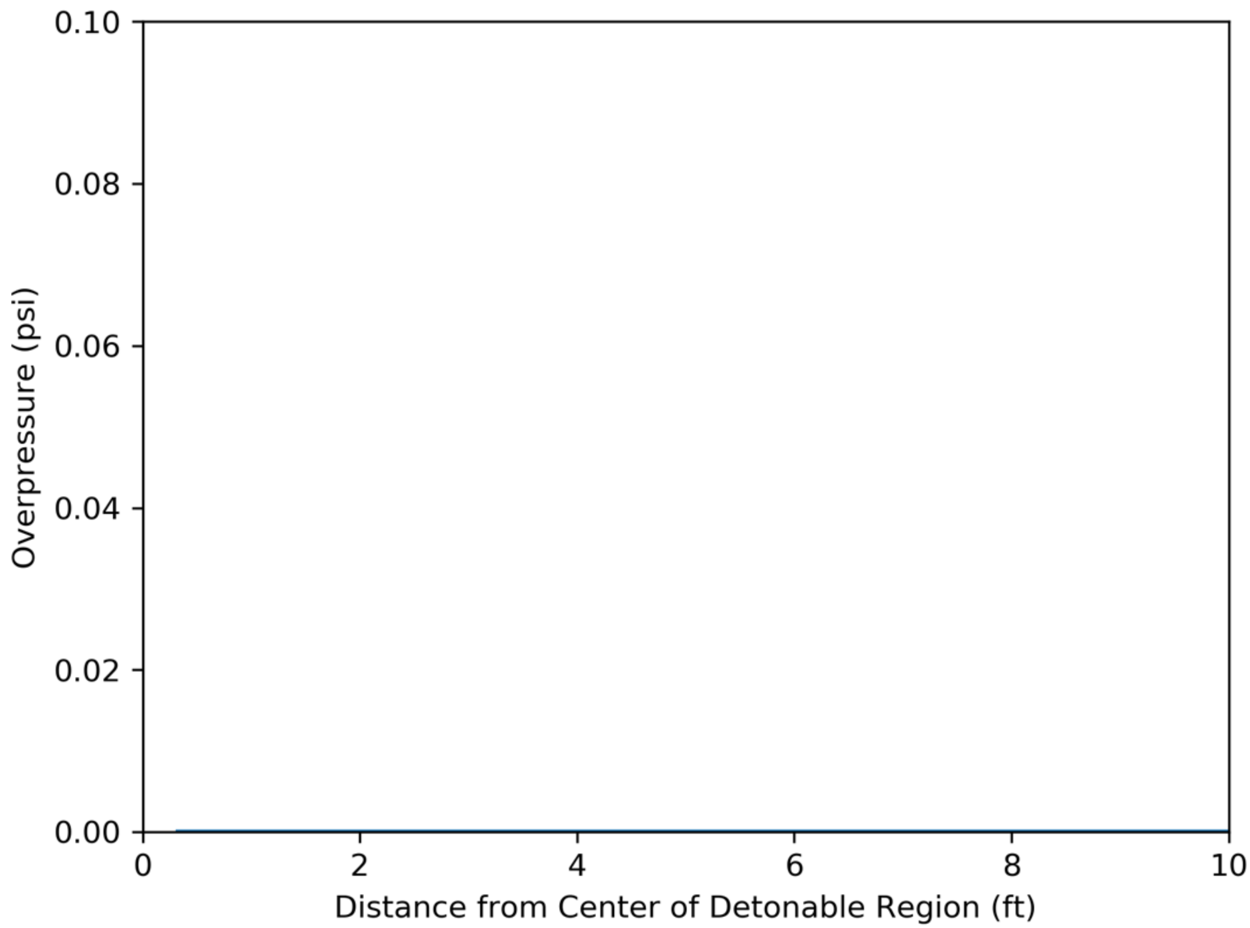


Figure A-34: Case 5b Overpressure Calculation

A.1.2.3. Case 8

Figure A-35 shows the detonable region calculations for Case 8a (full bore leak, t=0s).

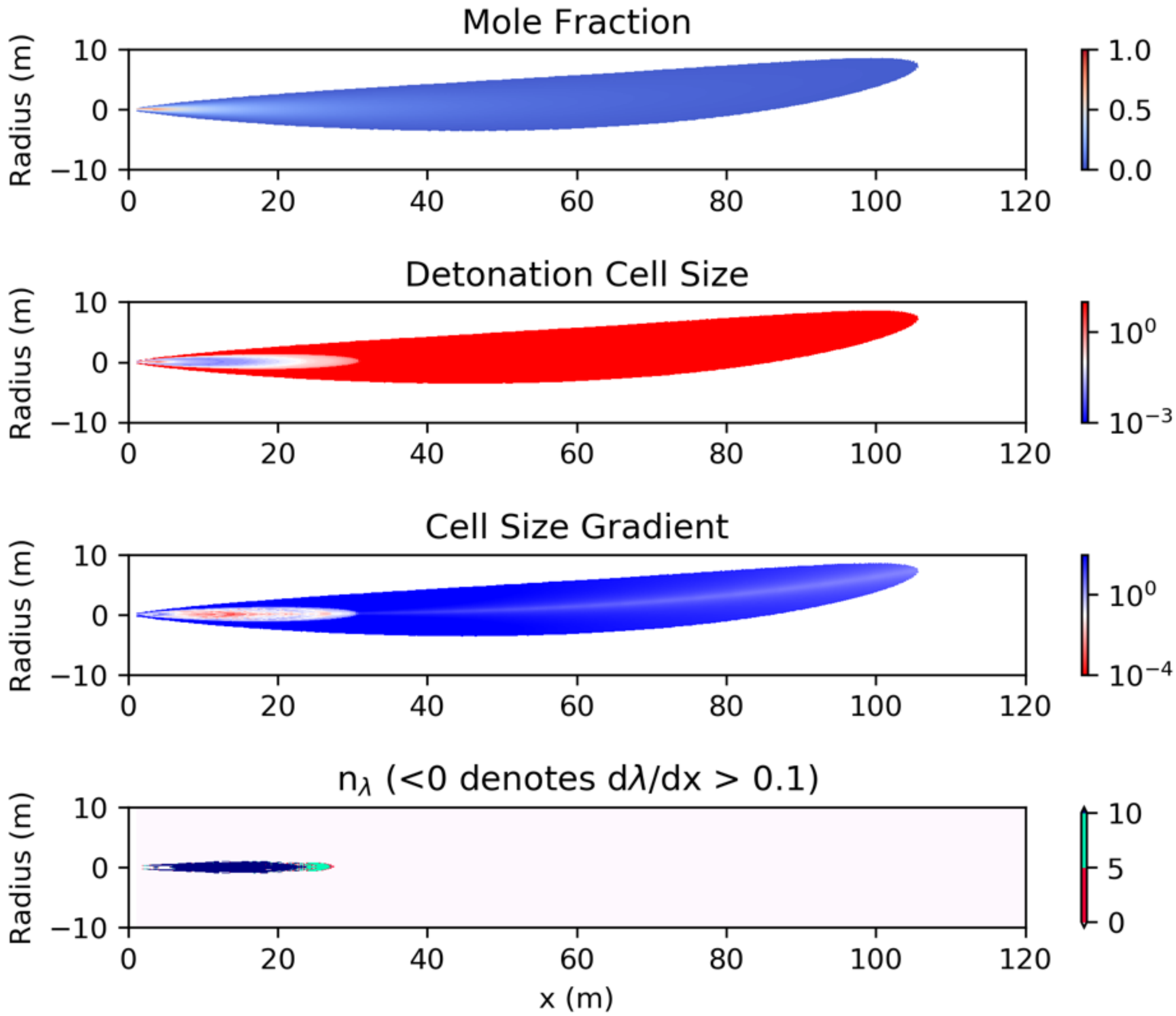


Figure A-35: Case 8a Detonable Region Calculations

Figure A-36 shows the resulting overpressure from the detonable region calculated previously. A dashed line is placed horizontally at 1 psi. The overpressure is shown to drop below 1 psi at around 75 ft from the leak location. The discrete overpressure at 73 ft from the center of the detonable region is 1.05 psi.

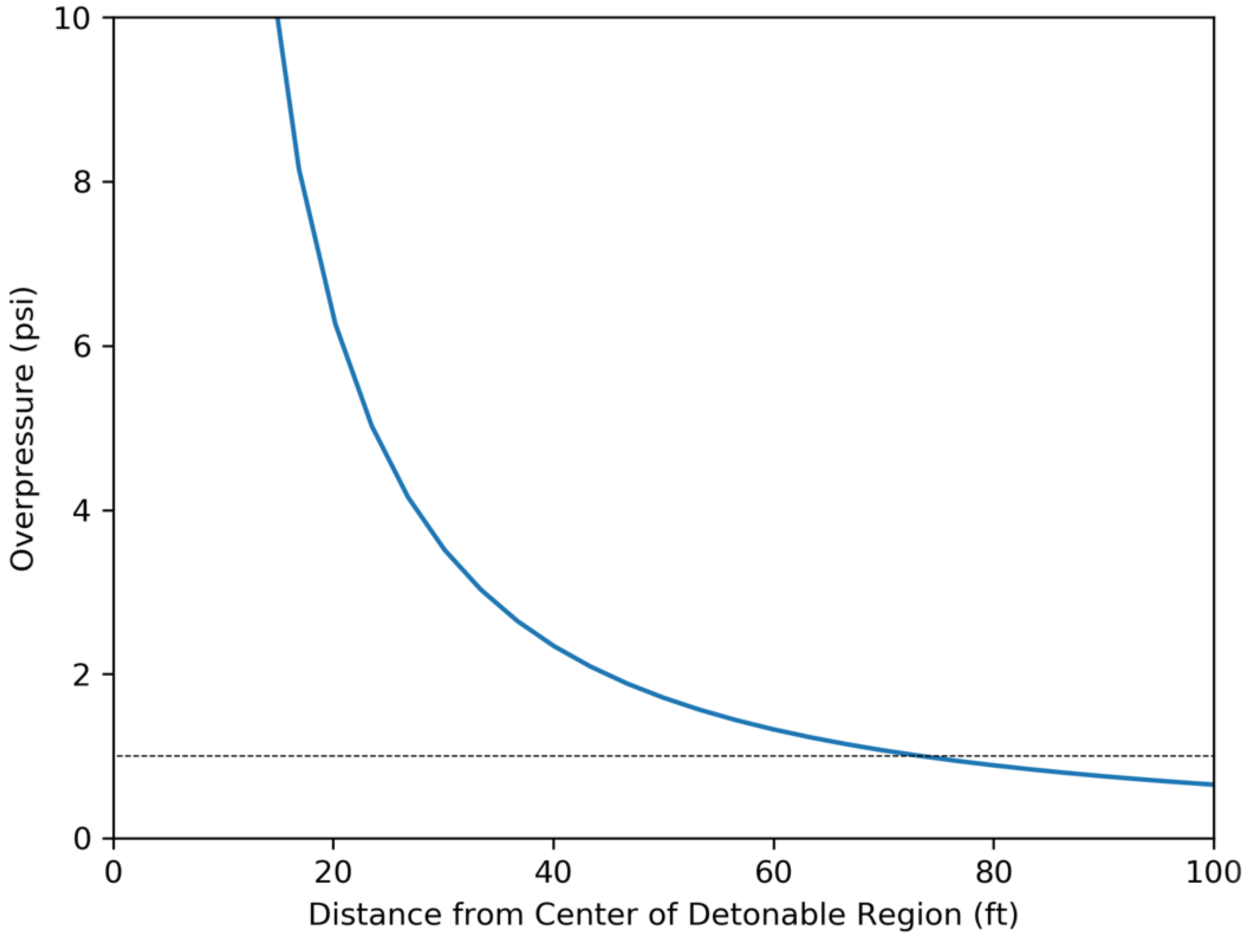


Figure A-36: Case 8a Overpressure Calculation

Figure A-37 shows the detonable region calculations for Case 8b (full bore leak, t=1s).

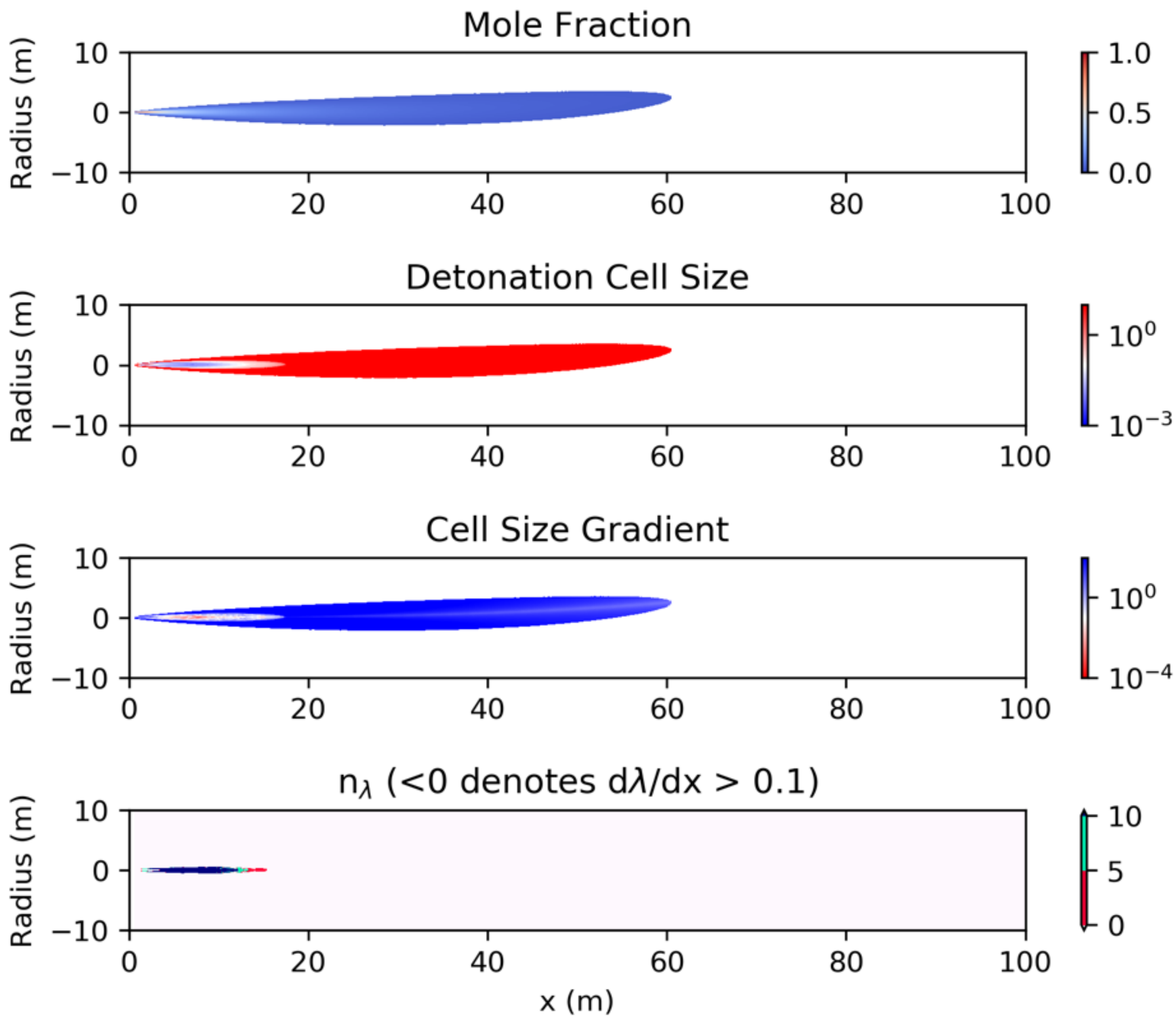


Figure A-37: Case 8b Detonable Region Calculations

Figure A-36 shows the resulting overpressure from the detonable region calculated previously. A dashed line is placed horizontally at 1 psi. The overpressure is shown to drop below 1 psi at around 35 ft from the leak location. The discrete overpressure at 73 ft from the center of the detonable region is 0.39 psi.

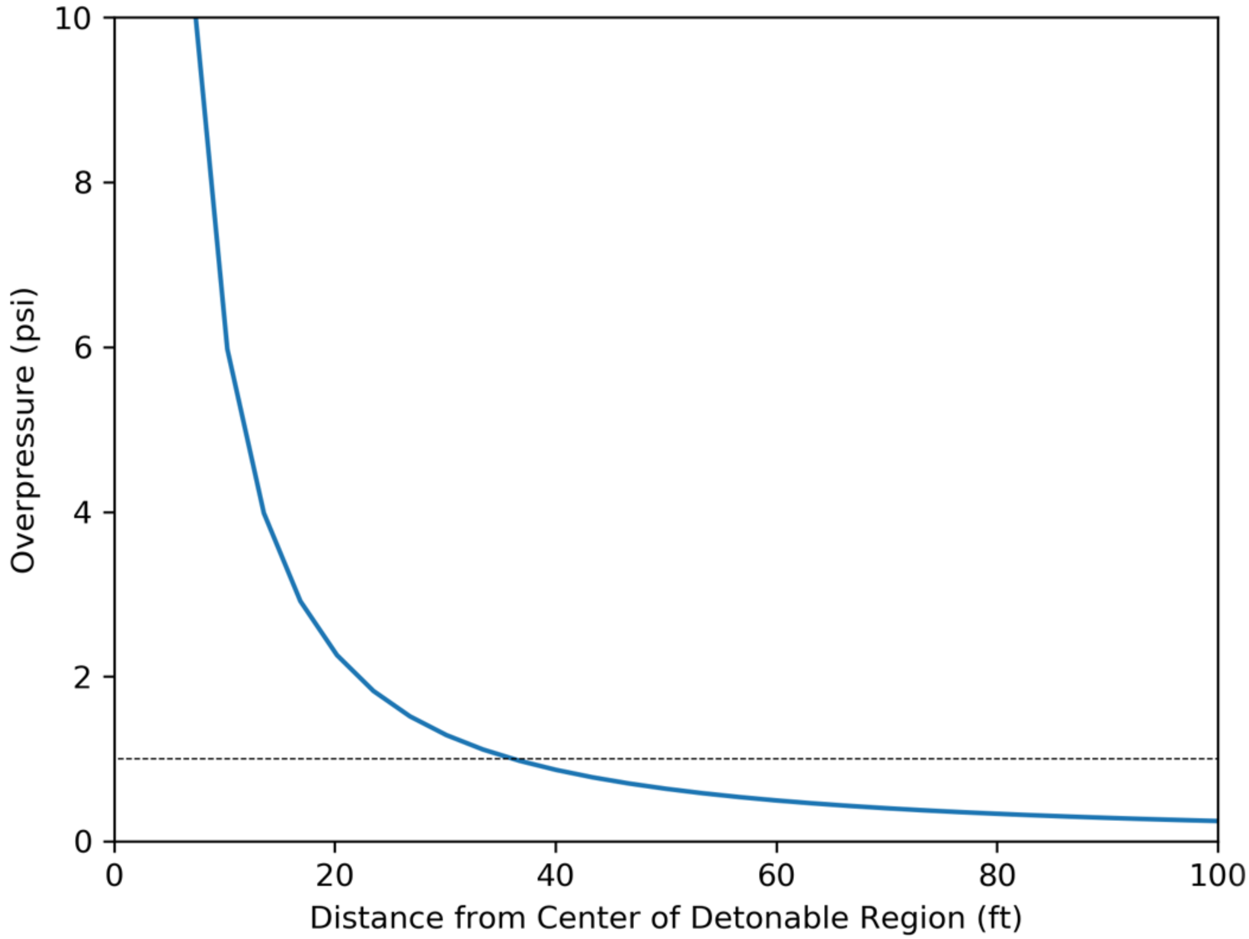


Figure A-38: Case 8b Overpressure Calculation

Figure A-39 shows the detonable region calculations for Case 8c (full bore leak, t=2s).

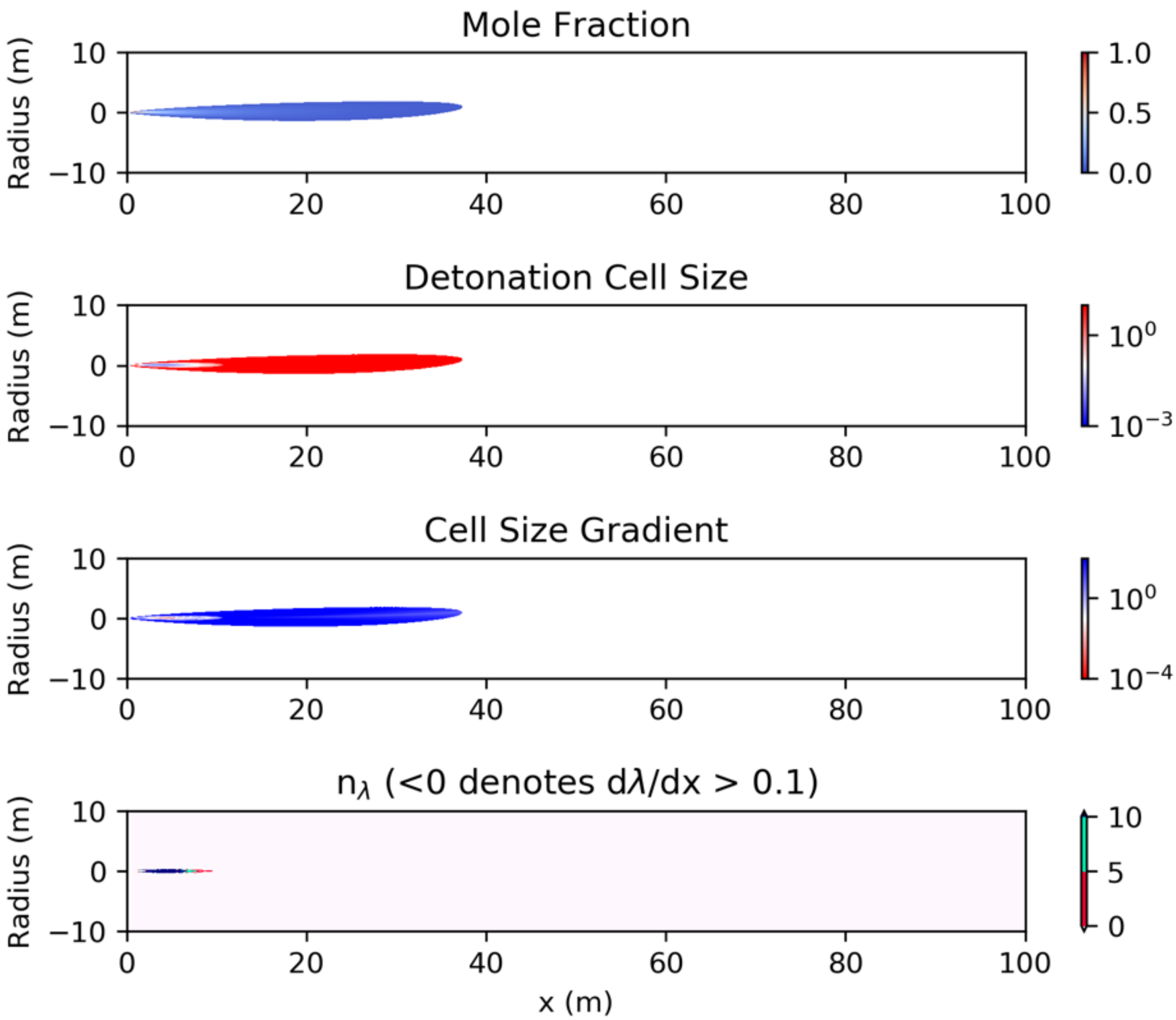


Figure A-39: Case 8c Detonable Region Calculations

Figure A-40 shows the resulting overpressure from the detonable region calculated previously. A dashed line is placed horizontally at 1 psi. The overpressure is shown to drop below 1 psi at around 20 ft from the leak location. The discrete overpressure at 73 ft from the center of the detonable region is 0.18 psi.

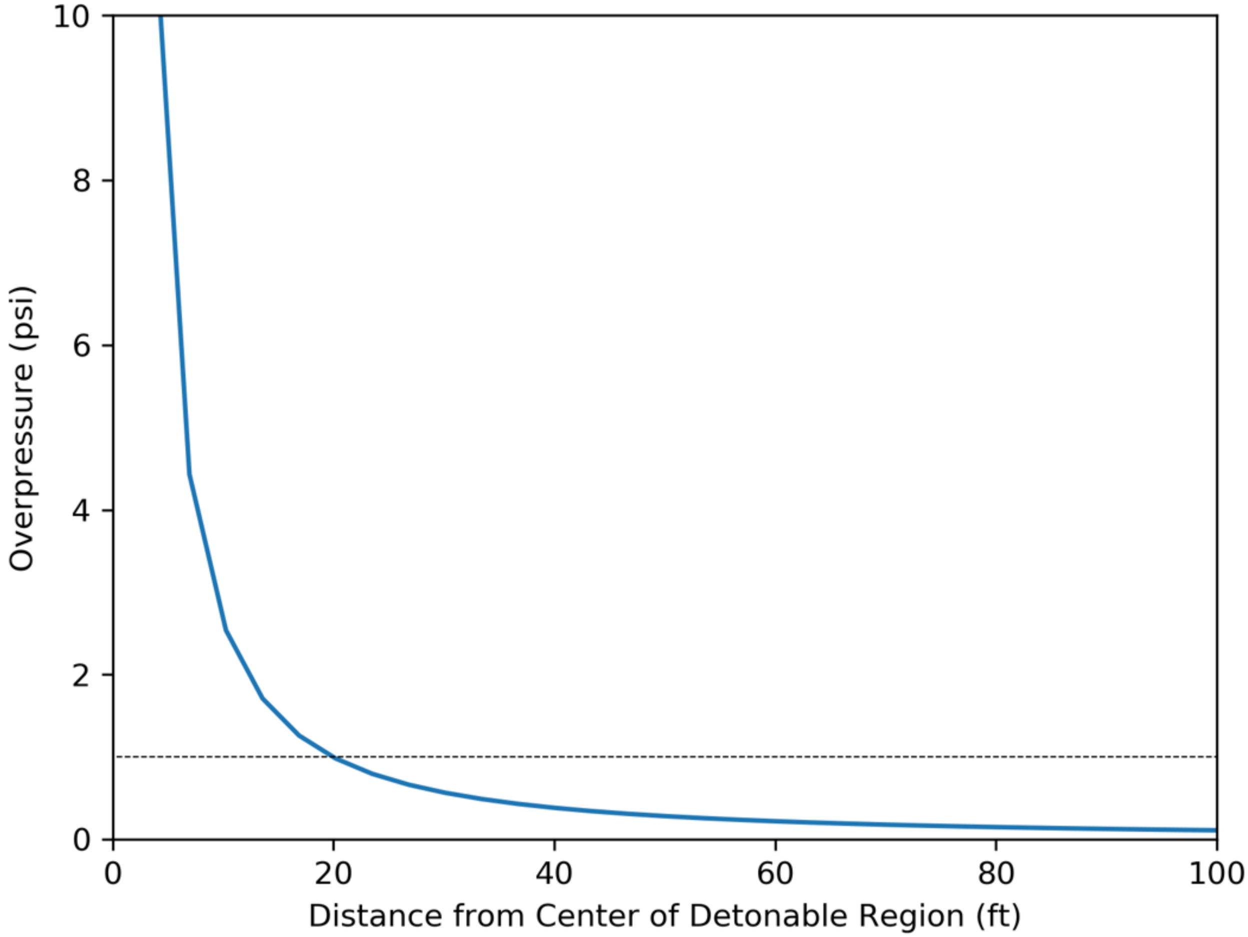


Figure A-40: Case 8c Overpressure Calculation

Figure A-41 shows the detonable region calculations for Case 8d (partial bore leak).

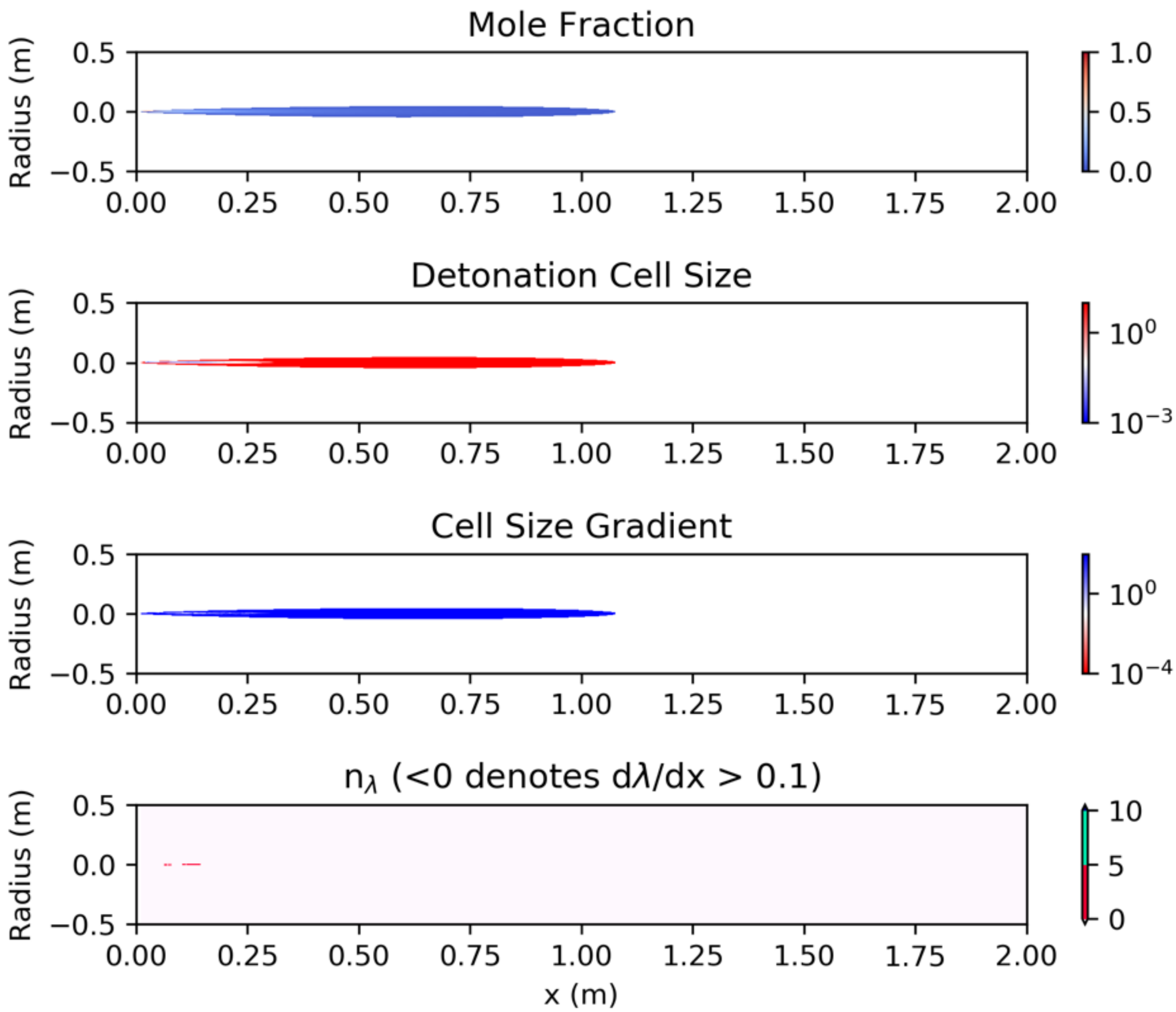


Figure A-41: Case 8d Detonable Region Calculations

Figure A-42 shows the resulting overpressure from the detonable region calculated previously. This case results in a negligible overpressure calculation.

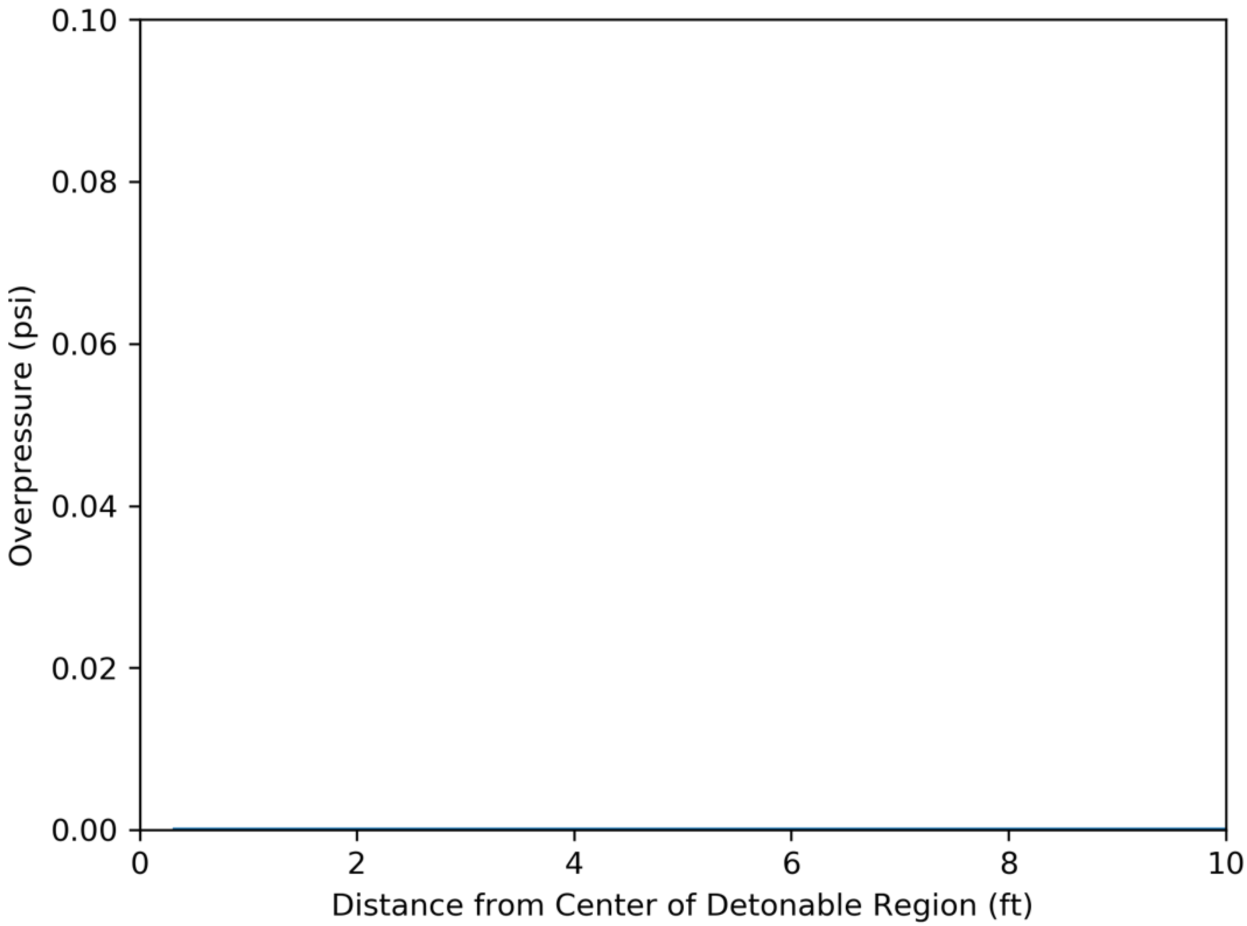


Figure A-42: Case 8d Overpressure Calculation