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Risk Analysis of a Hydrogen Generation Facility near a Nuclear Power Plant

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ABSTRACT

Nuclear power plants (NPPs) are considering flexible plant operations to take advantage of excess thermal and electrical energy. One option for NPPs is to pursue hydrogen production through high temperature electrolysis as an alternate revenue stream to remain economically viable. The intent of this study is to investigate the risk of a hydrogen production facility in close proximity to an NPP. A 100 MW, 500 MW, and 1,000 MW facility are evaluated herein. Previous analyses have evaluated preliminary designs of a hydrogen production facility in a conservative manner to determine if it is feasible to co-locate the facility within 1 km of an NPP. This analysis specifically evaluates the risk components of different hydrogen production facility designs, including the likelihood of a leak within the system and the associated consequence to critical NPP targets. This analysis shows that although the likelihood of a leak in an HTEF is not negligible, the consequence to critical NPP targets is not expected to lead to a failure given adequate distance from the plant.

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ACRONYMS AND TERMS

Acronym/Term	Definition
NPP	nuclear power plant
PRA	probabilistic risk assessment
PRD	pressure relief device
SOEC	solid oxide electrolyzer cell
TNT	trinitrotoluene

1. INTRODUCTION

Nuclear power plants (NPPs) may use flexible plant operations and generation to take advantage of excess thermal and electrical energy. However, NPPs must show that the operation of such a system is safe and does not pose a significant threat to the high consequence NPP facilities and structures. The risk associated with hydrogen production through high temperature electrolysis has been evaluated for preliminary facility designs [1]. The intent of this study is to investigate the risk associated with a more mature design of a 100 MW hydrogen generation facility. Additionally, 500 MW and 1,000 MW hydrogen facility designs are investigated. In this analysis, the hazards associated with a hydrogen generation facility are analyzed to determine the minimum distance at which it can be located with respect to an NPP. A facility component list was developed for the hydrogen generation facility designs. Next, the associated leak frequencies for the individual components in the hydrogen facility were evaluated to develop an overall facility leak frequency. The fragility of critical targets at the NPP site was used to inform the set-back distance calculations. Finally, the consequences resulting from a hydrogen jet release in the hydrogen production facility were calculated and compared to the target fragility. Several different leak scenarios were considered in the evaluation, including full-bore and partial breaks.

2. HYDROGEN FACILITY COMPONENT LIST

Three hydrogen generation plant sizes are evaluated in this report: 100 MW, 500 MW, and 1,000 MW. The conceptual design of a 100 MW facility provided by Sargent & Lundy was used to define the component list of the 100 MW facility [2], in addition to assumptions and engineering judgement. The design was then used as a basis to define the component list for the 500 MW and 1,000 MW designs.

2.1. 100 MW Plant Design

To develop the bottom-up leak frequency for the hydrogen generation facility, the components in the system need to be documented. This list was used in conjunction with component specific leak frequencies developed previously [1] to develop system level leak frequencies. The conceptual design of the overall facility was provided by Sargent & Lundy [2]. The hydrogen process flow diagram of the facility, from the electrolyzers to the offtake point, are shown in Figure 1. The design includes the important equipment, including the solid oxide electrolyzer cell (SOEC) modules, heat exchangers, compressors, etc. Additionally, the pipe size, length, and system parameters were defined in the conceptual design.

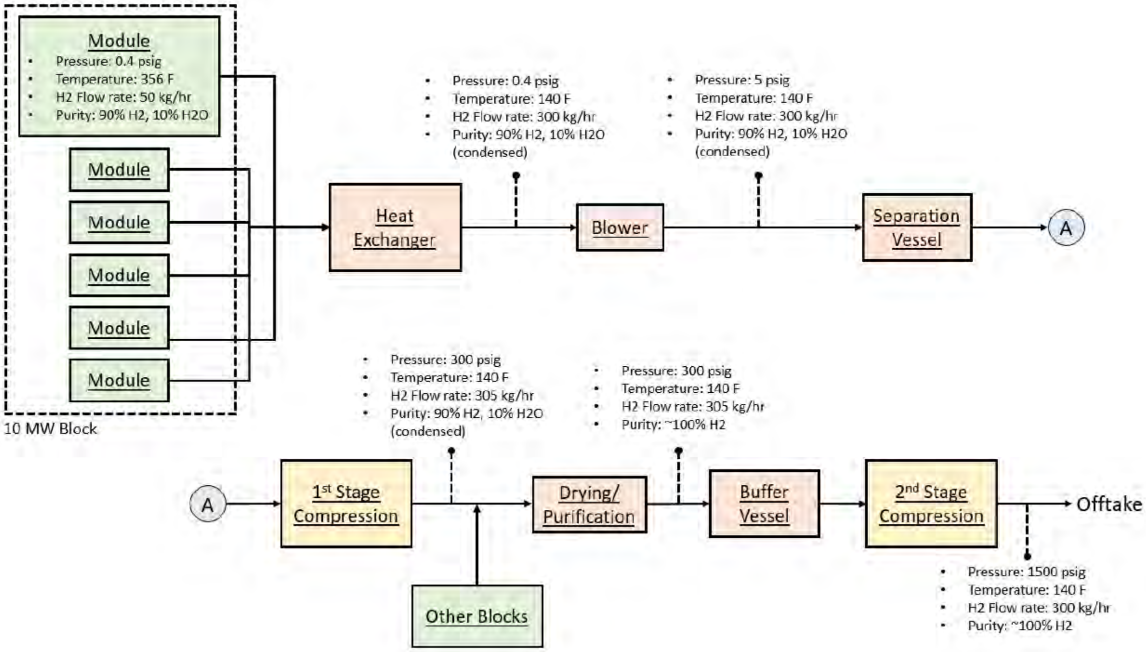

Figure 1: Simplified Flow Diagram of Hydrogen Process Piping within the Hydrogen Facility with Process Conditions [2]

However, this design did not explicitly define the number of secondary components, such as joints and valves, that are important in the leak frequency analysis. Therefore, the double-line hydrogen facility configuration was used as a basis for an estimate of the number of these components using assumptions and engineering judgement. Figure 2 shows the double-line hydrogen facility configuration used to estimate the component count in the facility downstream of the SOEC modules.

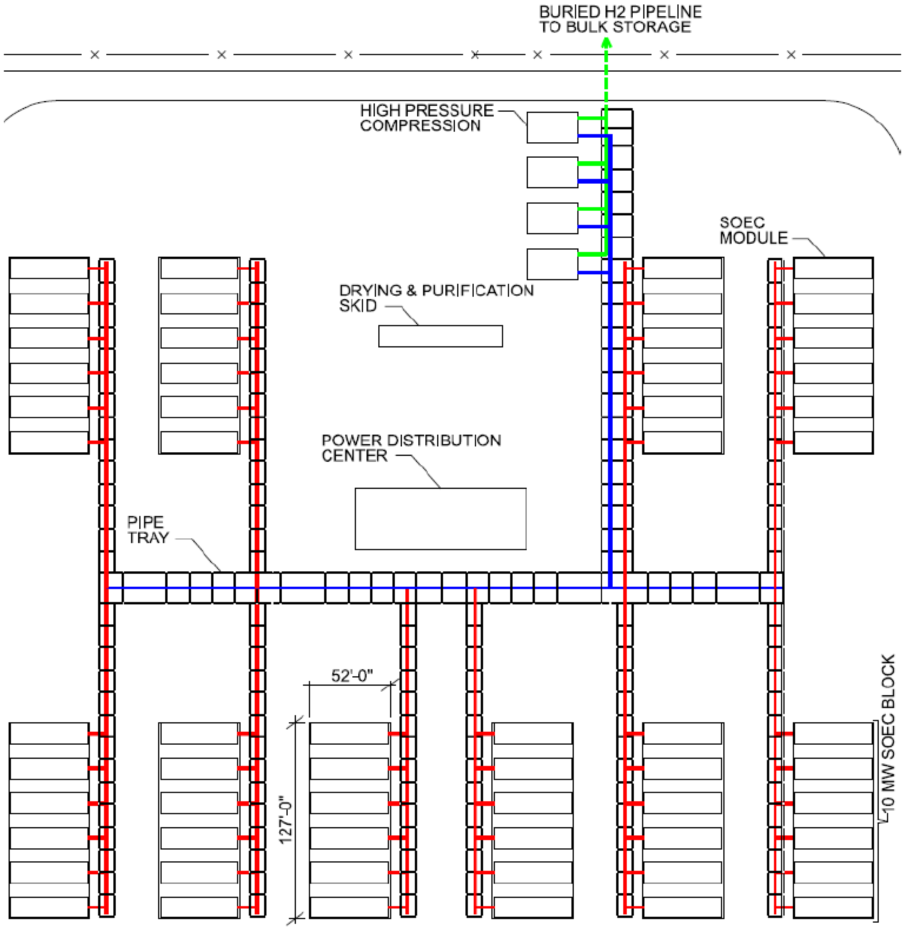

Figure 2: Double-line Configuration of 100 MW Hydrogen Facility [2]

The following estimates, and their basis, were used to define the number of components in the hydrogen generation facility downstream of the SOEC modules:

- Section 1: SOEC Module to Heat Exchanger
  - 60 SOEC Modules
  - 60 Joints (Tees, elbows, reducers, expanders, etc.)
    - Basis: joint for each SOEC module to common header
  - 60 Valves
    - Basis: isolation valve for each SOEC Module
  - 10 Heat Exchangers
    - Basis: after combined into common header, the flow is condensed by a heat exchanger
- Section 2: Heat Exchanger to Blower
  - 10 Joints
    - Basis: joint for each header for connection between heat exchanger and blower
  - 10 Valves
    - Basis: isolation valve for each header
  - 10 blowers

        - Basis: pressure is increased by a blower immediately downstream of the heat exchanger
- Section 3: Blower to 1st Stage Compression
    - 10 Joints
        - Basis: joint for each common header from blower to separation vessel
    - 10 Valves
        - Basis: isolation valve for each header
    - 10 Separation Vessels
        - Basis: separation vessel for each common header prior to compression
    - 10 Compressors
        - Basis: compressor for each common header
- Section 4: 1st Stage Compression to Drying/Purification
    - 1 Joint
        - Basis: joint for purification vessel
    - 1 Valve
        - Basis: isolation valve downstream of 1st compression
    - 1 Vessel
        - Basis: purification vessel downstream of 1st compression
- Section 5: Purification to 2nd Stage Compression
    - 4 Joints
        - Basis: joint for purification vessel and buffer vessel
    - 4 Valve
        - Basis: isolation valves downstream of 2nd compression
    - 4 Compressors
        - Basis: 4 high-pressure compressors shown
    - 1 Vessel
        - Basis: buffer vessel
- Section 6: Downstream of 2nd Stage Compression
    - 1 Valve
        - Basis: isolation valve in offtake header
    - 1 Joint
        - Basis: joint for offtake

The pipe length of each of the sections was documented in the preconceptual design. The double-line configuration pipe length was listed as 4318 ft (1,316 m) for all sections combined. This pipe length is used in the leak frequency analysis herein. A summary of the components downstream of the SOEC modules is documented in Table 1.

Table 1: 100 MW Facility Component List Downstream of SOEC Modules

Components	Count
Cylinder (vessel, separator, heat exchanger)	22
Valve	86
Joint (tee, elbow, reducer, expander)	86
Compressor	14
Pump/Blower	10
Pipe length (m)	1,316

For the individual SOEC modules, engineering judgement and the design of previous facilities were used as a basis for the component count since the detailed design of the SOEC modules was not available. Based on the component count documented in Appendix A of the previous analysis [1], Table 2 shows the component count for a single SOEC module. Note, that the number of each of the components is based on the hydrogen generation and purification systems from the previous design. However, the pipe length was not explicitly defined for a single module previously. For this analysis, it was estimated that each module would contain 200 ft (60.96 m) of internal piping, which is approximately 4x the width of a single module.

Table 2: SOEC Module Component List

SOEC Module Components	Count
Cylinder (vessel, separator, heat exchanger)	16
Valve	19
Joint (Tee, elbow, reducer, etc.)	3
Compressor	2
Pump/Blower	3
Piping within each Unit (m)	60.96

Noting that there are 60 SOEC modules in the 100 MW design, the facility component list is documented in Table 3. This component list is used in conjunction with the component level leak frequencies to define the overall facility leak frequency.

Table 3: 100 MW Facility Component Quantity Summary

Components	Count
Cylinder (vessel, separator, heat exchanger)	982
Valve	1,226
Joint (tee, elbow, reducer, expander)	266
Compressor	134
Pump/Blower	190
Pipe length (m)	4,974

There is significant uncertainty in the facility component quantity summary due to the assumptions and engineering judgement. To address this uncertainty, a +/- 10% component count sensitivity case is evaluated in the system level leak frequency calculations to show the effect that the component quantity has on leak frequency. Table 4 shows the component counts for these sensitivity cases.

Table 4: 100 MW Component Quantity for Sensitivity Cases

Components		+10%	-10%
Cylinder	982	1,080	884
Valve	1,226	1,349	1,103
Joint	266	293	239
Compressor	134	147	121
Pump/Blower	190	209	171
Pipe length (m)	4,974	5,471	4,476

2.2. 500 MW Plant Design

The component list for the 500 MW hydrogen generation facility is defined by using the 100 MW design as a basis. It is assumed that the 500 MW facility will use the same 10 MW blocks as the 100 MW hydrogen generation facility. The following assumptions were used to develop the component count for the 500 MW facility.

- General Design Assumptions
    - It is assumed that there will be a total of 50 10 MW blocks in the 500 MW design.
    - It is assumed that the 10 MW blocks will be stacked 2-high in the 500 MW design. To account for this, additional vertical piping, tees, and elbows are added to the overall component count (see below).
    - After Section 3 in the 100 MW design, the piping from the individual 10 MW blocks is joined in a common header, which has been sized to accommodate the flow from 10 total 10 MW blocks. For the 500 MW design, it is assumed that there will be 5 parallel sets of piping for these sections, which each accommodate 10 total 10 MW blocks. This assumption increases the total pipe length for the facility but allows for the same pipe sizing as the 100 MW design.
    - It is assumed that downstream of Section 6 (second compression), all of the parallel piping will combine into an underground common header for transport to the storage facility. The pipe size will increase to account for the increase in flow due to the power increase. Because this is downstream of second compression, it will not affect the component count. However, it will affect the consequence analysis for the 500 MW plant.
- Section 1: SOEC Module to Heat Exchanger
    - For a 500 MW facility, there will be 50 10 MW blocks. The total component count for this section is 5x the 100 MW design.
        - 300 Joints (Tees, elbows, reducers, expanders, etc.)
        - 300 Valves
        - 50 Heat Exchangers
        - Pipe Length: 4,125’ (1,257 m)
- Section 2: Heat Exchanger to Blower
    - In the 100 MW design, there is a connection between the heat exchanger and blower for each 10 MW block. For the 500 MW facility, there will be 50 10 MW blocks. The total component count for this section is 5x the 100 MW design.
        - 50 Joints
        - 50 Valves
        - 50 blowers
        - Pipe Length: 6,600’ (2,012 m)
- Section 3: Blower to 1st Stage Compression
    - In the 100 MW design, there is a connection between the blower and 1st stage compression for each 10 MW block. Therefore, the total component count for this section in the 500 MW facility is 5x the 100 MW design
        - 50 Joints
        - 50 Valves
        - 50 Separation Vessels

        - 50 Compressors
- Section 3: Stacked 10 MW blocks
    - To save space in the larger facility designs, it is assumed that the 10 MW blocks will be stacked 2 high. This will introduce the need for additional tees and elbows to connect the stacked modules to the common headers. Additionally, it is assumed that there will be 10' of vertical pipe to connect the vertically stacked blocks downstream of Section 3 to 1st stage compression.
        - 50 Joints (25 tees and 25 elbows)
        - Pipe length: 10'/stack * 25 stacks = 250' (76 m)
- Section 4: 1st Stage Compression to Drying/Purification
    - In the 100 MW design, all 10 MW blocks are combined into a single header for this section. As stated previously, it is assumed there will be 5 parallel sets of headers for the 500 MW design. Therefore, the total component count for this section in the 500 MW facility is 5x the 100 MW design.
        - 5 Joints
        - 5 Valves
        - 5 Vessels
        - Pipe Length: 3,685' (1,123 m)
- Section 5: Purification to 2nd Stage Compression
    - As in Section 4, the component count for the 500 MW facility is 5x the 100 MW design.
        - 20 Joints
        - 20 Valve
        - 20 Compressors
        - 5 Vessel
        - Pipe Length: 1,265' (386 m)
- Section 6: Downstream of 2nd Stage Compression
    - The component count for the 500 MW facility is 5x the 100 MW design for this section as well.
        - 5 Valve
        - 5 Joint
        - Pipe Length: 965' (294 m)
    - SOEC Module Component List: There are 6 SOEC modules in each 10 MW block. For the 500 MW design, there will be a total of 300 individual SOEC modules. The total component contribution from the SOEC modules for the 500 MW design is documented below.
        - 4,800 Cylinders
        - 5,700 Valves
        - 900 Joints
        - 600 Compressors
        - 900 pumps/blowers
        - Pipe Length: 60,000' (18,288 m)

Table 5 documents the total component count of the 500 MW design. This component list is used in conjunction with the component level leak frequencies to define the overall facility leak frequency.

Table 5: 500 MW Facility Component Quantity Summary

Components	Count
Cylinder (vessel, separator, heat exchanger)	4,910
Valve	6,130
Joint (tee, elbow, reducer, expander)	1,380
Compressor	670
Pump/Blower	950
Pipe length (m)	24,945

There is significant uncertainty in the facility component quantity summary due to the assumptions and engineering judgement. To address this uncertainty, a +/- 10% component count sensitivity case is evaluated in the system level leak frequency calculations to show the effect that the component quantity has on leak frequency. Table 6 shows the component counts for these sensitivity cases.

Table 6: 500 MW Component Quantity for Sensitivity Cases

Components		+10%	-10%
Cylinder	4,910	5,401	4,419
Valve	6,130	6,743	5,517
Joint	1,380	1,518	1,242
Compressor	670	737	603
Pump/Blower	950	1045	855
Pipe length (m)	24,945	27,439	22,450

2.3. 1,000 MW Plant Design

The same assumptions from the 500 MW design are used to define the component list for the 1,000 MW design. There are a total of 100 10 MW blocks in the 1,000 MW design. The blocks are assumed to be stacked 2-high. Also, it is assumed that there will be 10 parallel sets of piping downstream of Section 3. Where in the 500 MW design assumptions the component count of the 100 MW facility was multiplied by 5, in the 1,000 MW design it is multiplied by 10. Table 7 documents the total component count of the 1,000 MW design. This component list is used in conjunction with the component level leak frequencies to define the overall facility leak frequency.

Table 7: 1,000 MW Facility Component Quantity Summary

Components	Count
Cylinder (vessel, separator, heat exchanger)	9,820
Valve	12,260
Joint (tee, elbow, reducer, expander)	2,760
Compressor	1,340
Pump/Blower	1,900
Pipe length (m)	49,890

There is significant uncertainty in the facility component quantity summary due to the assumptions and engineering judgement. To address this uncertainty, a +/- 10% component count sensitivity case is evaluated in the system level leak frequency calculations to show the effect that the component quantity has on leak frequency. Table 8 shows the component counts for these sensitivity cases.

Table 8: 1,000 MW Component Quantity for Sensitivity Cases

Components		+10%	-10%
Cylinder	9,820	10,802	8,838
Valve	12,260	13,486	11,034
Joint	2,760	3,036	2,484
Compressor	1,340	1,474	1,206
Pump/Blower	1,900	2,090	1,710
Pipe length (m)	49,890	54,879	44,901

3. LEAK FREQUENCY

To quantify the risk of a leak in a hydrogen generation facility, it is necessary to establish the types of accidents that can occur. To do this, component leakage frequencies representative of hydrogen components must be documented as a function of the normalized leak size. Subsequently, the system characteristics (e.g., system pressure) will be used to calculate the consequence of the accident. A Bayesian statistical method was used in the previous analysis to document the component level leak frequency [1]. Note, the types of leaks that are represented by these frequencies correspond to random failures and material degradation. These frequencies are not associated with accidents, weather, natural disasters, or human errors. Table 9 shows the component leak frequency values for the different normalized leak sizes from the previous analysis. Note, the leak fraction shown in the table is the ratio of the leak area to the total flow area of the pipe. As shown, no hydrogen specific data is available for the pumps. Therefore, these components do not have hydrogen specific leak frequency values and the generic leak frequencies are used in this analysis.

Table 9: Hydrogen Component Leak Frequencies (yr^{-1})

Component	Leak Fraction	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
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

Component	Leak Fraction	Generic Leak Frequencies				Hydrogen Leak Frequencies			
		Mean	5th	Median	95th	Mean	5th	Median	95th
	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

Hydrogen generation system leak frequencies were estimated via sampling. The leak frequency distributions for each component and leak size were sampled many times (N = 5e6). Each sample was then multiplied by the corresponding count of that component type in the hydrogen generation system to get system-wide component leak frequencies. This assumes that all components of a single type (e.g., valves) have the same leak frequencies within a single sample realization. The system-wide component leak frequencies were then added within each leak size bin to get the overall system leak frequency. For example, the frequency for 1% leaks for the hydrogen generation system is the sum of the 1% leak frequencies for all compressors, cylinders, joints, pipes, pumps, and valves.

This calculation can be summarized as follows. For a fixed component type, $c \in \{Compressors, Cylinders, Joints, Pipes, Pumps, Valves\}$, let N_c be the number of components of that type in the system. Let $F_{c,i}(s)$ denote the ith sampled leak frequency for leaks of size $s \in \{0.01\%\ 0.1\%, 1\%, 10\%, 100\%\}$ for component c. Then the system leak frequency, F_{system}, for the single realization, i, is:

$$F_{system,i}(s) = \sum_{c} (N_c \times F_{c,i}(s))$$

Sample statistics (5th percentile, median, mean, and 95th percentile) summarizing the system leak frequency were calculated from the 5e6 samples of $F_{system,i}(s)$ for each leak bin. This sample size proved more than sufficient for stable estimates of these statistics.

3.1. 100 MW Plant Design

Table 3 defines the total number of components in the 100 MW hydrogen generation facility, which corresponds directly to the leak frequencies listed in Table 9. Table 10 shows the total system frequency as a function of break size. Note, that the median leak frequency indicates that a very small leak size (normalized leak area of 0.0001) is fairly common (~ 17 expected occurrences/yr). However, a full rupture (normalized leak area of 1) is expected to occur less than 8 times every 100 years.

Table 10: 100 MW Hydrogen Facility System Frequency (yr^{-1})

Leak Size	HTEF System Frequency			
	Mean	5th	Median	95th
0.0001	1.80E+01	1.19E+01	1.74E+01	2.61E+01
0.001	3.50E+00	1.72E+00	3.18E+00	6.34E+00
0.01	1.09E+00	3.23E-01	8.43E-01	2.64E+00
0.1	1.57E-01	8.60E-02	1.48E-01	2.58E-01
1	8.57E-02	3.11E-02	7.23E-02	1.83E-01

For the sensitivity case in which there is +10% more components, Table 11 shows the resulting system frequency. As expected, the leak frequency increases due to the additional components. The median leak frequency indicates that a very small leak size would occur ~19 times a year, while a full rupture is expected to occur ~8 times every 100 years.

Table 11: 100 MW Sensitivity Case (+10%) System Frequency (yr^{-1})

Leak Size	HTEF System Frequency			
	Mean	5th	Median	95th
0.0001	1.97E+01	1.31E+01	1.91E+01	2.86E+01
0.001	3.84E+00	1.89E+00	3.50E+00	6.96E+00
0.01	1.19E+00	3.55E-01	9.26E-01	2.90E+00
0.1	1.73E-01	9.46E-02	1.63E-01	2.84E-01
1	9.44E-02	3.43E-02	7.95E-02	2.01E-01

For the sensitivity case in which there is -10% less components, Table 12 shows the resulting system frequency. The leak frequency decreases due to there being less components. The median leak frequency indicates that a very small leak size would occur ~16 times a year, while a full rupture is expected to occur ~7 times every 100 years.

Table 12: 100 MW Sensitivity Case (-10%) System Frequency (yr^{-1})

Leak Size	HTEF System Frequency			
	Mean	5th	Median	95th
0.0001	1.62E+01	1.07E+01	1.57E+01	2.35E+01
0.001	3.16E+00	1.56E+00	2.87E+00	5.72E+00
0.01	9.79E-01	2.91E-01	7.61E-01	2.39E+00
0.1	1.41E-01	7.74E-02	1.33E-01	2.32E-01
1	7.71E-02	2.80E-02	6.50E-02	1.64E-01

3.2. 500 MW Plant Design

Table 13 shows the total system frequency of the 500 MW design as a function of break size. Note, that the median leak frequency indicates that a very small leak size (normalized leak area of 0.0001) is expected to occur more frequently than the 100 MW design (almost 2 occurrences/week). However, a full rupture (normalized leak area of 1) is expected to occur ~43 times every 100 years.

Table 13: 500 MW Hydrogen Facility System Frequency (yr^{-1})

Leak Size	HTEF System Frequency			
	Mean	5th	Median	95th
0.0001	8.98E+01	5.95E+01	8.68E+01	1.30E+02
0.001	1.75E+01	8.63E+00	1.59E+01	3.17E+01
0.01	5.43E+00	1.62E+00	4.23E+00	1.32E+01
0.1	7.94E-01	4.35E-01	7.48E-01	1.31E+00
1	4.34E-01	1.57E-01	3.66E-01	9.27E-01

For the sensitivity case in which there is +10% more components, Table 14 shows the resulting system frequency. The median leak frequency indicates that a very small leak size would occur ~99 times a year, while a full rupture is expected to occur ~48 times every 100 years.

Table 14: 500 MW Sensitivity Case (+10%) System Frequency (yr^{-1})

Leak Size	HTEF System Frequency			
	Mean	5th	Median	95th
0.0001	9.88E+01	6.54E+01	9.55E+01	1.43E+02
0.001	1.93E+01	9.50E+00	1.75E+01	3.49E+01
0.01	5.98E+00	1.78E+00	4.65E+00	1.45E+01
0.1	8.73E-01	4.79E-01	8.23E-01	1.44E+00
1	4.78E-01	1.73E-01	4.02E-01	1.02E+00

For the sensitivity case in which there is -10% less components, Table 15 shows the resulting system frequency. The median leak frequency indicates that a very small leak size would occur ~81 times a year, while a full rupture is expected to occur ~39 times every 100 years.

Table 15: 500 MW Sensitivity Case (-10%) System Frequency (yr^{-1})

Leak Size	HTEF System Frequency			
	Mean	5th	Median	95th
0.0001	8.08E+01	5.35E+01	7.82E+01	1.17E+02
0.001	1.58E+01	7.77E+00	1.43E+01	2.86E+01
0.01	4.89E+00	1.46E+00	3.80E+00	1.19E+01
0.1	7.15E-01	3.92E-01	6.73E-01	1.18E+00
1	3.91E-01	1.42E-01	3.29E-01	8.34E-01

3.3. 1,000 MW Plant Design

Table 16 shows the total system frequency of the 1,000 MW design as a function of break size. Note, that the median leak frequency indicates that a very small leak size (normalized leak area of 0.0001) is expected to occur more frequently than the 100 MW design (~ nearly once every two days). However, a full rupture (normalized leak area of 1) is expected to occur ~87 times every 100 years.

Table 16: 1,000 MW Hydrogen Facility System Frequency (yr^{-1})

Leak Size	HTEF System Frequency			
	Mean	**5th**	**Median**	**95th**
0.0001	1.80E+02	1.19E+02	1.74E+02	2.61E+02
0.001	3.50E+01	1.73E+01	3.19E+01	6.35E+01
0.01	1.09E+01	3.24E+00	8.45E+00	2.65E+01
0.1	1.59E+00	8.71E-01	1.50E+00	2.62E+00
1	8.69E-01	3.15E-01	7.32E-01	1.85E+00

For the sensitivity case in which there is +10% more components, Table 17 shows the resulting system frequency. The median leak frequency indicates that a very small leak size would occur ~198 times a year, while a full rupture is expected to occur ~96 times every 100 years.

Table 17: 1,000 MW Sensitivity Case (+10%) System Frequency (yr^{-1})

Leak Size	HTEF System Frequency			
	Mean	**5th**	**Median**	**95th**
0.0001	1.98E+02	1.31E+02	1.91E+02	2.87E+02
0.001	3.85E+01	1.90E+01	3.51E+01	6.98E+01
0.01	1.20E+01	3.57E+00	9.30E+00	2.91E+01
0.1	1.75E+00	9.58E-01	1.65E+00	2.88E+00
1	9.56E-01	3.47E-01	8.05E-01	2.04E+00

For the sensitivity case in which there is -10% less components, Table 18 shows the resulting system frequency. The median leak frequency indicates that a very small leak size would occur ~162 times a year, while a full rupture is expected to occur ~78 times every 100 years.

Table 18: 1,000 MW Sensitivity Case (-10%) System Frequency (yr^{-1})

Leak Size	HTEF System Frequency			
	Mean	5th	Median	95th
0.0001	1.62E+02	1.07E+02	1.56E+02	2.35E+02
0.001	3.15E+01	1.56E+01	2.87E+01	5.71E+01
0.01	9.79E+00	2.92E+00	7.61E+00	2.38E+01
0.1	1.43E+00	7.84E-01	1.35E+00	2.36E+00
1	7.82E-01	2.84E-01	6.58E-01	1.67E+00

4. TARGET FRAGILITY

The fragility of a component at an NPP defines the hazard condition at which the component may fail to perform its specified function. NPPs must show that the operation of a hydrogen generation facility is safe and does not pose a significant threat to the high consequence NPP facilities and structures. Target fragilities are calculated for two hazards: detonation overpressure and fire heat flux.

4.1. Detonation Overpressure Fragility

Previously, the critical structures outside of the reactor building and their corresponding overpressure fragility have been identified [3]. Table 19 shows the blast overpressure fragilities of these critical structures. These effective pressures will be used in the consequence analysis herein to define distances from the leak at which these levels are reached.

Table 19: Blast Overpressure Fragilities of Critical Structures

Critical Structure	Effective Pressure (psi)	Total Fragility (Wind and Missiles)
All Category I Structures	0.59	0
	0.97	4.00E-04
	1.49	4.60E-03
	2.16	4.00E-02
Storage Tanks (CST, RWST, etc.)	0.59	2.10E-03
	0.97	2.80E-03
	1.49	1.60E-02
	2.16	5.40E-02
Circulating Water/Service Water Pump Area in Pump House	0.1	8.00E-04
	0.2	5.80E-02
	0.28	1.50E-01
	0.59	5.20E-01
	0.97	9.40E-01
	1.49	1.00E+00
	2.16	1.00E+00

Critical Structure	**Effective Pressure (psi)**	**Total Fragility (Wind and Missiles)**
Switchyard, General	0.32	3.78E-01
	0.48	9.74E-01
	0.71	1.00E+00
Transmission Tower	0.1	0.00E+00
	0.16	0.00E+00
	0.2	8.00E-01
	0.32	9.18E-01
	0.48	1.00E+00
	0.71	1.00E+00
Standby Auxiliary Transformer	0.32	1.99E-01
	0.48	2.68E-01
	0.71	3.11E-01

For the consequences evaluated herein, the distance from the leak at which each discrete overpressure value from Table 19 is reached is reported for input into the probabilistic risk assessment (PRA) model. Table 20 documents the discrete values evaluated in this report. Additionally, the general overpressure fragility value of 1 psi documented in Regulatory Guide 1.91 was evaluated [4].

Table 20: Discrete Fragility Overpressure Values

Effective Pressure	
psi	**kPa**
0.1	0.69
0.16	1.1
0.2	1.38
0.28	1.93
0.32	2.21
0.48	3.31
0.59	4.07
0.71	4.9
0.97	6.69
1.0	6.90
1.49	10.27
1.50	10.34
2.16	14.89

4.2. Radiative Heat Flux

In addition to the overpressure consequence, the thermal radiation from a jet fire event was quantified for the different leak scenarios. The thermal radiation contour levels used to define distances from the accident were based on industry values used in risk and safety analyses [5]. These values, and their definitions, are documented below.

- 37.5 kw/m2
    - Sufficient to cause damage to process equipment
- 25 kw/m2
    - Minimum energy required to ignite wood at indefinitely long exposure
- 12.5 kw/m2
    - Minimum energy required for piloted ignition of wood, and melting of plastic tubing. This value is typically used as a fatality number
- 9.5 kw/m2
    - Sufficient to cause pain in 8 seconds and 2nd degree burns in 20 seconds
- 5 kw/m2
    - Sufficient to cause pain in 20 seconds. 2nd degree burns are possible. 0 percent fatality. This value is often used as an injury threshold
- 1.6 kw/m2
    - Discomfort for long exposures

5. CONSEQUENCE EVALUATION METHODOLOGY

The consequence of an accident in the hydrogen generation facility is an important parameter in the overall risk assessment. 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 damaging overpressure. However, due to the strong concentration gradients in the hydrogen jet, the detonable region of the cloud 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 determine if a propagating detonation wave can be supported. The limits of the hydrogen concentration in the jet to support detonation reduce the portion of the flammable cloud that is available as fuel. The overpressure released through detonation of the large cloud can be calculated from the detonable region, which is compared to the target fragility criteria to determine if critical damage occurs [6]. In addition to an overpressure event, the hydrogen plume may ignite and result in a jet flame. In this case, the thermal radiation from the flame is the metric of concern in terms of consequence of the accident. Note that this analysis does not account for possible natural and man-made barriers between the detonation area and the targets (i.e., the facility walls were not credited to reduce the overpressure at the critical NPP targets).

HyRAM+ Version 5.0 was used to perform the consequence quantification for the leak scenarios at a hydrogen generation facility near an NPP. The HyRAM+ software toolkit integrates data and methods relevant to assessing the safety of the delivery, storage, and use of hydrogen and other alternative fuels. It incorporates experimentally validated models of various aspects of release and flame behavior. The technical reference manual details the methodology and equations that are used to evaluate overpressure and heat flux as a result of a hydrogen release [7]. The physics models utilized in this evaluation are listed below:

- For our base case evaluation of overpressure as a result of detonation of a hydrogen plume resulting from a leak in the hydrogen generation facility, the Bauwens method for unconfined overpressure was utilized. In this method, the detonable mass within the unconfined hydrogen plume is calculated and then the overpressure is based on detonation of that mass of fuel [7].
- An additional sensitivity evaluation for the overpressure analysis was performed using the Trinitrotoluene (TNT) equivalence method. This method is based on finding the mass of TNT that contains the same energy as the fuel being combusted [7].
- The radiative heat flux from an ignited hydrogen plume is calculated in HyRAM+ by using a weighted, multi-source model [7].

6. CONSEQUENCE ASSESSMENT

In order to perform the consequence assessment, the conceptual design of the hydrogen generation facility was reviewed to define the key accident impact scenarios. Next, the system properties for each of the scenarios were defined. The metrics of interest, overpressure and radiative heat flux, were then evaluated as a function of distance from the accident source to determine the extent of impact. All results are reported as the nearest whole meter that does not exceed the parameter of interest.

6.1. Accident Impact Scenarios

The accident impact scenarios are defined by the different sections outlined in the Sargent & Lundy conceptual design of the 100 MW hydrogen generation facility [2]. There are six sections in the conceptual design that have unique system parameters (pressure, temperature, etc.). A scenario was evaluated for each of these different sections to capture the full range of system parameters that are present in the facility. Table 21 outlines the different scenarios and corresponding system parameters. Note, that for each scenario, the composition of the gas was assumed to be 100% hydrogen. Also, for the scenarios that did not result in a choked flow condition from the leak (Scenarios 1, 2, and 3), the mass flowrate was used to define the hydrogen plume. Section 4 and 5 have the same system parameters, only the hydrogen percentage is different. Therefore, only a single evaluation was performed for these sections. These accident impact scenarios are applicable to the 500 MW and 1,000 MW designs as well, due to the assumptions made in the facility component list definition (see Sections 2.2 and 2.3).

Table 21: Accident Impact Scenarios and System Parameters

Scenario #	Description	System Parameters			Pipe size (SCH 40)	Pipe ID (in)
		Pressure (psig)	Temp (F)	$\dot{m}$ (lb/s)		
1	Module	0.4	356	0.031	1.5	1.61
2	Heat Exchanger	0.4	140	0.183	3	3.068
3	Blower	5	140	0.183	3	3.068
4	1st Compression	300	140	1.833	4	4.026
5	Purification	300	140	1.833	4	4.026
6	2nd Compression	1500	140	1.833	3	3.068

As noted in Section 2.2 and 2.3, it is assumed that the parallel piping in the 500 MW and 1,000 MW designs join in a common header downstream of 2nd compression. This line will then connect to a hydrogen storage facility that is assumed to have 1,000 kg of hydrogen storage. The storage facility is not co-located with the hydrogen generation facility. Accident impact scenarios are defined to evaluate the consequence of an overpressure event from the common headers and storage facility.

The common header downstream of 2nd compression is assumed to be underground and be encompassed by concrete piping. Therefore, there is mitigation to blast effects and radiative heat flux should a leak occur. Additionally, the confined space around the header would prevent the formation of a hydrogen plume. However, the unmitigated/unobstructed overpressure of a detonation event is evaluated herein to identify the potential impact of a leak from the common header and inform mitigation strategy. To perform this evaluation, the size of the common header is estimated based on the total expected flowrate for the 500 MW and 1,000 MW designs. The recommended range of flow velocity for gases in piping systems is between 10 and 30 m/s [8]. The minimum pipe size necessary to accommodate the total flow is estimated using a flow velocity of 30 m/s, the mass balance equation (assuming incompressible flow), and the flowrates and properties defined for Section 6 in the 100 MW conceptual design [2].

$$\dot{m} = vA\rho$$

Where:

$\dot{m}$ is the mass flow rate

For 500 MW, 9.165 lb/s (5x the flowrate defined in the 100 MW design) [2]

For 1,000 MW, 18.33 lb/s (10x the flowrate defined in the 100 MW design) [2]

ρ is the density of hydrogen at 140 °F and 1,514.7 psia, 0.4485 lb/ft^3 (calculated in HyRAM+)

v is the flow velocity, 30 m/s [8]

A is the cross-sectional area of the pipe, which is calculated for the 500 MW and 1,000 MW designs

The resulting minimum pipe diameter of the header for the 500 MW and 1,000 MW designs are 6.2 inches and 8.7 inches, respectively. To accommodate these minimum pipe diameters, an 8", SCH 40 steel pipe (ID 7.981") and 10", SCH 40 steel pipe (ID 10.020") [9] are used to define the common header accident impact scenarios for the 500 MW and 1,000 MW designs, respectively. Table 22 shows the accident impact scenarios evaluated to address the common header for the 500 MW and 1,000 MW designs.

Table 22: Accident Impact Scenarios and System Parameters for Common Headers

Scenario #	Description	System Parameters			Pipe size (SCH 40)	Pipe ID (in)
		Pressure (psig)	Temp (F)	$\dot{m}$ (lb/s)		
7	500 MW Common Header	1500	140	9.165	8	7.981
8	1,000 MW Common Header	1500	140	18.33	10	10.020

To address the consequence of a leak at the hydrogen storage facility, an accident impact scenario for a leak from a hydrogen storage tank is evaluated. It is assumed that the storage of 1,000 kg of hydrogen at the facility will be accomplished through the use of several transportable hydrogen storage tanks. A survey of commercially available hydrogen storage tanks yielded a 994 L, 23.9 kg hydrogen storage tank at 35 MPa (5,076 psi) and 15 °C (59 °F) [10]. It is assumed that the storage facility will use 42 of these tanks to store the 1,000 kg of hydrogen. The size of the leak from one of the storage tanks is defined by the orifice diameter of the pressure relief device (PRD) installed on the tank. PRDs are installed on high-pressure hydrogen systems as the main mitigation safeguard to prevent catastrophic failure. For hydrogen storage up to 95 MPa, a PRD with an orifice diameter of 0.25 inches has been shown to be effective in performing its venting function [11]. Therefore, it is assumed that the leak diameter for the hydrogen storage accident impact scenario is 0.25 inches.

Table 23: Accident Impact Scenarios and System Parameters for Storage Tank

Scenario #	Description	System Parameters			Leak Diameter (in)
		Pressure (psig)	Temp (F)	$\dot{m}$ (lb/s)	
9	Hydrogen Storage	5,076	59	N/A	0.25

Full-bore leaks were analyzed for each of the different scenarios as the bounding consequence in a given section. For Scenarios 4, 5, 6, 7, and 8partial leaks were also analyzed. The partial break sizes that were analyzed were 10% of leak area and 1% of leak area, which correspond to the leak frequency categories (see Section 3). Table 24 documents the leak diameter calculations for the partial break scenarios.

Table 24: Leak Diameter for Partial Break Scenarios

Relative Leak Area	**3.068" Pipe ID**		**4.029" Pipe ID**		**7.981" Pipe ID**		**10.020" Pipe ID**	
	D	**A**	**D**	**A**	**D**	**A**	**D**	**A**
1	3.07	7.39	4.03	12.74	7.98	50.00	10.02	78.81
0.1	0.97	0.74	1.27	1.27	2.52	5.00	3.17	7.88
0.01	0.31	0.074	0.40	0.13	0.80	0.50	1.00	0.79
0.001	0.10	0.0074	0.13	0.013	0.25	0.05	0.32	0.08
0.0001	0.03	0.00074	0.04	0.0013	0.08	0.005	0.10	0.008

6.2. Overpressure

This section documents the results of the overpressure consequence analysis for the scenarios outlined in Section 6.1. As stated previously, the Bauwens methodology to calculated unconfined overpressure was utilized to perform the base case simulations. Additionally, the TNT equivalence method was evaluated as a sensitivity to address uncertainty in the calculation methodology. See the HyRAM+ technical reference manual for more detail on these models [7]. Traceability figures for the calculations performed in HyRAM+ are included in Appendix A.

6.2.1. Scenario 1, 2 & 3

Due to the system parameters for Scenarios 1, 2, & 3, the leak flow is unchoked. For these cases, the mass flowrate was used in HyRAM+ to dictate the resulting hydrogen plume. Because none of the full-bore leak scenarios resulted in appreciable overpressure at distance, no partial breaks were evaluated for these cases. Table 25 shows the distance at which the overpressure generated from the detonation did not exceed the discrete fragility overpressure values. As shown, Scenario 3 is the limiting scenario in this set. The overpressure in this scenario is less than 0.1 psi at a distance of 30 meters from the accident location.

Table 25: Scenario 1, 2, & 3 Overpressure Results

Overpressure				
Effective Pressure		Scenario 1 Distance (m)	Scenario 2 Distance (m)	Scenario 3 Distance (m)
psi	kPa			
0.1	0.69	9	26	29
0.16	1.1	6	19	21
0.2	1.38	6	16	18
0.28	1.93	5	13	15
0.32	2.21	5	12	14
0.48	3.31	4	10	11
0.59	4.07	3	9	10
0.71	4.9	3	8	9
0.97	6.69	3	7	8
1	6.90	3	7	8
1.49	10.27	3	6	6
1.5	10.34	3	6	6
2.16	14.89	2	5	6

Figure 3 shows the overpressure as a function of distance from the leak location. As shown, the overpressure drops below 1 psi less than 10 meters from the leak location for each of the scenarios.

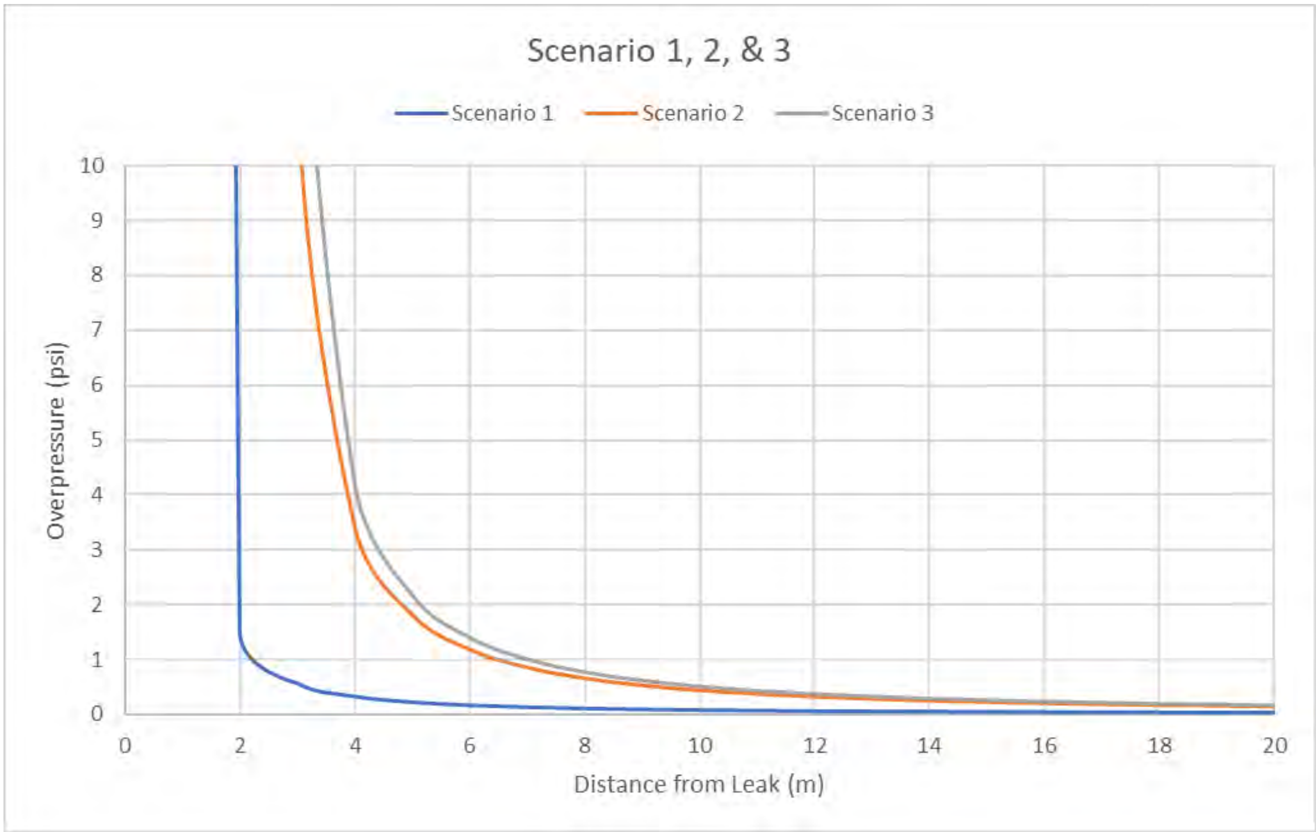

Figure 3: Scenario 1, 2, & 3 Overpressure Results

6.2.2. *Scenario 4 & 5*

As discussed previously, the system parameters for Scenario 4 & 5 are identical, so a single case was evaluated to cover both scenarios. However, for these scenarios, 10% and 1% area partial break cases were also evaluated. Table 26 shows the distance at which the overpressure generated from the detonation did not exceed the discrete fragility overpressure values. As shown, the overpressure drops below 1 psi at 34 meters for the full-bore break case. The partial break cases show that overpressure is reduced considerably as the leak size is reduced.

Table 26: Scenario 4 & 5 Overpressure Results

Scenario 4 & 5: Overpressure				
Effective Pressure		**100% Area Distance (m)**	**10% Area Distance (m)**	**1% Area Distance (m)**
psi	**kPa**			
0.1	0.69	140	37	9
0.16	1.1	102	27	6
0.2	1.38	88	23	6
0.28	1.93	71	19	5
0.32	2.21	65	18	4
0.48	3.31	51	14	4
0.59	4.07	45	12	3
0.71	4.9	41	11	3
0.97	6.69	34	10	3
1	6.90	34	10	3
1.49	10.27	28	8	2
1.5	10.34	28	8	2
2.16	14.89	24	7	2

Figure 4 shows the overpressure as a function of distance from the leak location. As shown, the overpressure drops below 1 psi in less than 10 meters for both of the partial breaks analyzed. The full-bore scenario drops below 1 psi at 34 meters from the leak location.

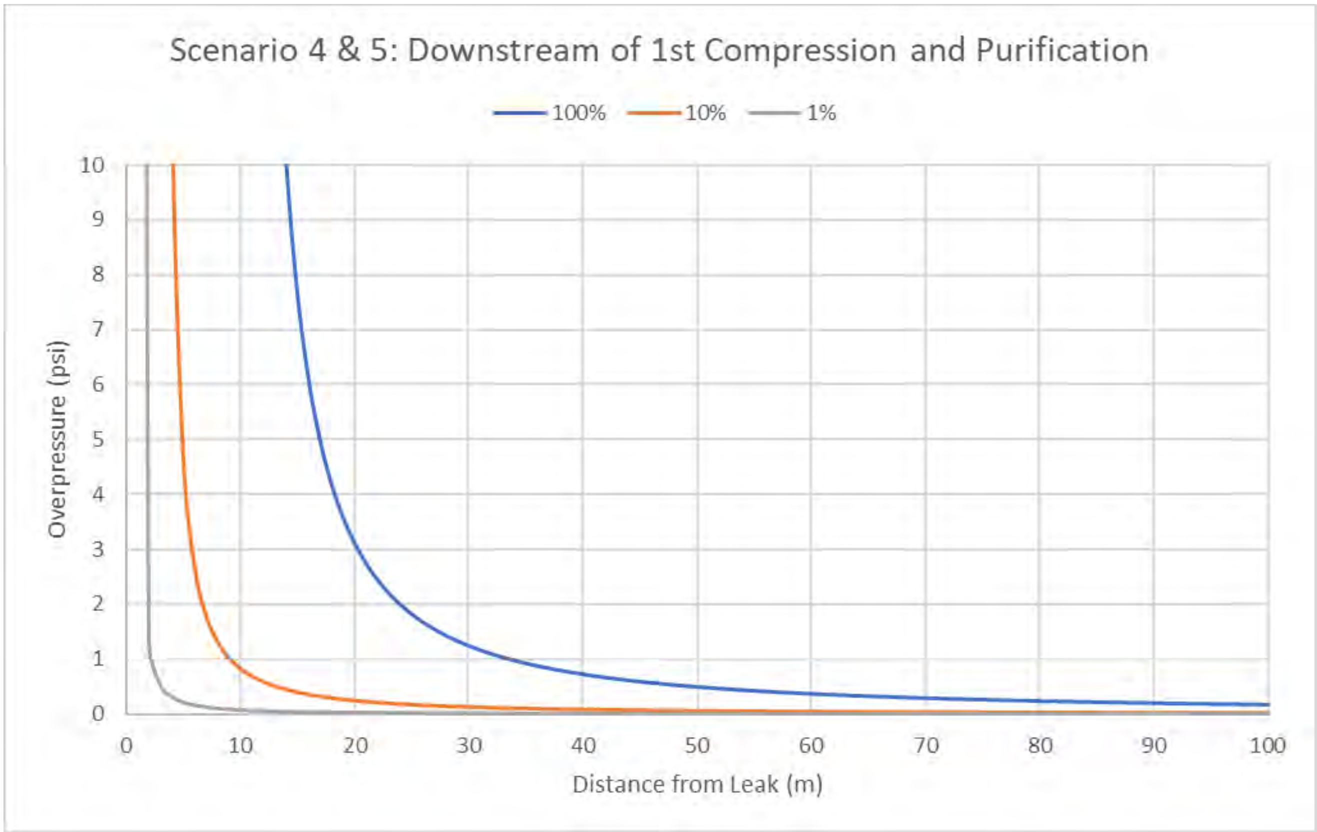

Figure 4: Scenario 4 & 5 Overpressure Results

6.2.3. Scenario 6

The system parameters for Scenario 6 represent the limiting conditions in terms of consequence in the 100 MW hydrogen generation facility. For this scenario, 10% and 1% area partial break cases were also evaluated. Table 27 shows the distance at which the overpressure generated from the detonation did not exceed the discrete fragility overpressure values. As shown, the overpressure drops below 1 psi at 61 meters for the full-bore break case. Similar to Scenario 4 & 5, the partial break cases show that overpressure is reduced considerably as the leak size is reduced.

Table 27: Scenario 6 Overpressure Results

Scenario 6: Overpressure				
Effective Pressure		100% Area Distance (m)	10% Area Distance (m)	1% Area Distance (m)
psi	kPa			
0.1	0.69	258	72	17
0.16	1.1	187	52	13
0.2	1.38	161	45	11
0.28	1.93	129	36	9
0.32	2.21	118	33	9
0.48	3.31	92	26	7
0.59	4.07	81	23	6
0.71	4.9	73	21	6
0.97	6.69	62	18	5
1	6.90	61	18	5
1.49	10.27	49	15	4
1.5	10.34	49	14	4
2.16	14.89	42	12	4

Figure 4 shows the overpressure as a function of distance from the leak location. As shown, the overpressure drops below 1 psi less than 20 meters for both of the partial breaks analyzed. The full-bore scenario drops below 1 psi at 61 meters from the leak location.

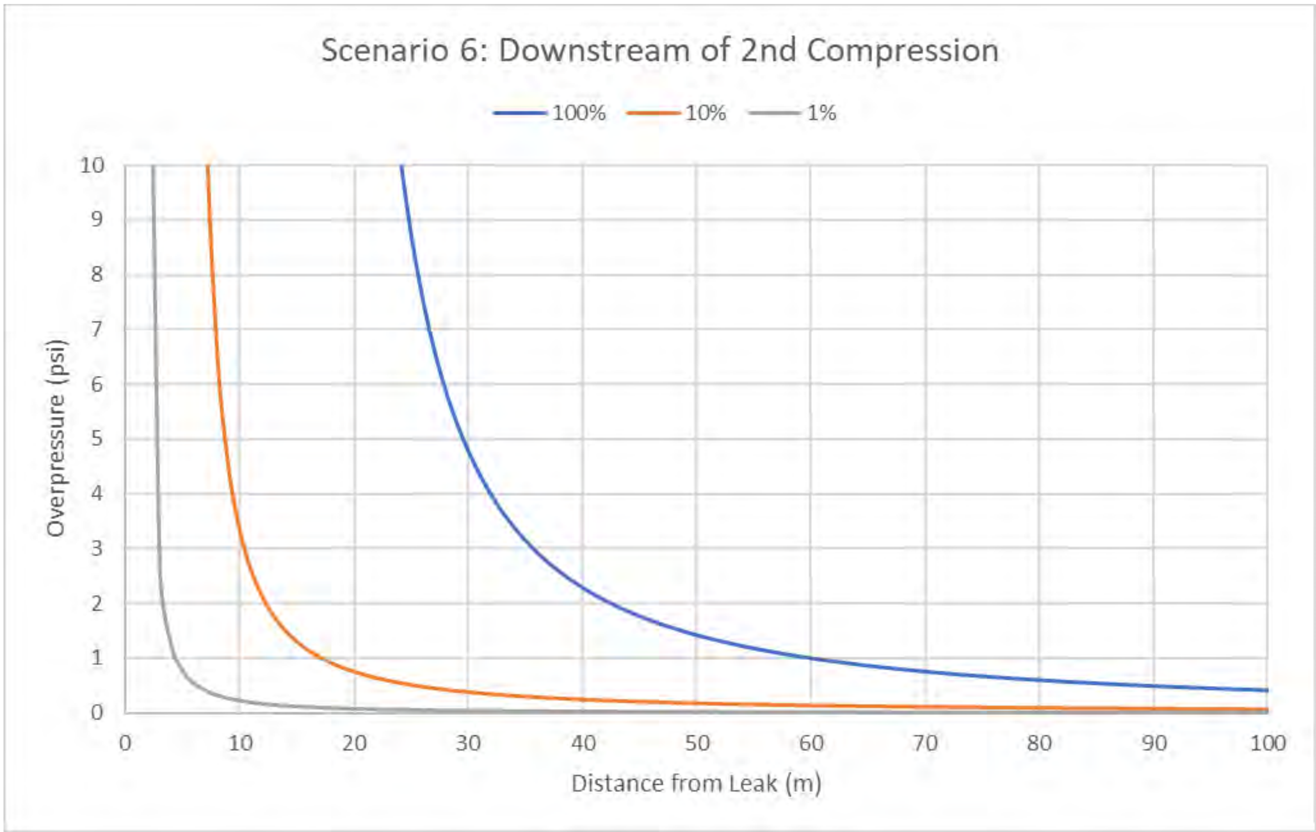

Figure 5: Scenario 6 Overpressure Results

6.2.4. *Scenario 7*

The system parameters for Scenario 7 are evaluated to inform the necessity for appropriate mitigation strategies for the 500 MW plant if a common header is used to transport the hydrogen to a storage facility. For this scenario, 10% and 1% area partial break cases were also evaluated. Table 28 shows the distance at which the overpressure generated from the detonation did not exceed the discrete fragility overpressure values. As shown, the overpressure drops below 1 psi at 168 meters for the full-bore break case. Similar to the other scenarios, the partial break cases show that overpressure is reduced considerably as the leak size is reduced.

Table 28: Scenario 7 Overpressure Results

Scenario 7: Overpressure				
Effective Pressure		**100% Area Distance (m)**	**10% Area Distance (m)**	**1% Area Distance (m)**
psi	**kPa**			
0.1	0.69	734	210	57
0.16	1.1	530	153	42
0.2	1.38	456	131	36
0.28	1.93	365	105	29
0.32	2.21	334	97	27
0.48	3.31	259	75	21
0.59	4.07	228	67	19
0.71	4.9	204	60	17
0.97	6.69	171	50	14
1	6.90	168	50	14
1.49	10.27	136	40	12
1.5	10.34	136	40	12
2.16	14.89	114	34	10

Figure 6 shows the overpressure as a function of distance from the leak location. As shown, the overpressure drops below 1 psi less than 50 meters for both of the partial breaks analyzed. The full-bore scenario drops below 1 psi at 168 meters from the leak location.

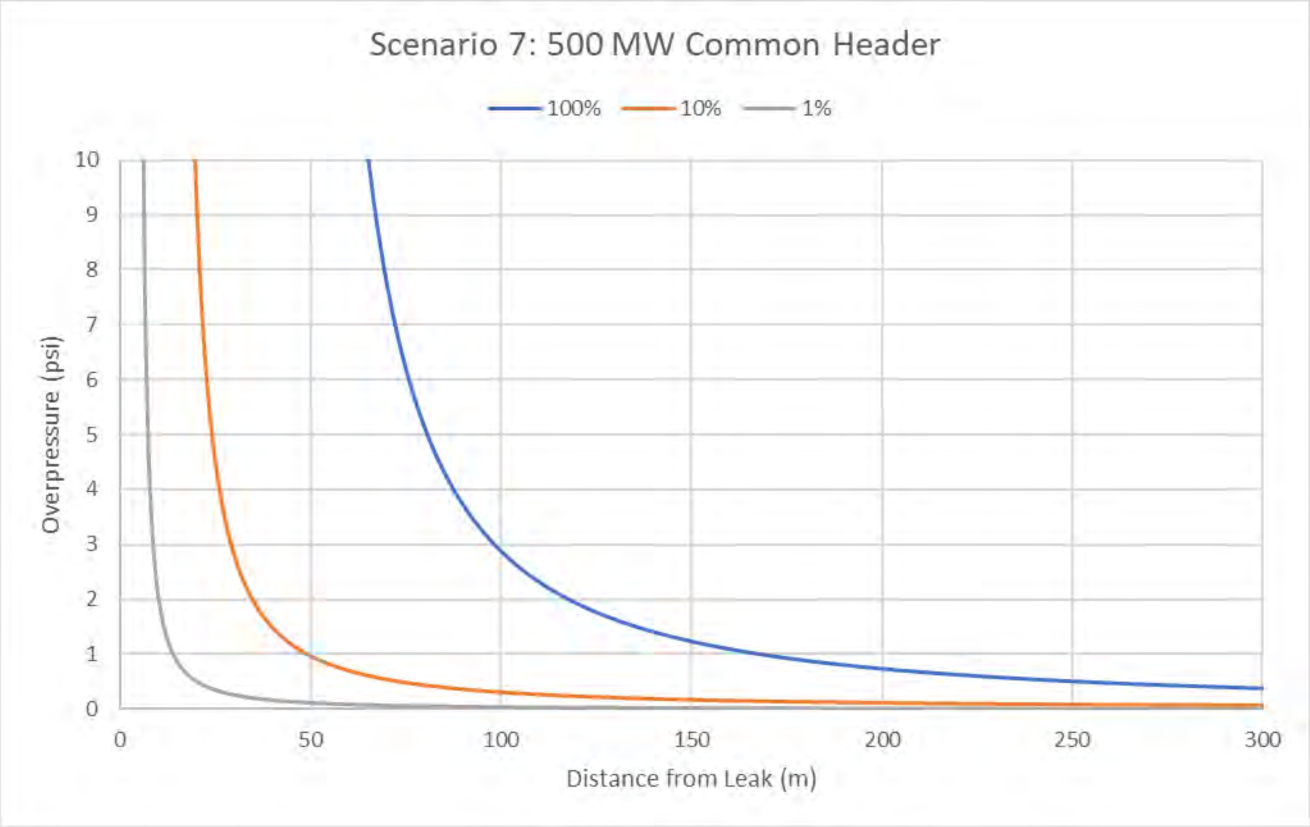

Figure 6: Scenario 7 Overpressure Results

6.2.5. *Scenario 8*

The system parameters for Scenario 8 are evaluated to inform the necessity for appropriate mitigation strategies for the 1,000 MW plant if a common header is used to transport the hydrogen to a storage facility. For this scenario, 10% and 1% area partial break cases were also evaluated. Table 29 shows the distance at which the overpressure generated from the detonation did not exceed the discrete fragility overpressure values. As shown, the overpressure drops below 1 psi at 215 meters for the full-bore break case. Similar to the other scenarios, the partial break cases show that overpressure is reduced considerably as the leak size is reduced.

Table 29: Scenario 8 Overpressure Results

Scenario 8: Overpressure				
Effective Pressure		**100% Area Distance (m)**	**10% Area Distance (m)**	**1% Area Distance (m)**
psi	**kPa**			
0.1	0.69	943	266	74
0.16	1.1	681	193	54
0.2	1.38	585	166	47
0.28	1.93	468	133	38
0.32	2.21	429	122	35
0.48	3.31	331	95	27
0.59	4.07	292	84	24
0.71	4.9	262	76	22
0.97	6.69	219	64	18
1	6.90	215	63	18
1.49	10.27	174	51	15
1.5	10.34	173	51	15
2.16	14.89	145	43	13

Figure 7 shows the overpressure as a function of distance from the leak location. As shown, the overpressure drops below 1 psi less than 65 meters for both of the partial breaks analyzed. The full-bore scenario drops below 1 psi at 215 meters from the leak location.

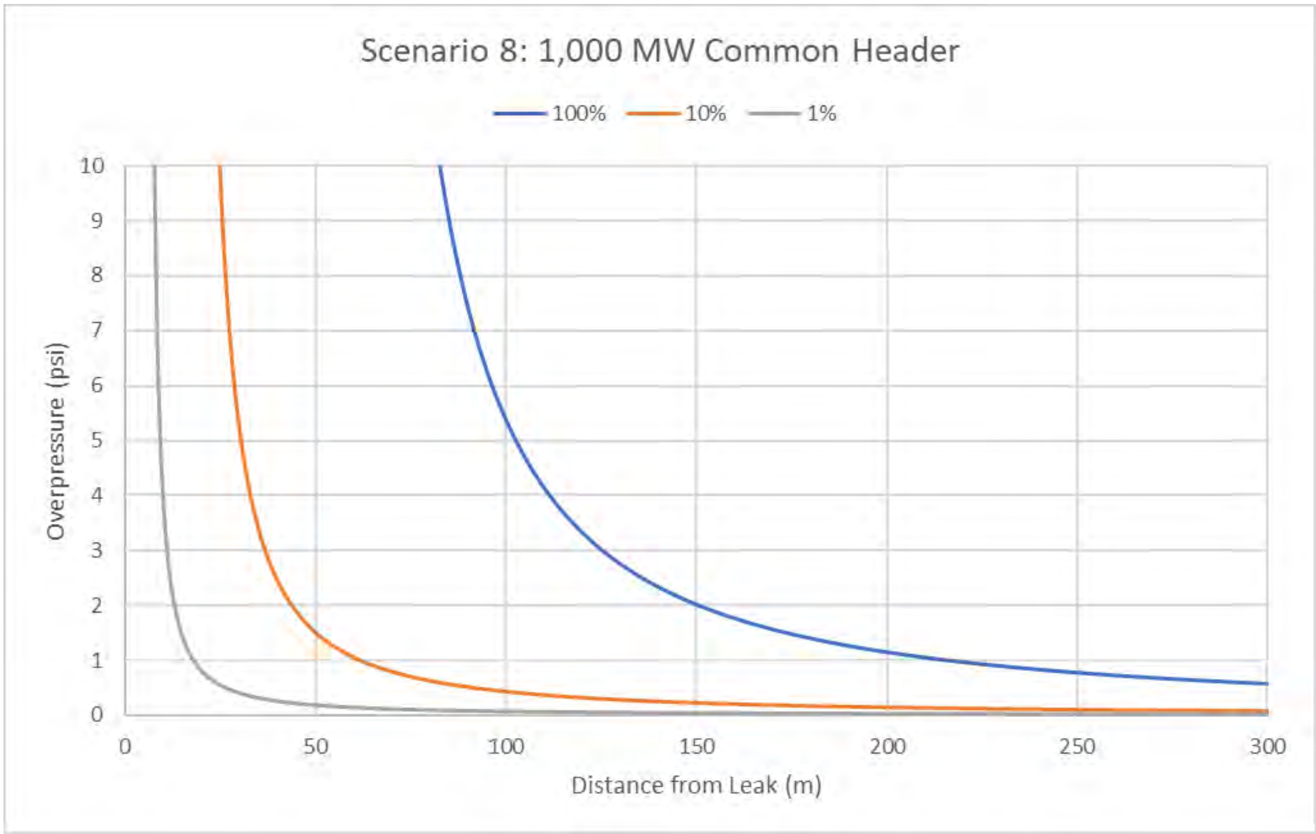

Figure 7: Scenario 8 Overpressure Results

6.2.6. Scenario 9

The system parameters for Scenario 9 are evaluated to inform the consequence of a leak from a nearby storage facility. There are many options that a utility can choose for hydrogen storage (tank size, pressure, PRD size, etc.). A commercially available tank was evaluated for a PRD release to illustrate a typical consequence at a storage facility. Because the full-bore leak scenario did not result in appreciable overpressure at distance, no partial breaks were evaluated for this case. Table 30 shows the distance at which the overpressure generated from the detonation did not exceed the discrete fragility overpressure values. As shown, the overpressure drops below 1 psi at 8 meters for the full-bore break case.

Table 30: Scenario 9 Overpressure Results

Effective Pressure		**Scenario 9 100% Area Distance (m)**
psi	**kPa**	
0.1	0.69	32
0.16	1.1	23
0.2	1.38	20
0.28	1.93	16
0.32	2.21	15
0.48	3.31	12
0.59	4.07	11
0.71	4.9	10
0.97	6.69	8
1	6.90	8
1.49	10.27	7
1.5	10.34	7
2.16	14.89	6

Figure 8 shows the overpressure as a function of distance from the leak location. As shown, the overpressure drops below 1 psi around 8 meters for the full-bore leak scenario.

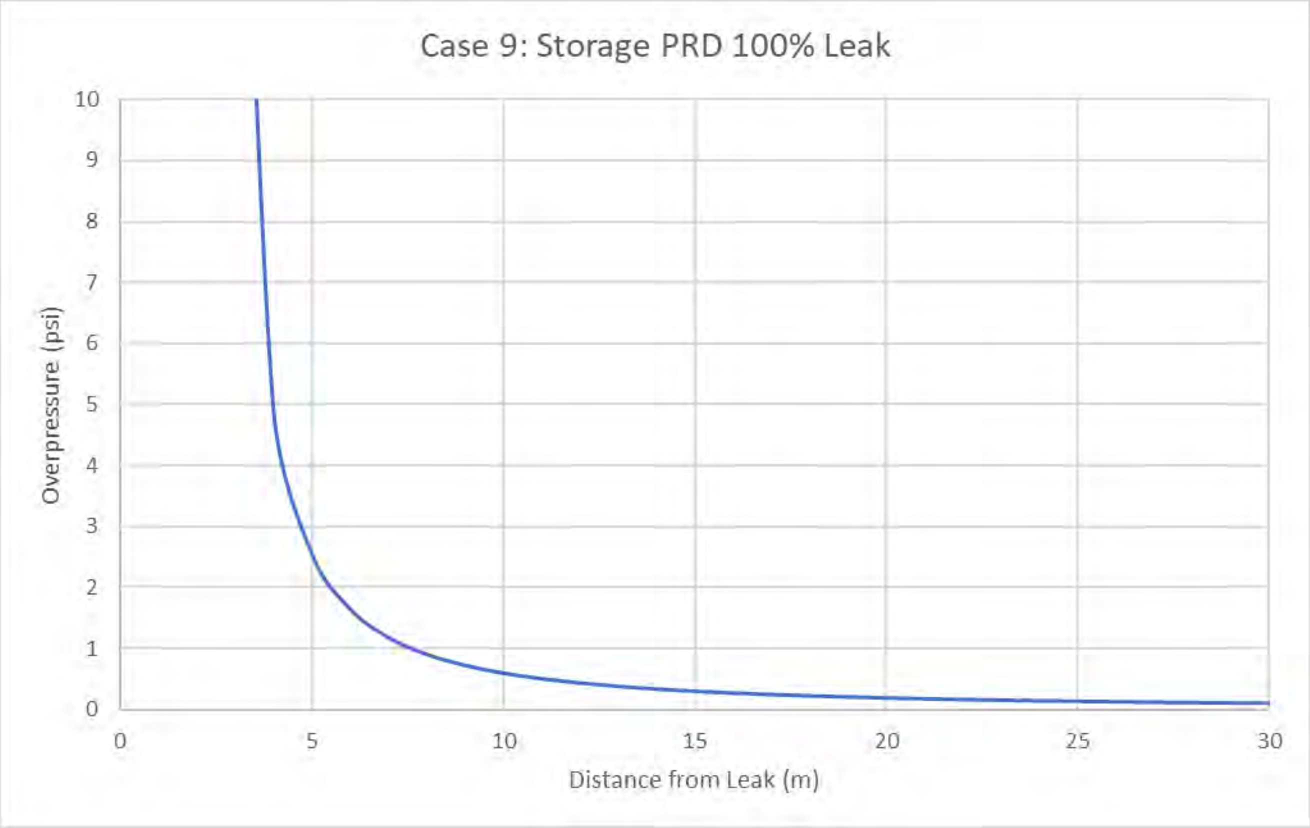

Figure 8: Scenario 9 Overpressure Results

6.2.7. Sensitivity Analysis

To quantify the uncertainty in the methodology used to calculate the overpressure results, a different unconfined overpressure method was used in a sensitivity analysis. The TNT equivalence method was evaluated for each of the scenarios to identify the difference in set-back distances between the two methods. The HyRAM+ technical reference manual includes details on the default inputs and equations used to perform the TNT equivalence calculations [7]. Note, a 3% equivalence factor is used to scale the flammable mass. This is the default value in HyRAM+ for TNT equivalence calculations, which is the recommended value from the Center for Chemical Process Safety [12]. Table 31 through Table 36 show the overpressure results from the TNT equivalence method sensitivity. The TNT equivalence method resulted in larger distances to the discrete overpressure values than that of the Bauwens methodology.

Table 31: Scenario 1, 2, & 3 TNT Equivalence Sensitivity Results

Overpressure				
Effective Pressure		Scenario 1 Distance (m)	Scenario 2 Distance (m)	Scenario 3 Distance (m)
psi	kPa			
0.48	3.31	7	16	16
0.59	4.07	6	14	14
0.71	4.9	6	12	13
0.97	6.69	5	10	11
1	6.90	5	10	10
1.49	10.27	4	8	8
1.5	10.34	4	8	8
2.16	14.89	3	7	7

Table 32: Scenario 4 & 5 TNT Equivalence Sensitivity Results

Scenario 4 & 5: Overpressure				
Effective Pressure		100% Area Distance (m)	10% Area Distance (m)	1% Area Distance (m)
psi	kPa			
0.48	3.31	80	26	8
0.59	4.07	69	22	7
0.71	4.9	61	20	7
0.97	6.69	51	16	5
1	6.90	49	16	5
1.49	10.27	39	13	4
1.5	10.34	39	13	4
2.16	14.89	33	11	4

Table 33: Scenario 6 TNT Equivalence Sensitivity Results

Scenario 6: Overpressure				
Effective Pressure		100% Area Distance (m)	10% Area Distance (m)	1% Area Distance (m)
psi	kPa			
0.48	3.31	131	42	14
0.59	4.07	113	36	12
0.71	4.9	101	32	11
0.97	6.69	83	27	9
1	6.90	81	26	9
1.49	10.27	64	21	7
1.5	10.34	64	21	7
2.16	14.89	53	17	6

Table 34: Scenario 7 TNT Equivalence Sensitivity Results

Scenario 7: Overpressure				
Effective Pressure		**100% Area Distance (m)**	**10% Area Distance (m)**	**1% Area Distance (m)**
psi	**kPa**			
0.48	3.31	331	108	35
0.59	4.07	285	93	30
0.71	4.9	254	83	27
0.97	6.69	209	68	22
1	6.90	204	67	22
1.49	10.27	161	53	17
1.5	10.34	161	53	17
2.16	14.89	135	44	14

Table 35: Scenario 8 TNT Equivalence Sensitivity Results

Scenario 8: Overpressure				
Effective Pressure		**100% Area Distance (m)**	**10% Area Distance (m)**	**1% Area Distance (m)**
psi	**kPa**			
0.48	3.31	408	136	44
0.59	4.07	352	117	38
0.71	4.9	314	104	34
0.97	6.69	258	86	28
1	6.90	252	84	27
1.49	10.27	199	66	21
1.5	10.34	199	66	21
2.16	14.89	167	55	18

Table 36: Scenario 9 TNT Equivalence Sensitivity Results

Effective Pressure		Scenario 9 100% Area Distance (m)
psi	kPa	
0.48	3.31	22
0.59	4.07	19
0.71	4.9	17
0.97	6.69	14
1	6.90	14
1.49	10.27	11
1.5	10.34	11
2.16	14.89	9

Figure 9 through Figure 14 show comparison plots between the two methodologies for each of the scenarios. As shown, the TNT method is limiting for each of the scenarios.

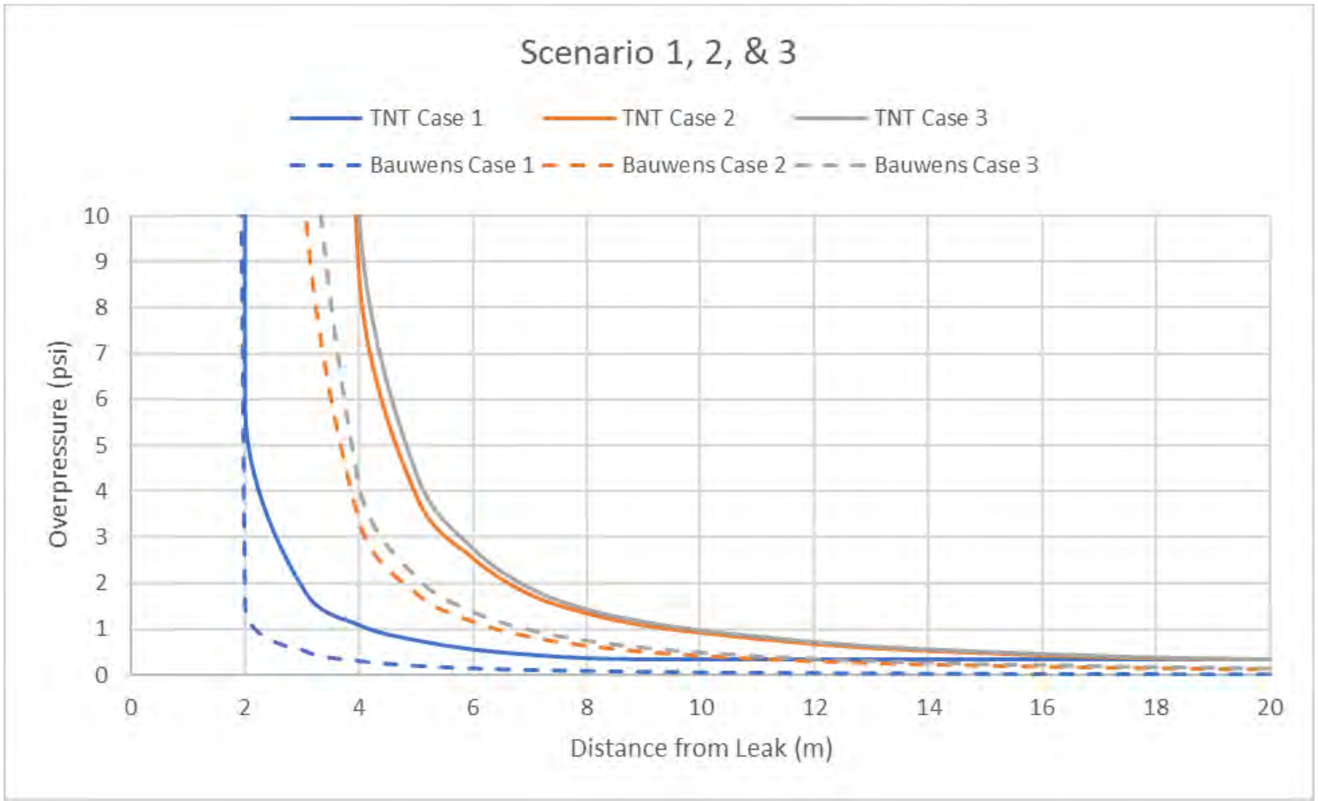

Figure 9: Scenario 1, 2, & 3 Sensitivity Results Comparison

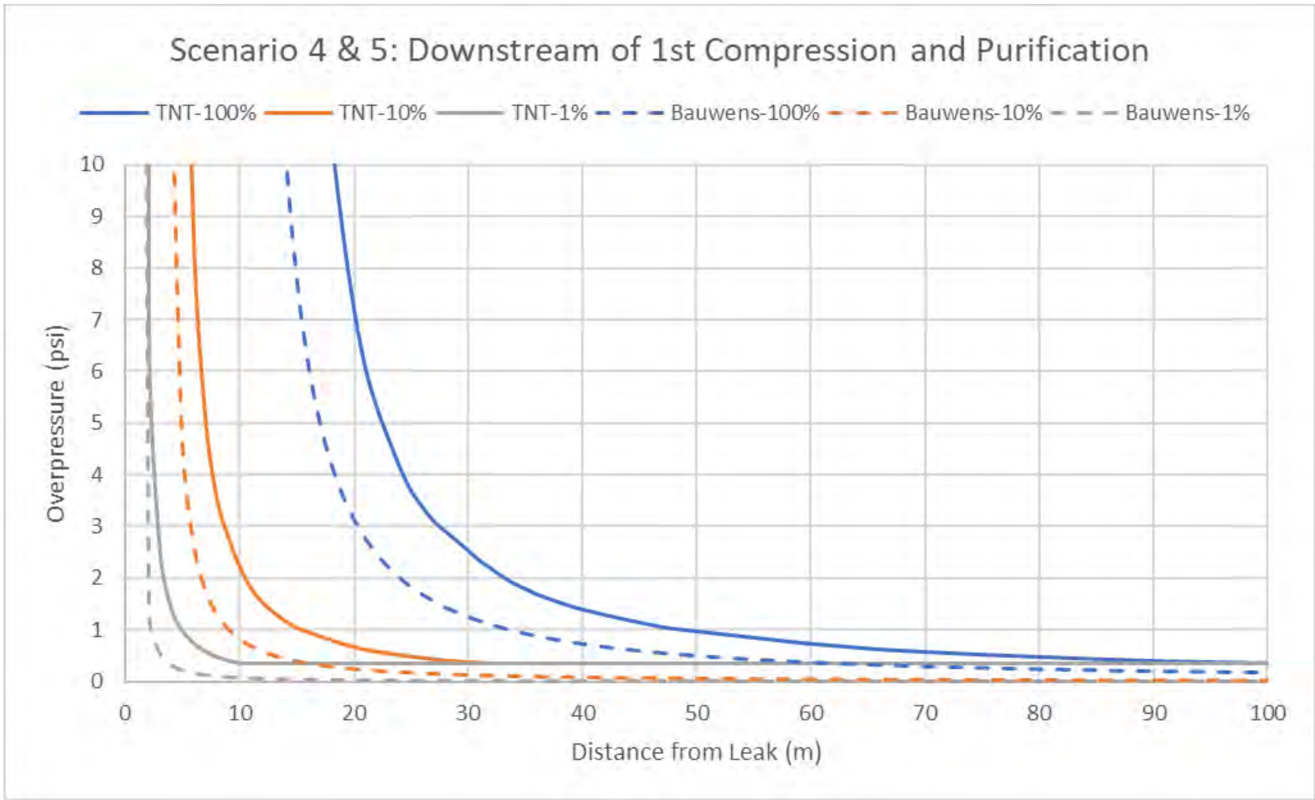

Figure 10: Scenario 4 & 5 Sensitivity Results Comparison

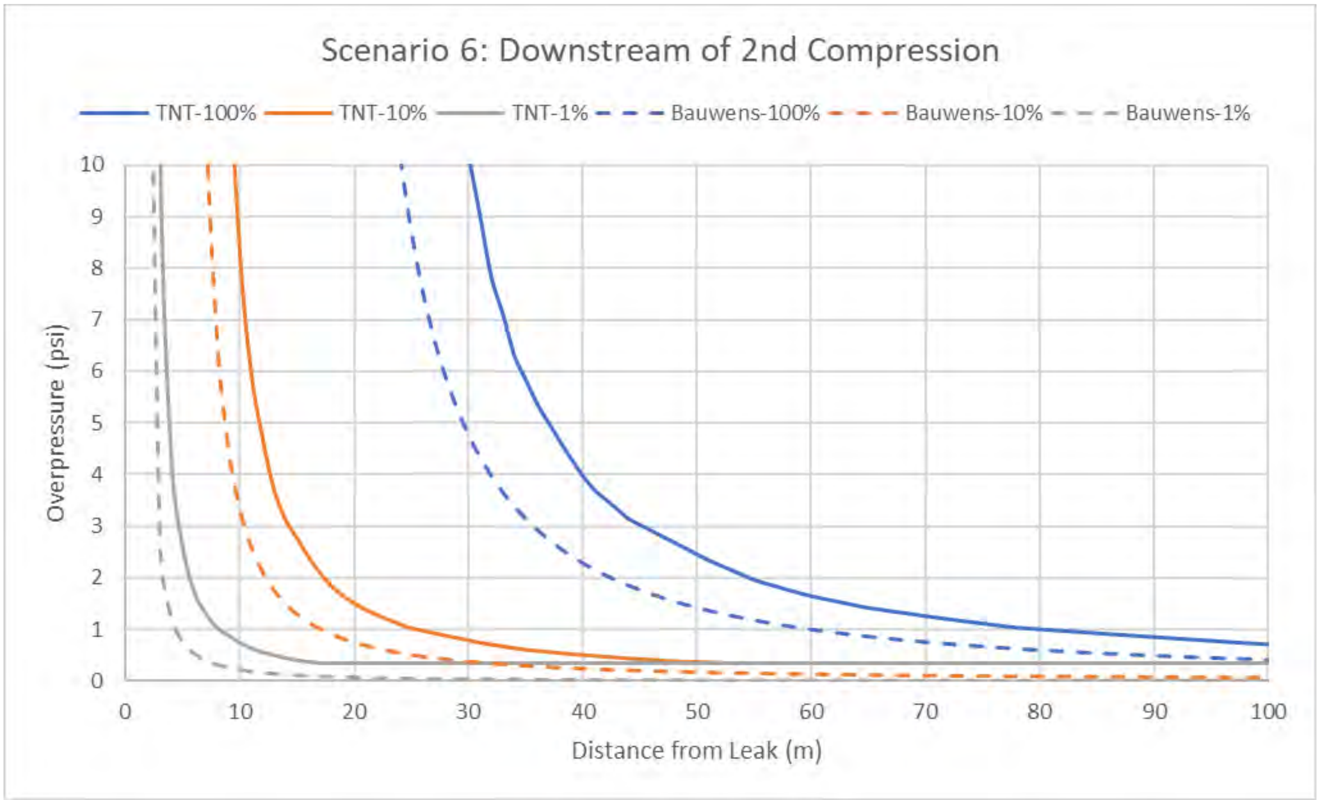

Figure 11: Scenario 6 Sensitivity Results Comparison

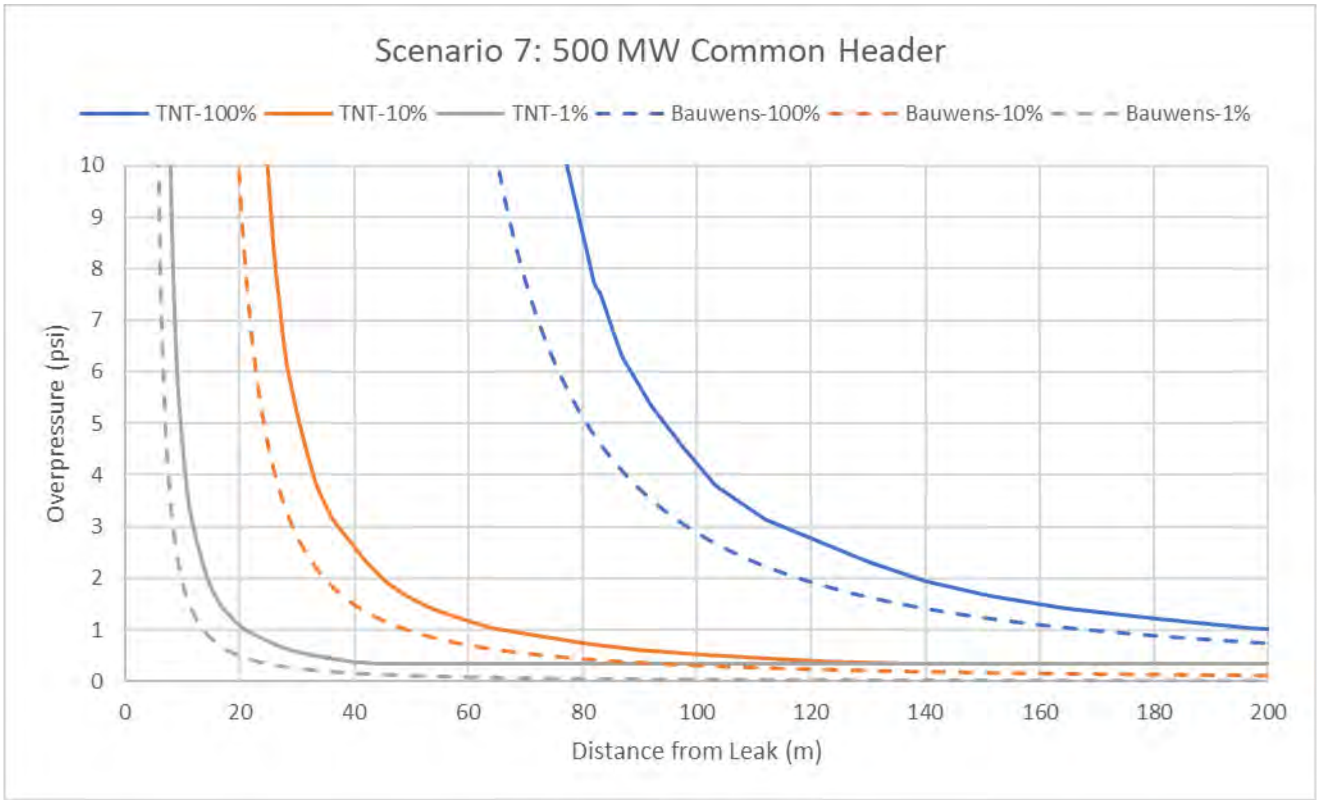

Figure 12: Scenario 7 Sensitivity Results Comparison

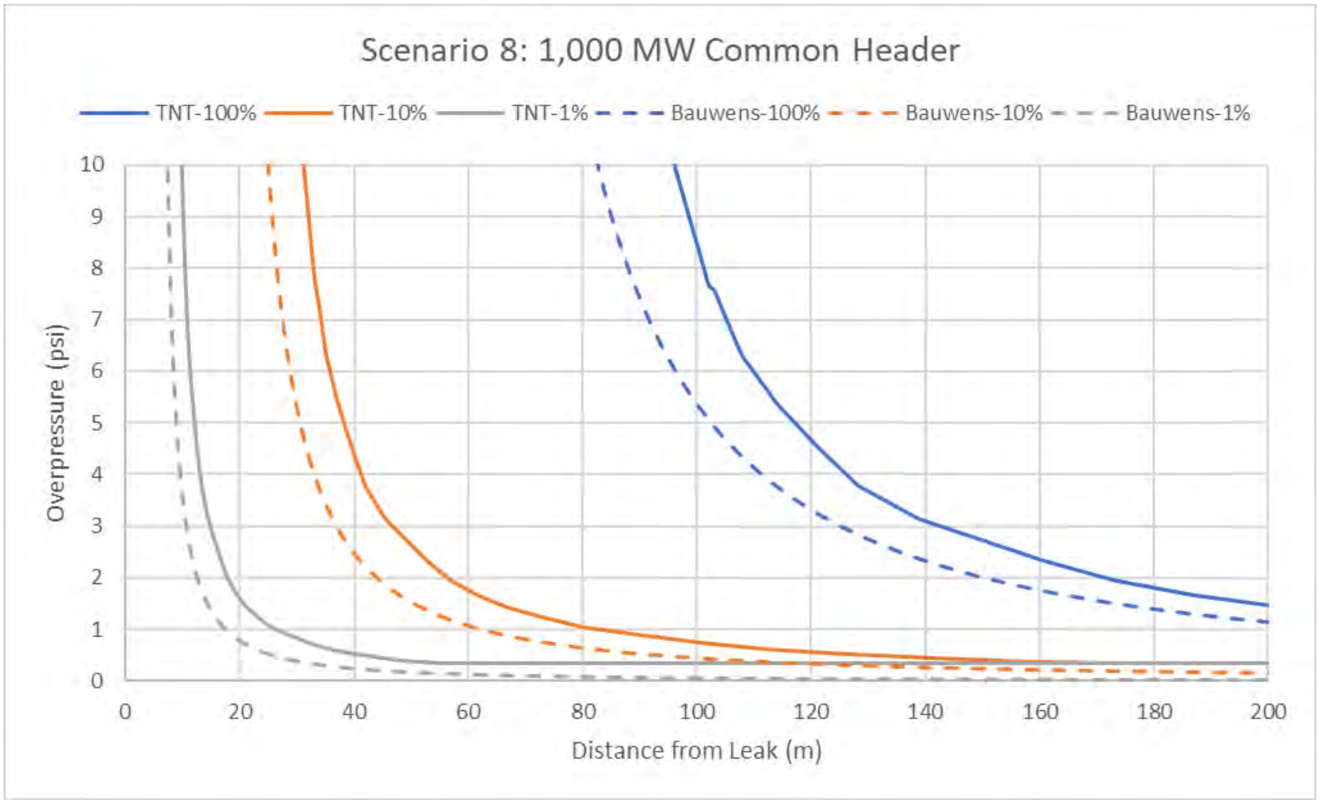

Figure 13: Scenario 8 Sensitivity Results Comparison

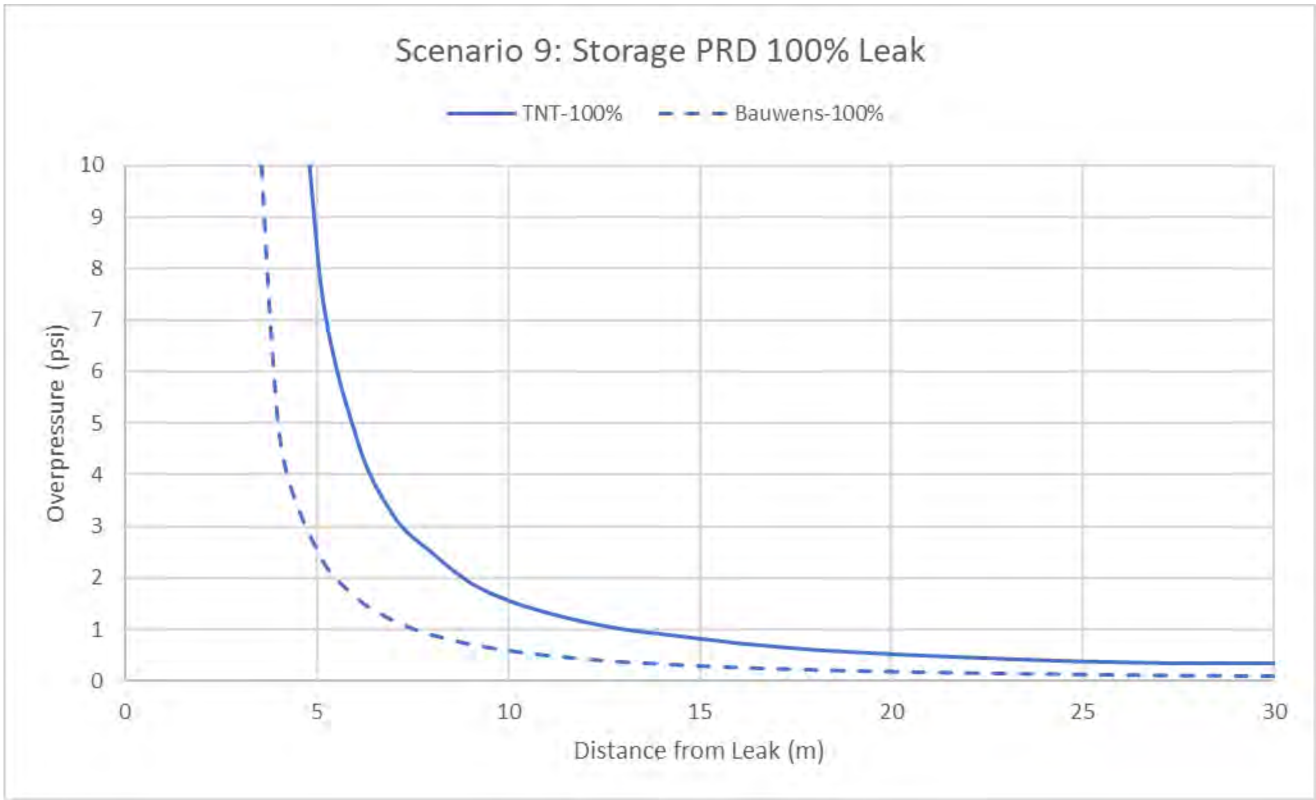

Figure 14: Scenario 9 Sensitivity Results Comparison

Table 37 through Table 42 shows a comparison of the results between the two methodologies. As mentioned, the TNT equivalence method results in larger distances at each of the discrete overpressure fragility values. Generally, the difference between the two models increases as the distance from the leak increases. For the 0.48 psi fragility value, the largest nominal difference was seen in Scenario 8 at 77 meters.

Table 37: Scenario 1, 2, & 3 Sensitivity Results Comparison

Scenario 1, 2 & 3: Overpressure							
Effective Pressure		% Increase for TNT Method			Nominal Increase for TNT Method		
		Case 1 Distance (m)	Case 2 Distance (m)	Case 3 Distance (m)	Case 1 Distance (m)	Case 2 Distance (m)	Case 3 Distance (m)
psi	kPa						
0.48	3.31	75%	60%	45%	3	6	5
0.59	4.07	100%	56%	40%	3	5	4
0.71	4.9	100%	50%	44%	3	4	4
0.97	6.69	67%	43%	38%	2	3	3
1	6.90	67%	43%	25%	2	3	2
1.49	10.27	33%	33%	33%	1	2	2
1.5	10.34	33%	33%	33%	1	2	2
2.16	14.89	50%	40%	17%	1	2	1
		Average % Increase for TNT Method			Average Nominal Increase for TNT Method		
		66%	45%	34%	2	3.375	2.875

Table 38: Scenario 4 & 5 Sensitivity Results Comparison

Scenario 4 & 5: Overpressure							
Effective Pressure		% Increase for TNT Method			Nominal Increase for TNT Method		
		100% Area Distance (m)	10% Area Distance (m)	1% Area Distance (m)	100% Area Distance (m)	10% Area Distance (m)	1% Area Distance (m)
psi	kPa						
0.48	3.31	57%	86%	100%	29	12	4
0.59	4.07	53%	83%	133%	24	10	4
0.71	4.9	49%	82%	133%	20	9	4
0.97	6.69	50%	60%	67%	17	6	2
1	6.90	44%	60%	67%	15	6	2
1.49	10.27	39%	63%	100%	11	5	2
1.5	10.34	39%	63%	100%	11	5	2
2.16	14.89	38%	57%	100%	9	4	2
		Average % Increase for TNT Method			Average Nominal Increase for TNT Method		
		46%	69%	100%	17	7.125	2.75

Table 39: Scenario 6 Sensitivity Results Comparison

Scenario 6: Overpressure							
Effective Pressure		% Increase for TNT Method			Nominal Increase for TNT Method		
psi	kPa	100% Area Distance (m)	10% Area Distance (m)	1% Area Distance (m)	100% Area Distance (m)	10% Area Distance (m)	1% Area Distance (m)
0.48	3.31	42%	62%	100%	39	16	7
0.59	4.07	40%	57%	100%	32	13	6
0.71	4.9	38%	52%	83%	28	11	5
0.97	6.69	34%	50%	80%	21	9	4
1	6.90	33%	44%	80%	20	8	4
1.49	10.27	31%	40%	75%	15	6	3
1.5	10.34	31%	50%	75%	15	7	3
2.16	14.89	26%	42%	50%	11	5	2
		Average % Increase for TNT Method			Average Nominal Increase for TNT Method		
		34%	50%	80%	22.625	9.375	4.25

Table 40: Scenario 7 Sensitivity Results Comparison

Scenario 7: Overpressure							
Effective Pressure		% Increase for TNT Method			Nominal Increase for TNT Method		
psi	kPa	100% Area Distance (m)	10% Area Distance (m)	1% Area Distance (m)	100% Area Distance (m)	10% Area Distance (m)	1% Area Distance (m)
0.48	3.31	28%	44%	67%	72	33	14
0.59	4.07	25%	39%	58%	57	26	11
0.71	4.9	25%	38%	59%	50	23	10
0.97	6.69	22%	36%	57%	38	18	8
1	6.90	21%	34%	57%	36	17	8
1.49	10.27	18%	33%	42%	25	13	5
1.5	10.34	18%	33%	42%	25	13	5
2.16	14.89	18%	29%	40%	21	10	4
		Average % Increase for TNT Method			Average Nominal Increase for TNT Method		
		22%	36%	53%	40.5	19.125	8.125

Table 41: Scenario 8 Sensitivity Results Comparison

Scenario 8: Overpressure							
Effective Pressure		% Increase for TNT Method			Nominal Increase for TNT Method		
psi	kPa	100% Area Distance (m)	10% Area Distance (m)	1% Area Distance (m)	100% Area Distance (m)	10% Area Distance (m)	1% Area Distance (m)
0.48	3.31	23%	43%	63%	77	41	17
0.59	4.07	21%	39%	58%	60	33	14
0.71	4.9	20%	37%	55%	52	28	12
0.97	6.69	18%	34%	56%	39	22	10
1	6.90	17%	33%	50%	37	21	9
1.49	10.27	14%	29%	40%	25	15	6
1.5	10.34	15%	29%	40%	26	15	6
2.16	14.89	15%	28%	38%	22	12	5
		Average % Increase for TNT Method			Average Nominal Increase for TNT Method		
		18%	34%	50%	42.25	23.375	9.875

Table 42: Scenario 9Sensitivity Results Comparison

Scenario 9: Overpressure			
Effective Pressure		% Increase for TNT Method	Nominal Increase for TNT Method
		100% Area Distance (m)	100% Area Distance (m)
psi	kPa		
0.48	3.31	83%	10
0.59	4.07	73%	8
0.71	4.9	70%	7
0.97	6.69	75%	6
1	6.90	75%	6
1.49	10.27	57%	4
1.5	10.34	57%	4
2.16	14.89	50%	3
		Average % Increase for TNT Method	Average Nominal Increase for TNT Method
		68%	6

6.3. Radiative Heat Flux

The radiative heat flux from a jet flame resulting from an ignited hydrogen leak was also evaluated as a potential consequence. HyRAM+ was utilized to perform the radiative heat flux calculations as a function of distance [7]. Note, the jet flame resulting from an ignited hydrogen leak does not remain completely horizontal due to buoyancy. Therefore, the y-value (height) at which the heat flux is reported is not zero. The jet flame will rise at different rates based on the varying input parameters. The heat flux reported in these results is at the y-coordinate that represents 75% of the visible flame length along the streamline of the jet flame, which is different for each case. Note, this is the default behavior in HyRAM+ [7].

6.3.1. Scenarios 1, 2, & 3

Similar to the overpressure evaluation, only full-bore leaks were evaluated for Scenario 1, 2, and 3. Table 43 shows the results for the different radiation levels outlined in Section 4. As shown, even for the lowest radiation fragility value, the set-back distance is within 15 m from the leak source.

Table 43: Scenario 1, 2, & 3 Heat Flux Results

Heat Flux			
Radiation Level (kw/m^2)	**Scenario 1 Distance (m)**	**Scenario 2 Distance (m)**	**Scenario 3 Distance (m)**
1.6	6	13	13
5	5	10	10
9.5	5	9	9
12.5	5	9	9
25	4	8	8
37.5	4	8	8

Figure 15 shows the heat flux as a function of distance from the leak for Scenario 1, 2, & 3. As shown, the heat flux drops rapidly as the distance from the leak increases.

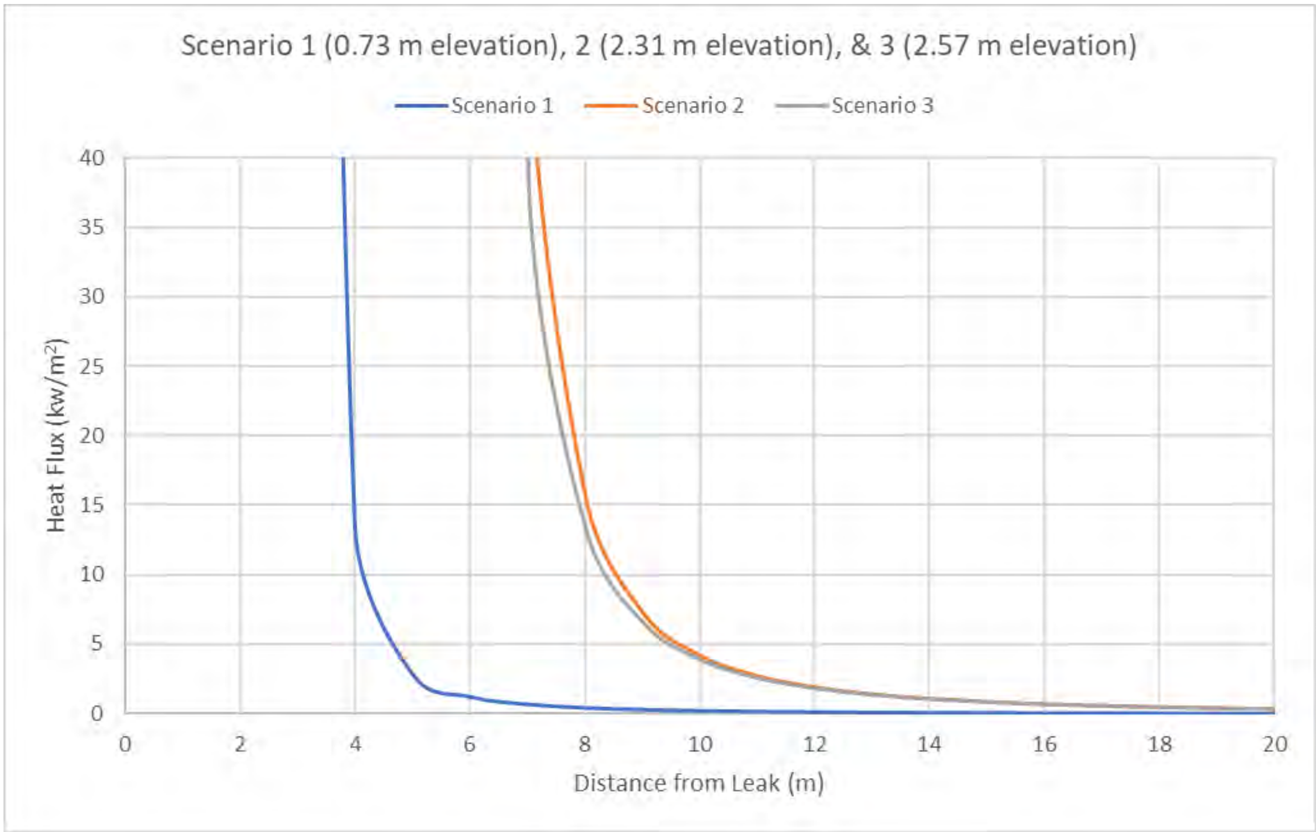

Figure 15: Scenario 1, 2, & 3 Heat Flux Results

6.3.2. *Scenarios 4 & 5*

Full-bore, 10%, and 1% area partial break cases were evaluated for Scenario 4 and 5. Table 44 shows the results for the different radiation levels outlined in Section 4. As shown, the minimum heat flux sufficient to cause damage to process equipment (37.5 kw/m^2) occurs at 56 meters for the full-bore leak. As with overpressure, the heat flux is significantly reduced as the break size decreases.

Table 44: Scenario 4 & 5 Heat Flux Results

Scenario 4 & 5: Heat Flux			
Radiation Level (kw/m^2)	**100% Area Distance (m)**	**10% Area Distance (m)**	**1% Area Distance (m)**
1.6	115	35	10
5	82	26	8
9.5	70	23	7
12.5	66	22	7
25	59	20	6
37.5	56	19	6

Figure 16 shows the heat flux as a function of distance from the leak for Scenario 4 & 5. Similar to the overpressure, the full-bore leak results in much further distances to discrete heat flux values than the partial leak cases.

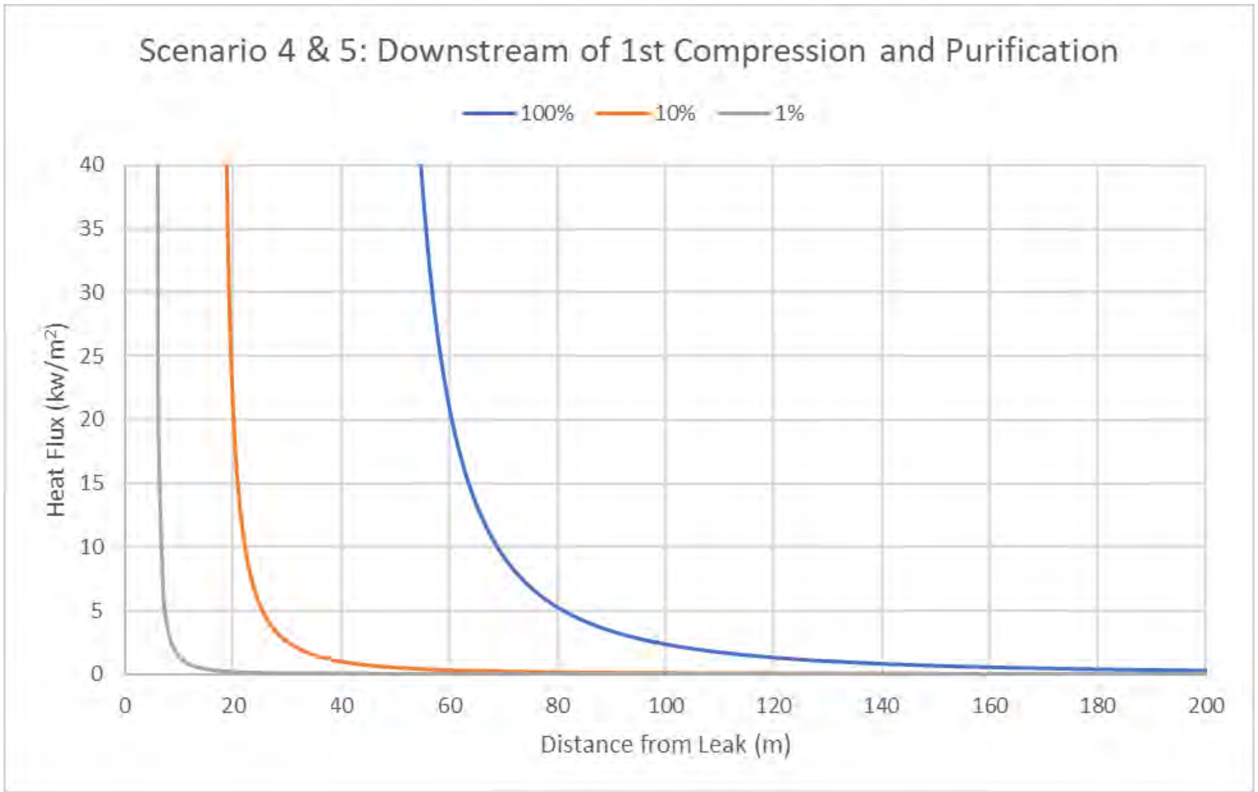

Figure 16: Scenario 4 & 5 Heat Flux Results

6.3.3. *Scenario 6*

The system parameters for Scenario 6 represent the limiting conditions in terms of consequence in the 100 MW hydrogen generation facility for heat flux as well. For this scenario, 10% and 1% area partial break cases were also evaluated. Table 45 shows the results for the different radiation levels outlined in Section 4. As shown, the minimum heat flux sufficient to cause damage to process equipment (37.5 kw/m^2) occurs at 88 meters for the full-bore leak. As with overpressure, the heat flux is significantly reduced as the break size decreases.

Table 45: Scenario 6 Heat Flux Results

Scenario 6: Heat Flux			
Radiation Level (kw/m^2)	**100% Area Distance (m)**	**10% Area Distance (m)**	**1% Area Distance (m)**
1.6	192	60	17
5	135	44	13
9.5	115	38	12
12.5	108	36	11
25	94	33	11
37.5	88	31	10

Figure 17 shows the heat flux as a function of distance from the leak for Scenario 6. Similar to the overpressure, the full-bore leak results in much further distances to discrete heat flux values than the partial leak cases.

Figure 17: Scenario 6 Heat Flux Results

6.3.4. *Scenario 7*

The system parameters for Scenario 7 represent the limiting conditions in terms of consequence in the 500 MW hydrogen generation facility. For this scenario, 10% and 1% area partial break cases were also evaluated. Table 46 shows the results for the different radiation levels outlined in Section 4. As shown, the minimum heat flux sufficient to cause damage to process equipment (37.5 kw/m^2) occurs at 208 meters for the full-bore leak. As with overpressure, the heat flux is significantly reduced as the break size decreases.

Table 46: Scenario 7 Heat Flux Results

Scenario 7: Heat Flux			
Radiation Level (kw/m^2)	**100% Area Distance (m)**	**10% Area Distance (m)**	**1% Area Distance (m)**
1.6	503	157	48
5	344	111	36
9.5	286	94	31
12.5	266	89	30
25	226	78	27
37.5	208	74	26

Figure 18 shows the heat flux as a function of distance from the leak for Scenario 7. Similar to the overpressure, the full-bore leak results in much further distances to discrete heat flux values than the partial leak cases.

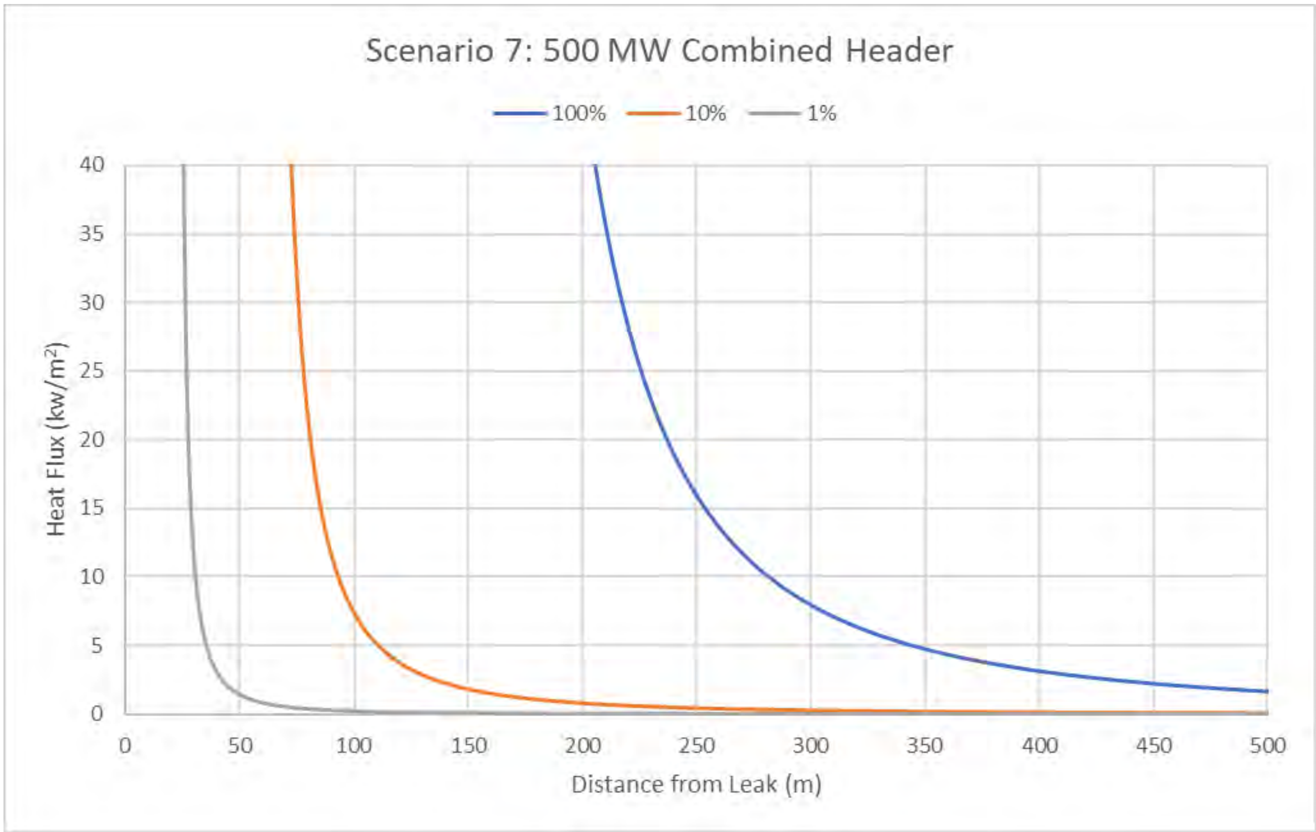

Figure 18: Scenario 7 Heat Flux Results

6.3.5. *Scenario 8*

The system parameters for Scenario 8 represent the limiting conditions in terms of consequence in the 1,000 MW hydrogen generation facility. For this scenario, 10% and 1% area partial break cases were also evaluated. Table 47 shows the results for the different radiation levels outlined in Section 4. As shown, the minimum heat flux sufficient to cause damage to process equipment (37.5 kw/m^2) occurs at 255 meters for the full-bore leak. As with overpressure, the heat flux is significantly reduced as the break size decreases.

Table 47: Scenario 8 Heat Flux Results

Scenario 8: Heat Flux			
Radiation Level (kw/m^2)	**100% Area Distance (m)**	**10% Area Distance (m)**	**1% Area Distance (m)**
1.6	629	199	62
5	428	140	45
9.5	354	118	39
12.5	328	111	37
25	278	97	34
37.5	255	91	32

Figure 19 shows the heat flux as a function of distance from the leak for Scenario 8. Similar to the overpressure, the full-bore leak results in much further distances to discrete heat flux values than the partial leak cases.

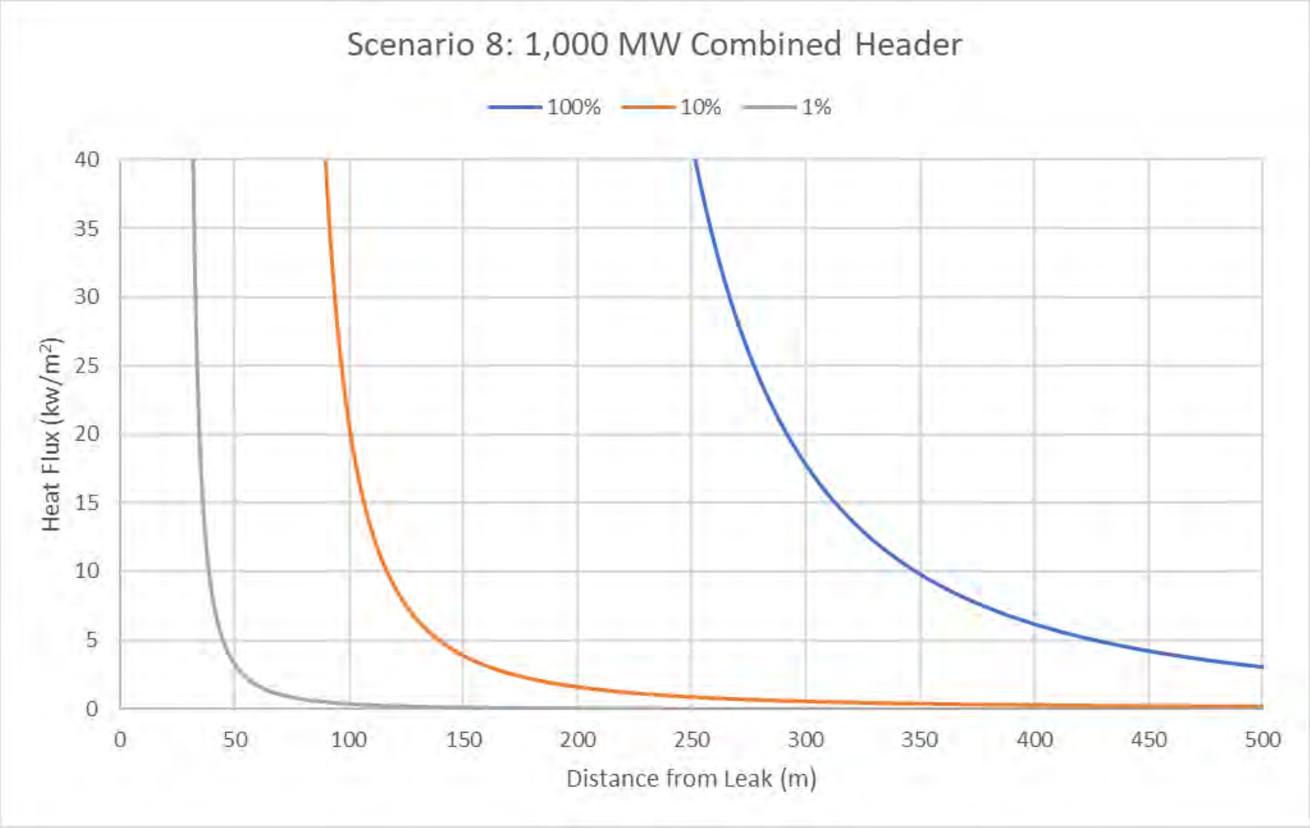

Figure 19: Scenario 8 Heat Flux Results

6.3.6. Scenario 9

The system parameters for Scenario 9 represent a leak scenario at the hydrogen storage facility. For this scenario, only a full-bore break case was evaluated. Table 48 shows the results for the different radiation levels outlined in Section 4. As shown, the minimum heat flux sufficient to cause damage to process equipment (37.5 kw/m^2) occurs at 15 meters for the full-bore leak.

Table 48: Scenario 9 Heat Flux Results

Radiation Level (kw/m^2)	100% Area Distance (m)
1.6	27
5	20
9.5	18
12.5	17
25	16
37.5	15

Figure 20 shows the heat flux as a function of distance from the leak for Scenario 9.

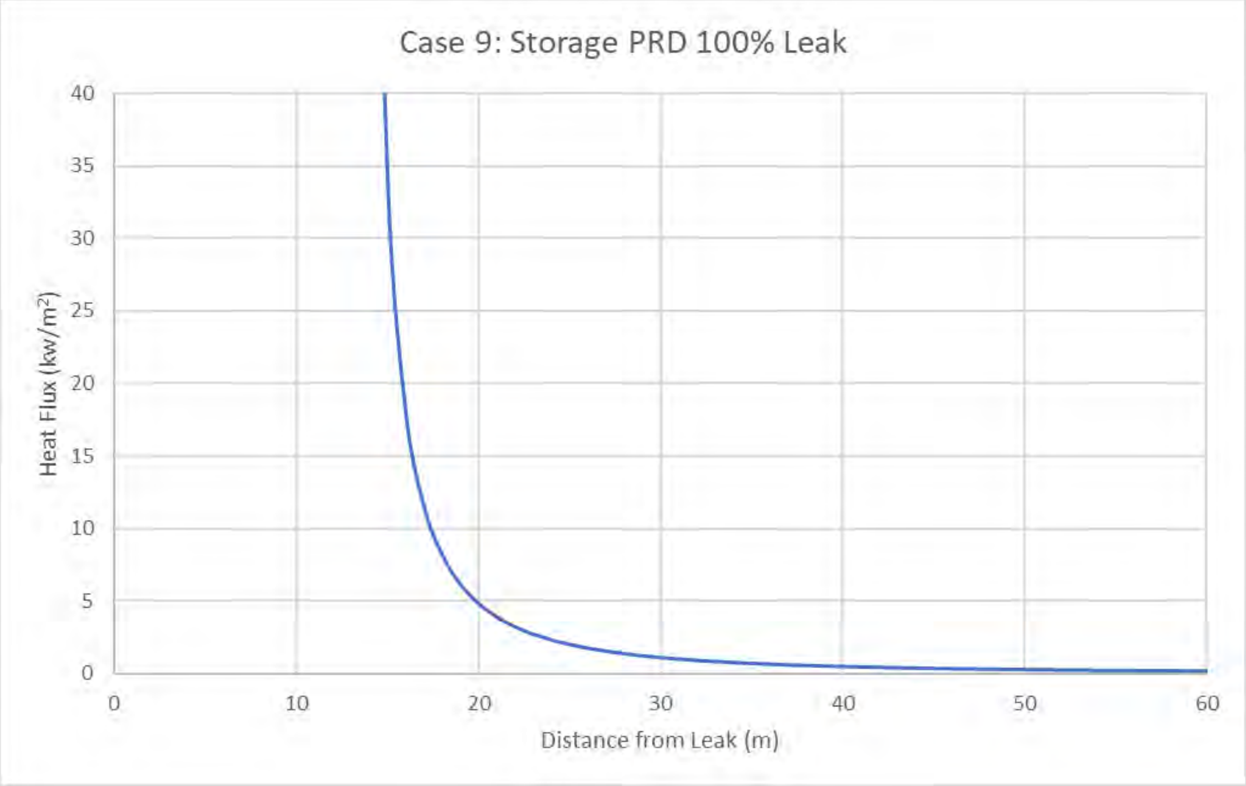

Figure 20: Scenario 9 Heat Flux Results

6.4. Regulatory Guide 1.91

Regulatory Guide 1.91 describes approved methods for evaluating postulated explosions at facilities in close proximity to NPPs [4]. This guide dictates the use of the TNT equivalence method to calculate the minimum safe distance from the NPP. Additionally, it documents a general fragility criterion of 1 psi. The methods used in this analysis differ somewhat to what was defined in the regulatory guide. A different method for calculating overpressure was used in this analysis, which was developed specifically for hydrogen (Bauwens). Additionally, the discrete fragility values are defined for different components, most of which are more conservative than the 1 psi fragility criterion. For comparison, the TNT equivalence method results are compared to the 1 psi fragility comparison to address the methodology prescribed in the regulatory guide. Note, the guidance states that scenario specifics should be used to justify the value for yield used in the TNT equivalence method. As stated, a 3% yield is the default value used in HyRAM+, which is the recommended value from the Center for Chemical Process Safety [12]. Table 49 shows the results from the TNT equivalence method compared to the 1 psi fragility comparison. As shown, the maximum distance is seen in Scenario 8 at 252 meters.

Table 49: Regulatory Guide 1.91 Results

Scenario	Distance to 1 psi (m)
Scenario 1	5
Scenario 2	10
Scenario 3	10
Scenario 4 & 5: 100%	49
Scenario 4 & 5: 10%	16
Scenario 4 & 5: 1%	5
Scenario 6: 100%	81
Scenario 6: 10%	26
Scenario 6: 1%	9
Scenario 7: 100%	204
Scenario 7: 10%	67
Scenario 7: 1%	22
Scenario 8: 100%	252
Scenario 8: 10%	84
Scenario 8: 1%	27
Scenario 9: 100%	14

7. CONCLUSION

The risk of a hydrogen generation facility located near an NPP has been evaluated herein, including the likelihood of an accident and the consequence. The frequency was developed with a bottom-up approach by documenting the components in the facility and calculating the frequency contribution from each component. For the 100 MW facility, the frequency of a leak in the evaluated system is fairly high (~14 expected occurrences/year for a very small leak and ~2 expected occurrences every 100 years for a full rupture). This is because there are 60 modular units that increase the number of components, which increases the likelihood of a leak. As expected, due to the additional components in the 500 MW and 1,000 MW designs, the frequency of a leak increases significantly for the higher power designs. Although the frequency of a leak is not negligible, the consequence of a detonation does not detrimentally affect critical targets at the NPP at a sufficient distance. For the 100 MW plant, the maximum safe distance from all of the scenarios evaluated was 161 meters at a fragility criterion of 0.2 psi. This occurred in Scenario 6, which is downstream of the second compression in the system. Due to the assumptions made for the 500 MW and 1,000 MW designs, this result is also applicable for the higher power designs. However, additional scenarios were evaluated for the 500 MW and 1,000 MW designs to evaluate the unmitigated consequence of a common header downstream of second compression that transports hydrogen to a storage facility. It is assumed that the header would be underground with concrete piping as a barrier, so the consequence is mitigated. Without mitigation, the overpressure consequence from the larger pipe diameter for the 500 MW and 1,000 MW designs is significantly greater than that of Scenario 6.

The consequence of radiative heat-flux was also quantified for all of the scenarios as an alternative consequence of a hydrogen leak. The maximum safe distance in terms of heat flux was 88 meters to the fragility criterion value of 37.5 kw/m^2 (heat flux sufficient to cause damage to process equipment). This occurred in Scenario 6 as well. As with overpressure, the unmitigated consequence of radiative heat-flux from a common header in the 500 MW and 1,000 MW designs would be significantly larger. Partial leak sizes were evaluated for each of the relevant scenarios to illustrate how the consequence diminishes for the smaller leak sizes.

Additionally, sensitivity evaluations for the overpressure results were run with the TNT equivalence methodology. These results were more conservative than the base-case methodology used herein. The TNT equivalence methodology was evaluated as a sensitivity because it is the prescribed overpressure calculation method in Regulatory Guide 1.91 [4]. However, the Bauwens model was used as the base case because it is specifically applicable to the consequence of interest for this application (detonation of a hydrogen plume). Based on the assumptions made about the design and system properties of the hydrogen generation facility, locations at distances greater than those calculated herein would allow for the safe colocation with NPPs.

REFERENCES

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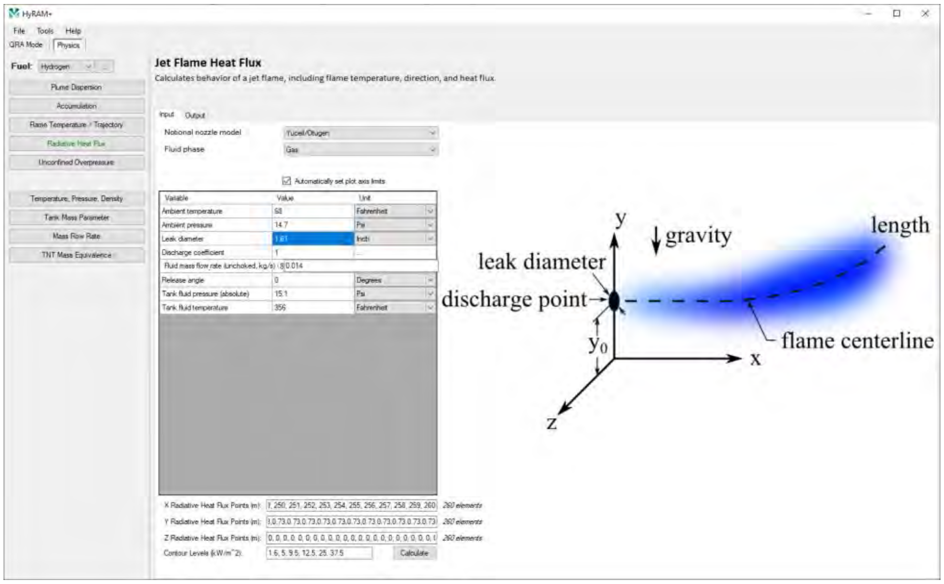
APPENDIX A. HYRAM+ TRACEABILITY FIGURES

This appendix contains the traceability figures from the HyRAM+ consequence calculations for both overpressure and radiative heat flux.

A.1. Scenario 1

A.1.1. Heat Flux



Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Fuel: Hydrogen

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	58	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	1.61	Inch
Discharge coefficient	1	...
Fluid mass flow rate (unchoked, kg/s) (8	0.014	
Release angle	0	Degrees
Tank fluid pressure (absolute)	15.1	Psi
Tank fluid temperature	356	Fahrenheit

X Radiative Heat Flux Points (m): 7, 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260 260 elements

Y Radiative Heat Flux Points (m): 3,0.73,0.73,0.73,0.73,0.73,0.73,0.73,0.73,0.73,0.73,0.73 260 elements

Z Radiative Heat Flux Points (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0 260 elements

Contour Levels (kW/m^2): 1.6, 5, 9.5, 12.5, 25, 37.5

Figure A-1: Scenario 1 Heat Flux Input Traceability Figure

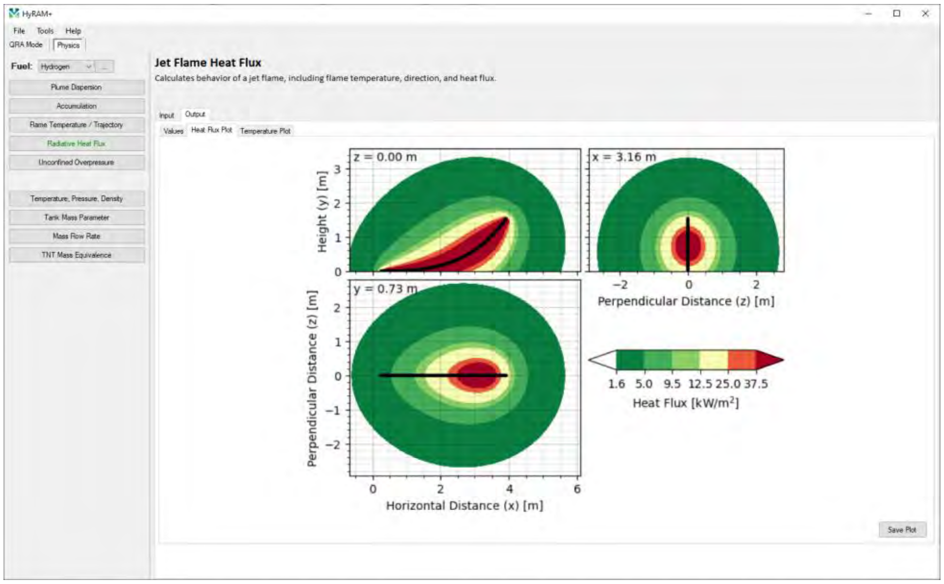
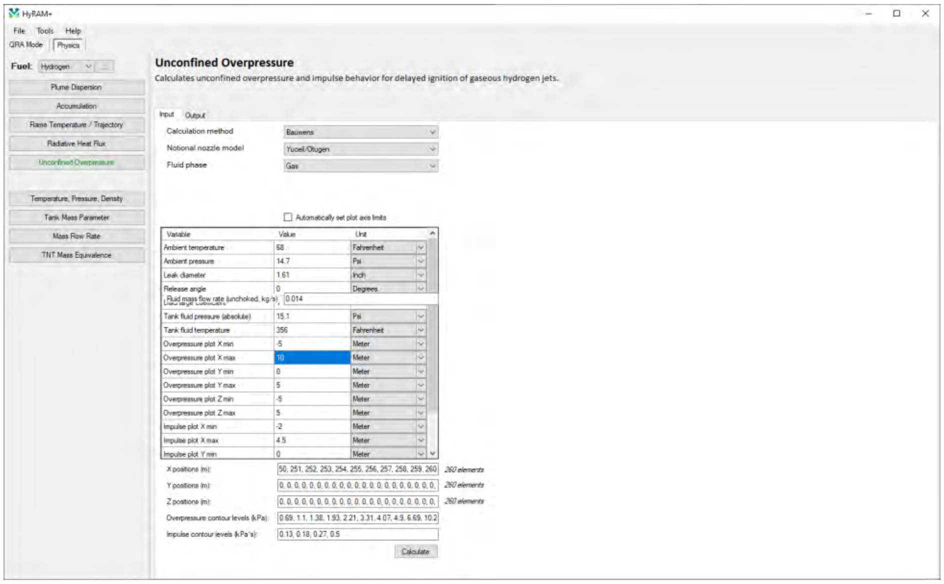


Figure A-2: Scenario 1 Heat Flux Output Traceability Figure

A.1.2. *Bauwens Overpressure*



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: Bauwens

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☐ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	1.61	Inch
Release angle	0	Degrees
Fluid mass flow rate (unchoked, kg/s)	0.014	
Tank fluid pressure (absolute)	15.1	Psi
Tank fluid temperature	356	Fahrenheit
Overpressure plot X min	-5	Meter
Overpressure plot X max	10	Meter
Overpressure plot Y min	0	Meter
Overpressure plot Y max	5	Meter
Overpressure plot Z min	-5	Meter
Overpressure plot Z max	5	Meter
Impulse plot X min	-2	Meter
Impulse plot X max	4.5	Meter
Impulse plot Y min	0	Meter

X positions (m): 50, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260 *260 elements*

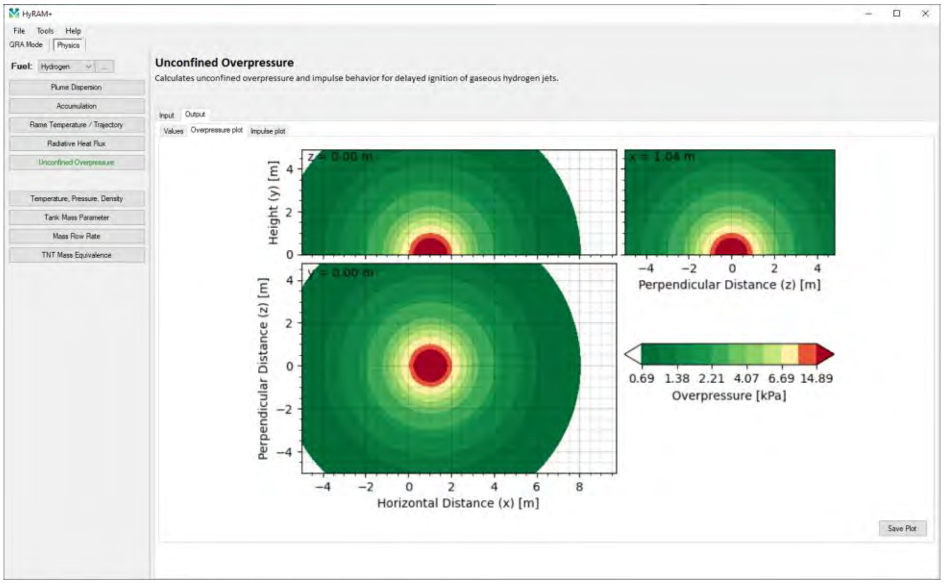
Y positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *260 elements*

Z positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *260 elements*

Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 10.2

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27, 0.5

Figure A-3: Scenario 1 Bauwens Overpressure Input Traceability Figure

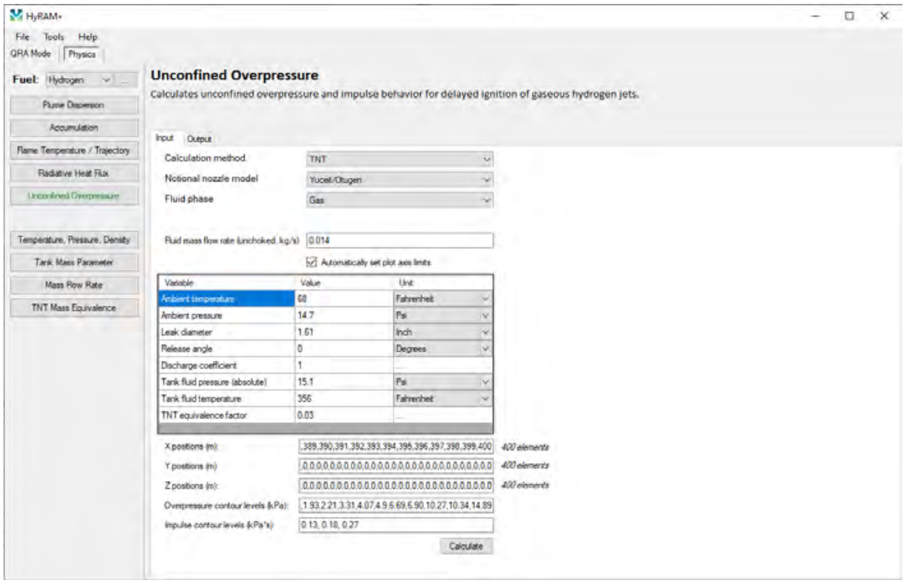


Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-4: Scenario 1 Bauwens Overpressure Output Traceability Figure

A.1.3. TNT Equivalence Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: TNT

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

Fluid mass flow rate (unchoked, kg/s): 0.014

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	1.61	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	15.1	Psi
Tank fluid temperature	356	Fahrenheit
TNT equivalence factor	0.03	...

X positions (m): ,389,390,391,392,393,394,395,396,397,398,399,400 400 elements

Y positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 400 elements

Z positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 400 elements

Overpressure contour levels (kPa): ,1.93,2.21,3.31,4.07,4.9,6.69,6.90,10.27,10.34,14.89

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-5: Scenario 1 TNT Overpressure Input Traceability Figure

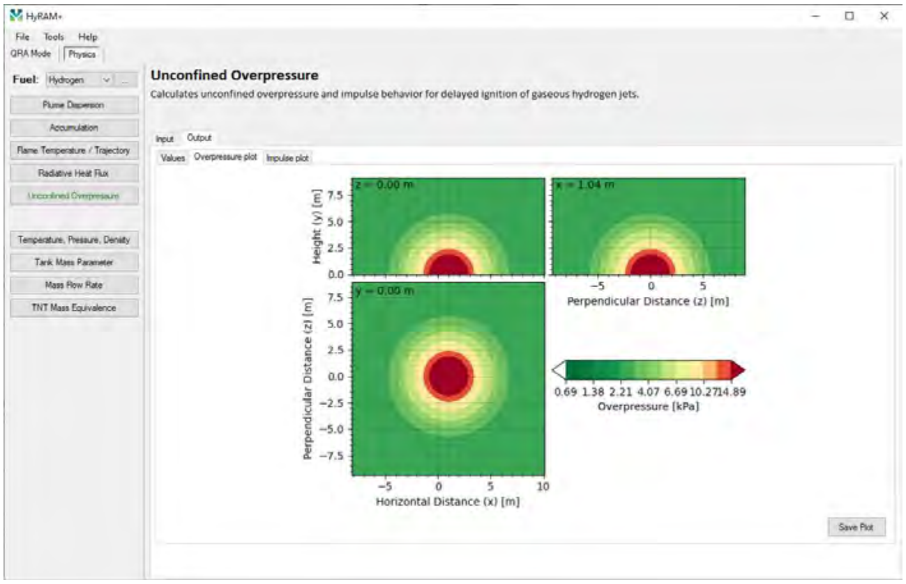
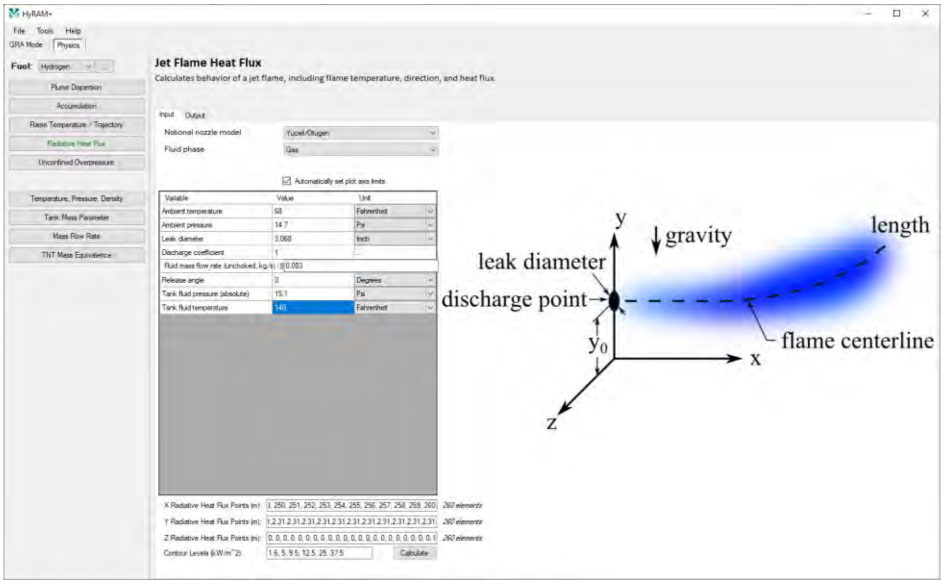


Figure A-6: Scenario 1 TNT Overpressure Output Traceability Figure

A.2. Scenario 2

A.2.1. Heat Flux



Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Fuel: Hydrogen

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	3.068	Inch
Discharge coefficient	1	...
Fluid mass flow rate (unchoked, kg/s) (8)	0.083	
Release angle	0	Degrees
Tank fluid pressure (absolute)	15.1	Psi
Tank fluid temperature	140	Fahrenheit

X Radiative Heat Flux Points (m):), 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260 *260 elements*

Y Radiative Heat Flux Points (m): 1,2.31,2.31,2.31,2.31,2.31,2.31,2.31,2.31,2.31,2.31,2.31 *260 elements*

Z Radiative Heat Flux Points (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, (*260 elements*

Contour Levels (kW/m^2): 1.6, 5, 9.5, 12.5, 25, 37.5

Figure A-7: Scenario 2 Heat Flux Input Traceability Figure

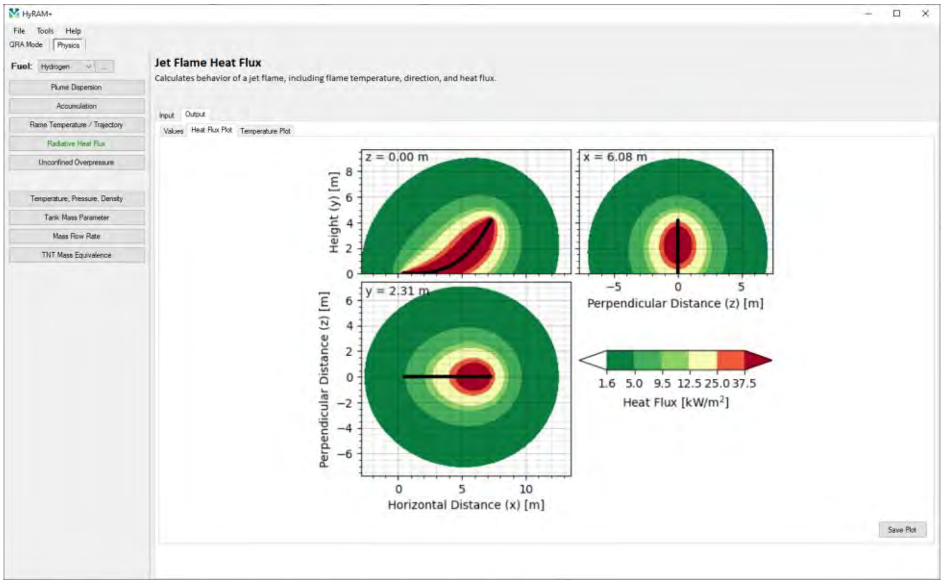
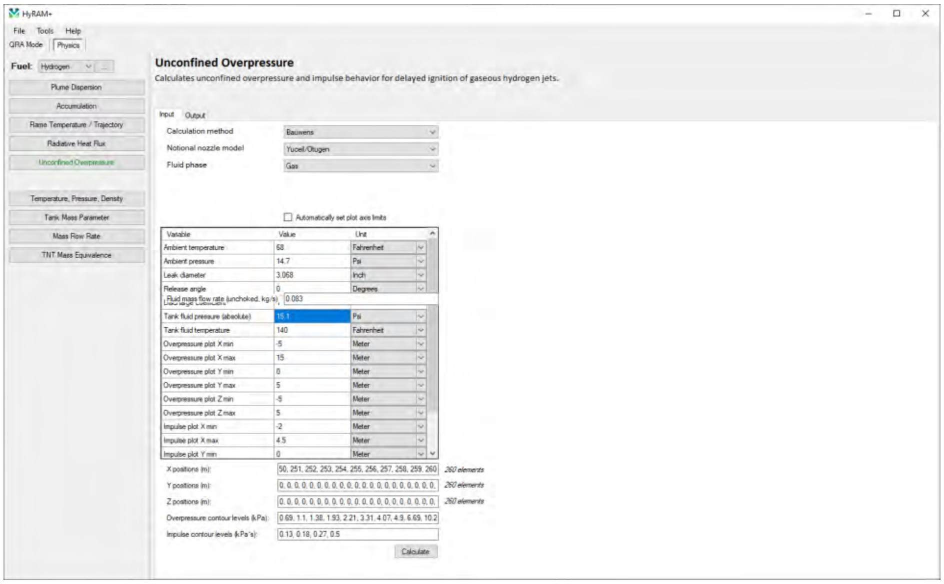


Figure A-8: Scenario 2 Heat Flux Output Traceability Figure

A.2.2. *Bauwens Overpressure*



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: Bauwens

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☐ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	3.068	Inch
Release angle	0	Degrees
Discharge coefficient	1	
Tank fluid pressure (absolute)	15.1	Psi
Tank fluid temperature	140	Fahrenheit
Overpressure plot X min	-5	Meter
Overpressure plot X max	15	Meter
Overpressure plot Y min	0	Meter
Overpressure plot Y max	5	Meter
Overpressure plot Z min	-5	Meter
Overpressure plot Z max	5	Meter
Impulse plot X min	-2	Meter
Impulse plot X max	4.5	Meter
Impulse plot Y min	0	Meter

Fluid mass flow rate (unchoked, kg/s) 0.083

X positions (m): 50, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260 *260 elements*

Y positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *260 elements*

Z positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *260 elements*

Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 10.2

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27, 0.5

Figure A-9: Scenario 2 Bauwens Overpressure Input Traceability Figure

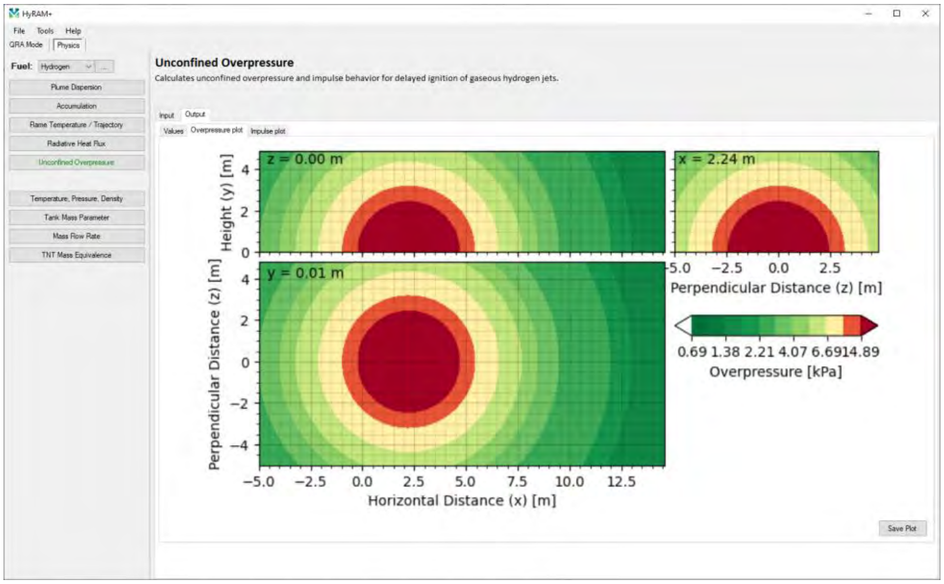
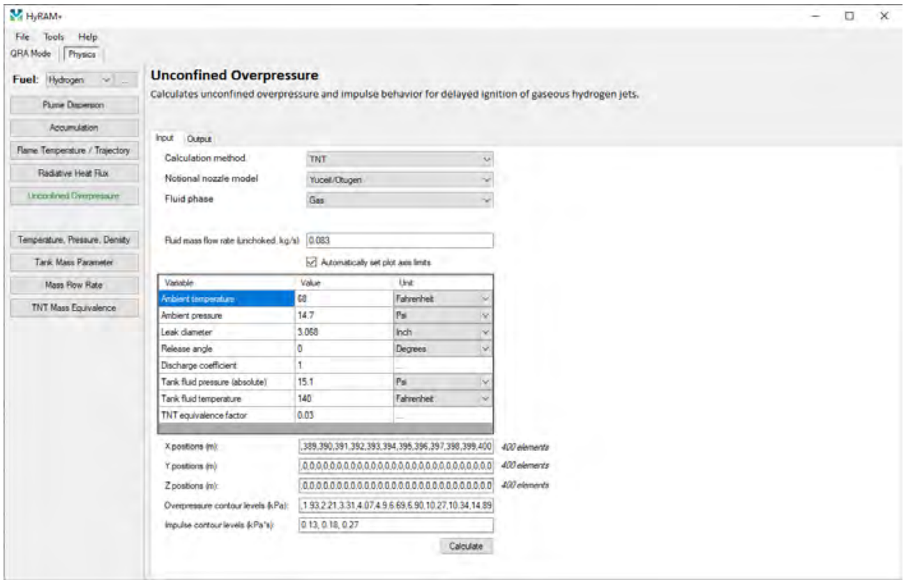


Figure A-10: Scenario 2 Bauwens Overpressure Output Traceability Figure

A.2.3. TNT Equivalence Overpressure



Fuel: Hydrogen

Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: TNT

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

Fluid mass flow rate (unchoked, kg/s): 0.083

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	3.068	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	15.1	Psi
Tank fluid temperature	140	Fahrenheit
TNT equivalence factor	0.03	...

X positions (m): ,389,390,391,392,393,394,395,396,397,398,399,400 400 elements

Y positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 400 elements

Z positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 400 elements

Overpressure contour levels (kPa): ,1.93,2.21,3.31,4.07,4.9,6.69,6.90,10.27,10.34,14.89

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-11: Scenario 2 TNT Overpressure Input Traceability Figure

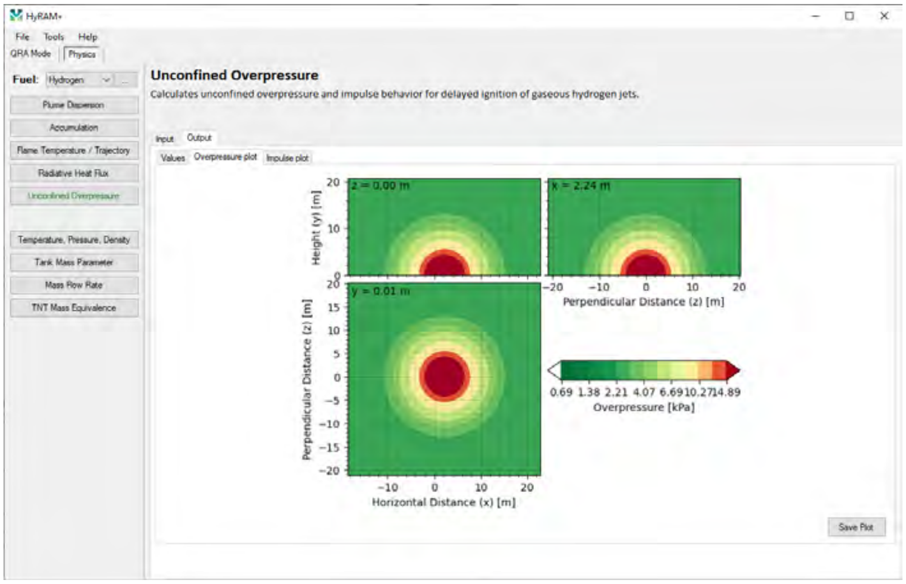
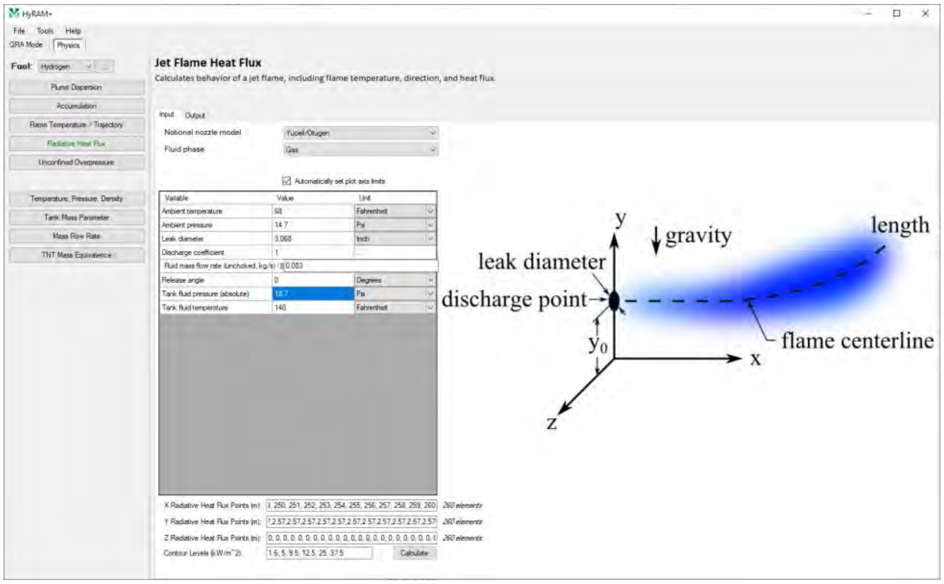


Figure A-12: Scenario 2 TNT Overpressure Output Traceability Figure

A.3. Scenario 3

A.3.1. Heat Flux



Fuel: Hydrogen

Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	3.068	Inch
Discharge coefficient	1	...
Fluid mass flow rate (unchoked, kg/s) (8	0.083	
Release angle	0	Degrees
Tank fluid pressure (absolute)	18.7	Psi
Tank fluid temperature	140	Fahrenheit

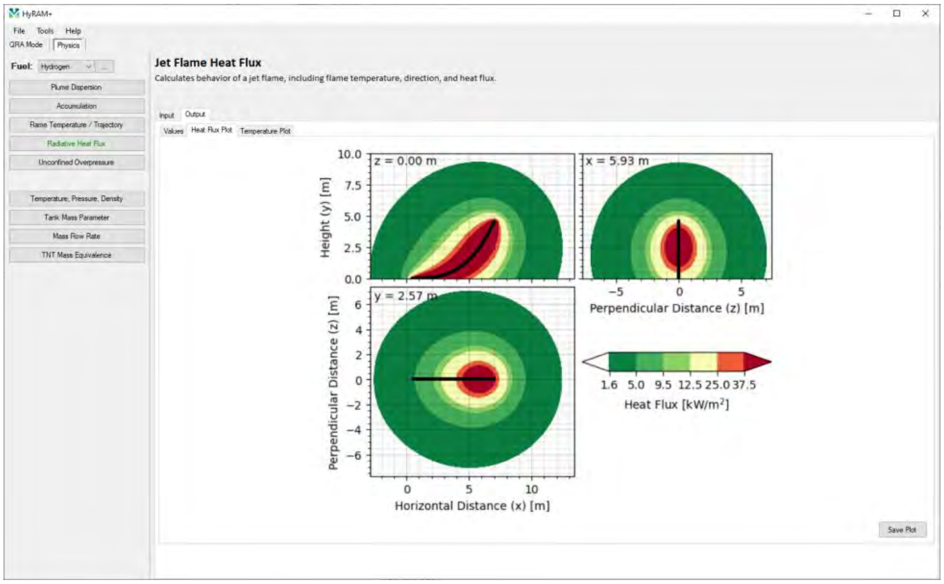
X Radiative Heat Flux Points (m):), 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260 — 260 elements

Y Radiative Heat Flux Points (m): 7,2.57,2.57,2.57,2.57,2.57,2.57,2.57,2.57,2.57,2.57,2.57 — 260 elements

Z Radiative Heat Flux Points (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, (— 260 elements

Contour Levels (kW/m^2): 1.6, 5, 9.5, 12.5, 25, 37.5

Figure A-13: Scenario 3 Heat Flux Input Traceability Figure

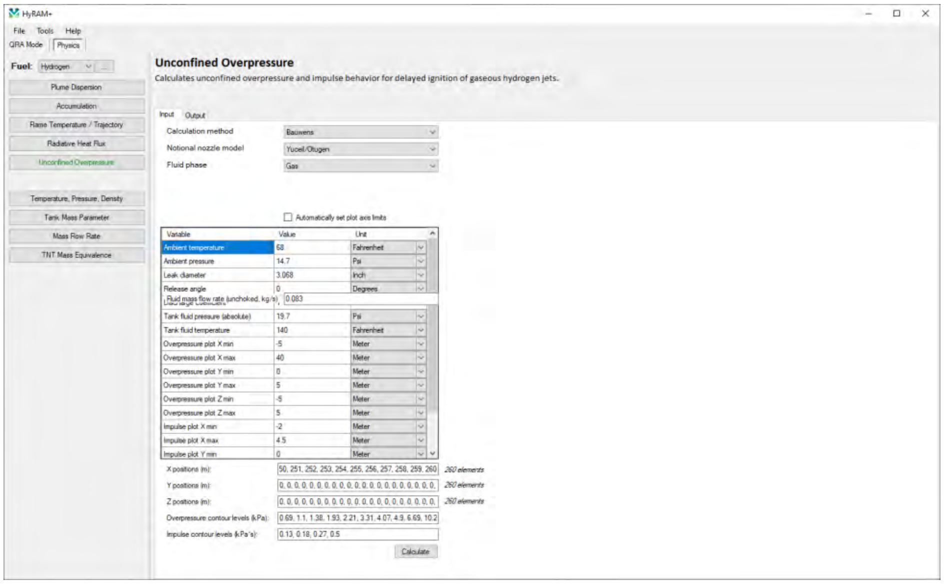


Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Figure A-14: Scenario 3 Heat Flux Output Traceability Figure

A.3.2. *Bauwens Overpressure*



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: Bauwens
Notional nozzle model: Yuceil/Otugen
Fluid phase: Gas

☐ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	3.068	Inch
Release angle	0	Degrees
Tank fluid pressure (absolute)	19.7	Psi
Tank fluid temperature	140	Fahrenheit
Overpressure plot X min	-5	Meter
Overpressure plot X max	40	Meter
Overpressure plot Y min	0	Meter
Overpressure plot Y max	5	Meter
Overpressure plot Z min	-5	Meter
Overpressure plot Z max	5	Meter
Impulse plot X min	-2	Meter
Impulse plot X max	4.5	Meter
Impulse plot Y min	0	Meter

Fluid mass flow rate (unchoked, kg/s): 0.083

X positions (m): 50, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260 *260 elements*
Y positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *260 elements*
Z positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *260 elements*
Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 10.2
Impulse contour levels (kPa*s): 0.13, 0.18, 0.27, 0.5

Figure A-15: Scenario 3 Bauwens Overpressure Input Traceability Figure

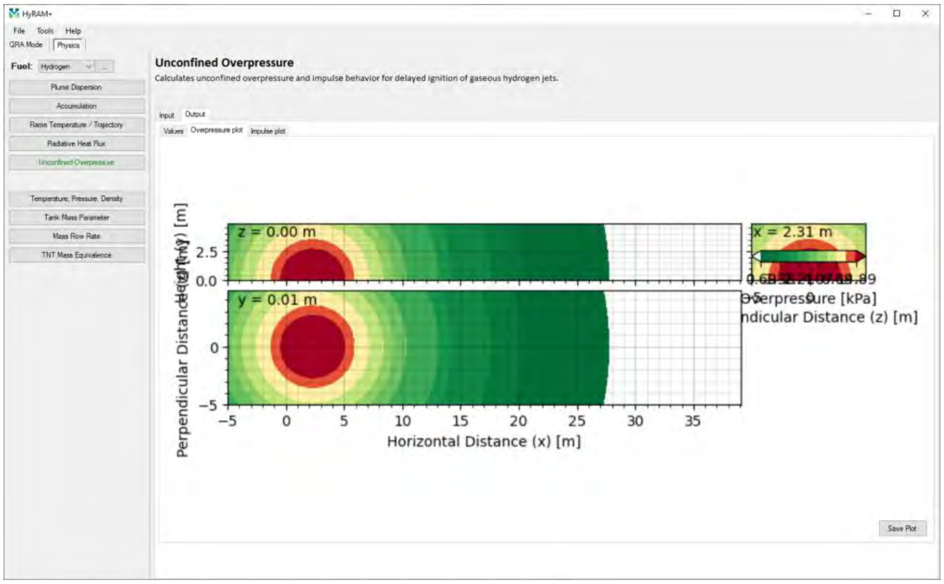
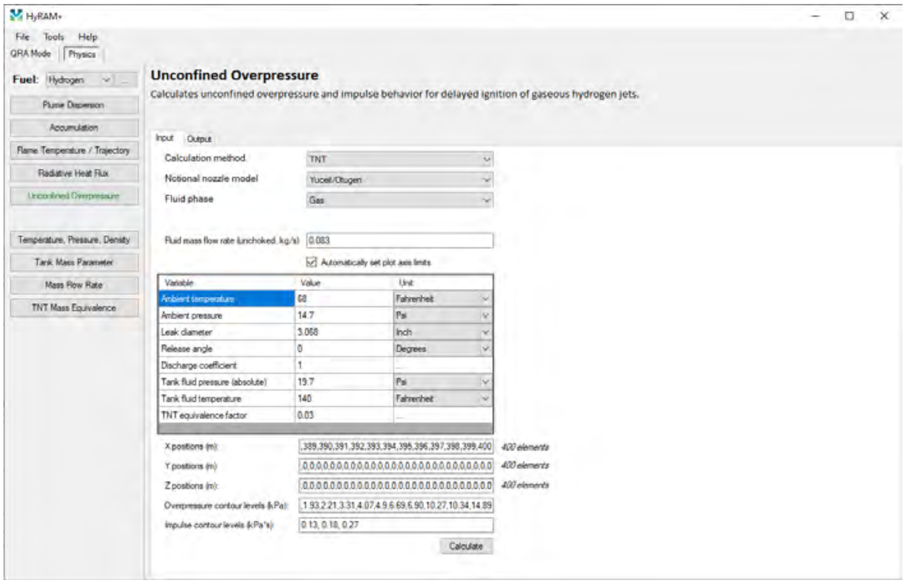


Figure A-16: Scenario 3 Bauwens Overpressure Output Traceability Figure

A.3.3. TNT Equivalence Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: TNT

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

Fluid mass flow rate (unchoked, kg/s): 0.083

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	3.068	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	19.7	Psi
Tank fluid temperature	140	Fahrenheit
TNT equivalence factor	0.03	...

X positions (m): ,389,390,391,392,393,394,395,396,397,398,399,400 400 elements

Y positions (m): ,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0 400 elements

Z positions (m): ,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0,0.0 400 elements

Overpressure contour levels (kPa): ,1.93,2.21,3.31,4.07,4.9,6.69,6.90,10.27,10.34,14.89

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-17: Scenario 3 TNT Overpressure Input Traceability Figure

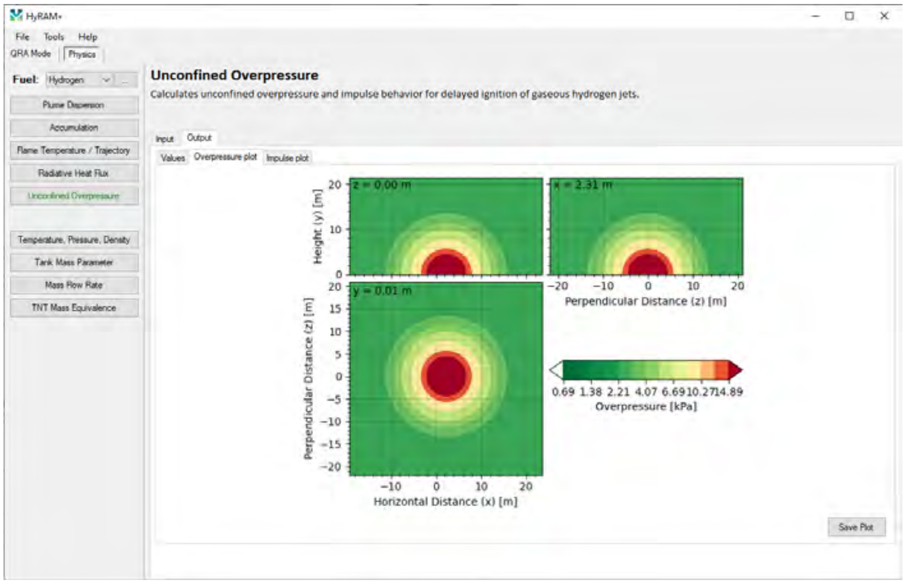
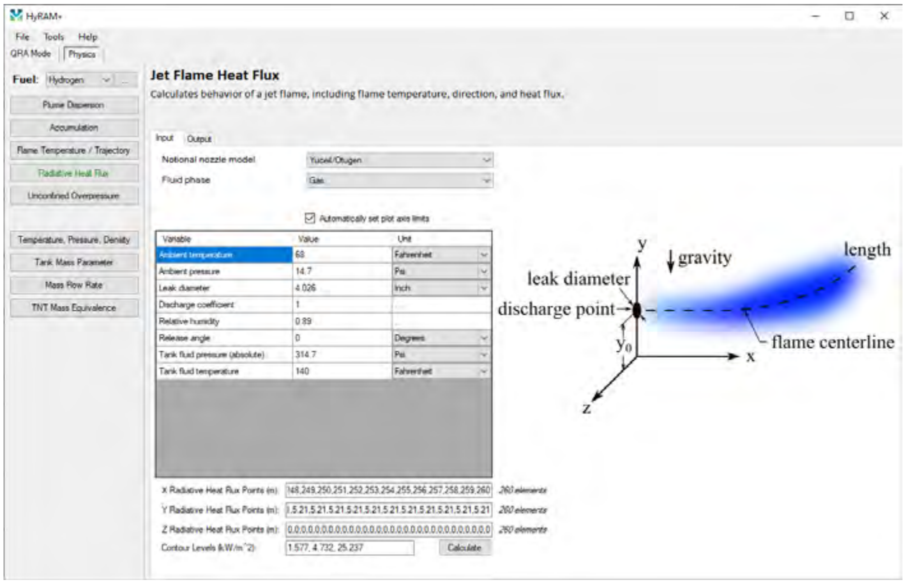


Figure A-18: Scenario 3 TNT Overpressure Output Traceability Figure

A.4. Scenario 4 & 5: 100% Leak Area

A.4.1. Heat Flux



Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	4.026	Inch
Discharge coefficient	1	...
Relative humidity	0.89	...
Release angle	0	Degrees
Tank fluid pressure (absolute)	314.7	Psi
Tank fluid temperature	140	Fahrenheit

X Radiative Heat Flux Points (m): 148,249,250,251,252,253,254,255,256,257,258,259,260 260 elements

Y Radiative Heat Flux Points (m): 1.5 21.5 21.5 21.5 21.5 21.5 21.5 21.5 21.5 21.5 21.5 21.5 21 260 elements

Z Radiative Heat Flux Points (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 260 elements

Contour Levels (kW/m^2): 1.577, 4.732, 25.237

Figure A-19: Scenario 4 & 5 (100% leak) Heat Flux Input Traceability Figure

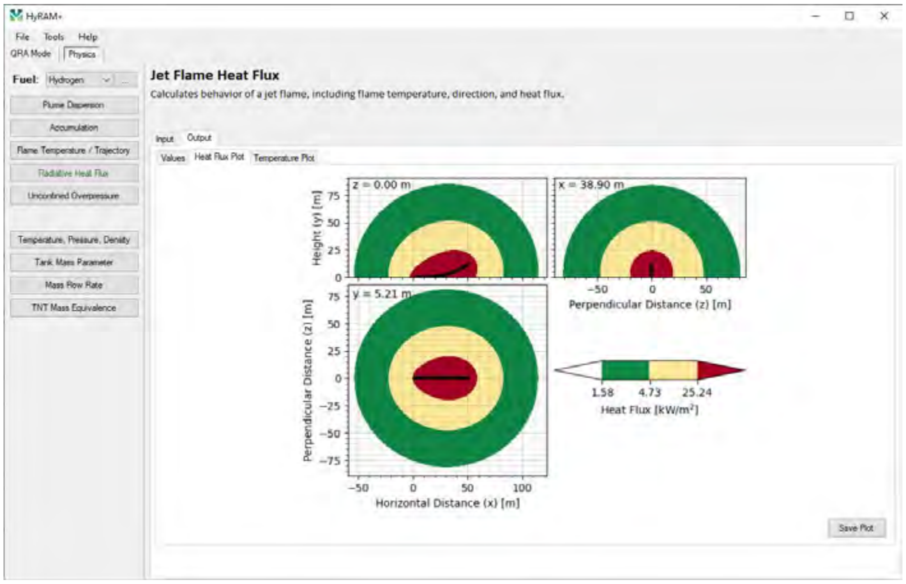
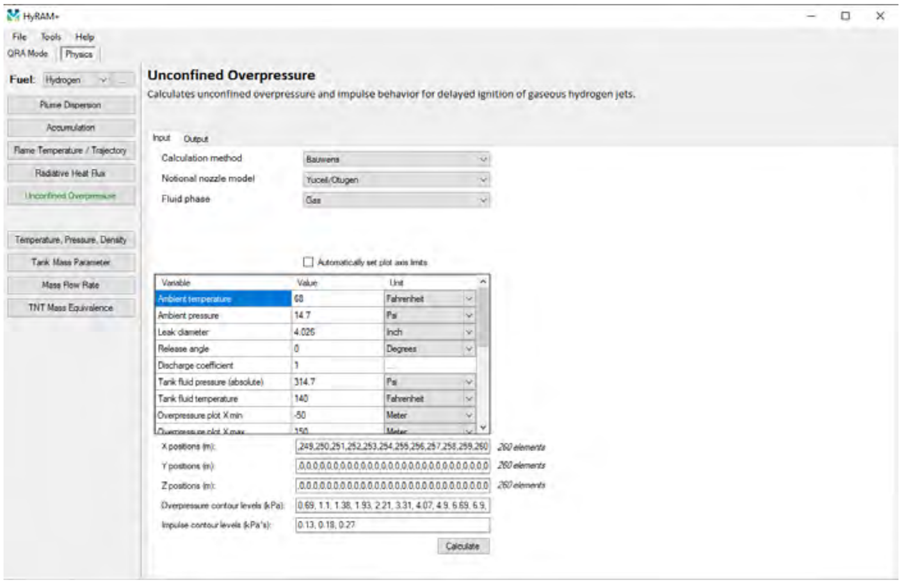


Figure A-20: Scenario 4 & 5 (100% leak) Heat Flux Output Traceability Figure

A.4.2. *Bauwens Overpressure*



Fuel: Hydrogen

Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: Bauwens

Notional nozzle model: Yucel/Otugen

Fluid phase: Gas

☐ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	4.026	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	314.7	Psi
Tank fluid temperature	140	Fahrenheit
Overpressure plot X min	-50	Meter
Overpressure plot X max	150	Meter

X positions (m): ,249,250,251,252,253,254,255,256,257,258,259,260 *260 elements*

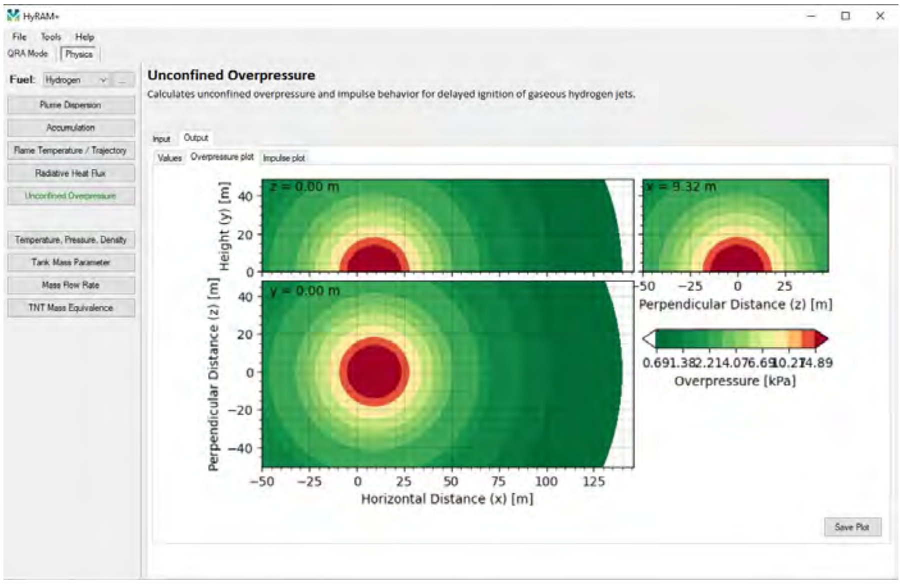
Y positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *260 elements*

Z positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *260 elements*

Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 6.9,

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-21: Scenario 4 & 5 (100% leak) Bauwens Overpressure Input Traceability Figure

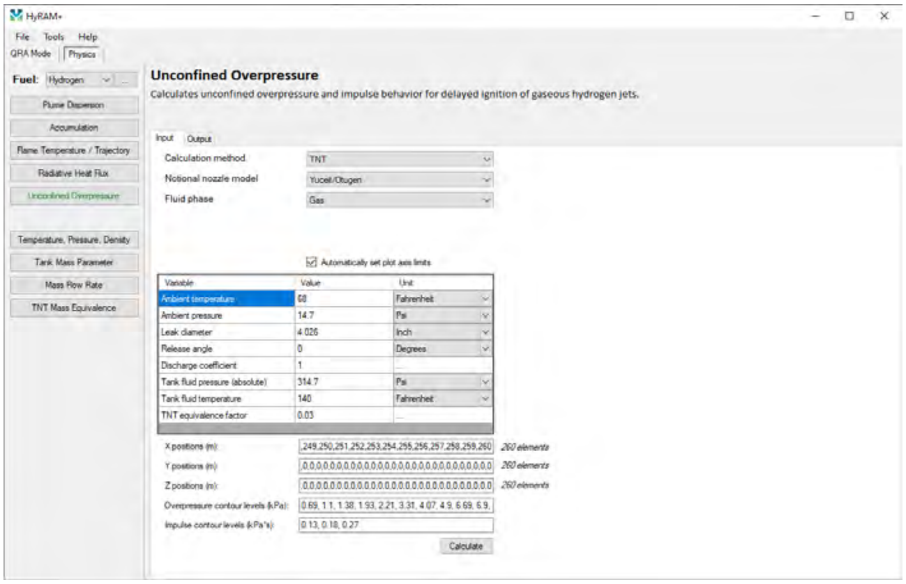


Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-22: Scenario 4 & 5 (100% leak) Bauwens Overpressure Output Traceability Figure

A.4.3. TNT Equivalence Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: TNT

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	4.026	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	314.7	Psi
Tank fluid temperature	140	Fahrenheit
TNT equivalence factor	0.03	...

X positions (m): ,249,250,251,252,253,254,255,256,257,258,259,260 *260 elements*

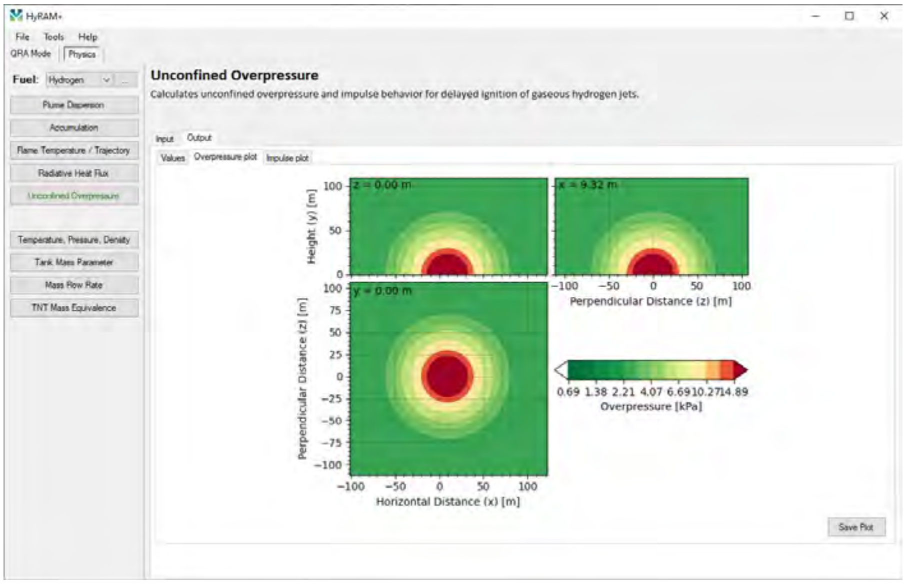
Y positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *260 elements*

Z positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *260 elements*

Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 6.9,

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-23: Scenario 4 & 5 (100% leak) TNT Overpressure Input Traceability Figure



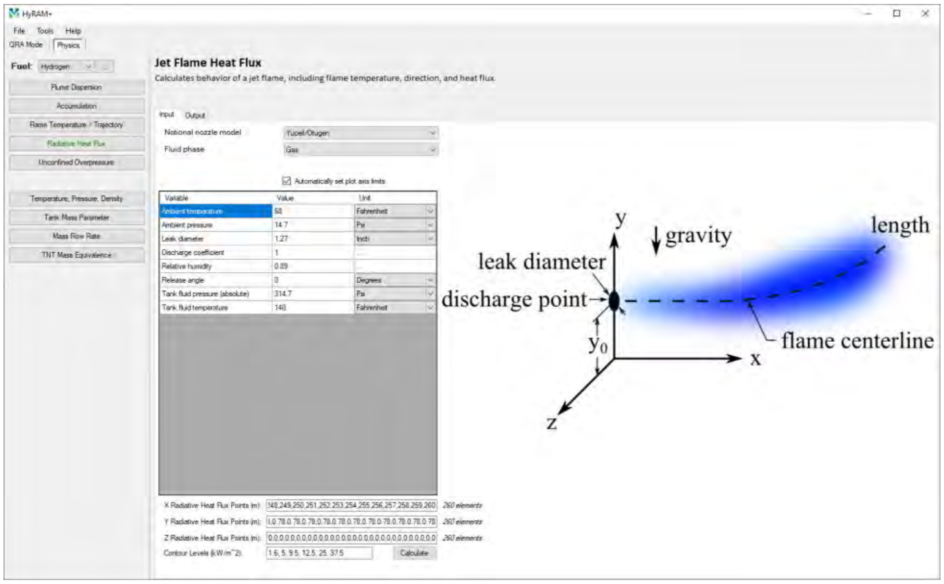
Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-24: Scenario 4 & 5 (100% leak) TNT Overpressure Output Traceability Figure

A.5. Scenario 4 & 5: 10% Leak Area

A.5.1. Heat Flux



Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	1.27	Inch
Discharge coefficient	1	...
Relative humidity	0.89	...
Release angle	0	Degrees
Tank fluid pressure (absolute)	314.7	Psi
Tank fluid temperature	140	Fahrenheit

X Radiative Heat Flux Points (m): 248,249,250,251,252,253,254,255,256,257,258,259,260 260 elements

Y Radiative Heat Flux Points (m): 3,0.78,0.78,0.78,0.78,0.78,0.78,0.78,0.78,0.78,0.78,0.78 260 elements

Z Radiative Heat Flux Points (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 260 elements

Contour Levels (kW/m^2): 1.6, 5, 9.5, 12.5, 25, 37.5

Figure A-25: Scenario 4 & 5 (10% leak) Heat Flux Input Traceability Figure

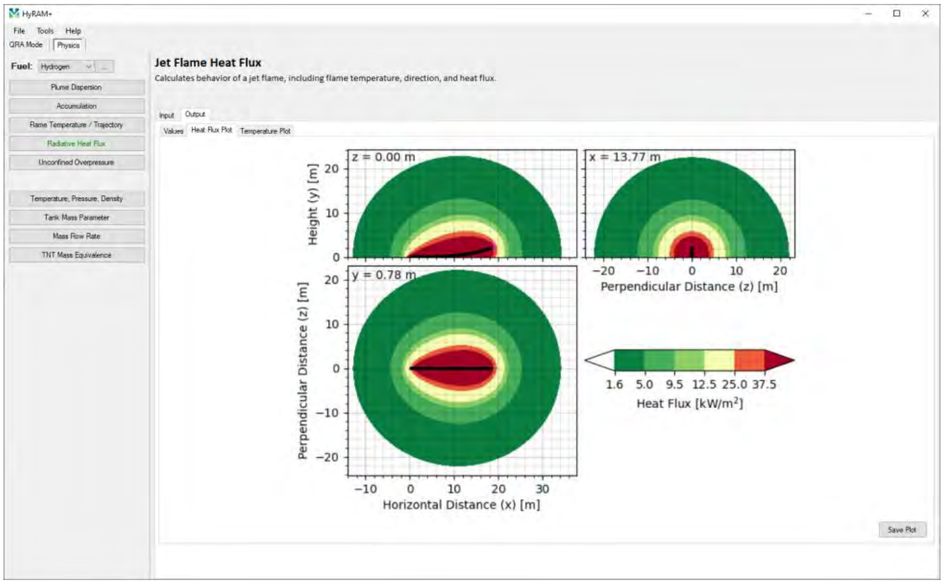
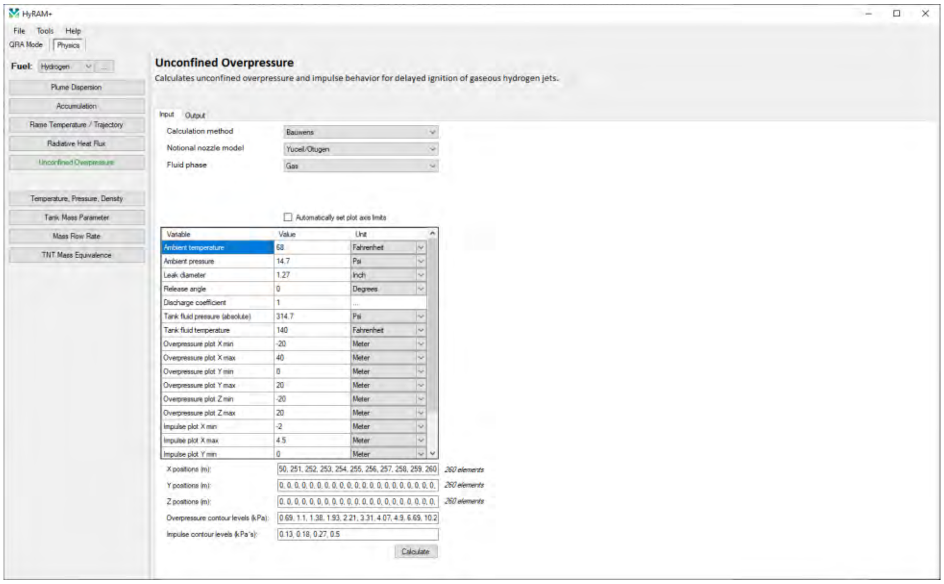


Figure A-26: Scenario 4 & 5 (10% leak) Heat Flux Output Traceability Figure

A.5.2. Bauwens Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: Bauwens
Notional nozzle model: Yuceil/Otugen
Fluid phase: Gas

☐ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	1.27	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	314.7	Psi
Tank fluid temperature	140	Fahrenheit
Overpressure plot X min	-20	Meter
Overpressure plot X max	40	Meter
Overpressure plot Y min	0	Meter
Overpressure plot Y max	20	Meter
Overpressure plot Z min	-20	Meter
Overpressure plot Z max	20	Meter
Impulse plot X min	-2	Meter
Impulse plot X max	4.5	Meter
Impulse plot Y min	0	Meter

X positions (m): 50, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260 *260 elements*
Y positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *260 elements*
Z positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *260 elements*
Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 10.2
Impulse contour levels (kPa*s): 0.13, 0.18, 0.27, 0.5

Figure A-27: Scenario 4 & 5 (10% leak) Bauwens Overpressure Input Traceability Figure

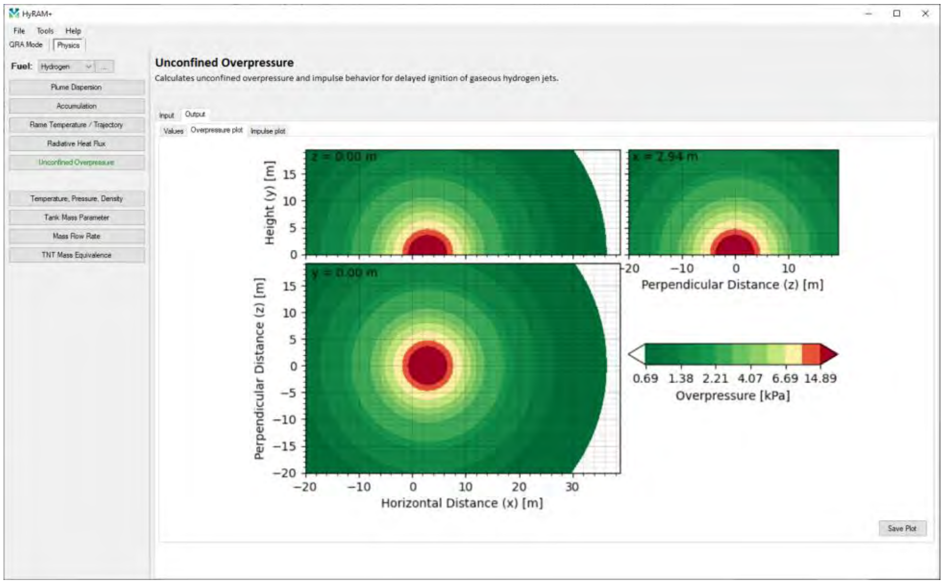
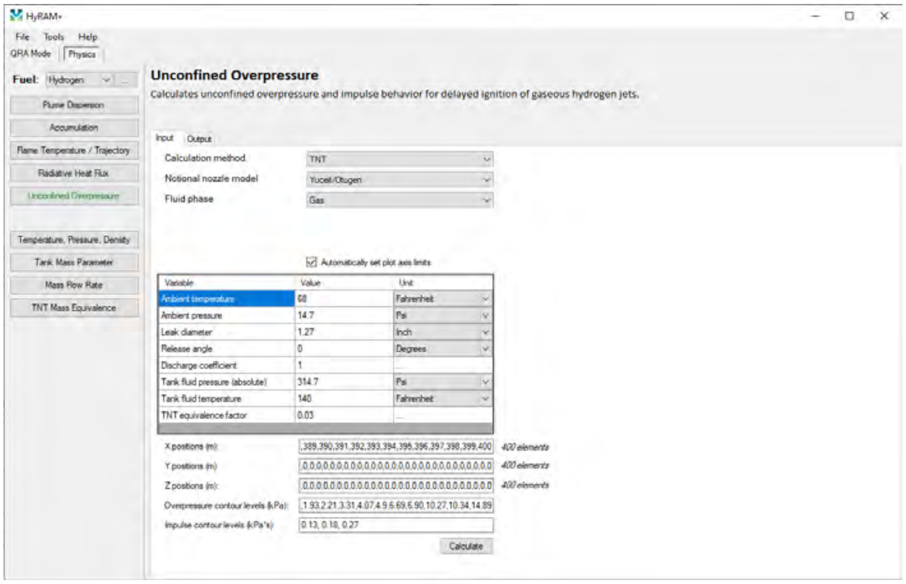


Figure A-28: Scenario 4 & 5 (10% leak) Bauwens Overpressure Output Traceability Figure

A.5.3. TNT Equivalence Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: TNT

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	1.27	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	314.7	Psi
Tank fluid temperature	140	Fahrenheit
TNT equivalence factor	0.03	...

X positions (m): ,389,390,391,392,393,394,395,396,397,398,399,400 *400 elements*

Y positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *400 elements*

Z positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *400 elements*

Overpressure contour levels (kPa): ,1.93,2.21,3.31,4.07,4.9,6.69,6.90,10.27,10.34,14.89

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-29: Scenario 4 & 5 (10% leak) TNT Overpressure Input Traceability Figure

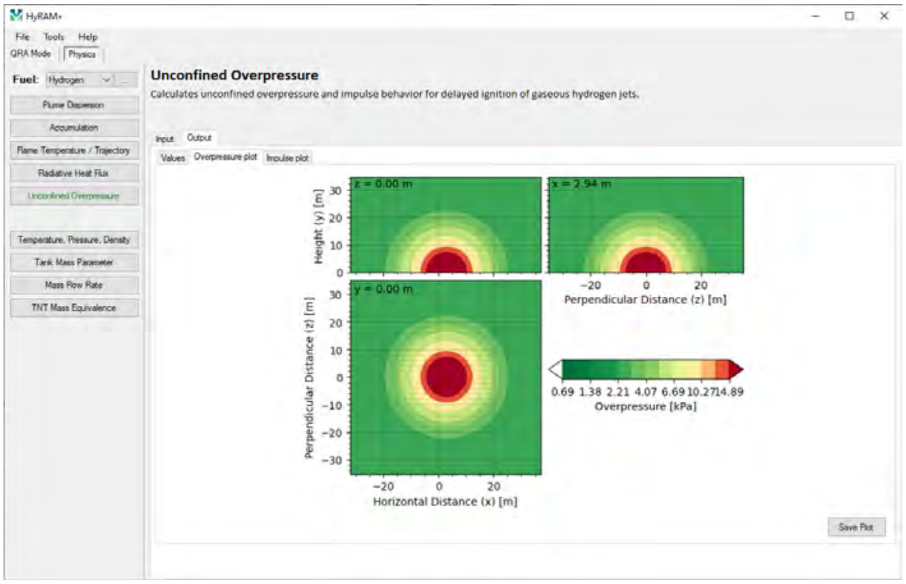
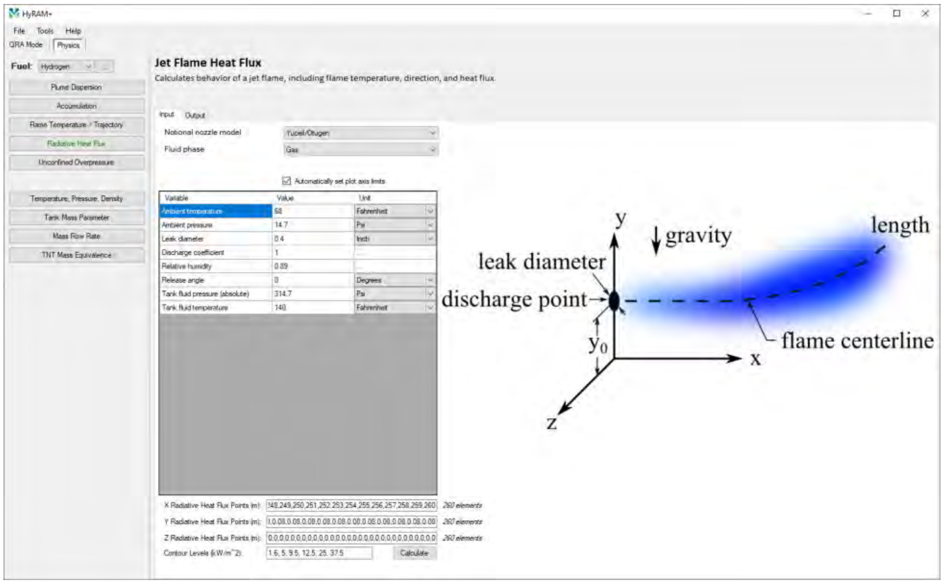


Figure A-30: Scenario 4 & 5 (10% leak) TNT Overpressure Output Traceability Figure

A.6. Scenario 4 & 5: 1% Leak Area

A.6.1. Heat Flux



Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	58	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	0.4	Inch
Discharge coefficient	1	...
Relative humidity	0.89	...
Release angle	0	Degrees
Tank fluid pressure (absolute)	314.7	Psi
Tank fluid temperature	140	Fahrenheit

X Radiative Heat Flux Points (m): 248,249,250,251,252,253,254,255,256,257,258,259,260 260 elements

Y Radiative Heat Flux Points (m): 3,0.08,0.08,0.08,0.08,0.08,0.08,0.08,0.08,0.08,0.08,0.08 260 elements

Z Radiative Heat Flux Points (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 260 elements

Contour Levels (kW/m^2): 1.6, 5, 9.5, 12.5, 25, 37.5

Calculate

Figure A-31: Scenario 4 & 5 (1% leak) Heat Flux Input Traceability Figure

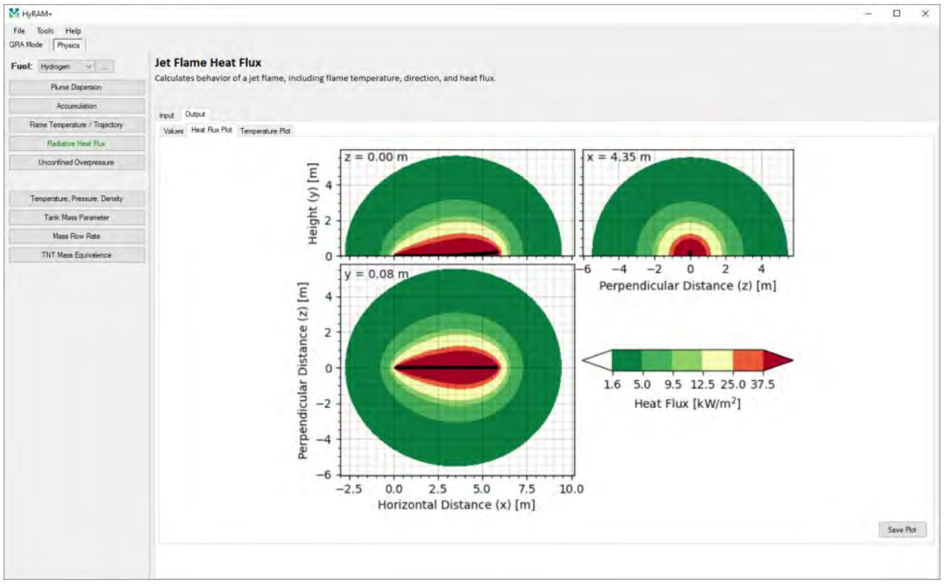
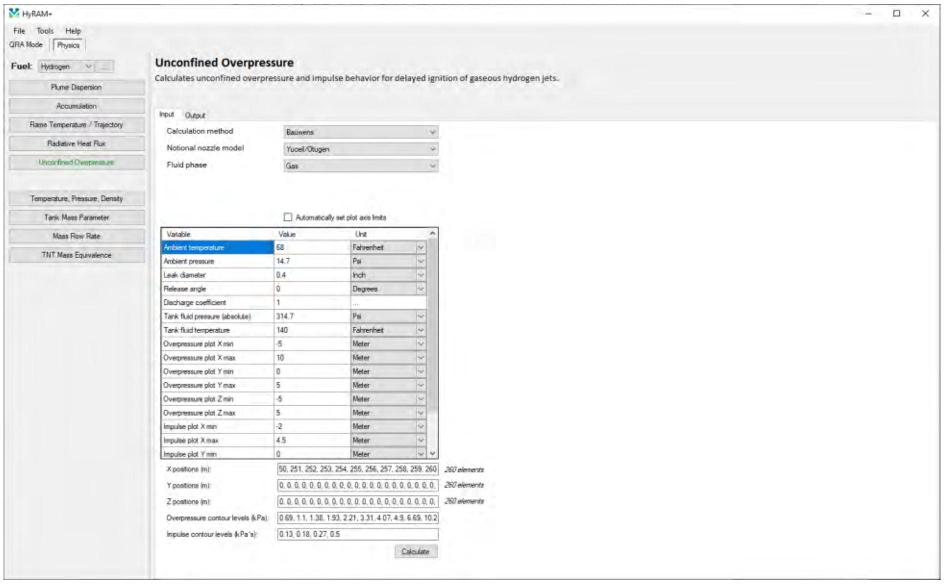


Figure A-32: Scenario 4 & 5 (1% leak) Heat Flux Output Traceability Figure

A.6.2. Bauwens Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: Bauwens

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☐ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	0.4	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	314.7	Psi
Tank fluid temperature	140	Fahrenheit
Overpressure plot X min	-5	Meter
Overpressure plot X max	10	Meter
Overpressure plot Y min	0	Meter
Overpressure plot Y max	5	Meter
Overpressure plot Z min	-5	Meter
Overpressure plot Z max	5	Meter
Impulse plot X min	-2	Meter
Impulse plot X max	4.5	Meter
Impulse plot Y min	0	Meter

X positions (m): 50, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260 *260 elements*

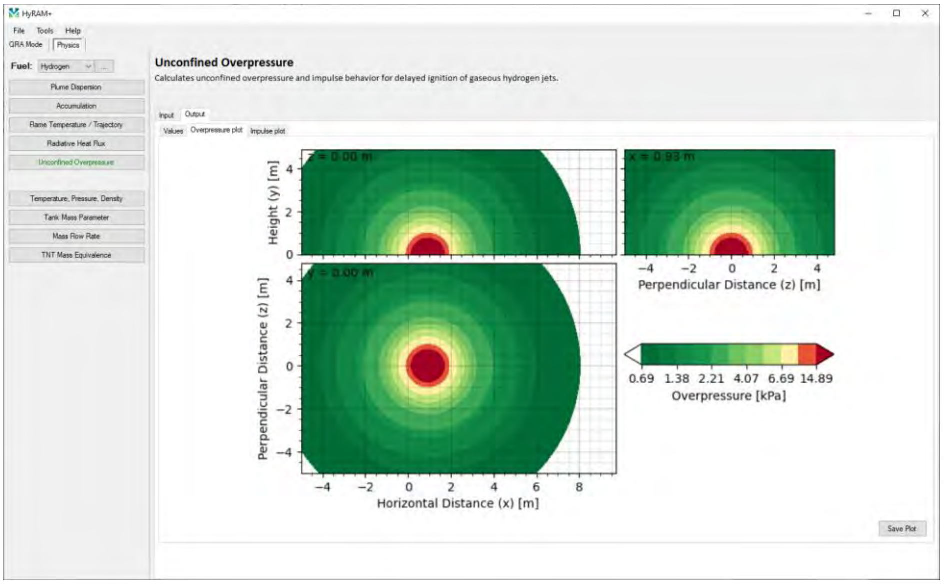
Y positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *260 elements*

Z positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *260 elements*

Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 10.2

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27, 0.5

Figure A-33: Scenario 4 & 5 (1% leak) Bauwens Overpressure Input Traceability Figure

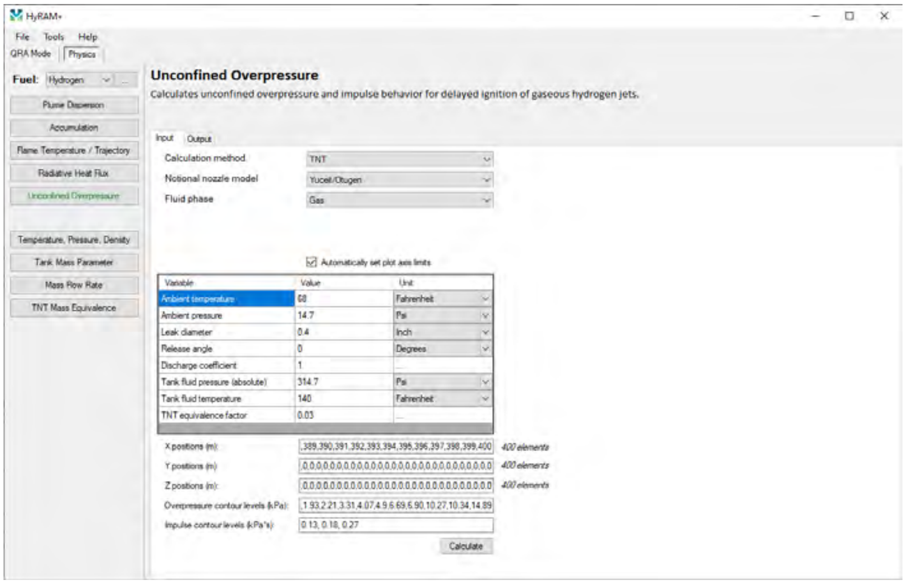


Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-34: Scenario 4 & 5 (1% leak) Bauwens Overpressure Output Traceability Figure

A.6.3. TNT Equivalence Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: TNT

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	0.4	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	314.7	Psi
Tank fluid temperature	140	Fahrenheit
TNT equivalence factor	0.03	...

X positions (m): ,389,390,391,392,393,394,395,396,397,398,399,400 400 elements

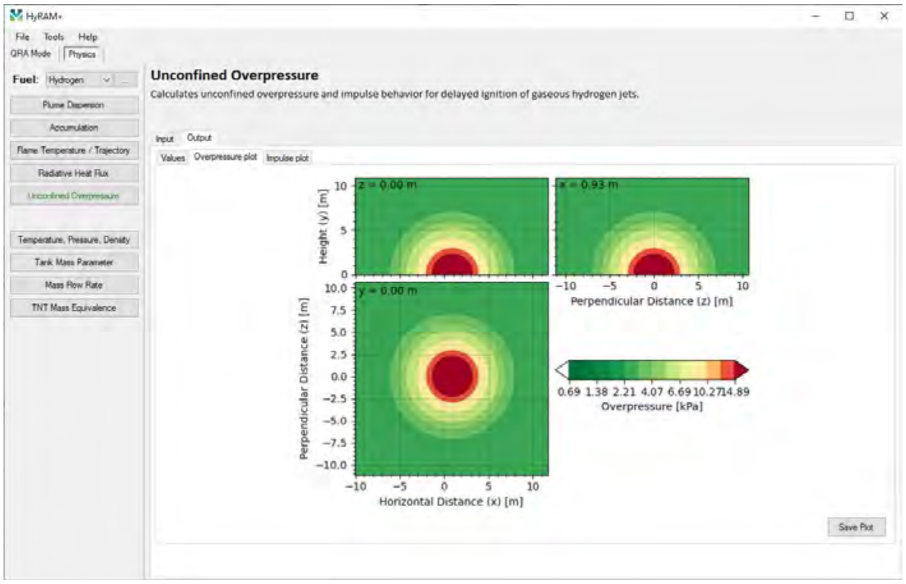
Y positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 400 elements

Z positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 400 elements

Overpressure contour levels (kPa): ,1.93,2.21,3.31,4.07,4.9,6.69,6.90,10.27,10.34,14.89

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-35: Scenario 4 & 5 (1% leak) TNT Overpressure Input Traceability Figure



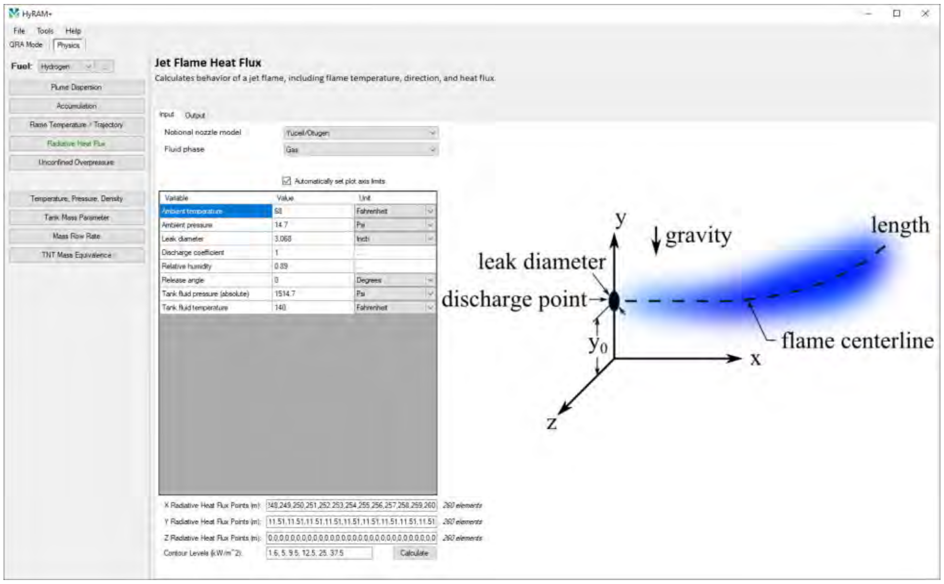
Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-36: Scenario 4 & 5 (1% leak) TNT Overpressure Output Traceability Figure

A.7. Scenario 6: 100% Leak Area

A.7.1. Heat Flux



Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Fuel: Hydrogen

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	3.068	Inch
Discharge coefficient	1	...
Relative humidity	0.89	...
Release angle	0	Degrees
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit

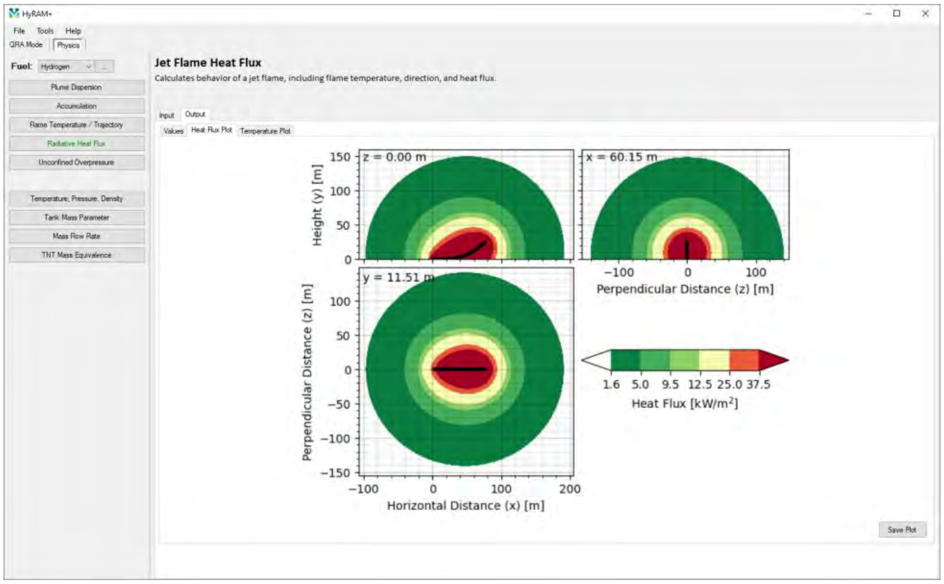
X Radiative Heat Flux Points (m): 248,249,250,251,252,253,254,255,256,257,258,259,260 — 260 elements

Y Radiative Heat Flux Points (m): 11.51,11.51,11.51,11.51,11.51,11.51,11.51,11.51,11.51 — 260 elements

Z Radiative Heat Flux Points (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 — 260 elements

Contour Levels (kW/m^2): 1.6, 5, 9.5, 12.5, 25, 37.5

Figure A-37: Scenario 6 (100% leak) Heat Flux Input Traceability Figure

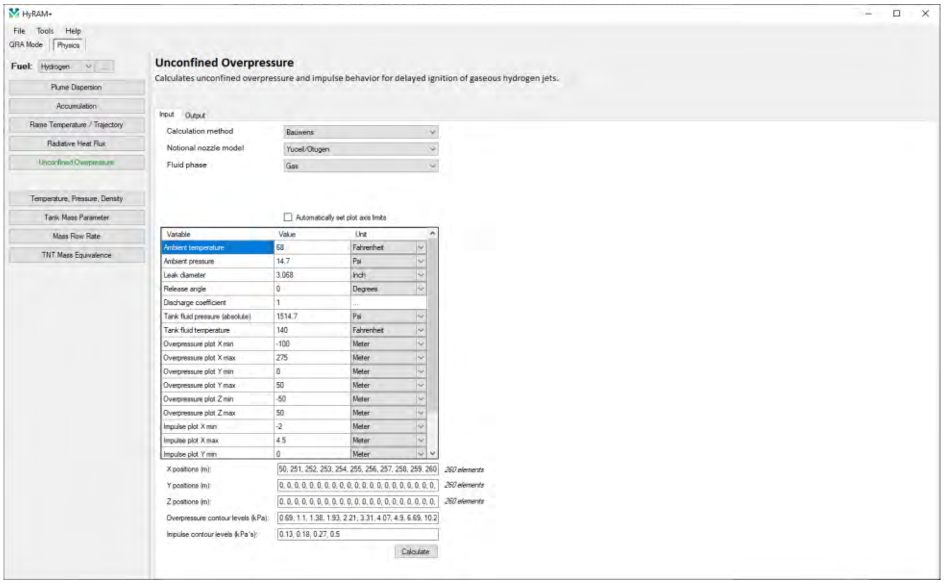


Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Figure A-38: Scenario 6 (100% leak) Heat Flux Output Traceability Figure

A.7.2. Bauwens Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

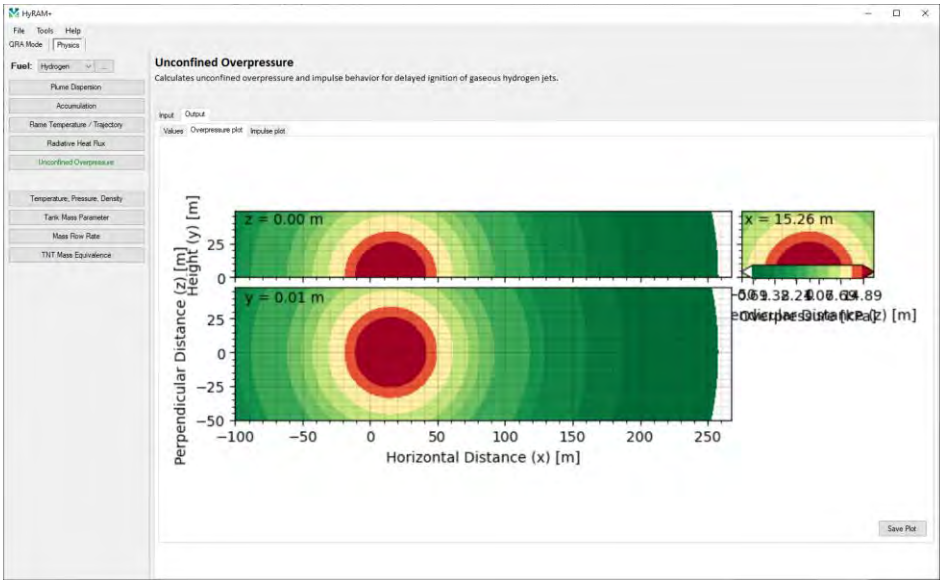
Calculation method: Bauwens
Notional nozzle model: Yuceil/Otugen
Fluid phase: Gas

☐ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	3.068	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
Overpressure plot X min	-100	Meter
Overpressure plot X max	275	Meter
Overpressure plot Y min	0	Meter
Overpressure plot Y max	50	Meter
Overpressure plot Z min	-50	Meter
Overpressure plot Z max	50	Meter
Impulse plot X min	-2	Meter
Impulse plot X max	4.5	Meter
Impulse plot Y min	0	Meter

X positions (m): 50, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260 *260 elements*
Y positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *260 elements*
Z positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *260 elements*
Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 10.2
Impulse contour levels (kPa*s): 0.13, 0.18, 0.27, 0.5

Figure A-39: Scenario 6 (100% leak) Bauwens Overpressure Input Traceability Figure

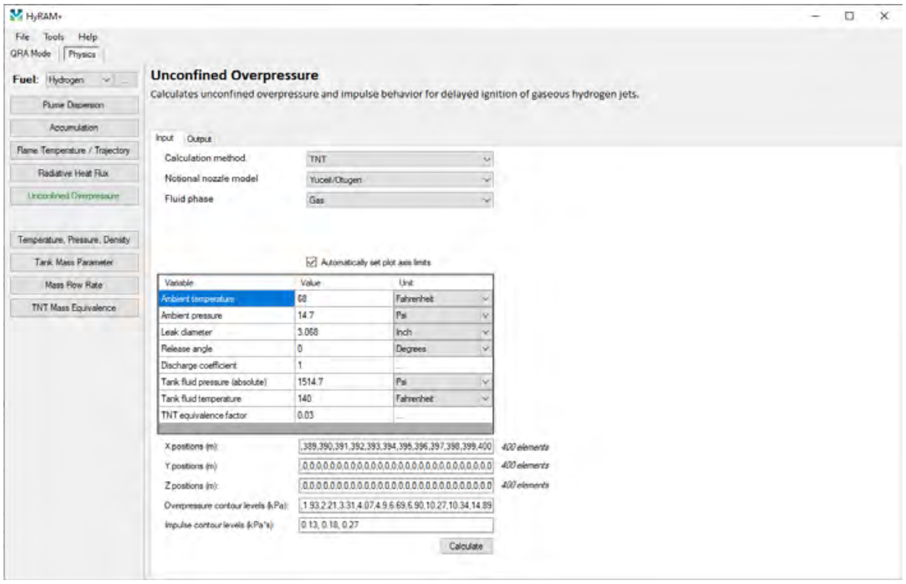


Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-40: Scenario 6 (100% leak) Bauwens Overpressure Output Traceability Figure

A.7.3. TNT Equivalence Overpressure



Fuel: Hydrogen

Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: TNT

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	3.068	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
TNT equivalence factor	0.03	...

X positions (m): ,389,390,391,392,393,394,395,396,397,398,399,400 *400 elements*

Y positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *400 elements*

Z positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *400 elements*

Overpressure contour levels (kPa): ,1.93,2.21,3.31,4.07,4.9,6.69,6.90,10.27,10.34,14.89

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-41: Scenario 6 (100% leak) TNT Overpressure Input Traceability Figure

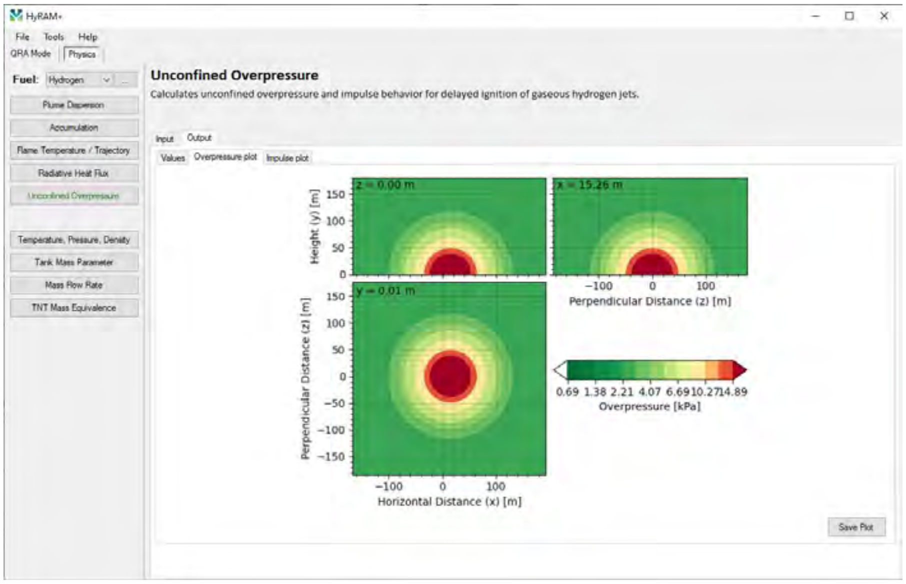
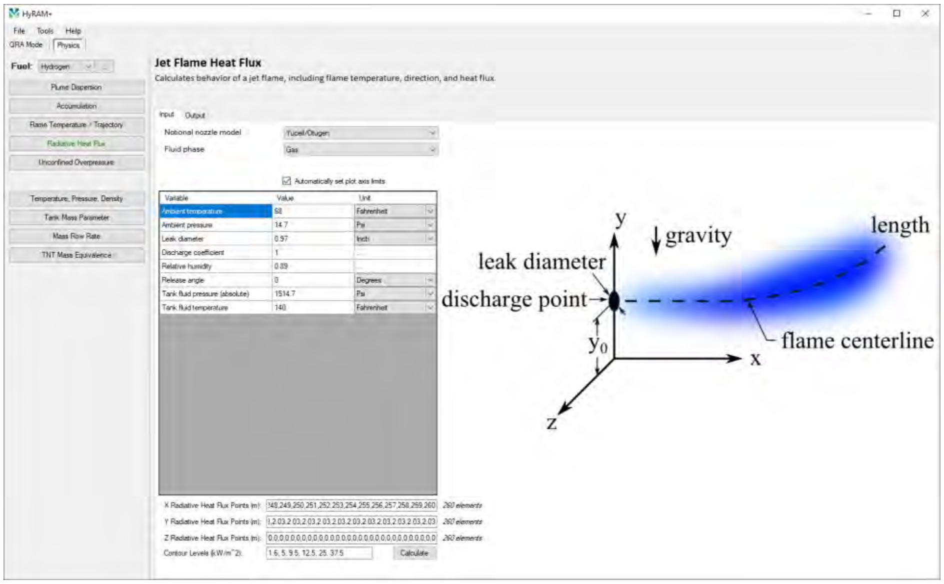


Figure A-42: Scenario 6 (100% leak) TNT Overpressure Output Traceability Figure

A.8. Scenario 6: 10% Leak Area

A.8.1. Heat Flux



Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	58	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	0.57	Inch
Discharge coefficient	1	...
Relative humidity	0.89	...
Release angle	0	Degrees
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit

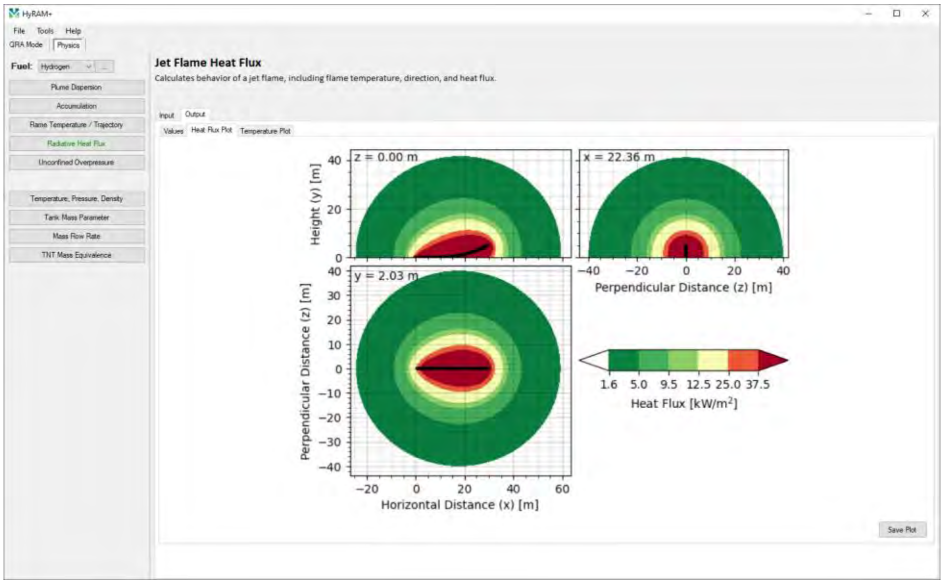
X Radiative Heat Flux Points (m): 248,249,250,251,252,253,254,255,256,257,258,259,260 260 elements

Y Radiative Heat Flux Points (m): 3,2.03,2.03,2.03,2.03,2.03,2.03,2.03,2.03,2.03,2.03,2.03 260 elements

Z Radiative Heat Flux Points (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 260 elements

Contour Levels (kW/m^2): 1.6, 5, 9.5, 12.5, 25, 37.5

Figure A-43: Scenario 6 (10% leak) Heat Flux Input Traceability Figure

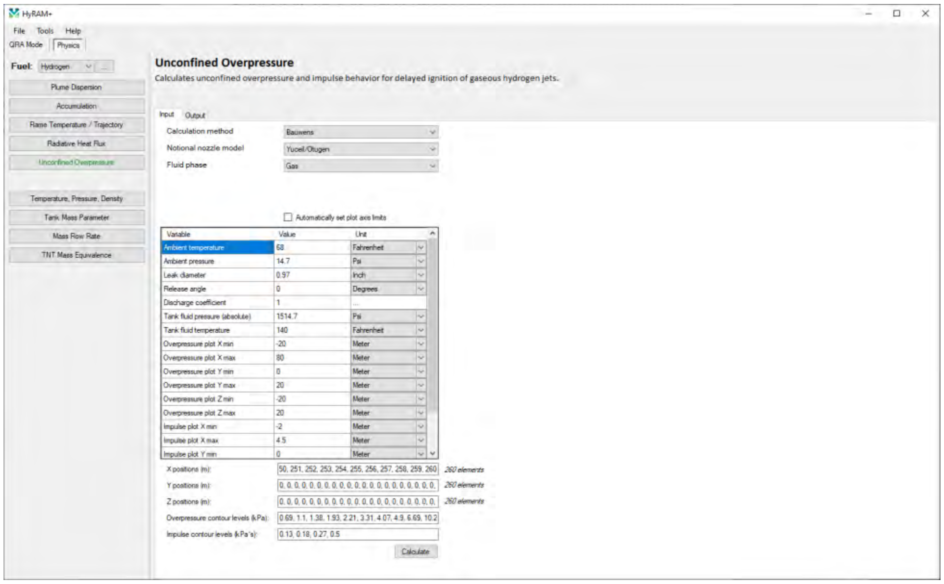


Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Figure A-44: Scenario 6 (10% leak) Heat Flux Output Traceability Figure

A.8.2. Bauwens Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Fuel: Hydrogen

Calculation method: Bauwens

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☐ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	0.97	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
Overpressure plot X min	-20	Meter
Overpressure plot X max	80	Meter
Overpressure plot Y min	0	Meter
Overpressure plot Y max	20	Meter
Overpressure plot Z min	-20	Meter
Overpressure plot Z max	20	Meter
Impulse plot X min	-2	Meter
Impulse plot X max	4.5	Meter
Impulse plot Y min	0	Meter

X positions (m): 50, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260 — 260 elements

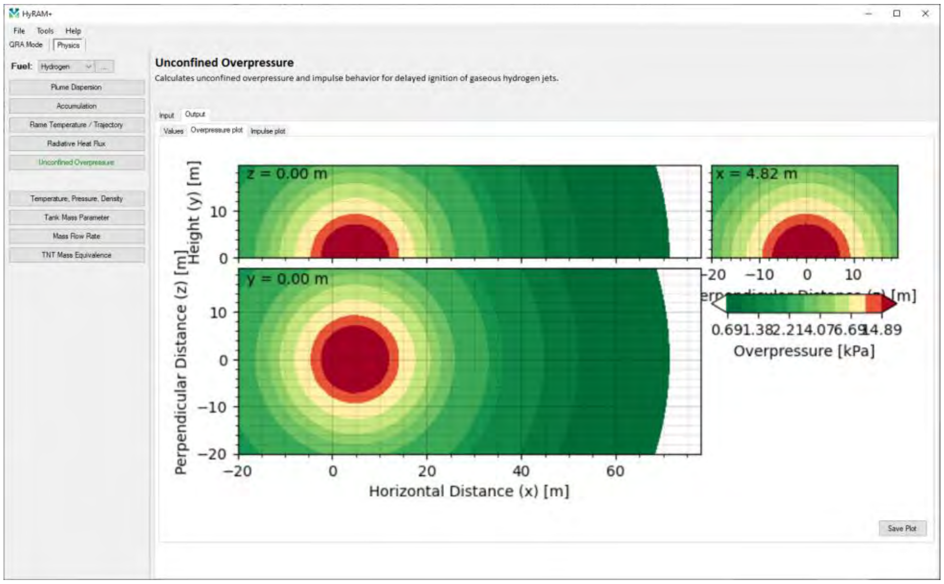
Y positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, — 260 elements

Z positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, — 260 elements

Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 10.2

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27, 0.5

Figure A-45: Scenario 6 (10% leak) Bauwens Overpressure Input Traceability Figure

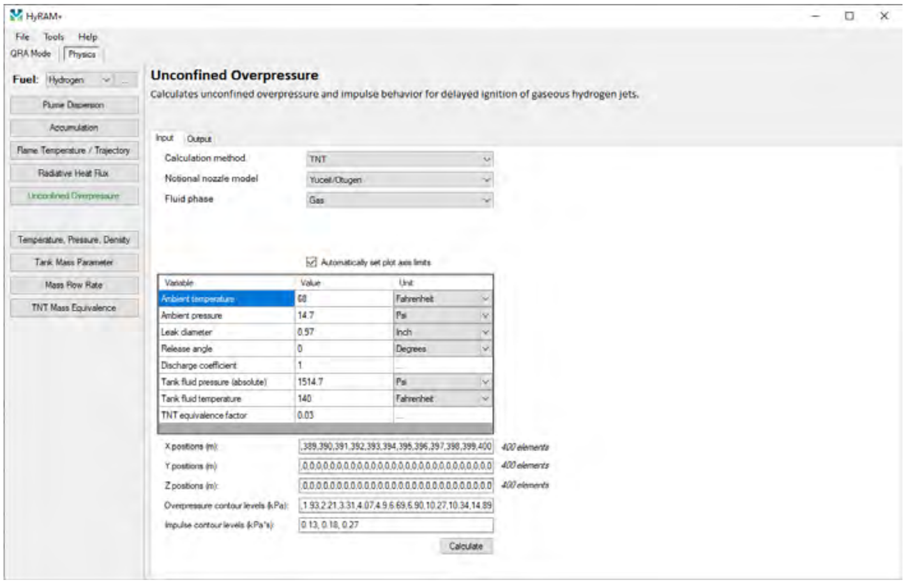


Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-46: Scenario 6 (10% leak) Bauwens Overpressure Output Traceability Figure

A.8.3. TNT Equivalence Overpressure



Fuel: Hydrogen

Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: TNT

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	0.57	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
TNT equivalence factor	0.03	...

X positions (m): ,389,390,391,392,393,394,395,396,397,398,399,400 *400 elements*

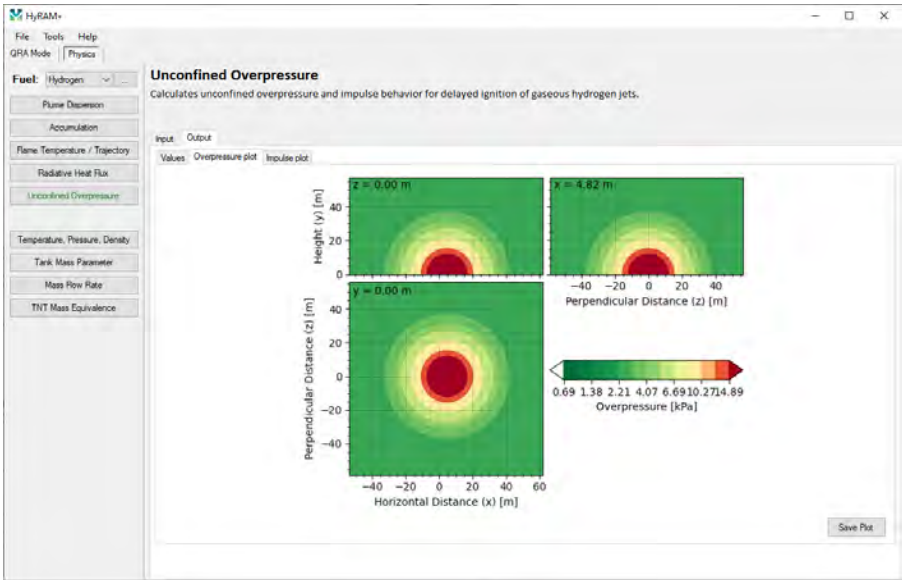
Y positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *400 elements*

Z positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *400 elements*

Overpressure contour levels (kPa): ,1.93,2.21,3.31,4.07,4.9,6.69,6.90,10.27,10.34,14.89

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-47: Scenario 6 (10% leak) TNT Overpressure Input Traceability Figure



Fuel: Hydrogen

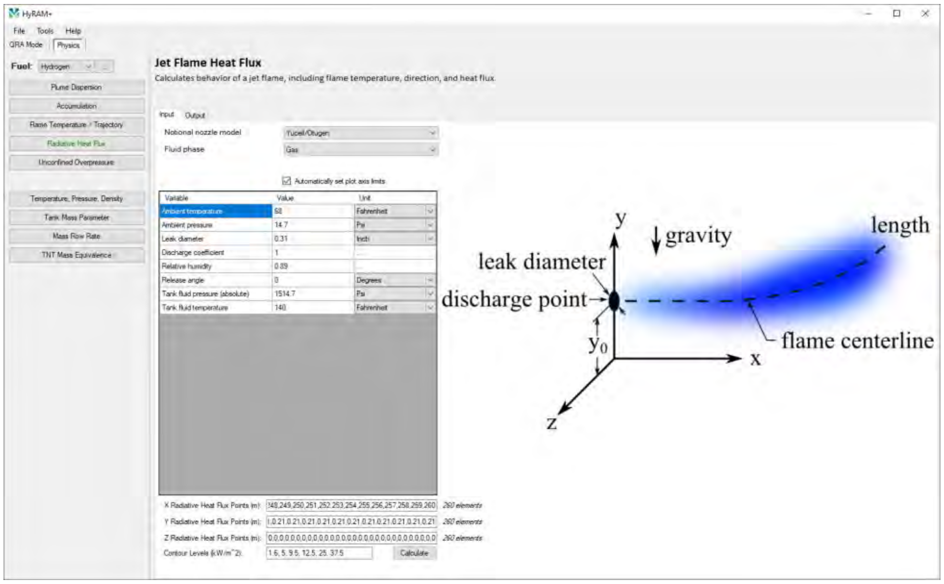
Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-48: Scenario 6 (10% leak) TNT Overpressure Output Traceability Figure

A.9. Scenario 6: 1% Leak Area

A.9.1. Heat Flux



Fuel: Hydrogen

Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	0.31	Inch
Discharge coefficient	1	...
Relative humidity	0.89	...
Release angle	0	Degrees
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit

X Radiative Heat Flux Points (m): 248,249,250,251,252,253,254,255,256,257,258,259,260 *260 elements*

Y Radiative Heat Flux Points (m): 1,0.21,0.21,0.21,0.21,0.21,0.21,0.21,0.21,0.21,0.21,0.21 *260 elements*

Z Radiative Heat Flux Points (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *260 elements*

Contour Levels (kW/m^2): 1.6, 5, 9.5, 12.5, 25, 37.5

Figure A-49: Scenario 6 (1% leak) Heat Flux Input Traceability Figure

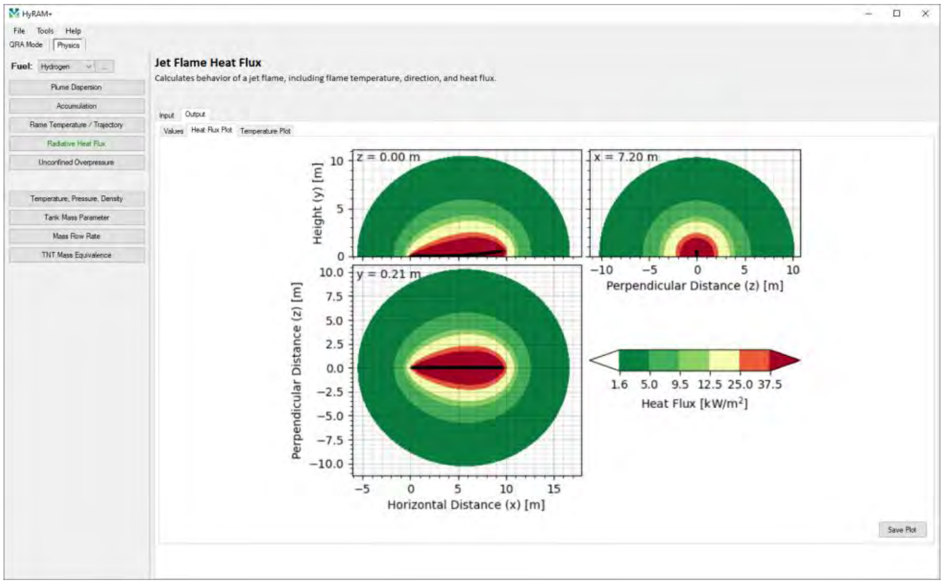
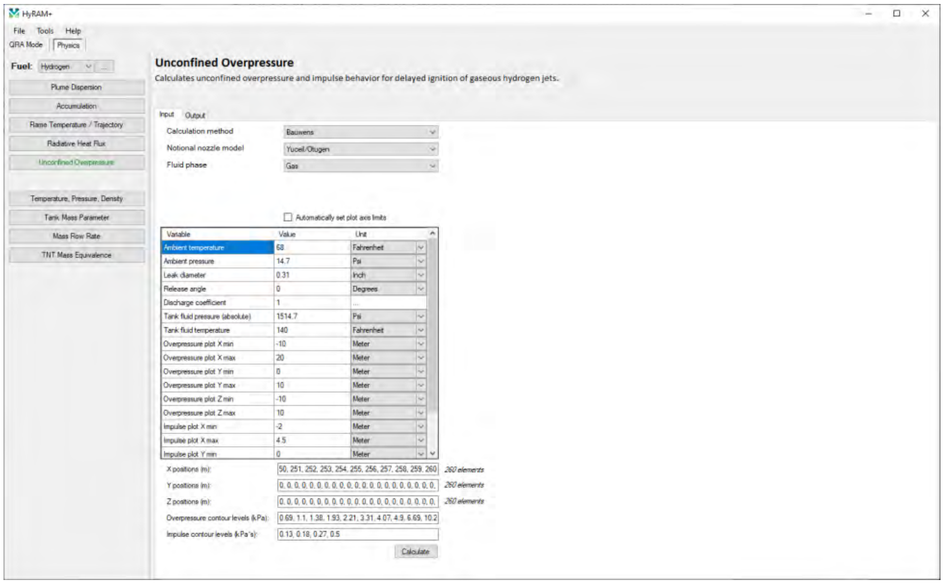


Figure A-50: Scenario 6 (1% leak) Heat Flux Output Traceability Figure

A.9.2. Bauwens Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: Bauwens

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☐ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	0.31	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
Overpressure plot X min	-10	Meter
Overpressure plot X max	20	Meter
Overpressure plot Y min	0	Meter
Overpressure plot Y max	10	Meter
Overpressure plot Z min	-10	Meter
Overpressure plot Z max	10	Meter
Impulse plot X min	-2	Meter
Impulse plot X max	4.5	Meter
Impulse plot Y min	0	Meter

X positions (m): 50, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260 *260 elements*

Y positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *260 elements*

Z positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *260 elements*

Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 10.2

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27, 0.5

Figure A-51: Scenario 6 (1% leak) Bauwens Overpressure Input Traceability Figure

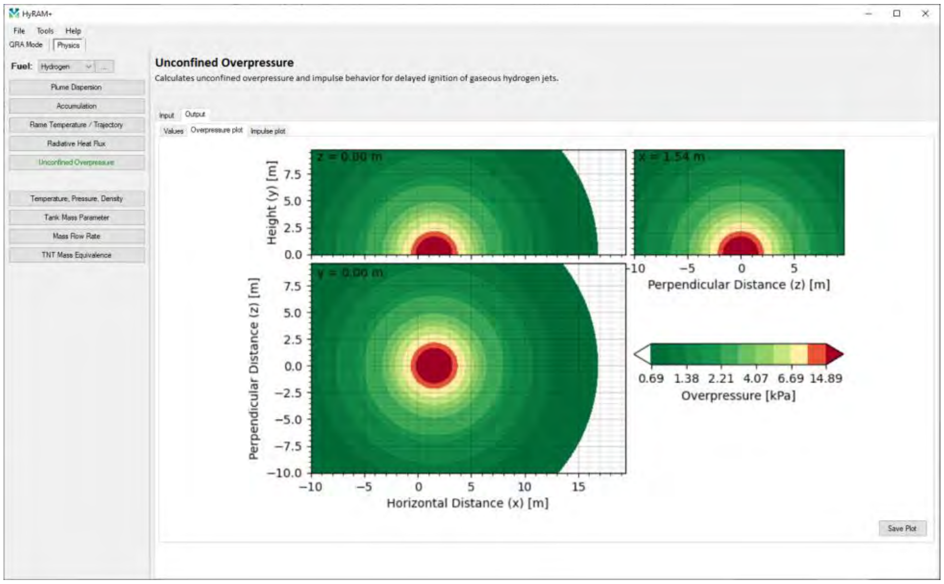
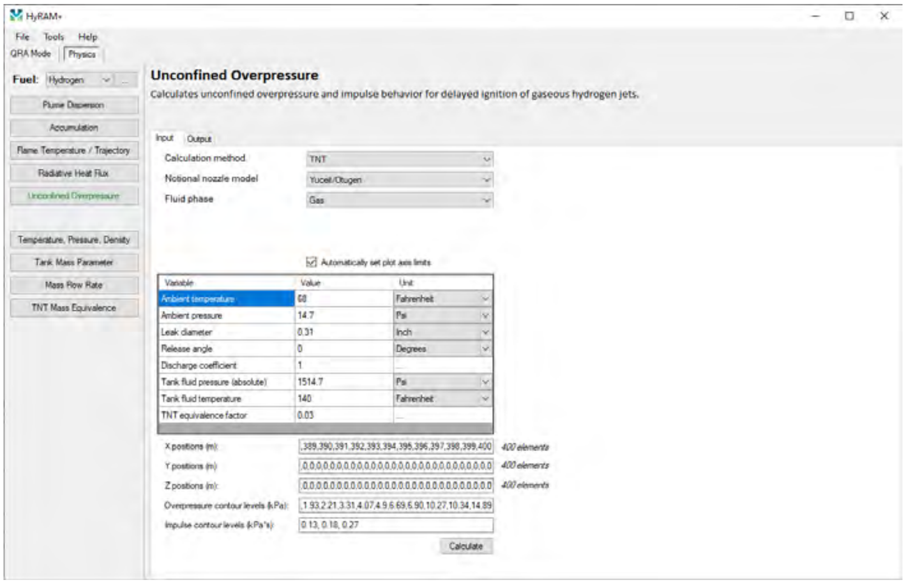


Figure A-52: Scenario 6 (1% leak) Bauwens Overpressure Output Traceability Figure

A.9.3. TNT Equivalence Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: TNT
Notional nozzle model: Yuceil/Otugen
Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	0.31	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
TNT equivalence factor	0.03	...

X positions (m): ,389,390,391,392,393,394,395,396,397,398,399,400 *400 elements*
Y positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *400 elements*
Z positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *400 elements*
Overpressure contour levels (kPa): ,1.93,2.21,3.31,4.07,4.9,6.69,6.90,10.27,10.34,14.89
Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-53: Scenario 6 (1% leak) TNT Overpressure Input Traceability Figure

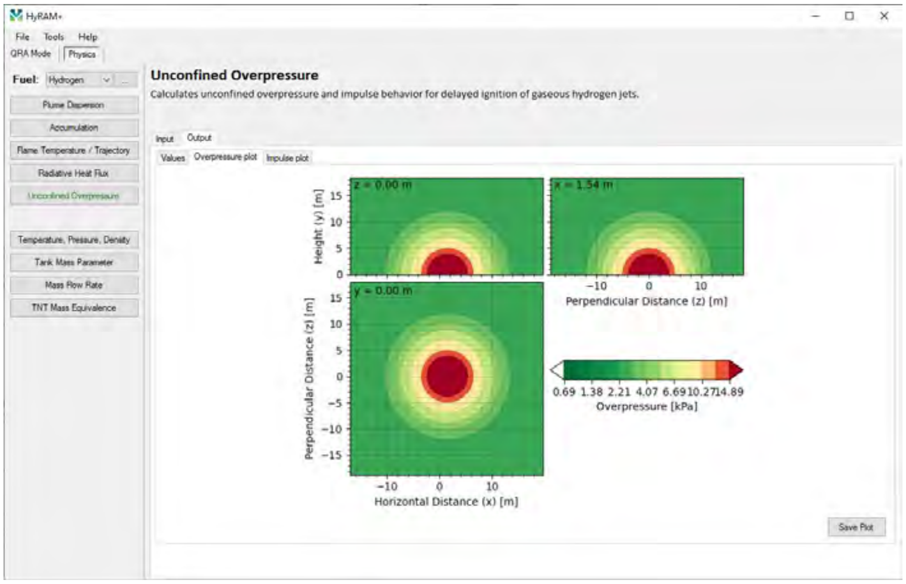
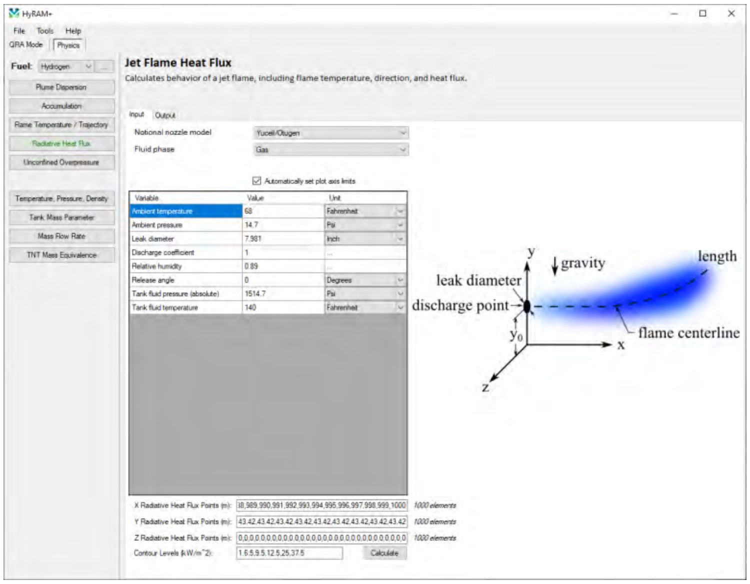


Figure A-54: Scenario 6 (1% leak) TNT Overpressure Output Traceability Figure

A.10. Scenario 7: 100% Leak Area

A.10.1. Heat Flux



Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	7.981	Inch
Discharge coefficient	1	...
Relative humidity	0.89	...
Release angle	0	Degrees
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit

X Radiative Heat Flux Points (m): 38,989,990,991,992,993,994,995,996,997,998,999,1000 *1000 elements*

Y Radiative Heat Flux Points (m): 43.42,43.42,43.42,43.42,43.42,43.42,43.42,43.42,43.42 *1000 elements*

Z Radiative Heat Flux Points (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *1000 elements*

Contour Levels (kW/m^2): 1.6,5.9,5,12.5,25,37.5

Figure A-55: Scenario 7 (100% leak) Heat Flux Input Traceability Figure

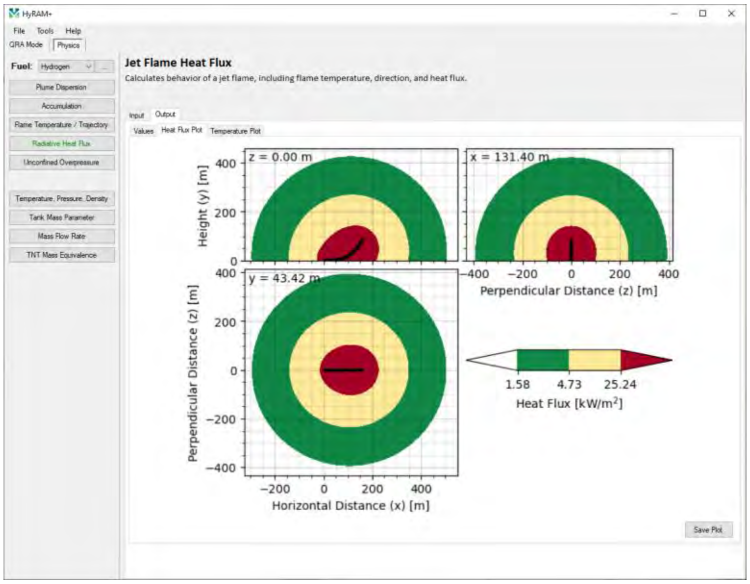
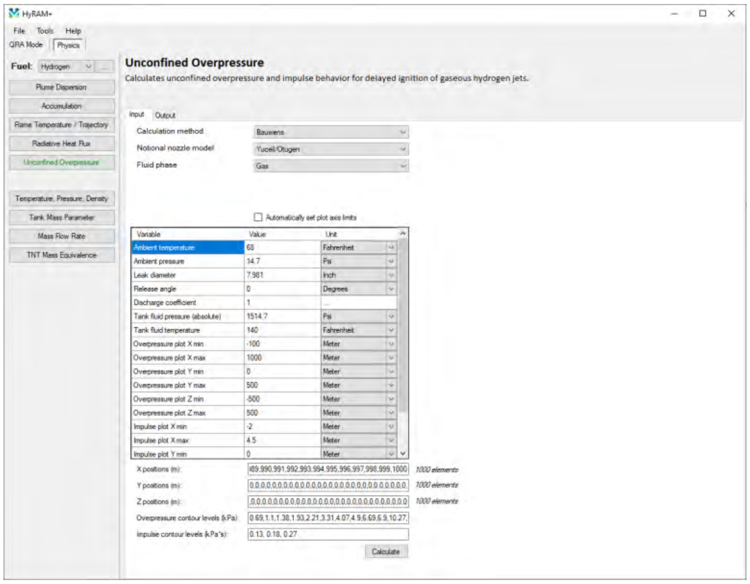


Figure A-56: Scenario 7 (100% leak) Heat Flux Output Traceability Figure

A.10.2. Bauwens Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: Bauwens

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☐ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	7.981	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
Overpressure plot X min	-100	Meter
Overpressure plot X max	1000	Meter
Overpressure plot Y min	0	Meter
Overpressure plot Y max	500	Meter
Overpressure plot Z min	-500	Meter
Overpressure plot Z max	500	Meter
Impulse plot X min	-2	Meter
Impulse plot X max	4.5	Meter
Impulse plot Y min	0	Meter

X positions (m): 89,990,991,992,993,994,995,996,997,998,999,1000 *1000 elements*

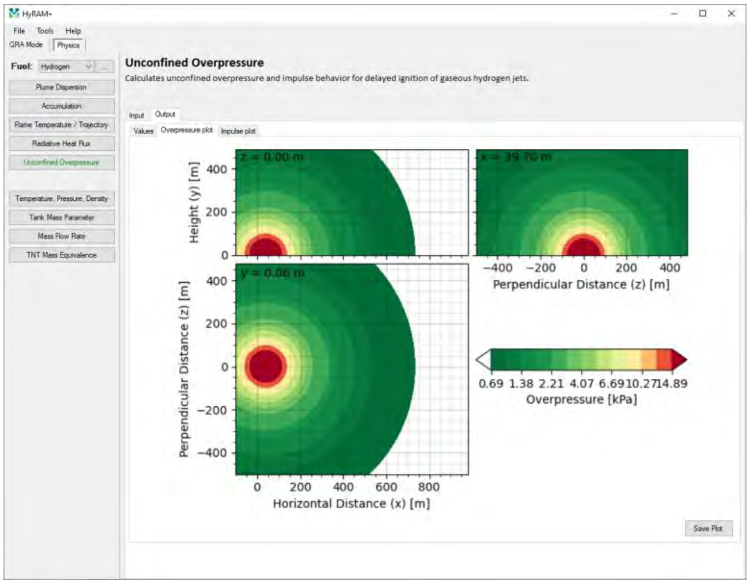
Y positions (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0, *1000 elements*

Z positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *1000 elements*

Overpressure contour levels (kPa): 0.69,1.1,1.38,1.93,2.21,3.31,4.07,4.9,6.69,6.9,10.27,

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-57: Scenario 7 (100% leak) Bauwens Overpressure Input Traceability Figure

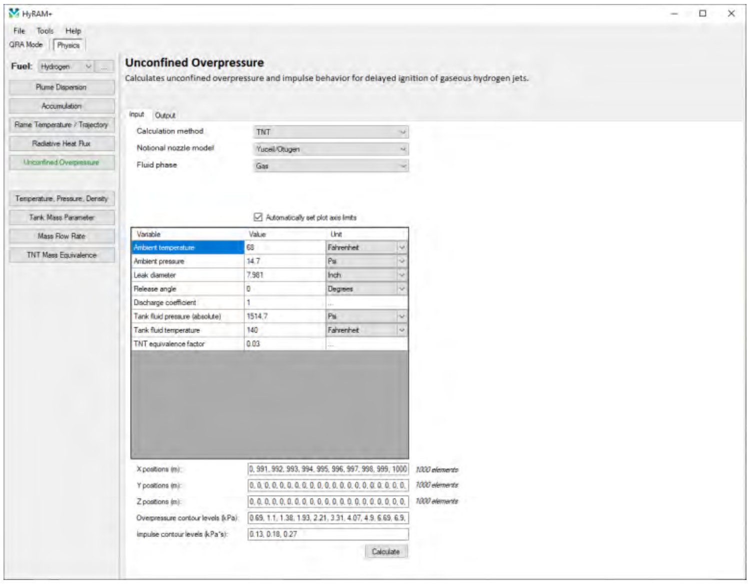


Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-58: Scenario 7 (100% leak) Bauwens Overpressure Output Traceability Figure

A.10.3. TNT Equivalence Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: TNT

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	7.981	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
TNT equivalence factor	0.03	...

X positions (m): 0, 991, 992, 993, 994, 995, 996, 997, 998, 999, 1000 *1000 elements*

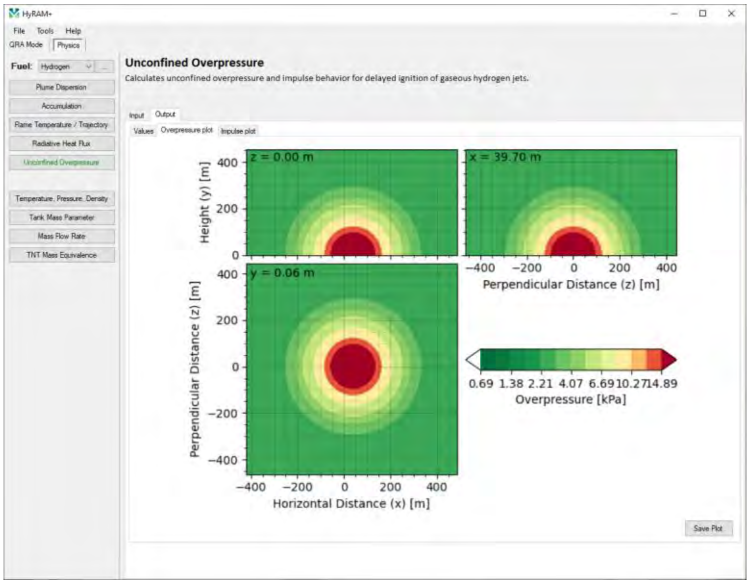
Y positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *1000 elements*

Z positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *1000 elements*

Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 6.9,

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-59: Scenario 7 (100% leak) TNT Overpressure Input Traceability Figure



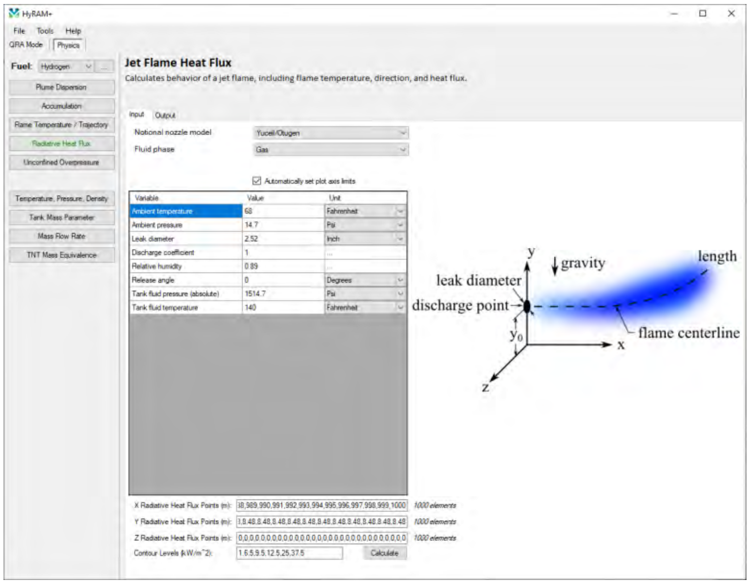
Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-60: Scenario 7 (100% leak) TNT Overpressure Output Traceability Figure

A.11. Scenario 7: 10% Leak Area

A.11.1. Heat Flux



Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	2.52	Inch
Discharge coefficient	1	...
Relative humidity	0.89	...
Release angle	0	Degrees
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit

X Radiative Heat Flux Points (m): 38,989,990,991,992,993,994,995,996,997,998,999,1000 1000 elements

Y Radiative Heat Flux Points (m): 3,8.48,8.48,8.48,8.48,8.48,8.48,8.48,8.48,8.48,8.48,8.48 1000 elements

Z Radiative Heat Flux Points (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 1000 elements

Contour Levels (kW/m^2): 1.6,5,9.5,12.5,25,37.5

Figure A-61: Scenario 7 (10% leak) Heat Flux Input Traceability Figure

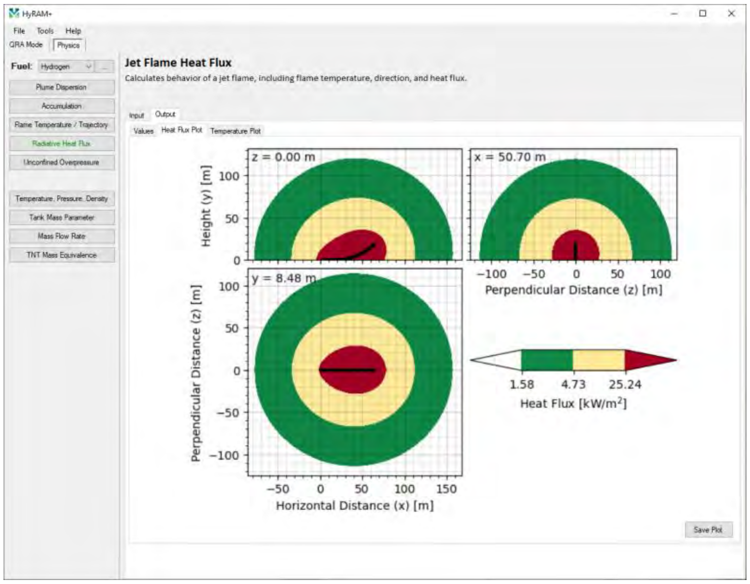
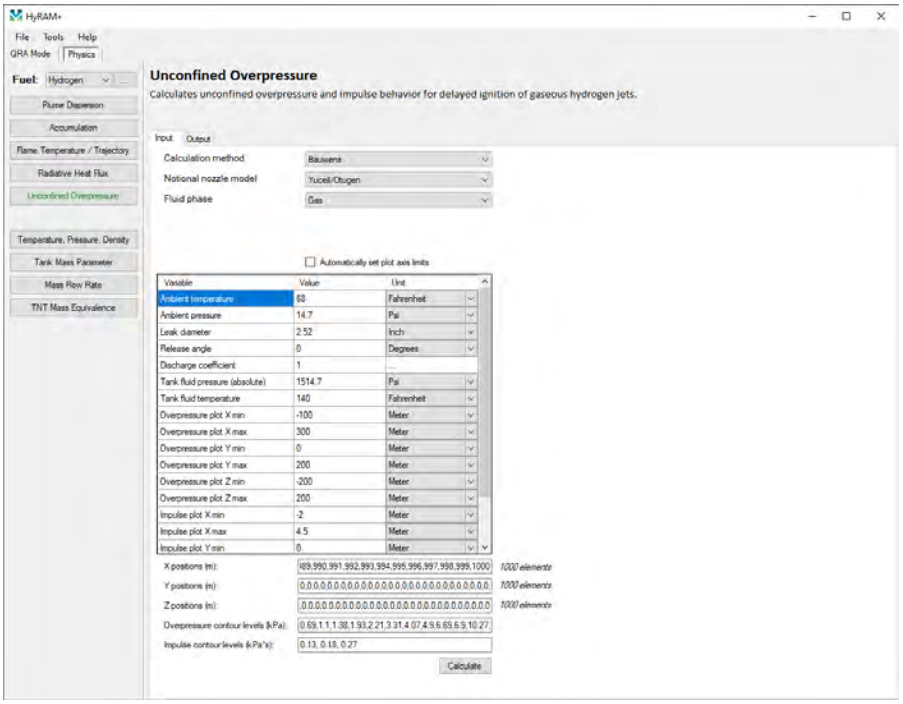


Figure A-62: Scenario 7 (10% leak) Heat Flux Output Traceability Figure

A.11.2. Bauwens Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: Bauwens

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☐ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	2.52	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
Overpressure plot X min	-100	Meter
Overpressure plot X max	300	Meter
Overpressure plot Y min	0	Meter
Overpressure plot Y max	200	Meter
Overpressure plot Z min	-200	Meter
Overpressure plot Z max	200	Meter
Impulse plot X min	-2	Meter
Impulse plot X max	4.5	Meter
Impulse plot Y min	0	Meter

X positions (m): 89,990,991,992,993,994,995,996,997,998,999,1000 *1000 elements*

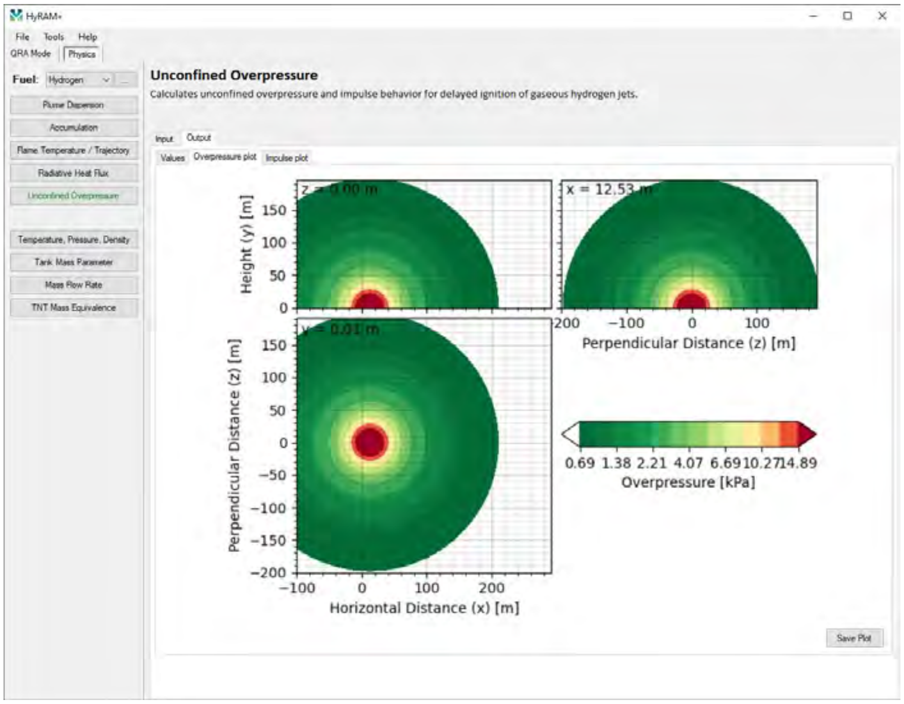
Y positions (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *1000 elements*

Z positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *1000 elements*

Overpressure contour levels (kPa): 0.69,1.1,1.38,1.93,2.21,3.31,4.07,4.9,6.69,6.9,10.27,

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-63: Scenario 7 (10% leak) Bauwens Overpressure Input Traceability Figure

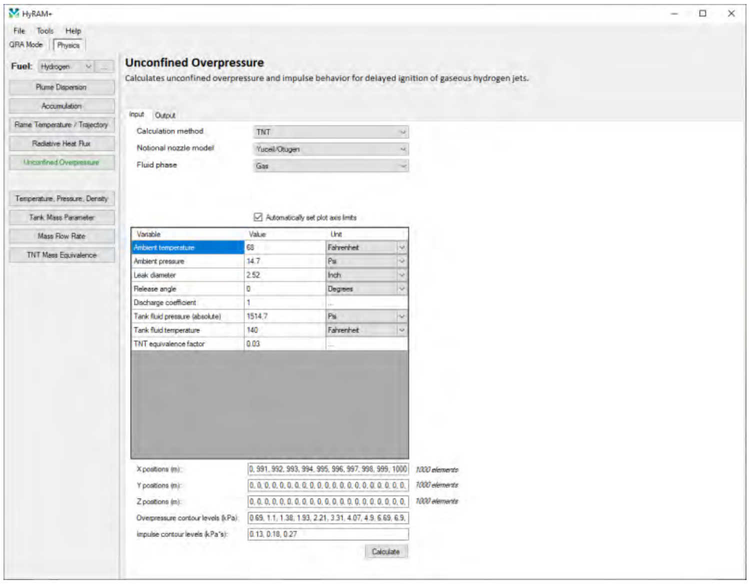


Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-64: Scenario 7 (10% leak) Bauwens Overpressure Output Traceability Figure

A.11.3. TNT Equivalence Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: TNT

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	2.52	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
TNT equivalence factor	0.03	...

X positions (m): 0, 991, 992, 993, 994, 995, 996, 997, 998, 999, 1000 *1000 elements*

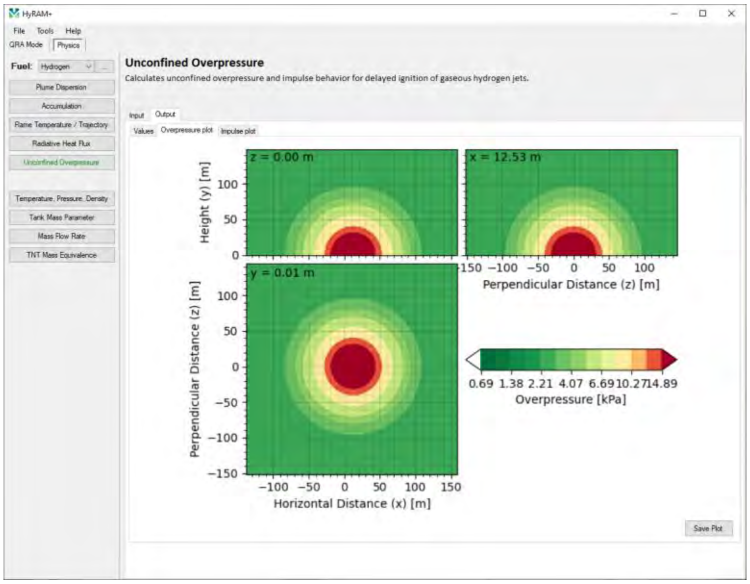
Y positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *1000 elements*

Z positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *1000 elements*

Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 6.9,

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-65: Scenario 7 (10% leak) TNT Overpressure Input Traceability Figure



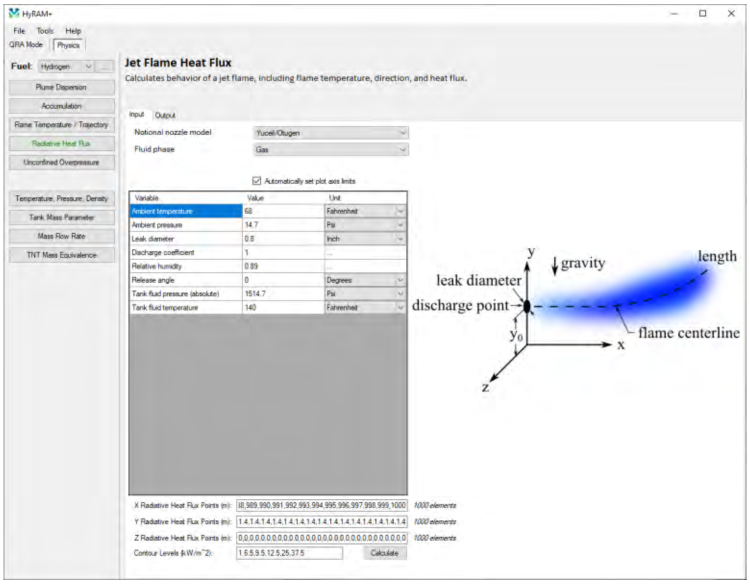
Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-66: Scenario 7 (10% leak) TNT Overpressure Output Traceability Figure

A.12. Scenario 7: 1% Leak Area

A.12.1. Heat Flux



Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Fuel: Hydrogen

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	0.8	Inch
Discharge coefficient	1	...
Relative humidity	0.89	...
Release angle	0	Degrees
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit

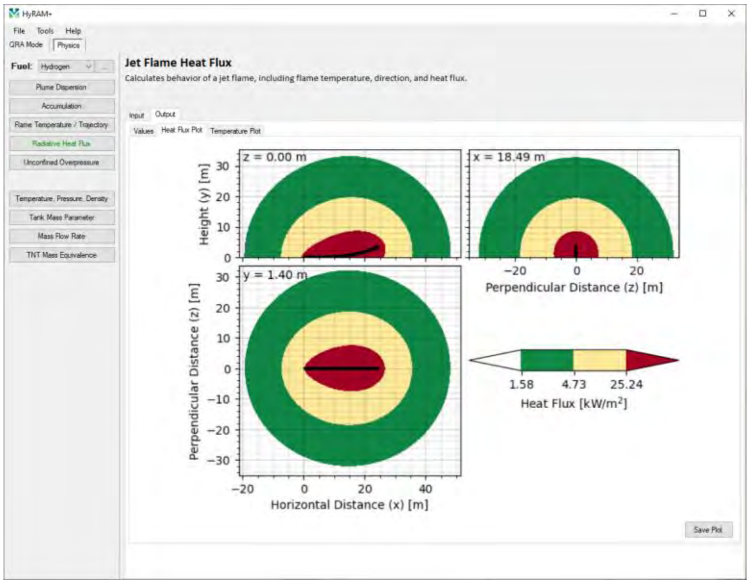
X Radiative Heat Flux Points (m): 38,989,990,991,992,993,994,995,996,997,998,999,1000 *1000 elements*

Y Radiative Heat Flux Points (m): 1.4,1.4,1.4,1.4,1.4,1.4,1.4,1.4,1.4,1.4,1.4,1.4,1.4,1.4 *1000 elements*

Z Radiative Heat Flux Points (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *1000 elements*

Contour Levels (kW/m^2): 1.6,5.9,5.12.5,25,37.5

Figure A-67: Scenario 7 (1% leak) Heat Flux Input Traceability Figure

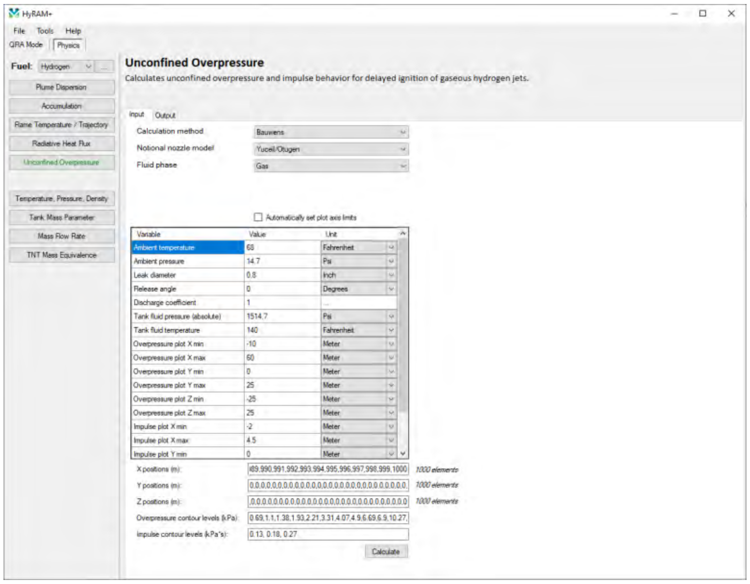


Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Figure A-68: Scenario 7 (1% leak) Heat Flux Output Traceability Figure

A.12.2. Bauwens Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

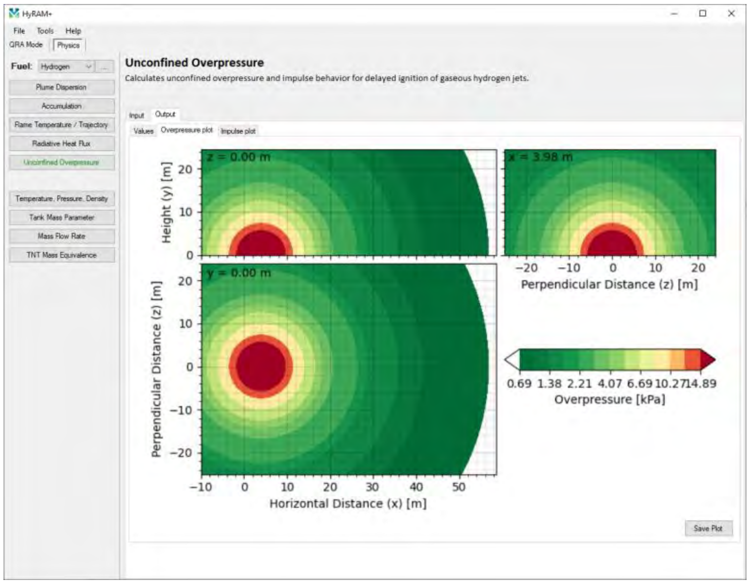
Calculation method: Bauwens
Notional nozzle model: Yuceil/Otugen
Fluid phase: Gas

☐ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	0.8	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
Overpressure plot X min	-10	Meter
Overpressure plot X max	60	Meter
Overpressure plot Y min	0	Meter
Overpressure plot Y max	25	Meter
Overpressure plot Z min	-25	Meter
Overpressure plot Z max	25	Meter
Impulse plot X min	-2	Meter
Impulse plot X max	4.5	Meter
Impulse plot Y min	0	Meter

X positions (m): 89,990,991,992,993,994,995,996,997,998,999,1000 *1000 elements*
Y positions (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0, *1000 elements*
Z positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *1000 elements*
Overpressure contour levels (kPa): 0.69,1.1,1.38,1.93,2.21,3.31,4.07,4.9,6.69,6.9,10.27,
Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-69: Scenario 7 (1% leak) Bauwens Overpressure Input Traceability Figure

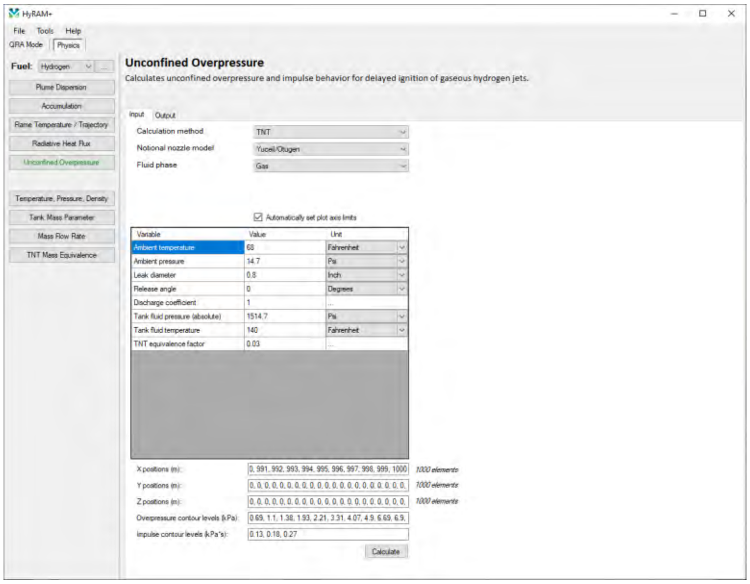


Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-70: Scenario 7 (1% leak) Bauwens Overpressure Output Traceability Figure

A.12.3. TNT Equivalence Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

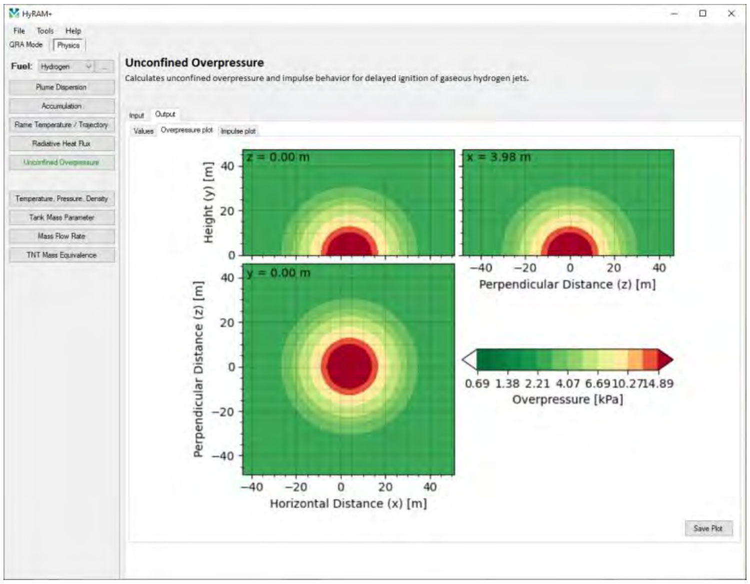
Calculation method: TNT
Notional nozzle model: Yuceil/Otugen
Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	0.8	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
TNT equivalence factor	0.03	...

X positions (m): 0, 991, 992, 993, 994, 995, 996, 997, 998, 999, 1000 *1000 elements*
Y positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *1000 elements*
Z positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *1000 elements*
Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 6.9,
Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-71: Scenario 7 (1% leak) TNT Overpressure Input Traceability Figure



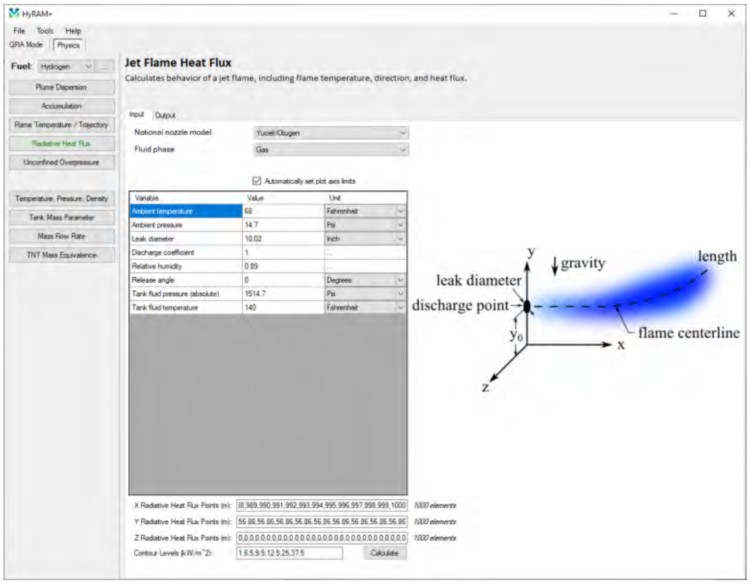
Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-72: Scenario 7 (1% leak) TNT Overpressure Output Traceability Figure

A.13. Scenario 8: 100% Leak Area

A.13.1. Heat Flux



Fuel: Hydrogen

Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	10.02	Inch
Discharge coefficient	1	...
Relative humidity	0.89	...
Release angle	0	Degrees
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit

X Radiative Heat Flux Points (m): 8,989,990,991,992,993,994,995,996,997,998,999,1000 *1000 elements*

Y Radiative Heat Flux Points (m): 56.86,56.86,56.86,56.86,56.86,56.86,56.86,56.86,56.86 *1000 elements*

Z Radiative Heat Flux Points (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *1000 elements*

Contour Levels (kW/m^2): 1.6,5,9.5,12.5,25,37.5

Figure A-73: Scenario 8 (100% leak) Heat Flux Input Traceability Figure

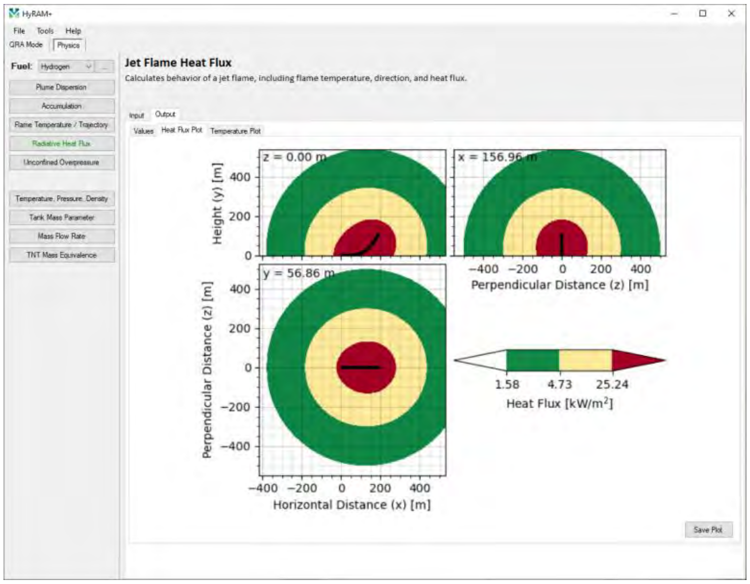
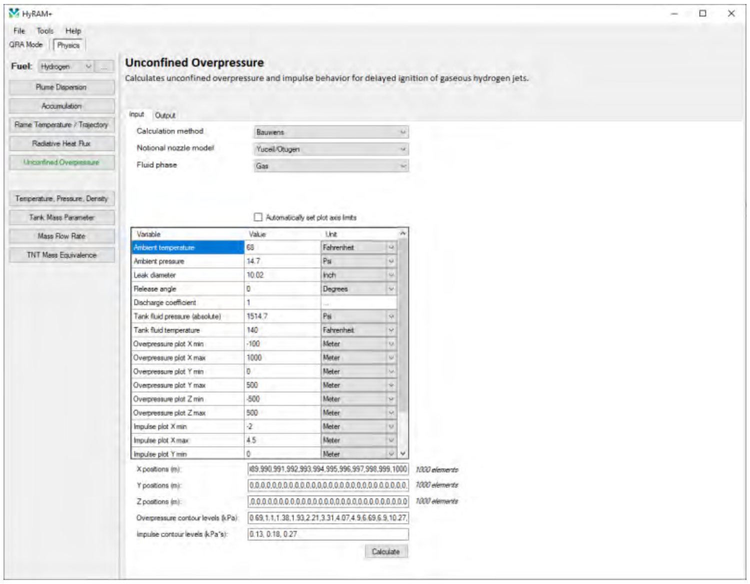


Figure A-74: Scenario 8 (100% leak) Heat Flux Output Traceability Figure

A.13.2. Bauwens Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

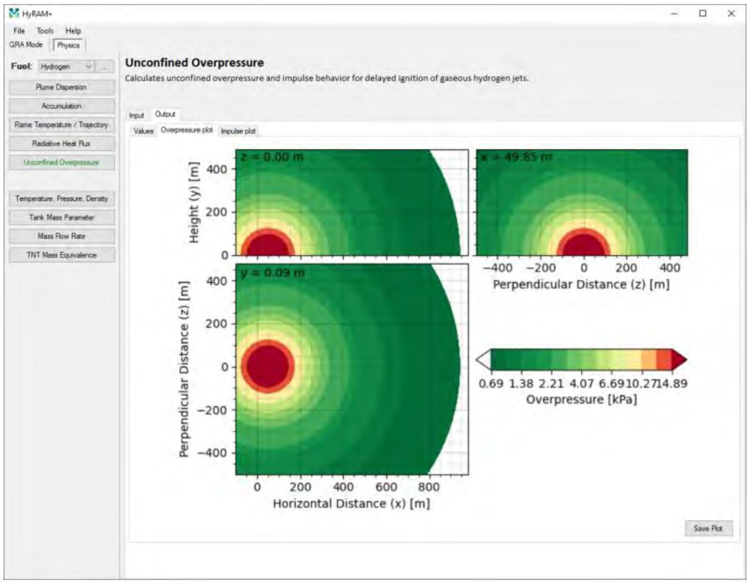
Calculation method: Bauwens
Notional nozzle model: Yuceil/Otugen
Fluid phase: Gas

☐ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	10.02	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
Overpressure plot X min	-100	Meter
Overpressure plot X max	1000	Meter
Overpressure plot Y min	0	Meter
Overpressure plot Y max	500	Meter
Overpressure plot Z min	-500	Meter
Overpressure plot Z max	500	Meter
Impulse plot X min	-2	Meter
Impulse plot X max	4.5	Meter
Impulse plot Y min	0	Meter

X positions (m): 89,990,991,992,993,994,995,996,997,998,999,1000 *1000 elements*
Y positions (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0, *1000 elements*
Z positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *1000 elements*
Overpressure contour levels (kPa): 0.69,1.1,1.38,1.93,2.21,3.31,4.07,4.9,6.69,6.9,10.27,
Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-75: Scenario 8 (100% leak) Bauwens Overpressure Input Traceability Figure

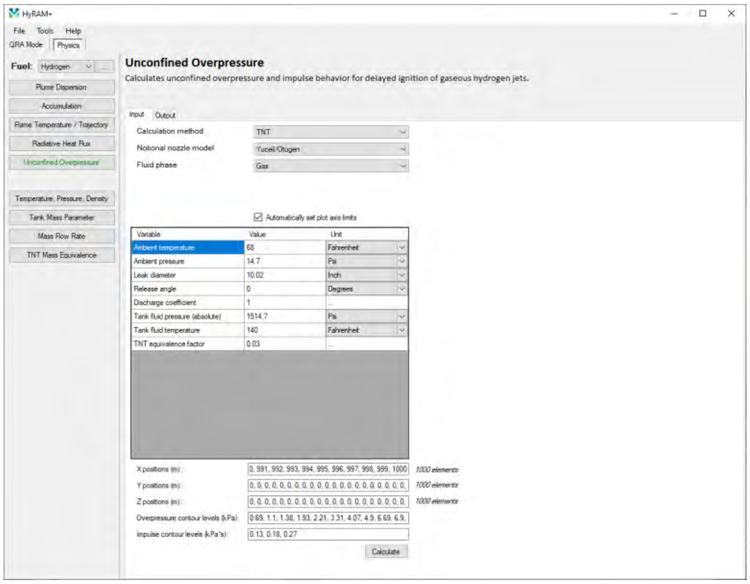


Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-76: Scenario 8 (100% leak) Bauwens Overpressure Output Traceability Figure

A.13.3. TNT Equivalence Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: TNT

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	10.02	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
TNT equivalence factor	0.03	...

X positions (m): 0, 991, 992, 993, 994, 995, 996, 997, 998, 999, 1000 *1000 elements*

Y positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *1000 elements*

Z positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *1000 elements*

Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 6.9,

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-77: Scenario 8 (100% leak) TNT Overpressure Input Traceability Figure

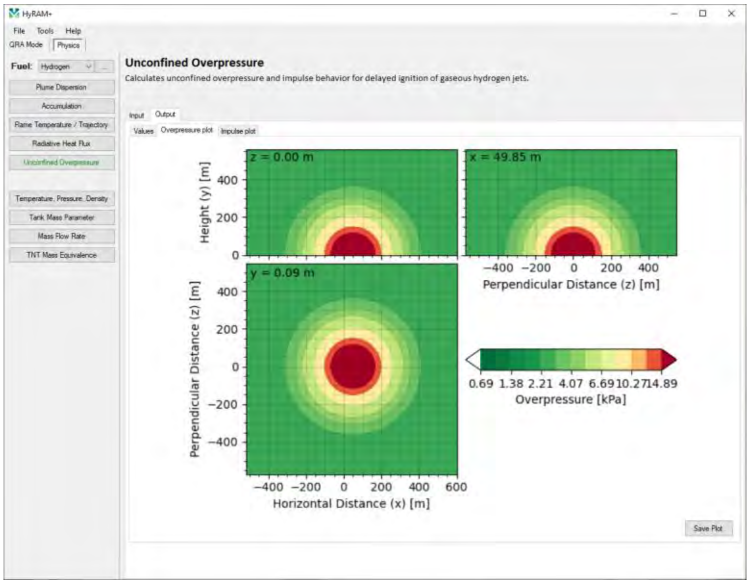
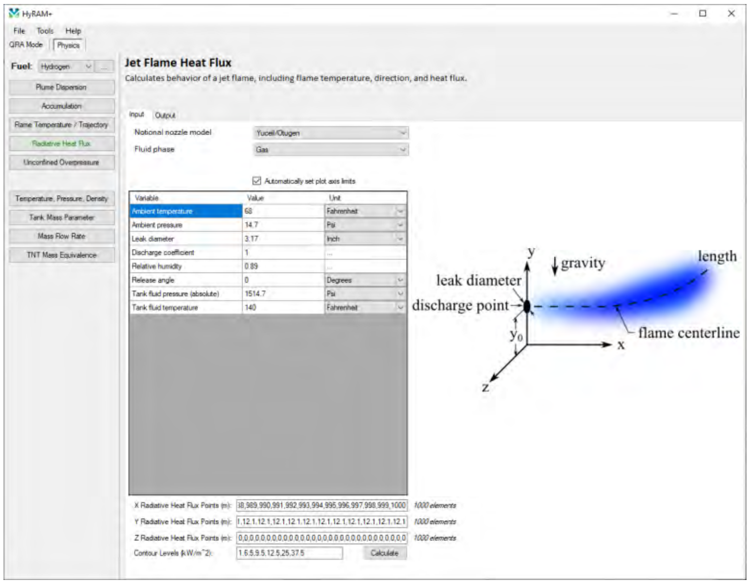


Figure A-78: Scenario 8 (100% leak) TNT Overpressure Output Traceability Figure

A.14. Scenario 8: 10% Leak Area

A.14.1. Heat Flux



Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	3.17	Inch
Discharge coefficient	1	...
Relative humidity	0.89	...
Release angle	0	Degrees
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit

X Radiative Heat Flux Points (m): 38,989,990,991,992,993,994,995,996,997,998,999,1000 *1000 elements*

Y Radiative Heat Flux Points (m): 1,12.1,12.1,12.1,12.1,12.1,12.1,12.1,12.1,12.1,12.1,12.1,12.1 *1000 elements*

Z Radiative Heat Flux Points (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *1000 elements*

Contour Levels (kW/m^2): 1.6,5,9.5,12.5,25,37.5

Figure A-79: Scenario 8 (10% leak) Heat Flux Input Traceability Figure

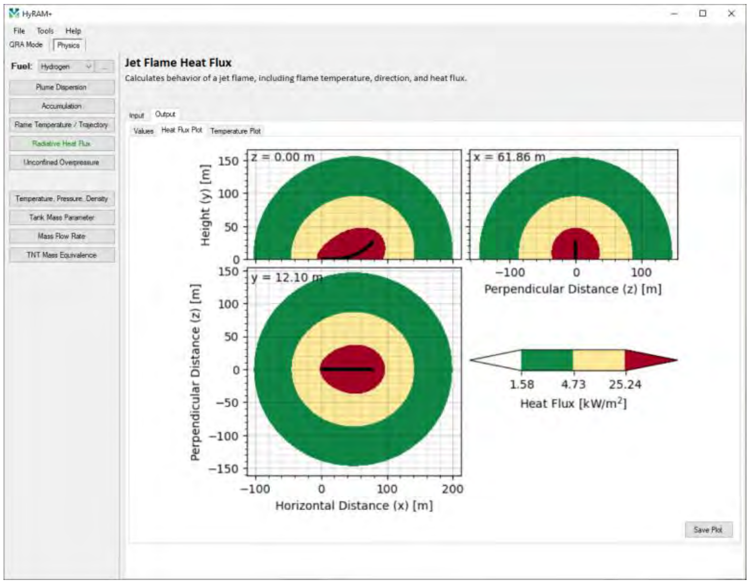
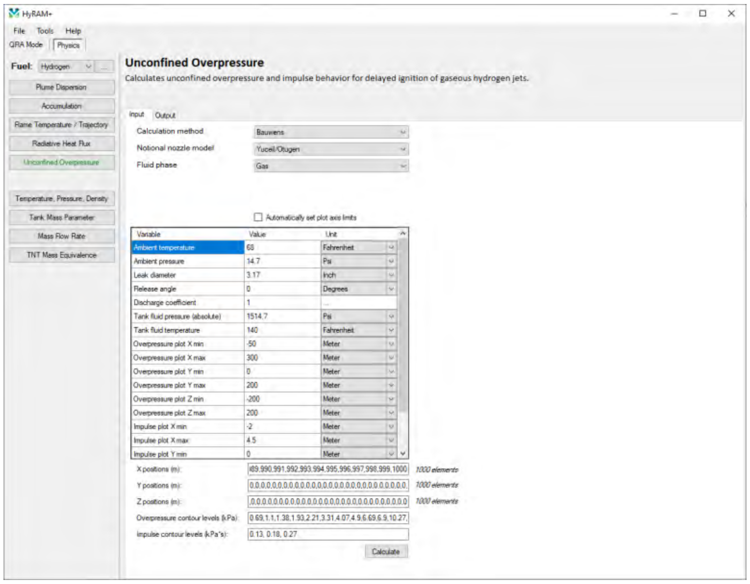


Figure A-80: Scenario 8 (10% leak) Heat Flux Output Traceability Figure

A.14.2. Bauwens Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: Bauwens

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☐ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	3.17	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
Overpressure plot X min	-50	Meter
Overpressure plot X max	300	Meter
Overpressure plot Y min	0	Meter
Overpressure plot Y max	200	Meter
Overpressure plot Z min	-200	Meter
Overpressure plot Z max	200	Meter
Impulse plot X min	-2	Meter
Impulse plot X max	4.5	Meter
Impulse plot Y min	0	Meter

X positions (m): 89,990,991,992,993,994,995,996,997,998,999,1000 *1000 elements*

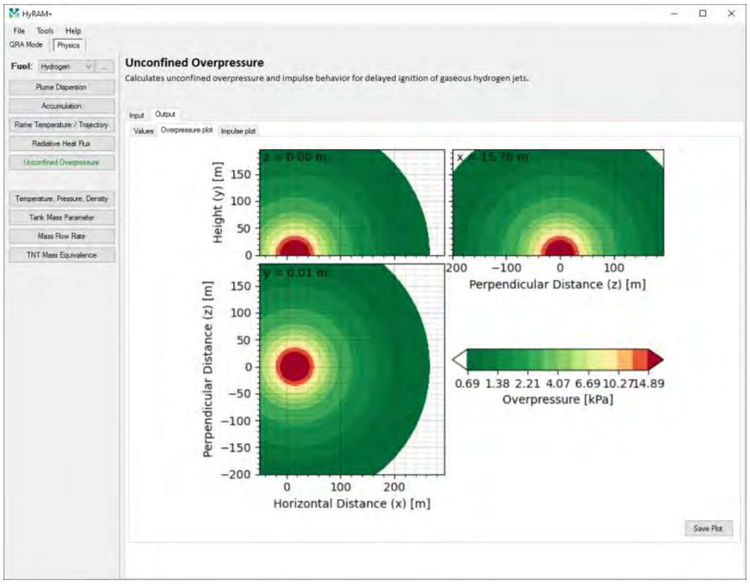
Y positions (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0, *1000 elements*

Z positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *1000 elements*

Overpressure contour levels (kPa): 0.69,1.1,1.38,1.93,2.21,3.31,4.07,4.9,6.69,6.9,10.27,

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-81: Scenario 8 (10% leak) Bauwens Overpressure Input Traceability Figure

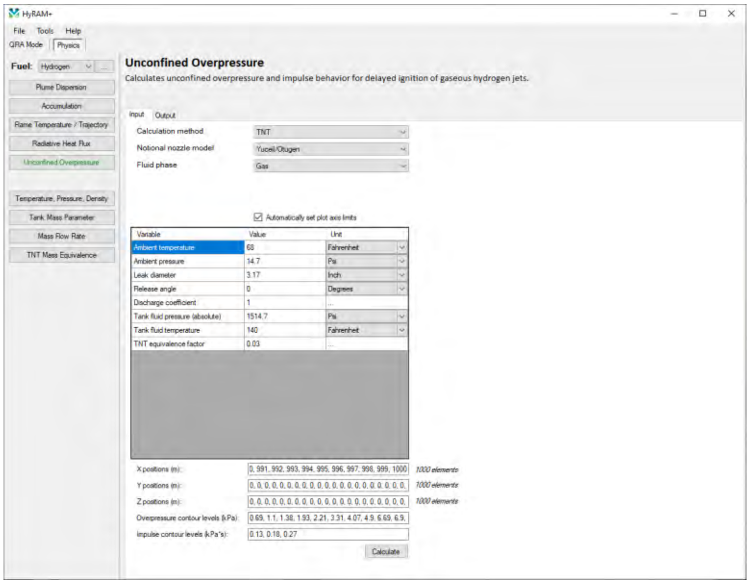


Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-82: Scenario 8 (10% leak) Bauwens Overpressure Output Traceability Figure

A.14.3. TNT Equivalence Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: TNT

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	3.17	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
TNT equivalence factor	0.03	...

X positions (m): 0, 991, 992, 993, 994, 995, 996, 997, 998, 999, 1000 1000 elements

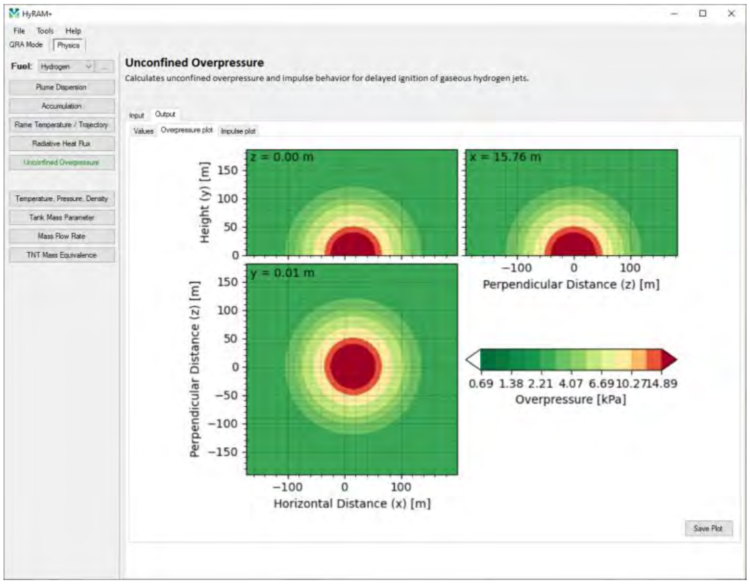
Y positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1000 elements

Z positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1000 elements

Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 6.9,

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-83: Scenario 8 (10% leak) TNT Overpressure Input Traceability Figure



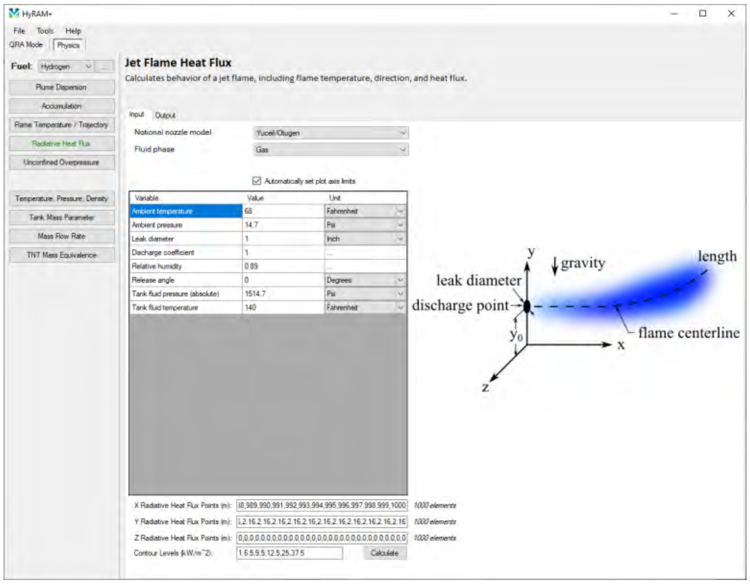
Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-84: Scenario 8 (10% leak) TNT Overpressure Output Traceability Figure

A.15. Scenario 8: 1% Leak Area

A.15.1. Heat Flux



Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	1	Inch
Discharge coefficient	1	...
Relative humidity	0.89	...
Release angle	0	Degrees
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit

X Radiative Heat Flux Points (m): 8,989,990,991,992,993,994,995,996,997,998,999,1000 *1000 elements*

Y Radiative Heat Flux Points (m): 2.16,2.16,2.16,2.16,2.16,2.16,2.16,2.16,2.16,2.16,2.16 *1000 elements*

Z Radiative Heat Flux Points (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *1000 elements*

Contour Levels (kW/m^2): 1.6,5,9.5,12.5,25,37.5

Figure A-85: Scenario 8 (1% leak) Heat Flux Input Traceability Figure

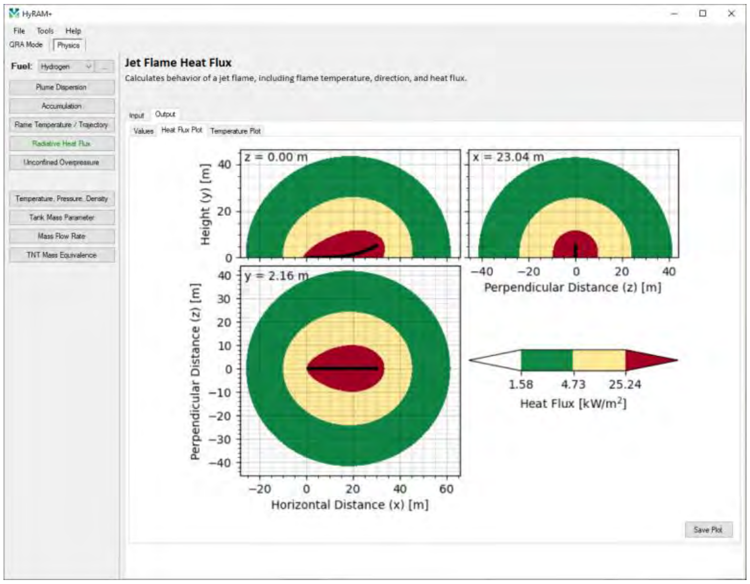
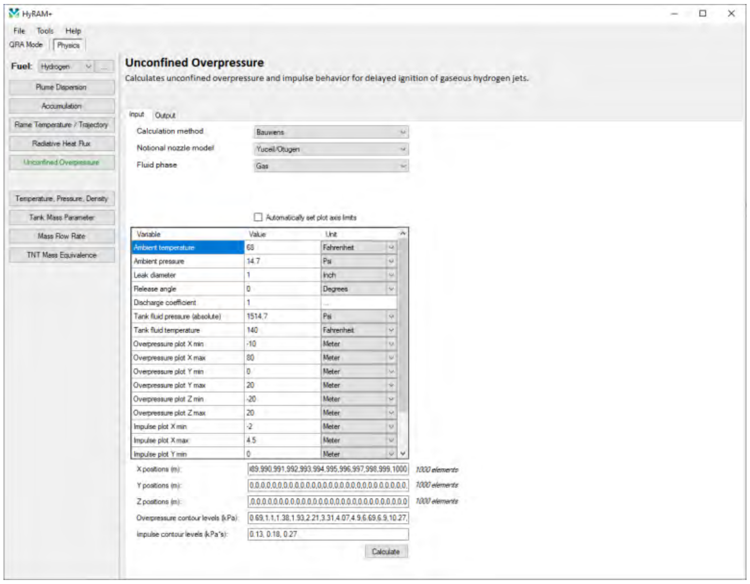


Figure A-86: Scenario 8 (1% leak) Heat Flux Output Traceability Figure

A.15.2. Bauwens Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: Bauwens

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☐ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	1	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
Overpressure plot X min	-10	Meter
Overpressure plot X max	80	Meter
Overpressure plot Y min	0	Meter
Overpressure plot Y max	20	Meter
Overpressure plot Z min	-20	Meter
Overpressure plot Z max	20	Meter
Impulse plot X min	-2	Meter
Impulse plot X max	4.5	Meter
Impulse plot Y min	0	Meter

X positions (m): i89,990,991,992,993,994,995,996,997,998,999,1000 *1000 elements*

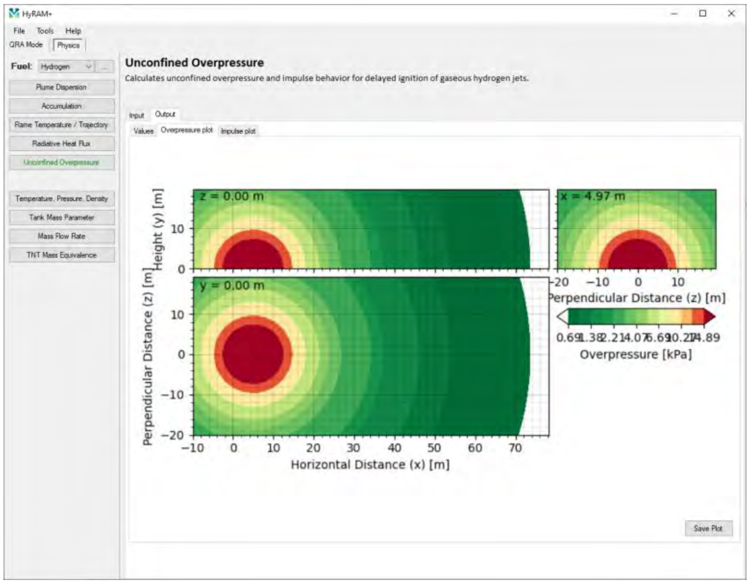
Y positions (m): 0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0, *1000 elements*

Z positions (m): ,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0 *1000 elements*

Overpressure contour levels (kPa): 0.69,1.1,1.38,1.93,2.21,3.31,4.07,4.9,6.69,6.9,10.27,

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-87: Scenario 8 (1% leak) Bauwens Overpressure Input Traceability Figure

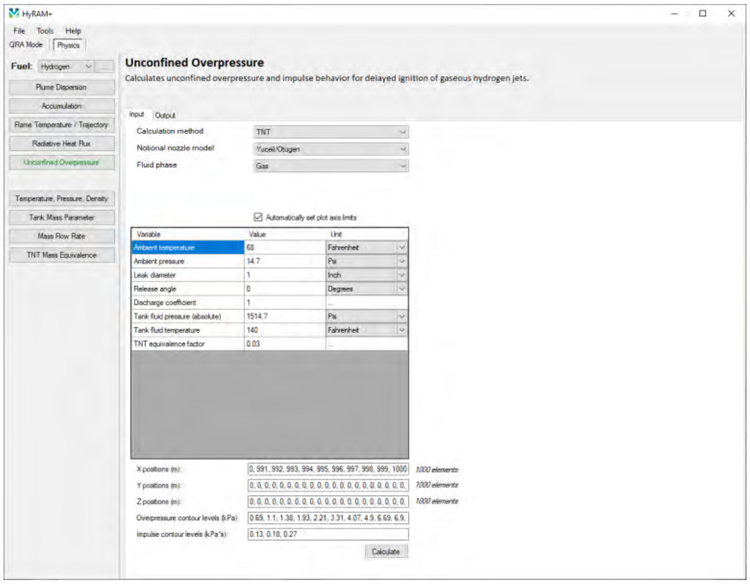


Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-88: Scenario 8 (1% leak) Bauwens Overpressure Output Traceability Figure

A.15.3. TNT Equivalence Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: TNT

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	1	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	1514.7	Psi
Tank fluid temperature	140	Fahrenheit
TNT equivalence factor	0.03	...

X positions (m): 0, 991, 992, 993, 994, 995, 996, 997, 998, 999, 1000 *1000 elements*

Y positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *1000 elements*

Z positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *1000 elements*

Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 6.9,

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-89: Scenario 8 (1% leak) TNT Overpressure Input Traceability Figure

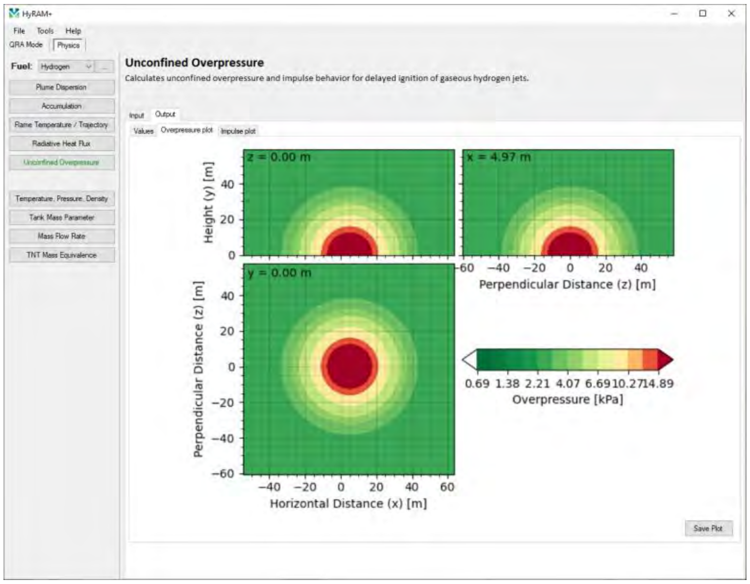
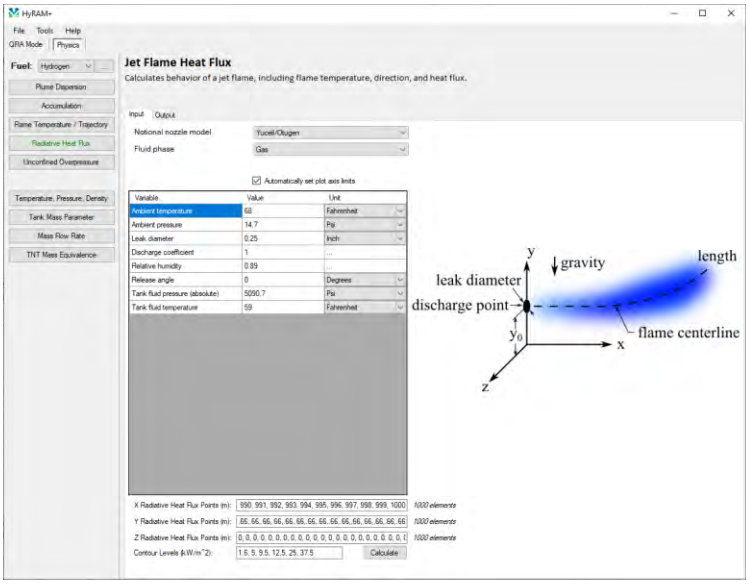


Figure A-90: Scenario 8 (1% leak) TNT Overpressure Output Traceability Figure

A.16. Scenario 9: 100% Leak Area

A.16.1. Heat Flux



Jet Flame Heat Flux

Calculates behavior of a jet flame, including flame temperature, direction, and heat flux.

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	0.25	Inch
Discharge coefficient	1	...
Relative humidity	0.89	...
Release angle	0	Degrees
Tank fluid pressure (absolute)	5090.7	Psi
Tank fluid temperature	59	Fahrenheit

X Radiative Heat Flux Points (m): 990, 991, 992, 993, 994, 995, 996, 997, 998, 999, 1000 — 1000 elements

Y Radiative Heat Flux Points (m): .66, .66, .66, .66, .66, .66, .66, .66, .66, .66, .66, .66, .66, .66, .66 — 1000 elements

Z Radiative Heat Flux Points (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0 — 1000 elements

Contour Levels (kW/m^2): 1.6, 5, 9.5, 12.5, 25, 37.5

Figure A-91: Scenario 9 (100% leak) Heat Flux Input Traceability Figure

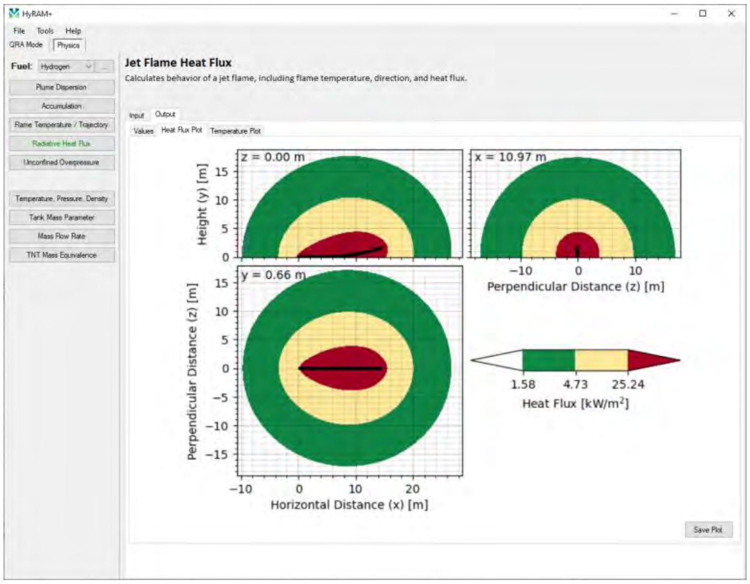
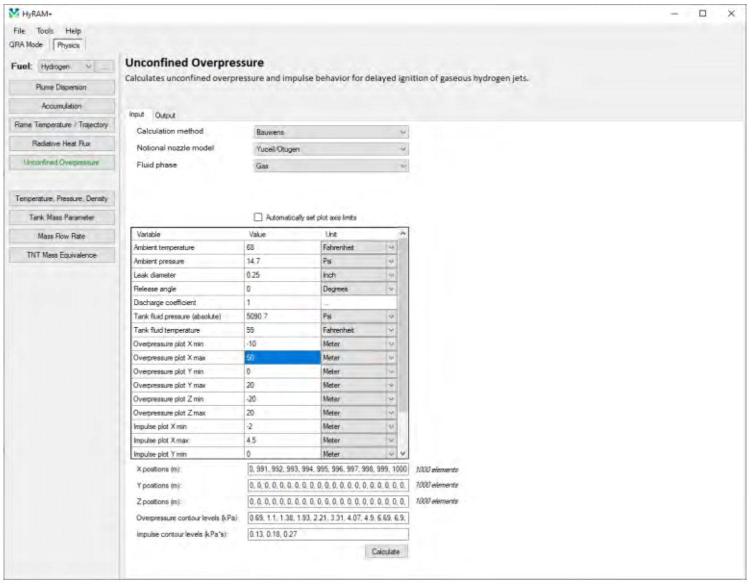


Figure A-92: Scenario 9 (100% leak) Heat Flux Output Traceability Figure

A.16.2. Bauwens Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

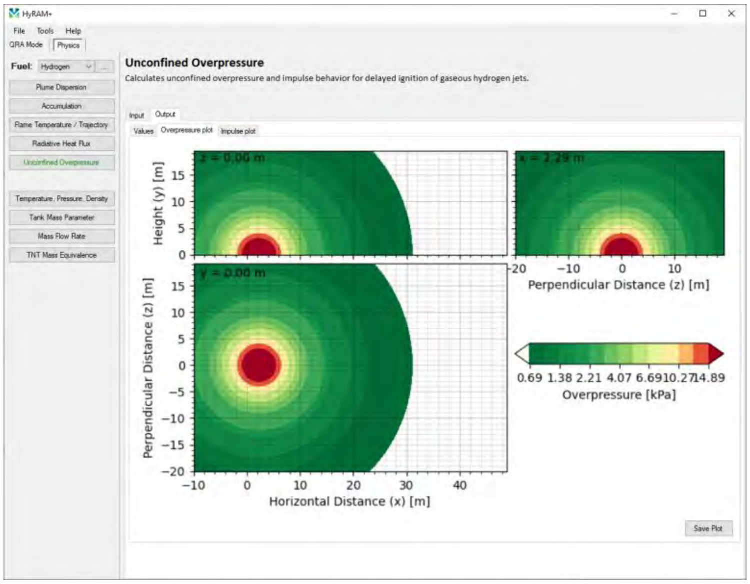
Calculation method: Bauwens
Notional nozzle model: Yuceil/Otugen
Fluid phase: Gas

☐ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	0.25	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	5090.7	Psi
Tank fluid temperature	59	Fahrenheit
Overpressure plot X min	-10	Meter
Overpressure plot X max	50	Meter
Overpressure plot Y min	0	Meter
Overpressure plot Y max	20	Meter
Overpressure plot Z min	-20	Meter
Overpressure plot Z max	20	Meter
Impulse plot X min	-2	Meter
Impulse plot X max	4.5	Meter
Impulse plot Y min	0	Meter

X positions (m): 0, 991, 992, 993, 994, 995, 996, 997, 998, 999, 1000 *1000 elements*
Y positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *1000 elements*
Z positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *1000 elements*
Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 6.9,
Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-93: Scenario 9 (100% leak) Bauwens Overpressure Input Traceability Figure

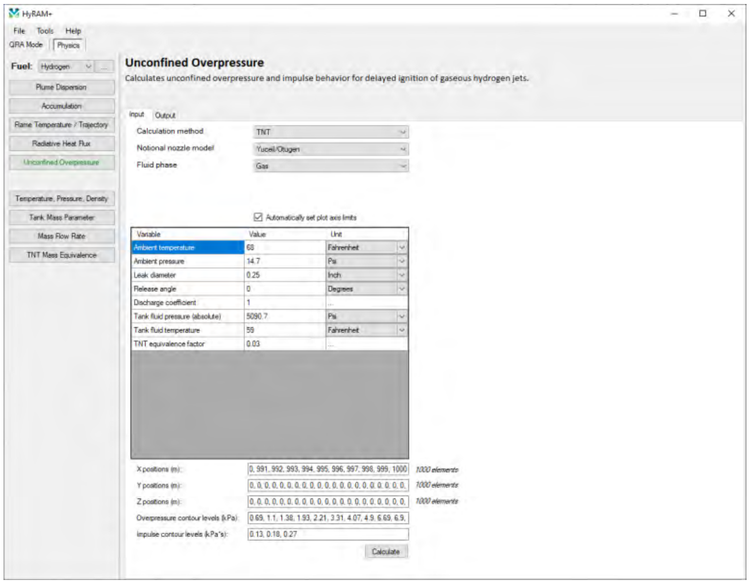


Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-94: Scenario 9 (100% leak) Bauwens Overpressure Output Traceability Figure

A.16.3. TNT Equivalence Overpressure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Calculation method: TNT

Notional nozzle model: Yuceil/Otugen

Fluid phase: Gas

☑ Automatically set plot axis limits

Variable	Value	Unit
Ambient temperature	68	Fahrenheit
Ambient pressure	14.7	Psi
Leak diameter	0.25	Inch
Release angle	0	Degrees
Discharge coefficient	1	...
Tank fluid pressure (absolute)	5090.7	Psi
Tank fluid temperature	59	Fahrenheit
TNT equivalence factor	0.03	...

X positions (m): 0, 991, 992, 993, 994, 995, 996, 997, 998, 999, 1000 *1000 elements*

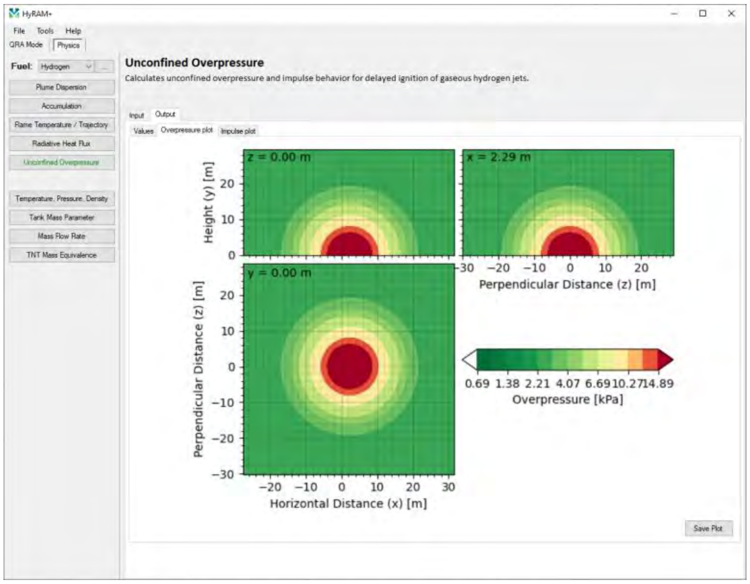
Y positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *1000 elements*

Z positions (m): 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, *1000 elements*

Overpressure contour levels (kPa): 0.69, 1.1, 1.38, 1.93, 2.21, 3.31, 4.07, 4.9, 6.69, 6.9,

Impulse contour levels (kPa*s): 0.13, 0.18, 0.27

Figure A-95: Scenario 9 (100% leak) TNT Overpressure Input Traceability Figure



Unconfined Overpressure

Calculates unconfined overpressure and impulse behavior for delayed ignition of gaseous hydrogen jets.

Figure A-96: Scenario 9 (100% leak) TNT Overpressure Output Traceability Figure

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