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Risk Analysis of a 100 MW 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 100 MW hydrogen production facility in close proximity to an NPP. 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 a 100 MW hydrogen production facility design, 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
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. In this analysis, the hazards associated with a 100 MW 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 100 MW hydrogen generation facility. 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

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.

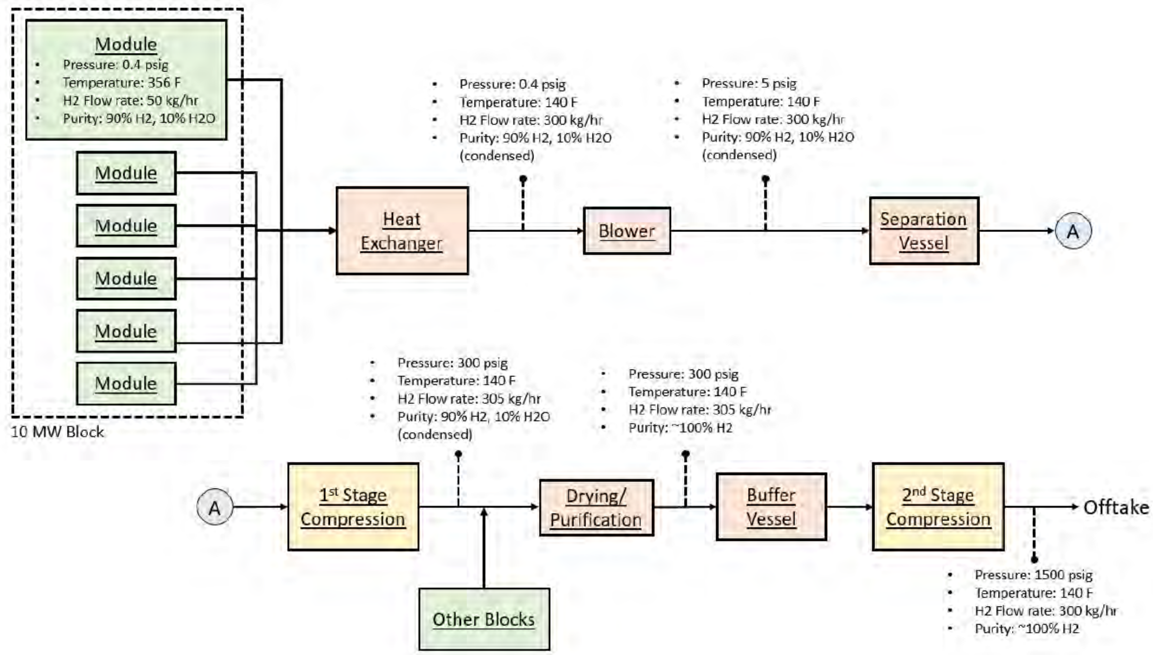

Figure 1: Simplified Flow Diagram of Hydrogen Process Piping within the Hydrogen Facility with Process Conditions [2]

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.

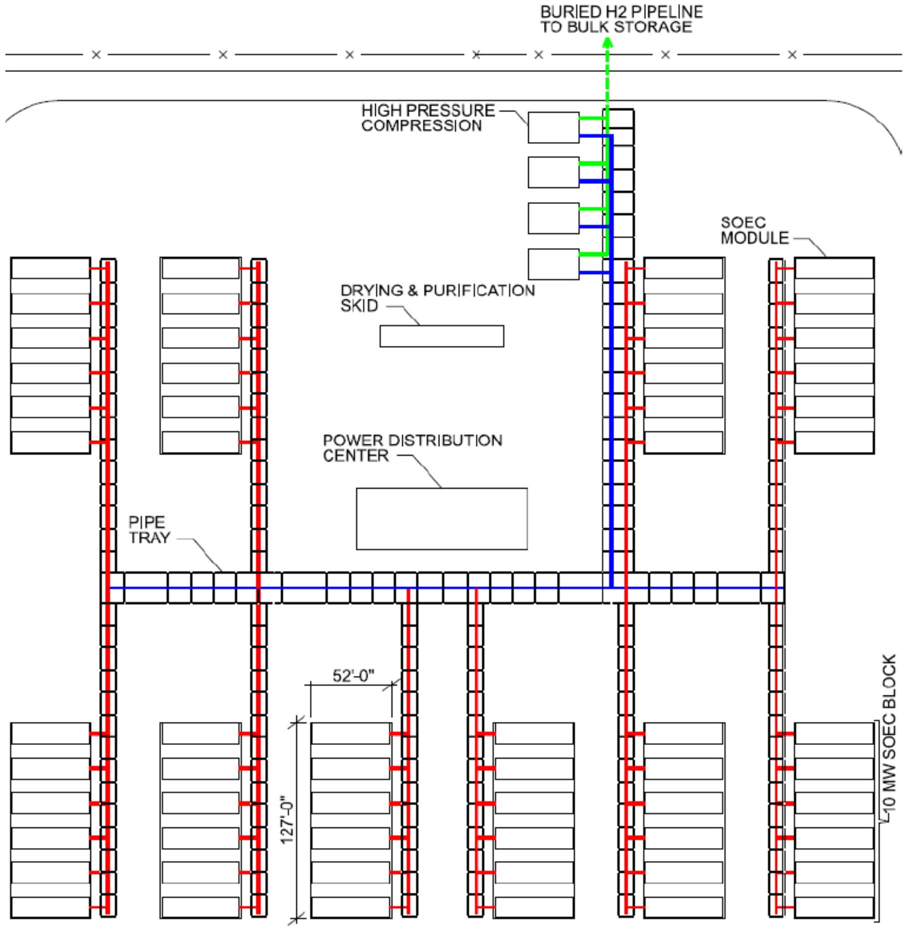

Figure 2: Double-line Configuration of 100 MW Hydrogen Facility [2]

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: 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: 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

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]. Table 5 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 5: 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
	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

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

Table 3 defines the total number of components in the hydrogen generation facility, which corresponds directly to the leak frequencies listed in Table 5. Table 6 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 6: 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 7 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 7: 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 8 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 8: 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

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 9 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 9: Blast Overpressure Fragilities of Critical Structures

Critical Structure	Effective Pressure (psi)	Total Fragility
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
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 9 is reached is reported for input into the probabilistic risk assessment (PRA) model. Table 10 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 10: 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 11 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.

Table 11: Accident Impact Scenarios and System Parameters

Scenario #	Description	System Parameters			Pipe size (SCH 40)	Pipe ID (in)
		Pressure (psig)	Temp (F)	$\dot{m}$ (kg/hr)		
1	Module	0.4	356	50	1.5	1.61
2	Heat Exchanger	0.4	140	300	3	3.068
3	Blower	5	140	300	3	3.068
4	1st Compression	300	140	305	4	4.026
5	Purification	300	140	305	4	4.026
6	2nd Compression	1500	140	300	3	3.068

Full-bore leaks were analyzed for each of the different scenarios as the bounding consequence in a given section. For Sections 4, 5, and 6, partial 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 12 documents the leak diameter calculations for the partial break scenarios.

Table 12: Leak Diameter for Partial Break Scenarios

Relative Leak Area	3.068" Pipe ID		4.029" Pipe ID	
	Diameter (in)	Area (in^2)	Diameter (in)	Area (in^2)
1	3.07	7.39	4.03	12.74
0.1	0.97	0.74	1.27	1.27
0.01	0.31	0.074	0.40	0.13
0.001	0.10	0.0074	0.13	0.013
0.0001	0.03	0.00074	0.04	0.0013

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 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 13 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 13: 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.

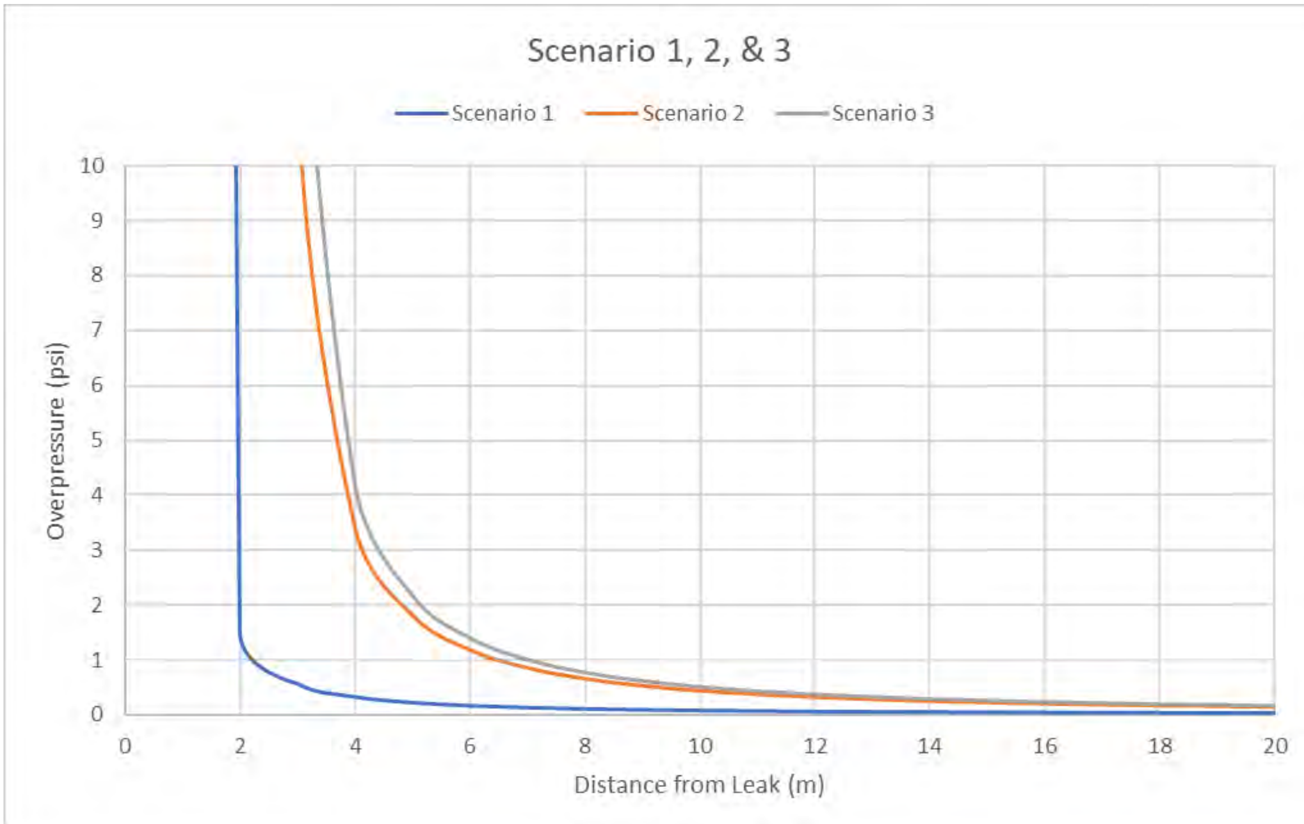

Figure 3: Scenario 1, 2, & 3 Overpressure Results

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 14 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 14: 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.

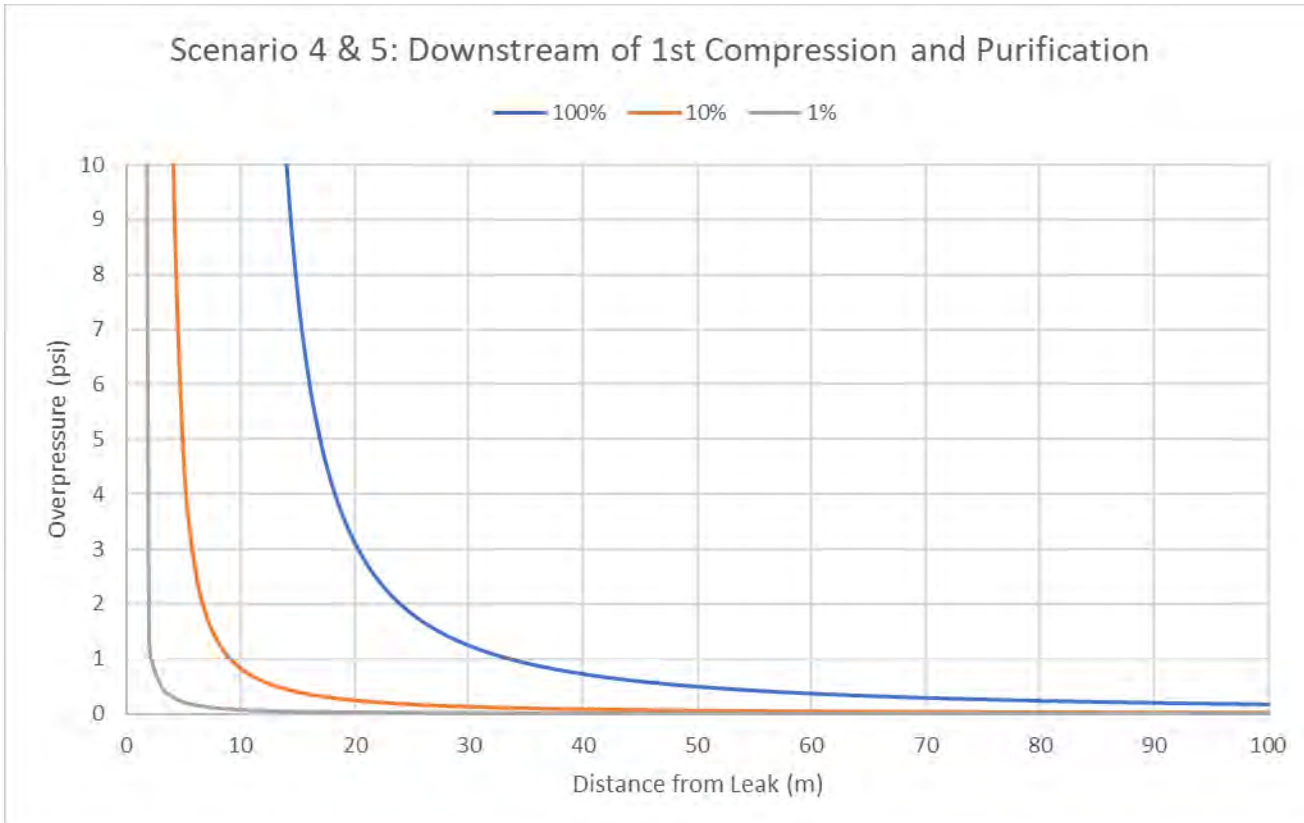

Figure 4: Scenario 4 & 5 Overpressure Results

6.2.3. *Scenario 6*

The system parameters for Scenario 6 represent the limiting conditions in terms of consequence in the hydrogen generation facility. For this scenario, 10% and 1% area partial break cases were also evaluated. Table 15 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 15: 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.

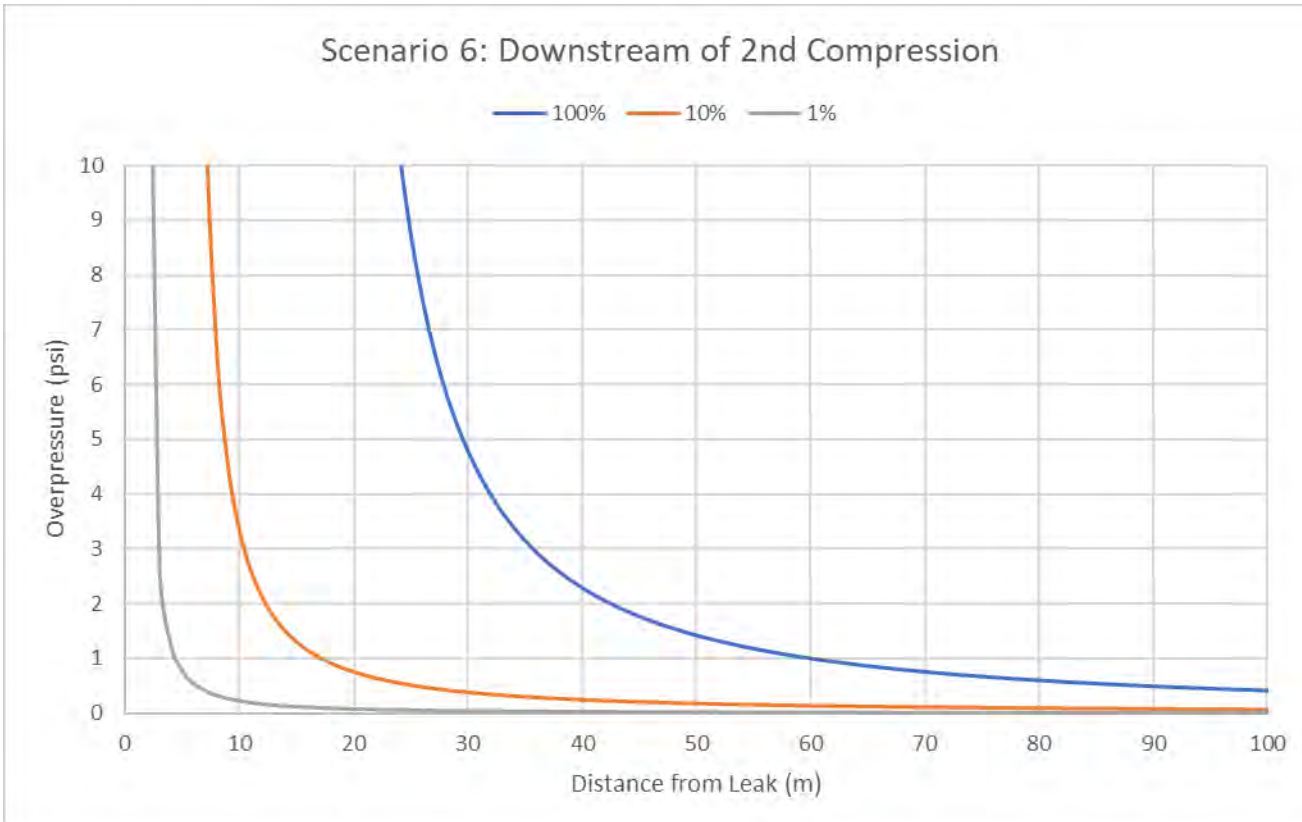

Figure 5: Scenario 6 Overpressure Results

6.2.4. Sensitivity Analysis

To quantify the uncertainty in the methodology used to calculate the overpressure results, a different 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 [8]. Table 16, Table 17, and Table 18 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 16: 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 17: 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 18: 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

Figure 6, Figure 7, and Figure 8 show comparison plots between the two methodologies for each of the scenarios. As shown, the TNT method is limiting for each of the scenarios.

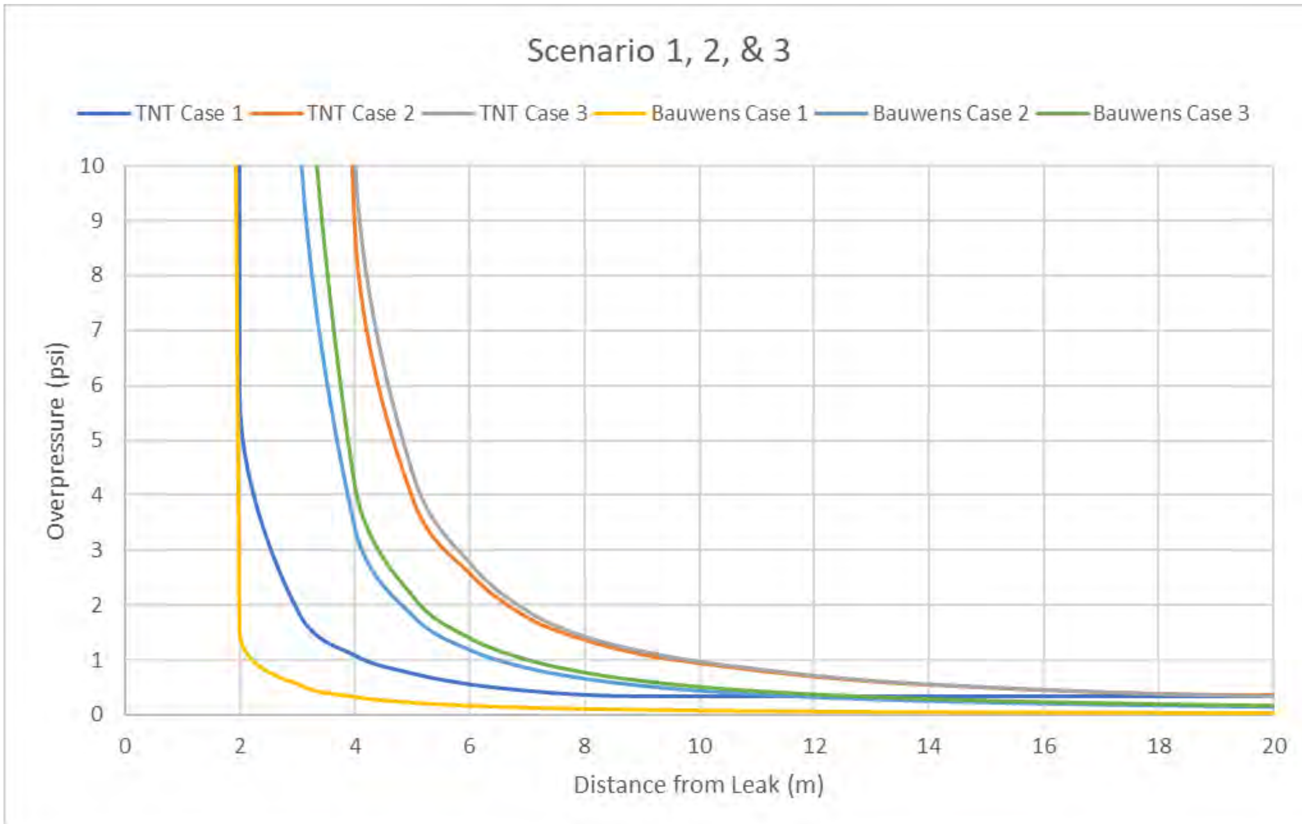

Figure 6: Scenario 1, 2, & 3 Sensitivity Results Comparison

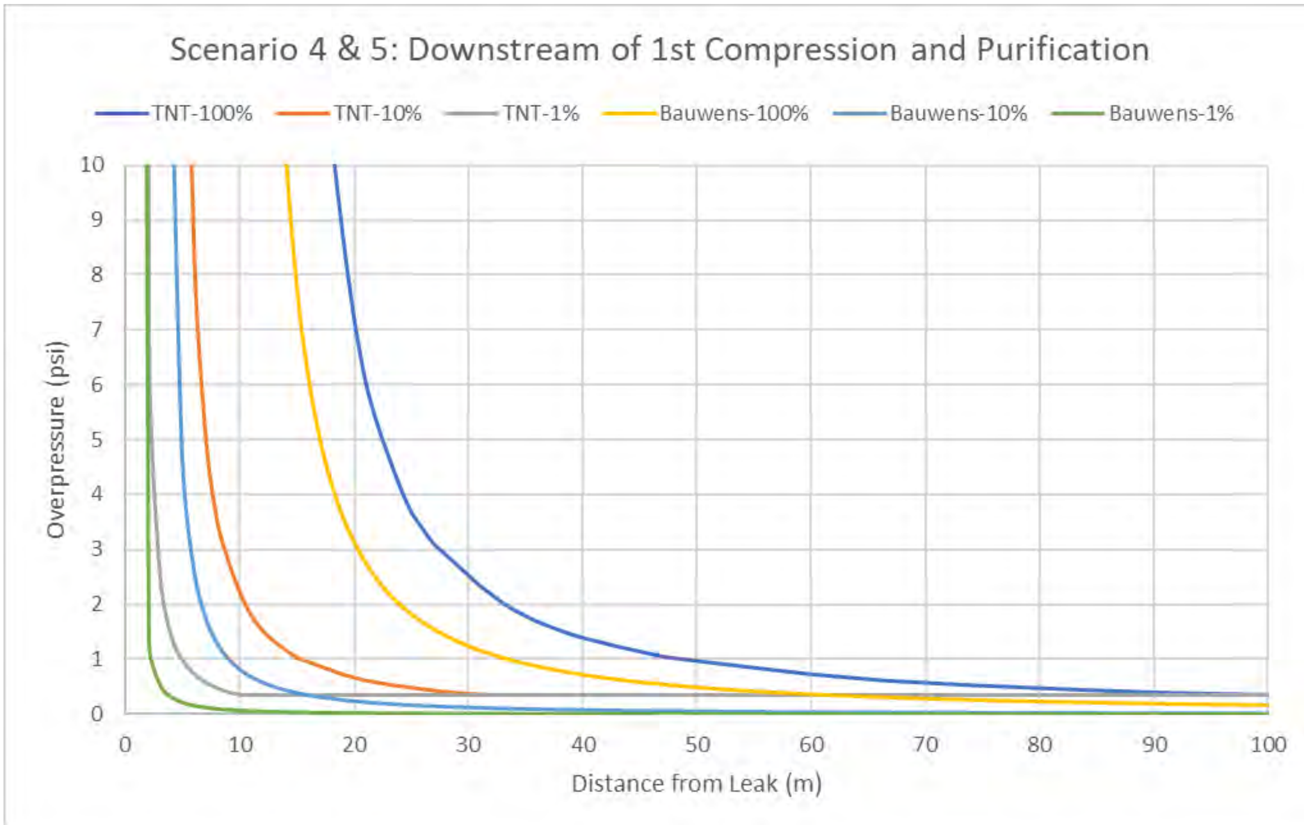

Figure 7: Scenario 4 & 5 Sensitivity Results Comparison

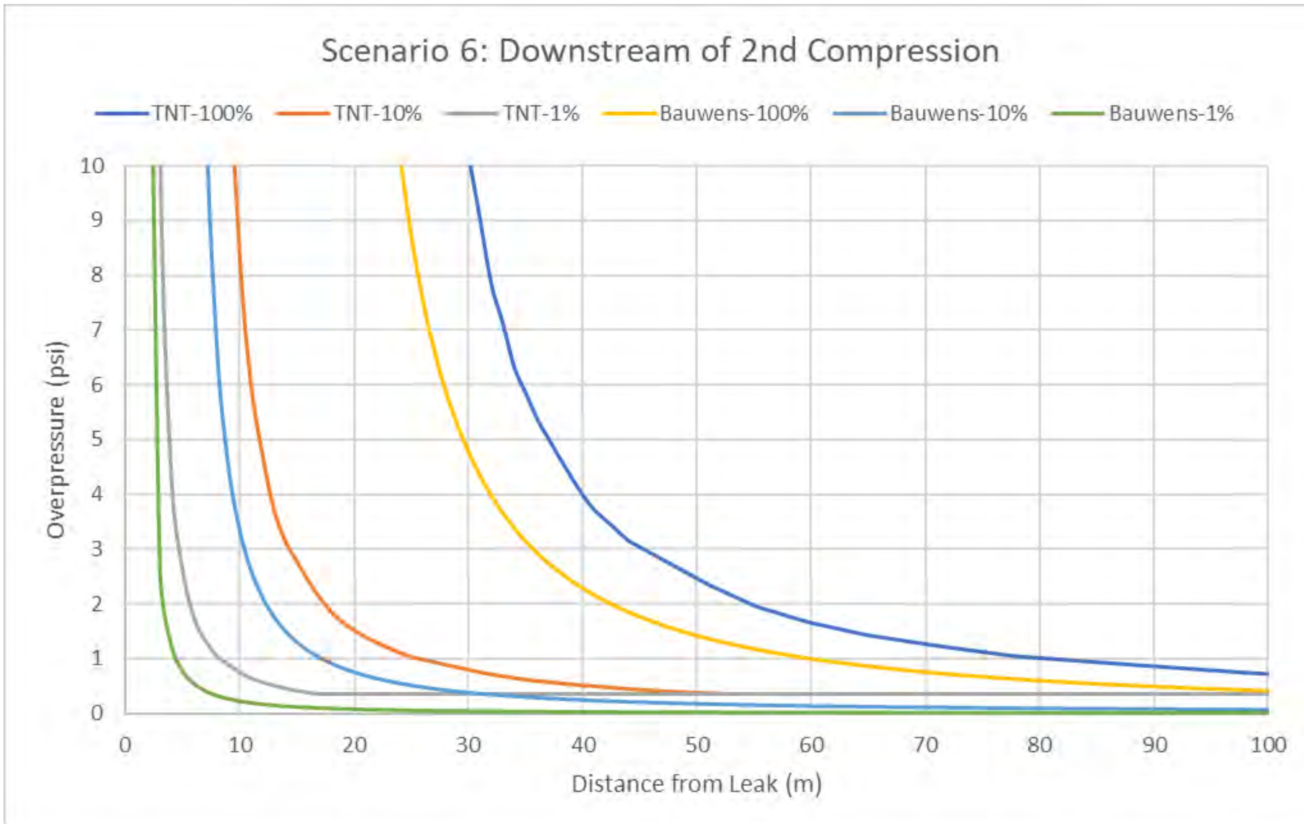

Figure 8: Scenario 6 Sensitivity Results Comparison

Table 19, Table 20, and Table 21 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 6 at 39 meters.

Table 19: 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 20: Scenario 4 & 5 Sensitivity Results Comparison

Scenario 4 & 5: 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	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 21: 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

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 22 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 22: 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 9 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.

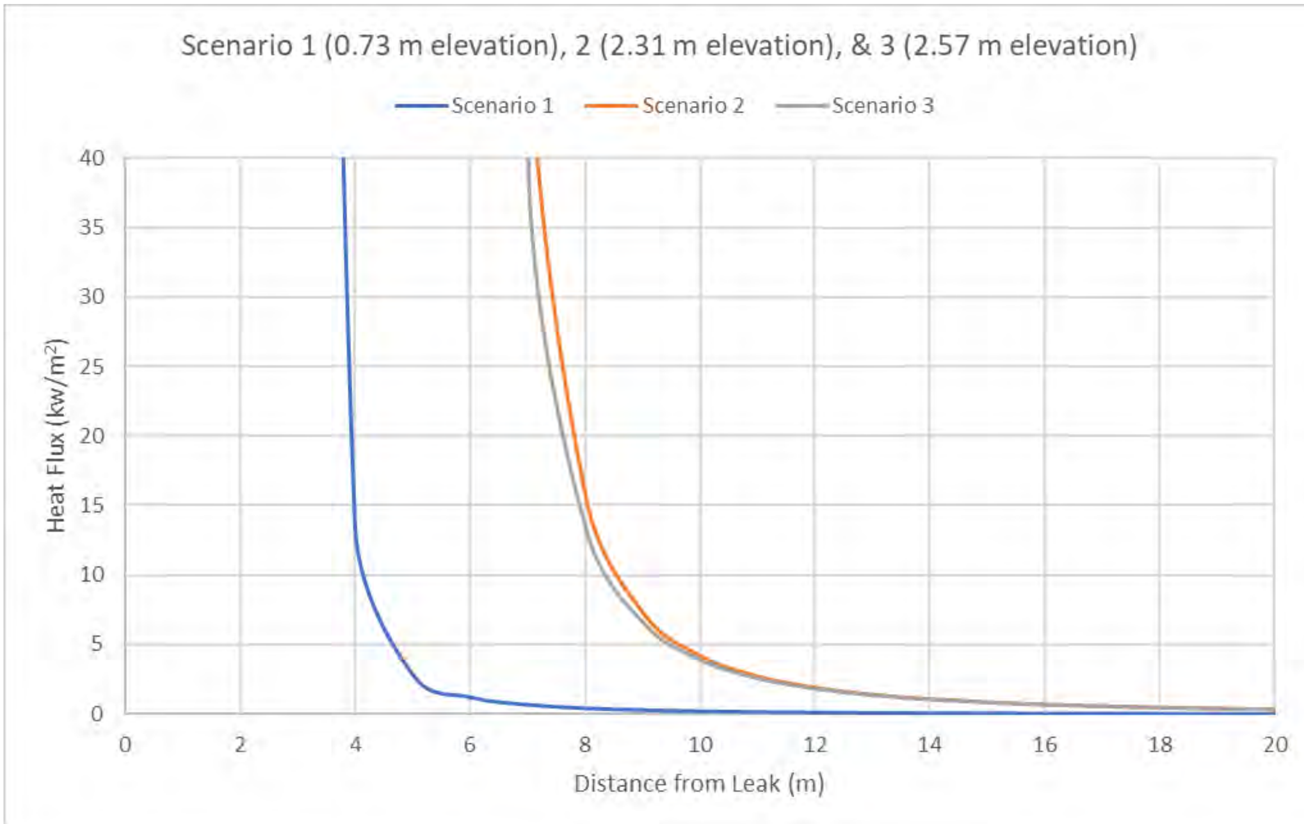

Figure 9: Scenario 1, 2, & 3 Heat Flux Results

6.3.2. Scenarios 4 & 5

Full-bore, 10%, and 1% area partial break cases were evaluated for Scenario 4 and 5. Table 23 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 23: 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 10 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.

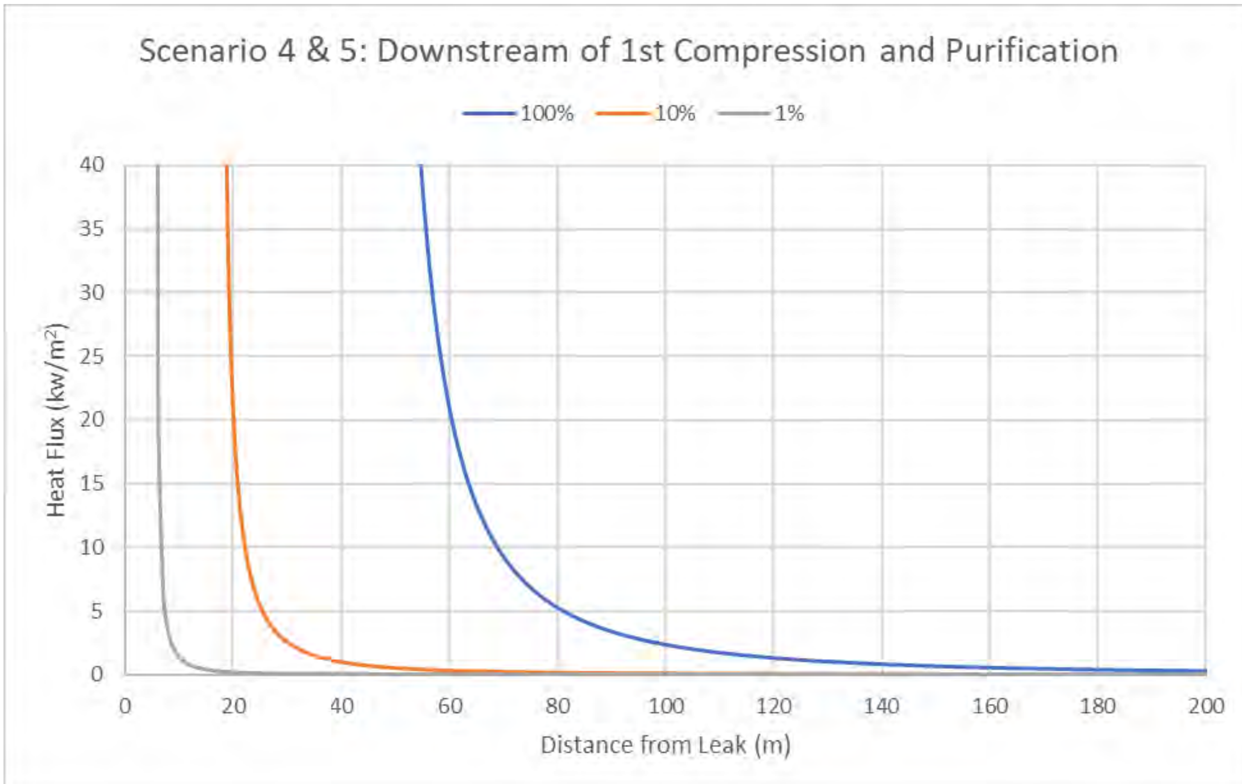

Figure 10: Scenario 4 & 5 Heat Flux Results

6.3.3. *Scenario 6*

The system parameters for Scenario 6 represent the limiting conditions in terms of consequence in the hydrogen generation facility for heat flux as well. For this scenario, 10% and 1% area partial break cases were also evaluated. Table 24 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 24: 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 11 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.

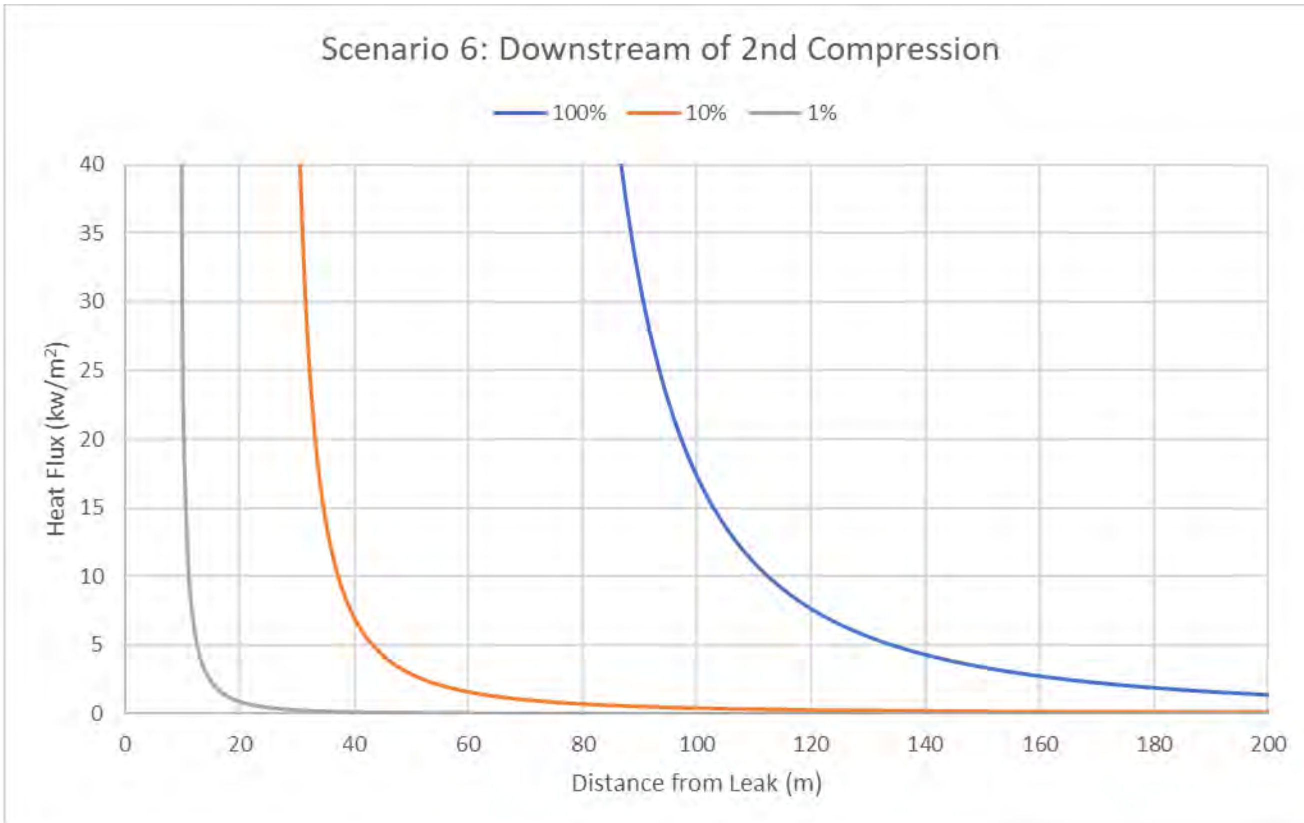

Figure 11: Scenario 6 Heat Flux Results

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 [8]. Table 25 shows the results from the TNT equivalence method compared to the 1 psi fragility comparison. As shown, the maximum distance is seen in Scenario 6 at 81 meters.

Table 25: 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
Sccenario 6: 1%	9

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. 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. 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. 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. Also, the consequence of radiative heat-flux was 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). Note, that consequences for both full-bore and partial leak sizes were evaluated for each of the relevant scenarios. Additionally, sensitivity evaluations for the overpressure results were ran 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). Note, the maximum nominal difference in set-back distance between the two calculation methods was 39 meters at a fragility criterion of 0.49 psi. Locating the hydrogen generation facility at distances greater than those calculated herein would allow for the safe colocation with NPPs.

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[8] Center for Chemical Process Safety, "Guidelines for Vapopr Cloud Explosion, Pressure Vessel Burst, BLEVE, and Flash Fire Hazards," 2010.

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

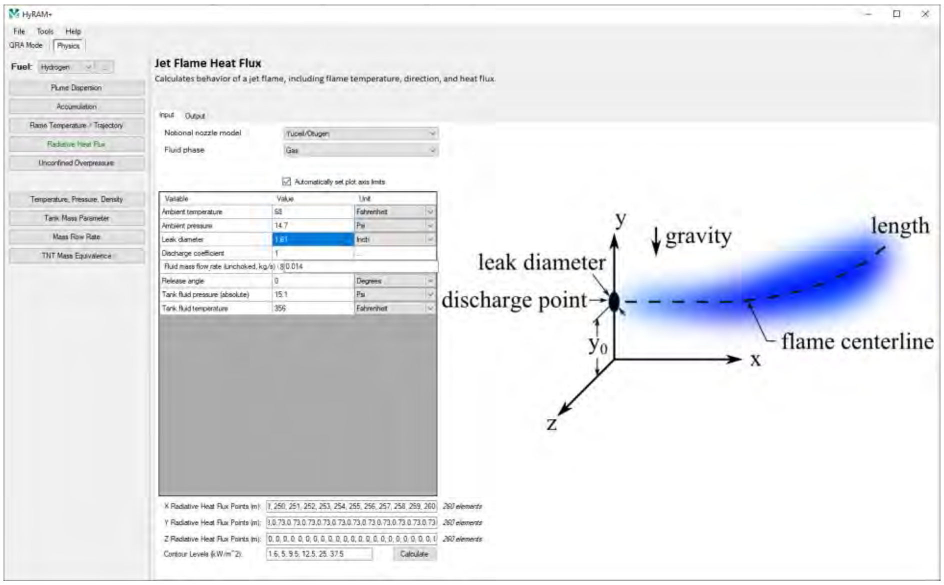

Figure A-1: Scenario 1 Heat Flux Input Traceability Figure

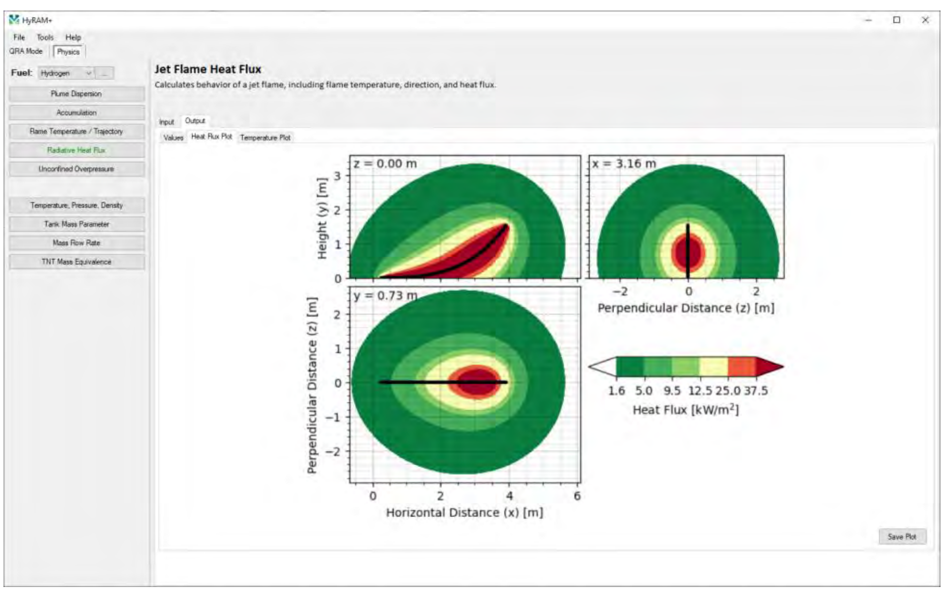

Figure A-2: Scenario 1 Heat Flux Output Traceability Figure

A.1.2. Bauwens Overpressure

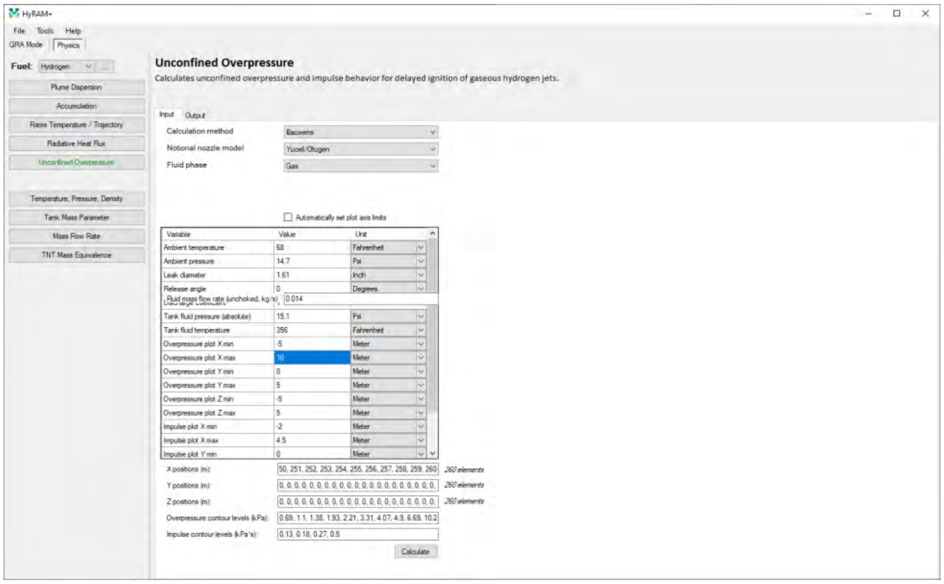

Figure A-3: Scenario 1 Bauwens Overpressure Input Traceability Figure

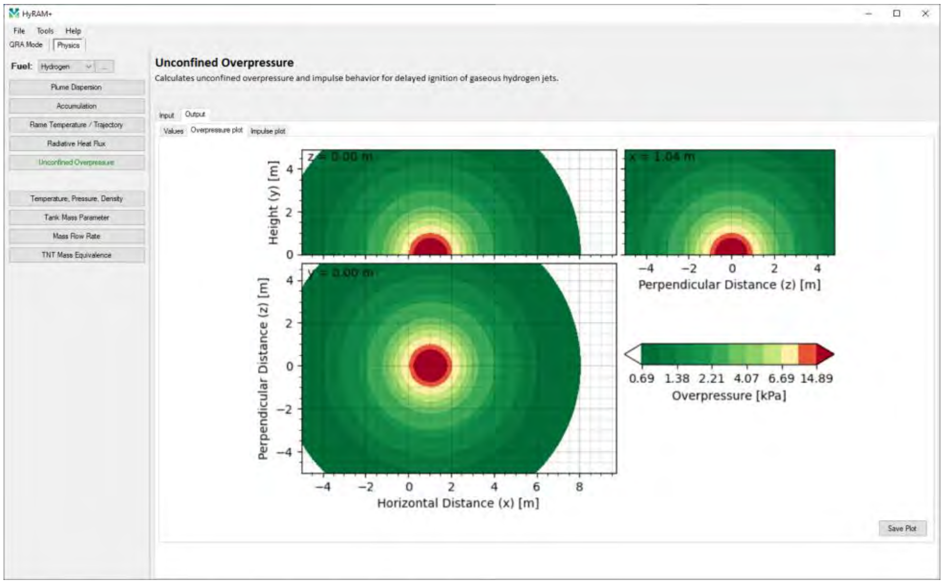

Figure A-4: Scenario 1 Bauwens Overpressure Output Traceability Figure

A.1.3. TNT Equivalence Overpressure

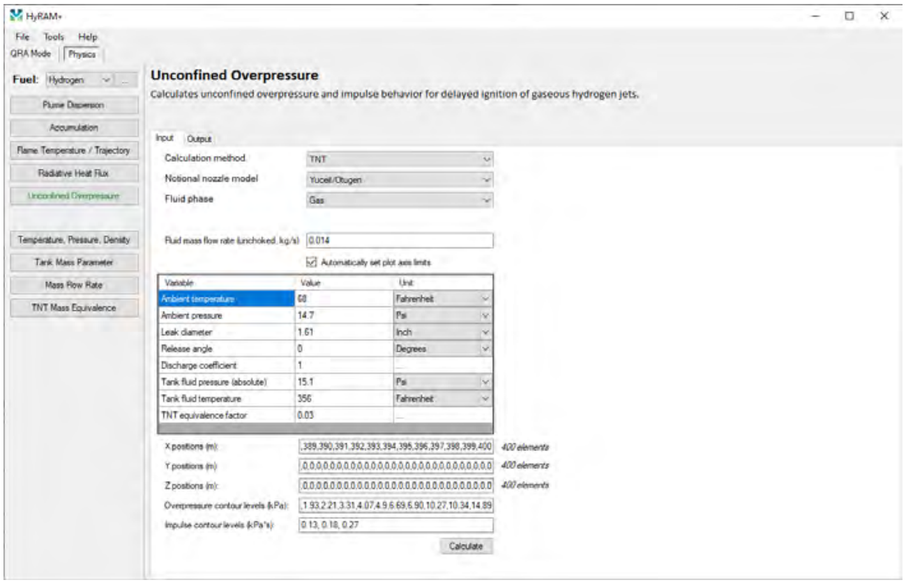

Figure A-5: Scenario 1 TNT Overpressure Input Traceability Figure

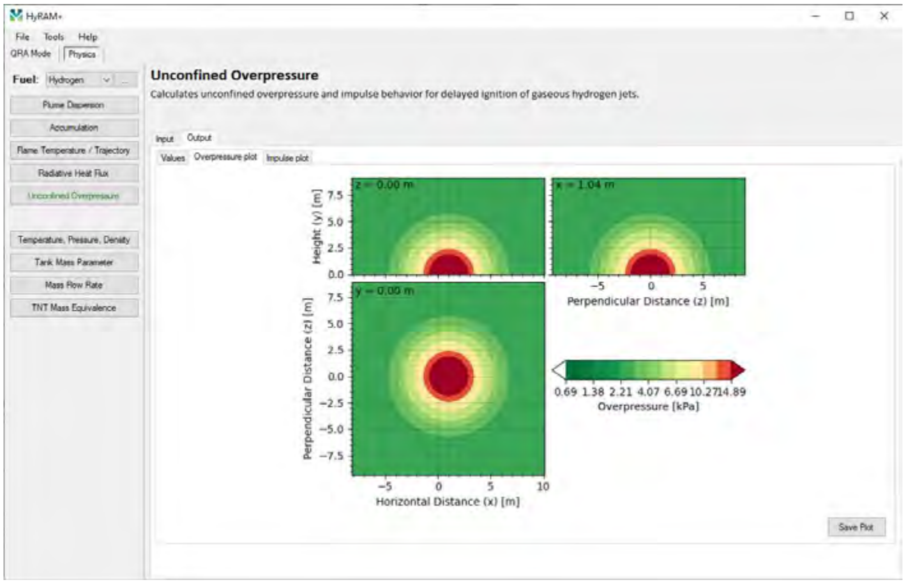

Figure A-6: Scenario 1 TNT Overpressure Output Traceability Figure

A.2. Scenario 2

A.2.1. Heat Flux

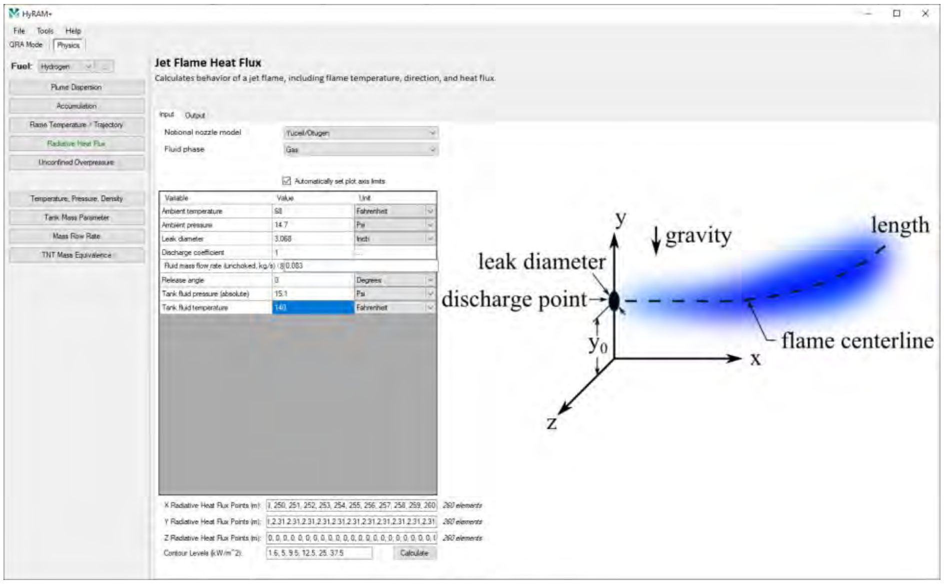

Figure A-7: Scenario 2 Heat Flux Input Traceability Figure

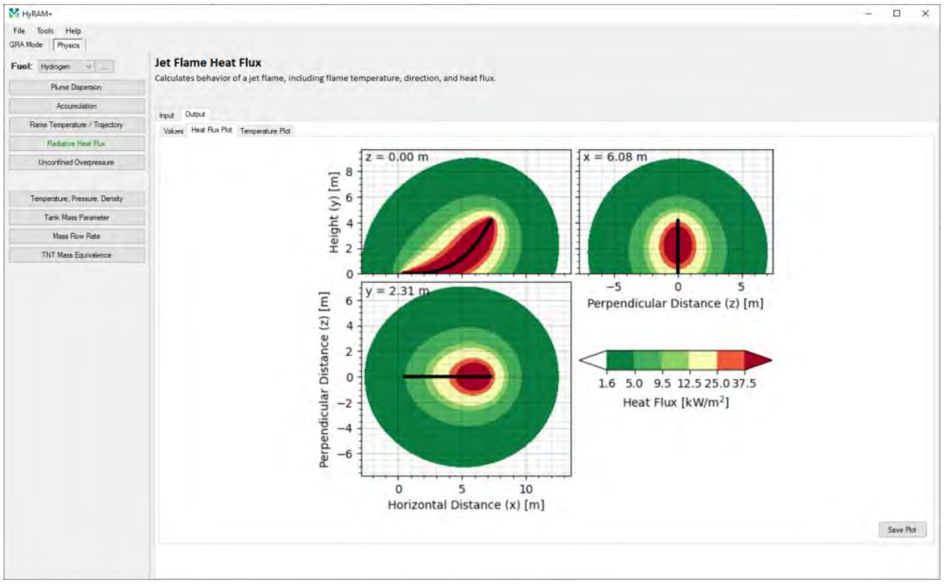

Figure A-8: Scenario 2 Heat Flux Output Traceability Figure

A.2.2. Bauwens Overpressure

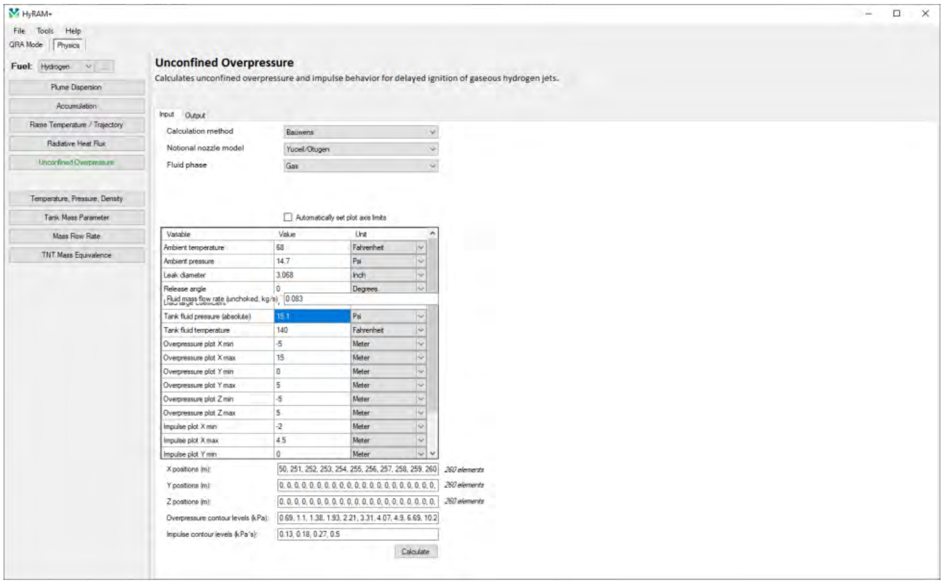

Figure A-9: Scenario 2 Bauwens Overpressure Input Traceability Figure

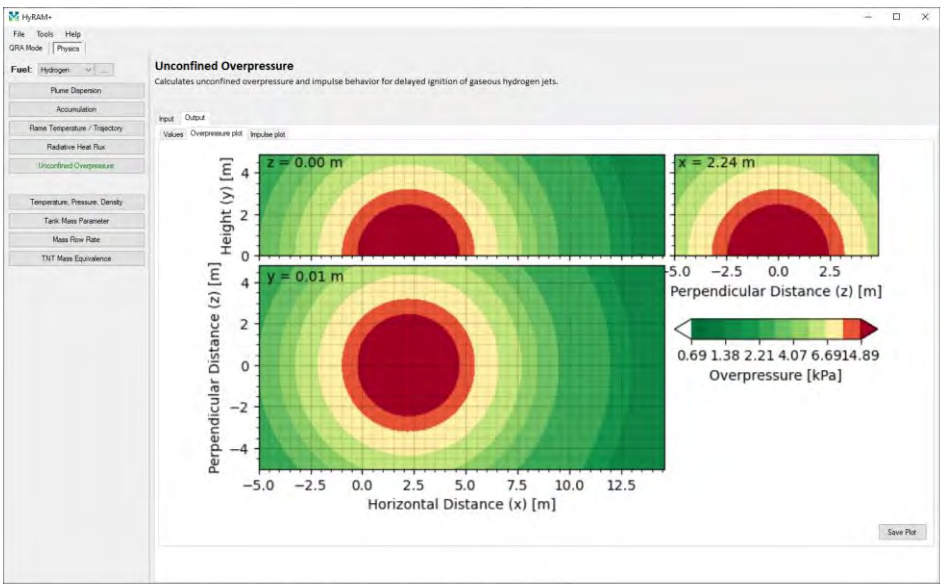

Figure A-10: Scenario 2 Bauwens Overpressure Output Traceability Figure

A.2.3. TNT Equivalence Overpressure

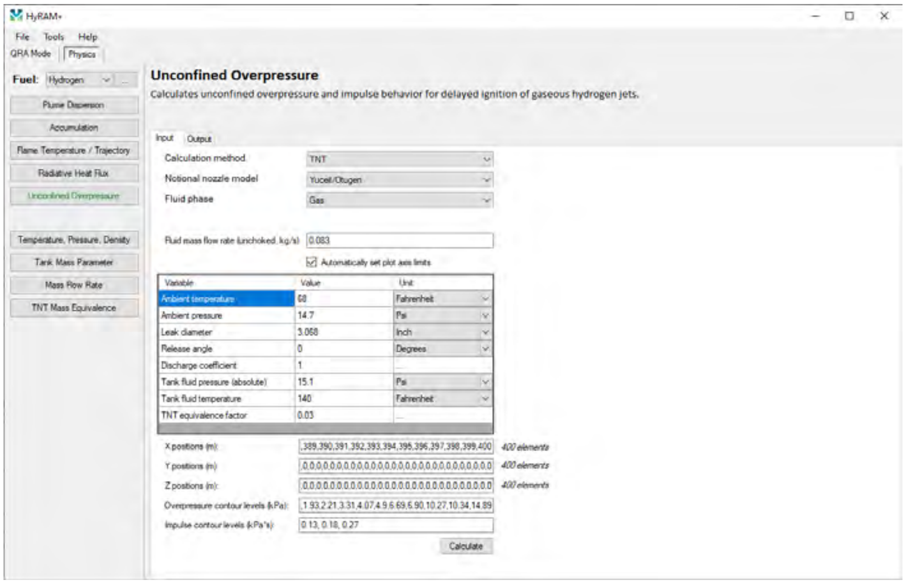

Figure A-11: Scenario 2 TNT Overpressure Input Traceability Figure

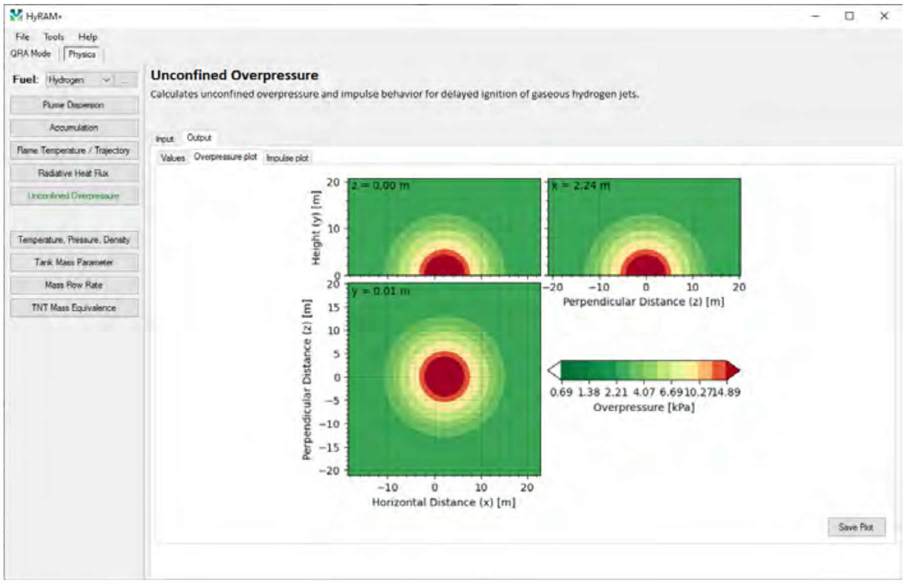

Figure A-12: Scenario 2 TNT Overpressure Output Traceability Figure

A.3. Scenario 3

A.3.1. Heat Flux

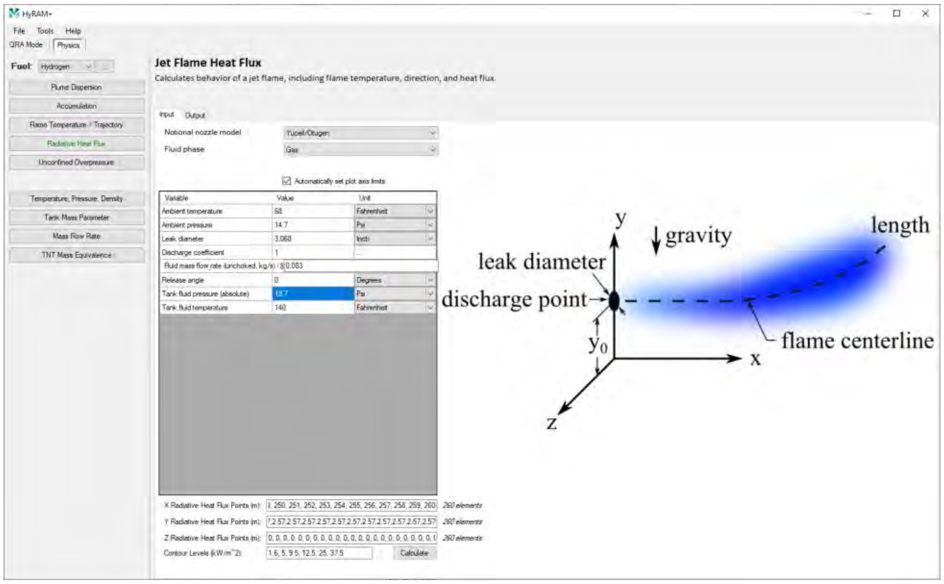

Figure A-13: Scenario 3 Heat Flux Input Traceability Figure

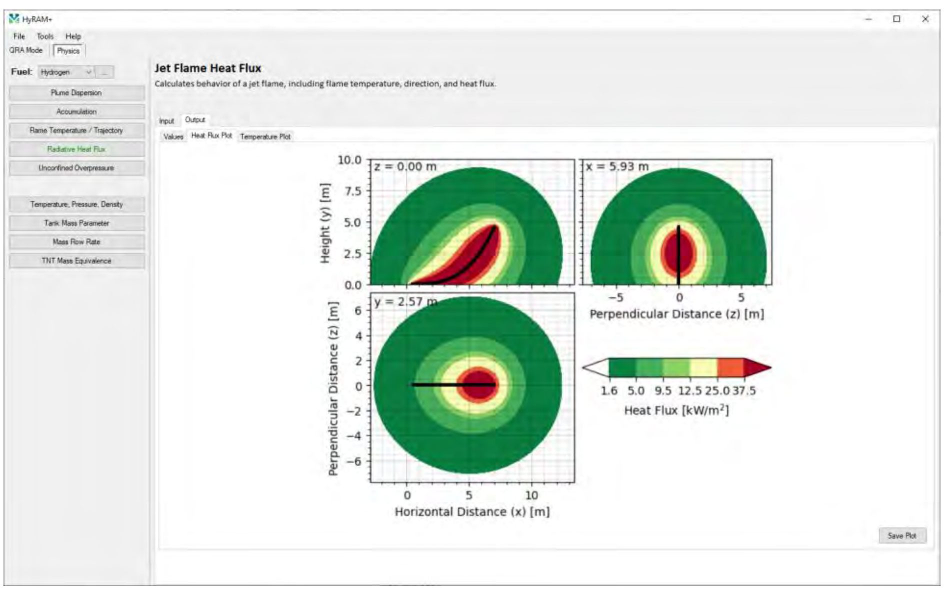

Figure A-14: Scenario 3 Heat Flux Output Traceability Figure

A.3.2. Bauwens Overpressure

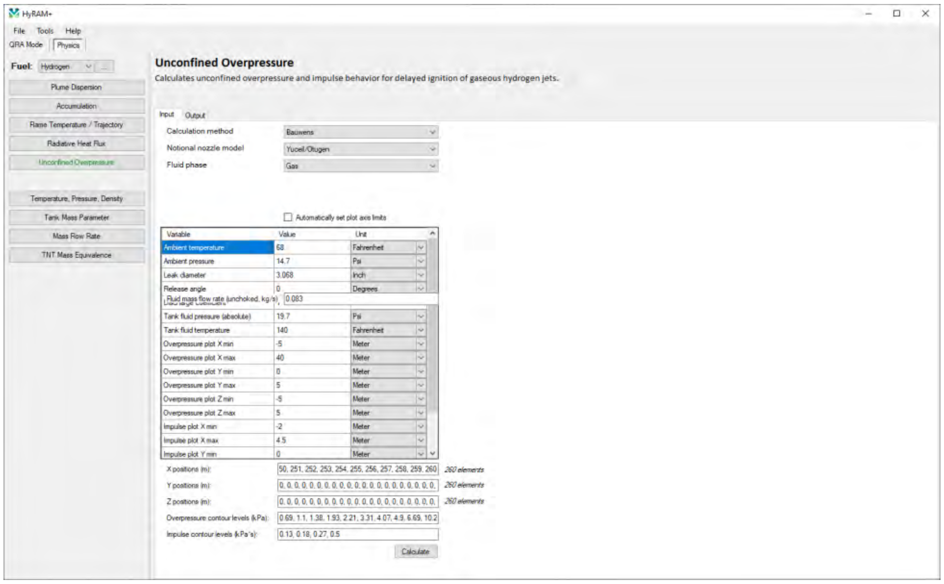

Figure A-15: Scenario 3 Bauwens Overpressure Input Traceability Figure

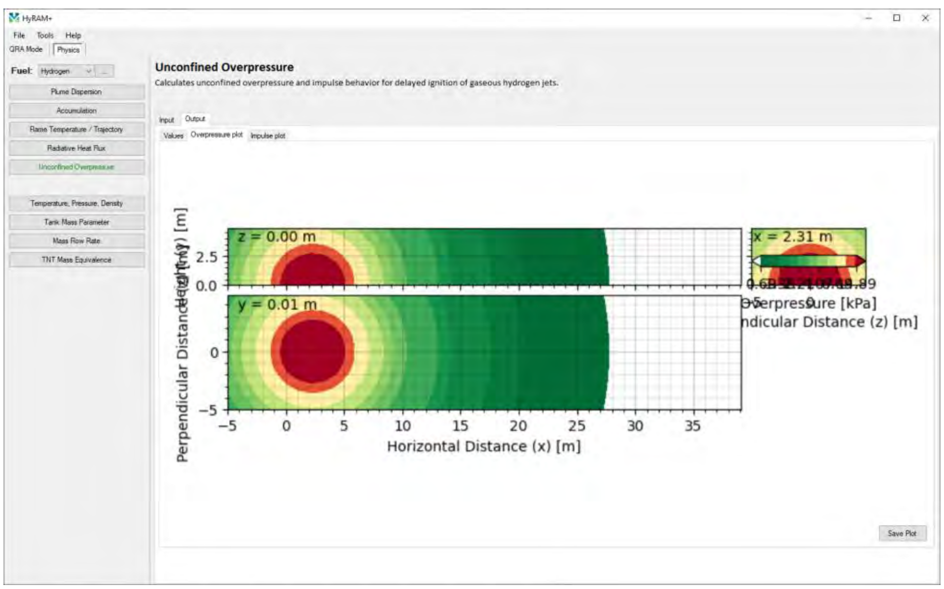

Figure A-16: Scenario 3 Bauwens Overpressure Output Traceability Figure

A.3.3. TNT Equivalence Overpressure

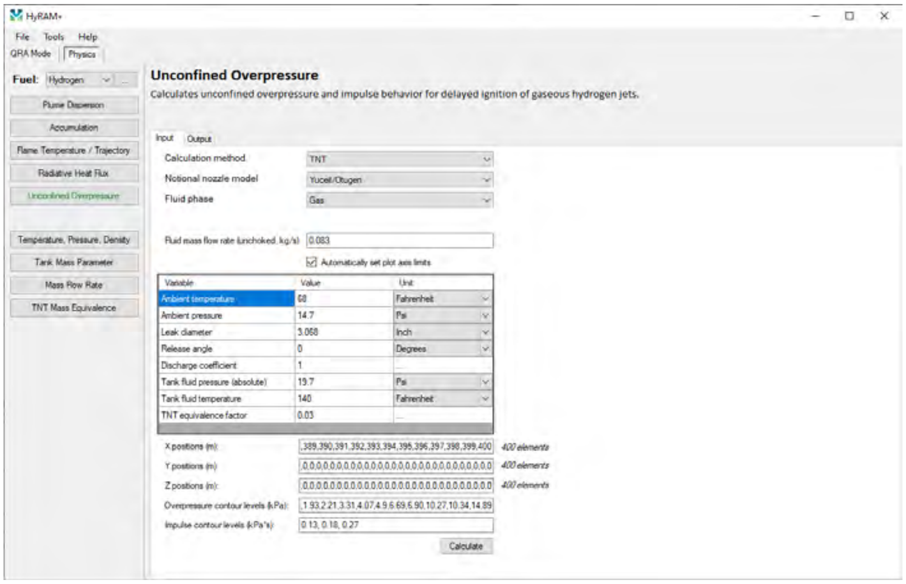

Figure A-17: Scenario 3 TNT Overpressure Input Traceability Figure

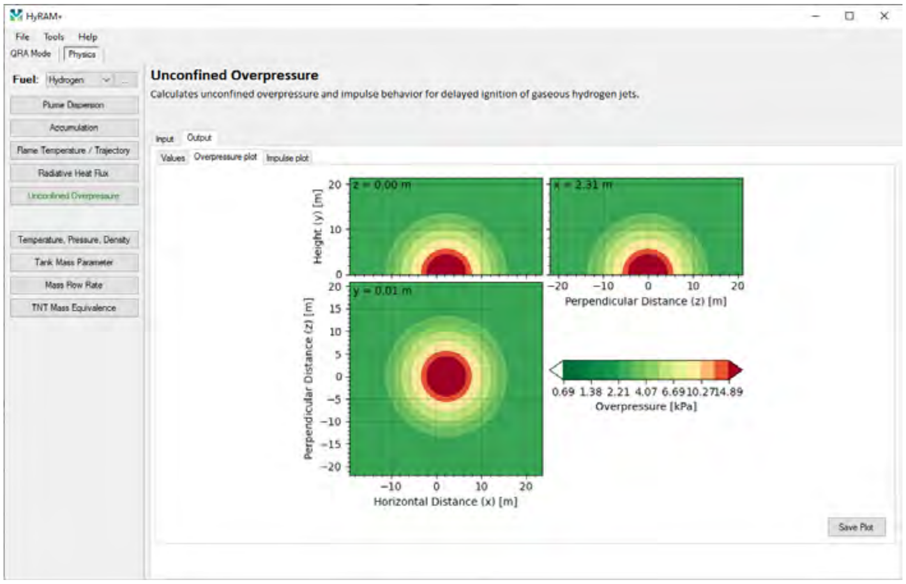

Figure A-18: Scenario 3 TNT Overpressure Output Traceability Figure

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

A.4.1. Heat Flux

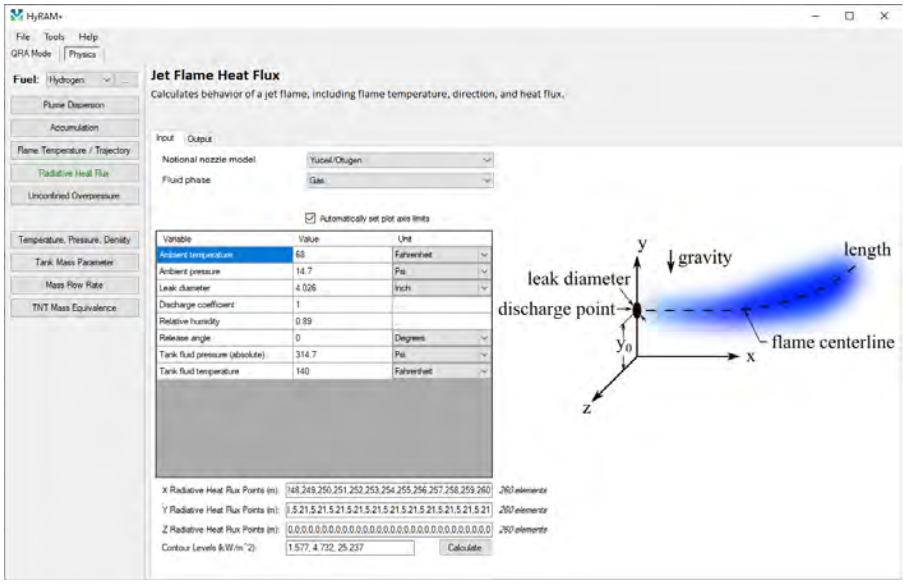

Figure A-19: Scenario 4 & 5 (100% leak) Heat Flux Input Traceability Figure

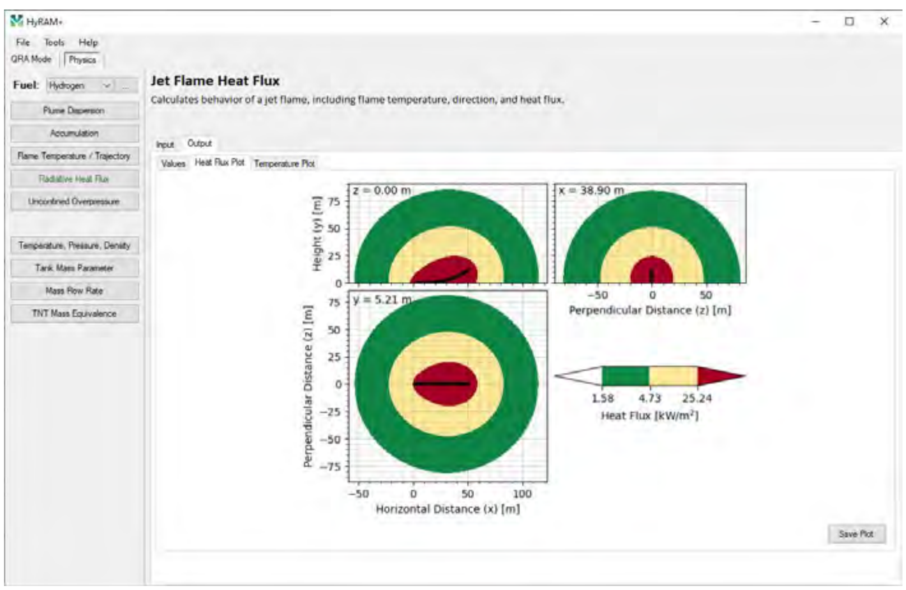

Figure A-20: Scenario 4 & 5 (100% leak) Heat Flux Output Traceability Figure

A.4.2. Bauwens Overpressure

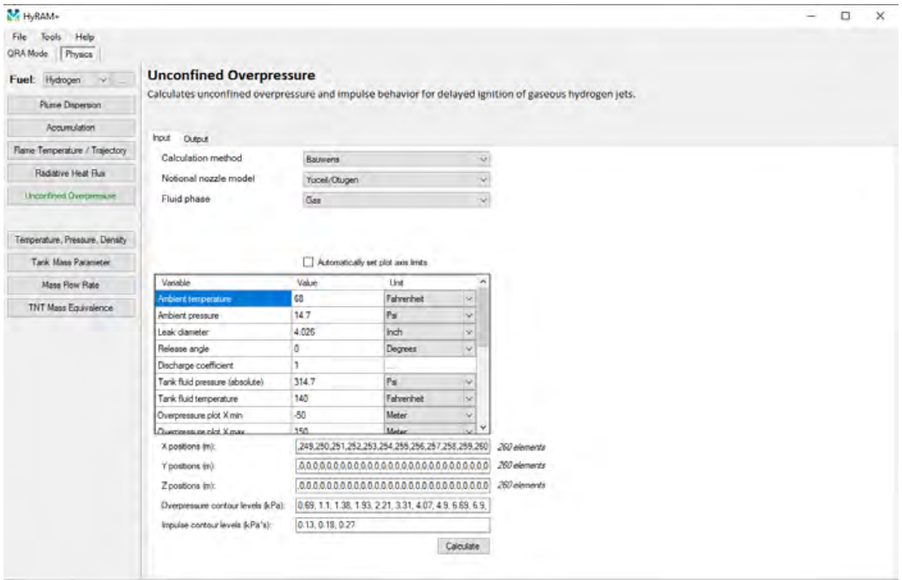

Figure A-21: Scenario 4 & 5 (100% leak) Bauwens Overpressure Input Traceability Figure

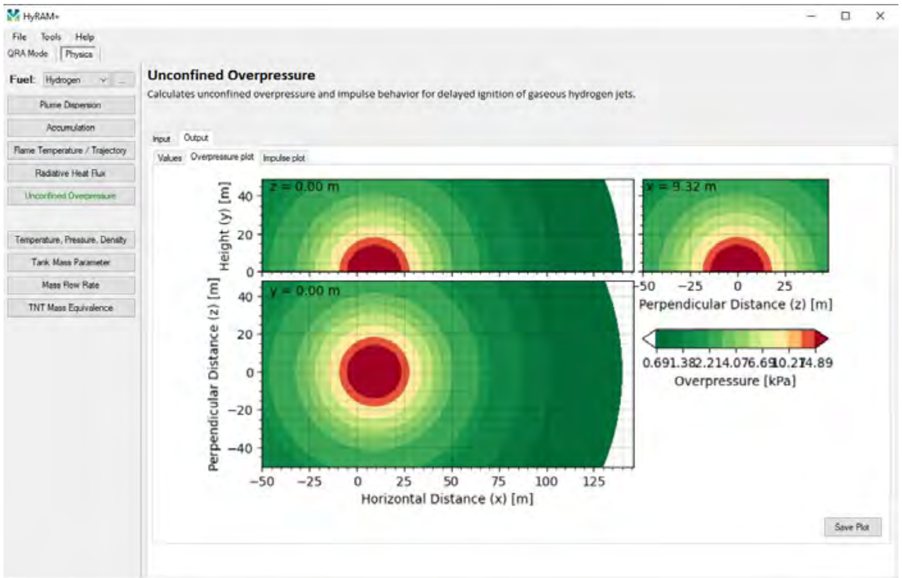

Figure A-22: Scenario 4 & 5 (100% leak) Bauwens Overpressure Output Traceability Figure

A.4.3. TNT Equivalence Overpressure

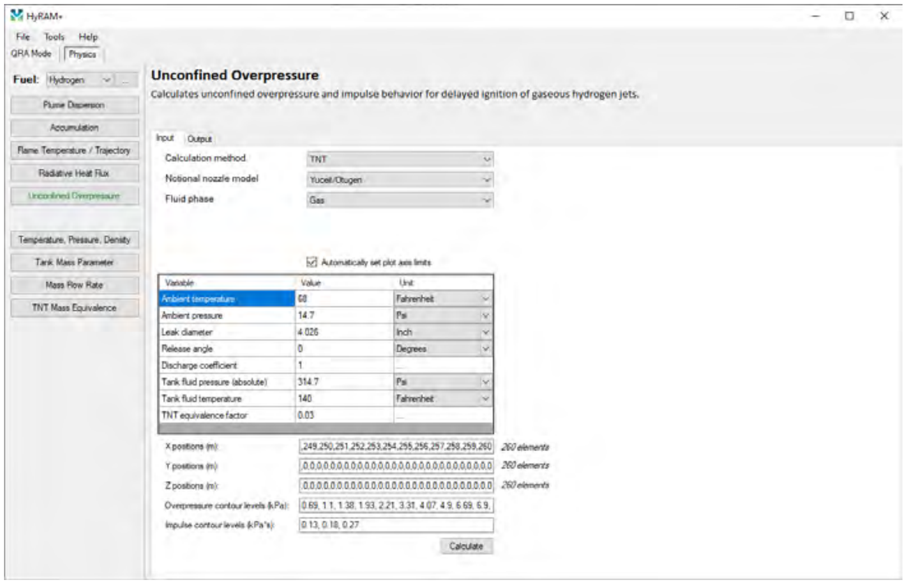

Figure A-23: Scenario 4 & 5 (100% leak) TNT Overpressure Input Traceability Figure

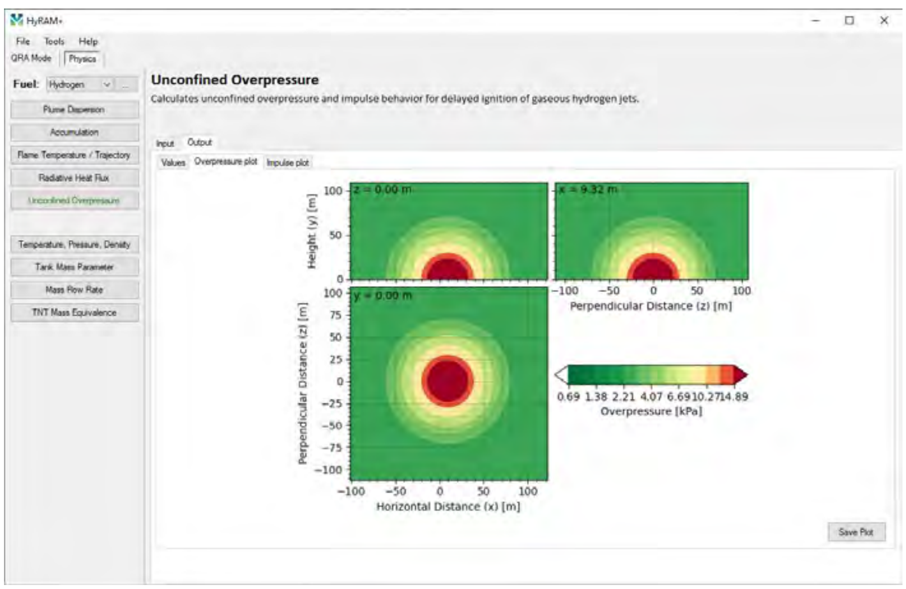

Figure A-24: Scenario 4 & 5 (100% leak) TNT Overpressure Output Traceability Figure

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

A.5.1. Heat Flux

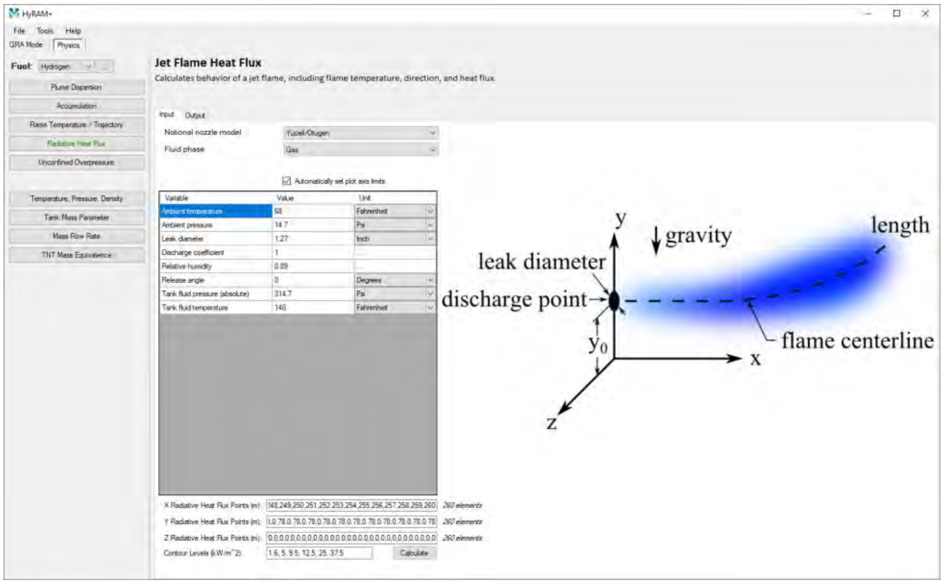

Figure A-25: Scenario 4 & 5 (10% leak) Heat Flux Input Traceability Figure

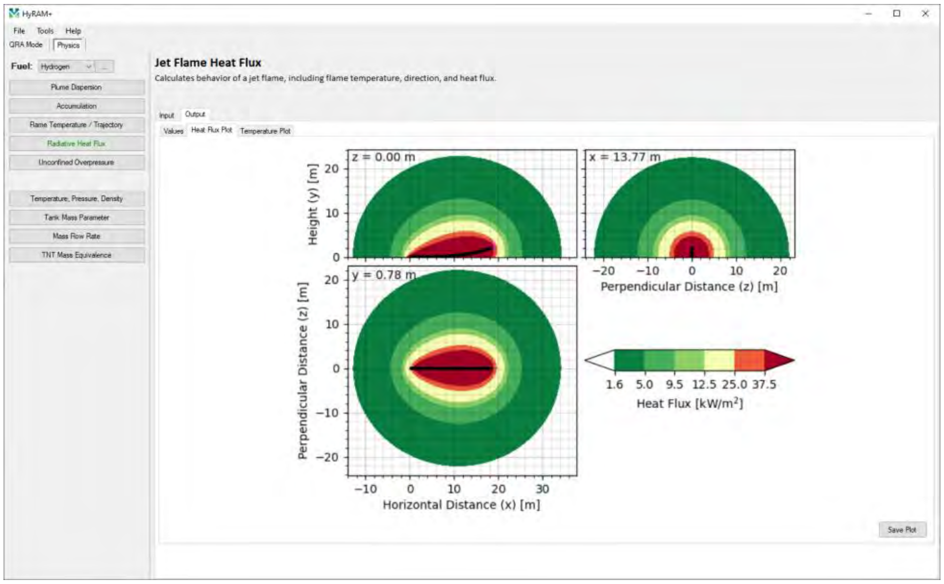

Figure A-26: Scenario 4 & 5 (10% leak) Heat Flux Output Traceability Figure

A.5.2. Bauwens Overpressure

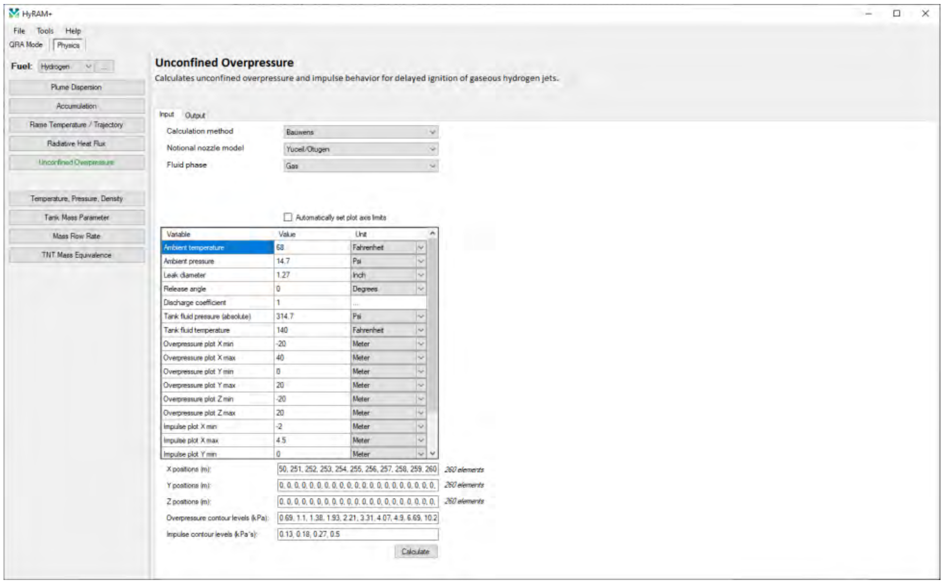

Figure A-27: Scenario 4 & 5 (10% leak) Bauwens Overpressure Input Traceability Figure

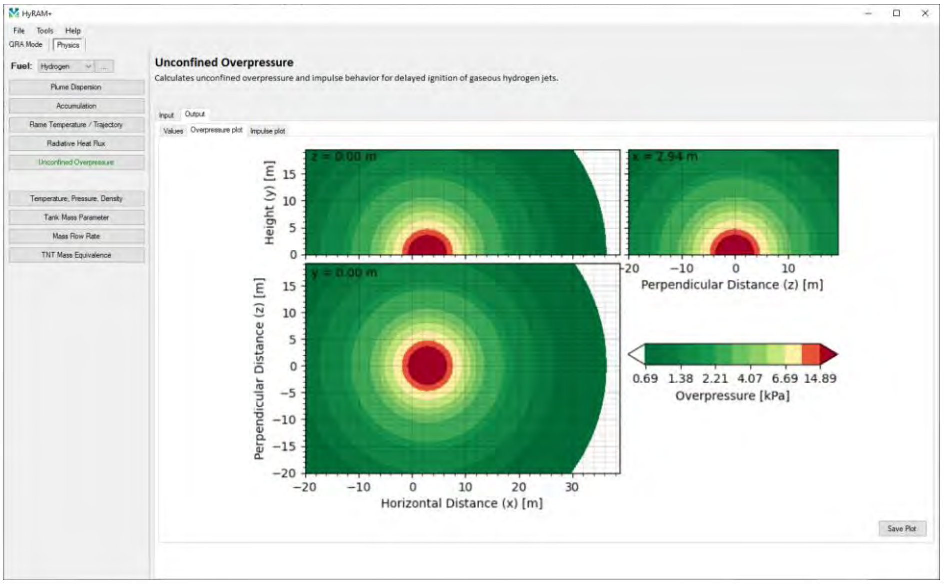

Figure A-28: Scenario 4 & 5 (10% leak) Bauwens Overpressure Output Traceability Figure

A.5.3. TNT Equivalence Overpressure

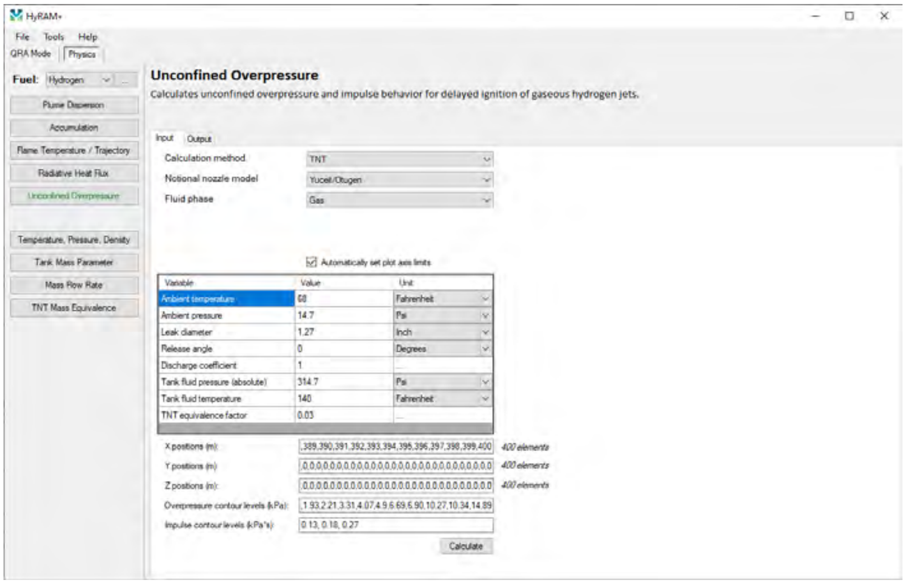

Figure A-29: Scenario 4 & 5 (10% leak) TNT Overpressure Input Traceability Figure

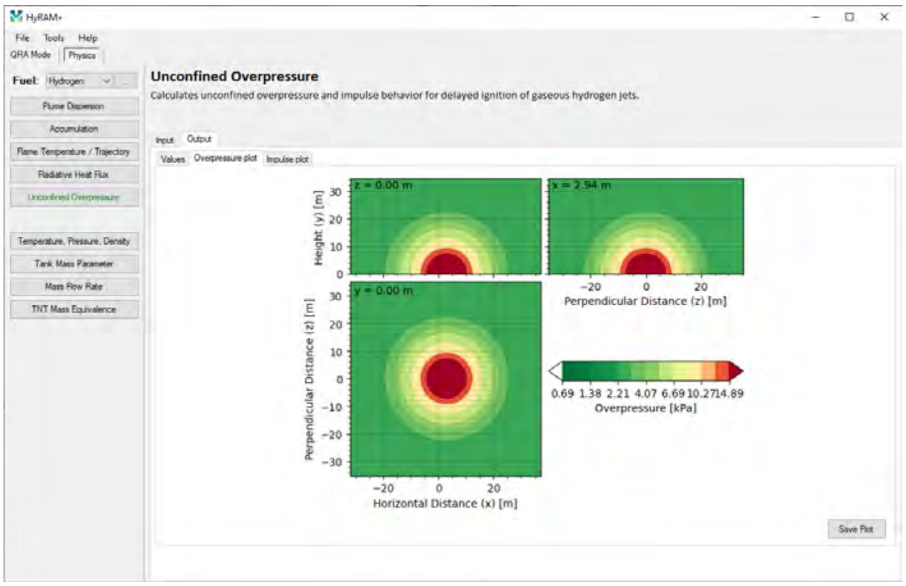

Figure A-30: Scenario 4 & 5 (10% leak) TNT Overpressure Output Traceability Figure

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

A.6.1. Heat Flux

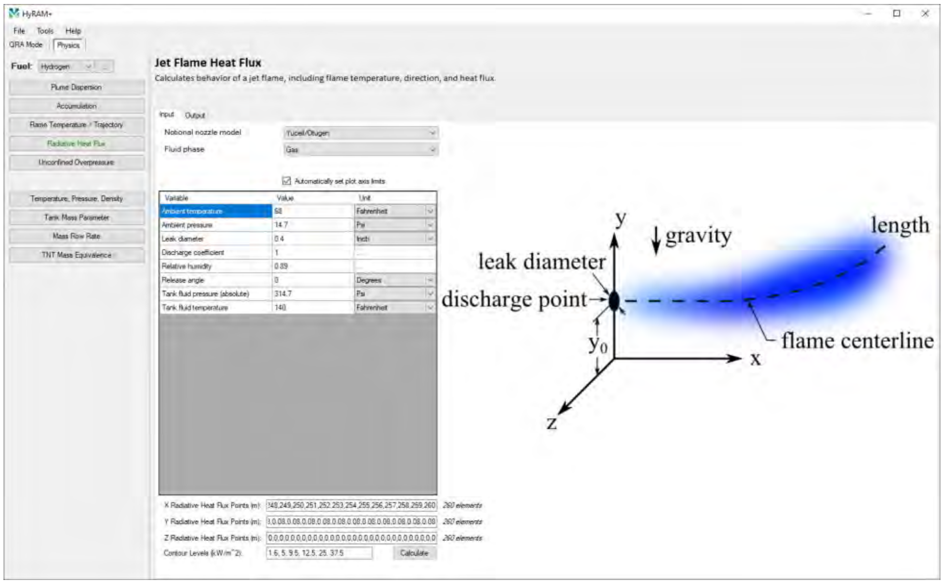

Figure A-31: Scenario 4 & 5 (1% leak) Heat Flux Input Traceability Figure

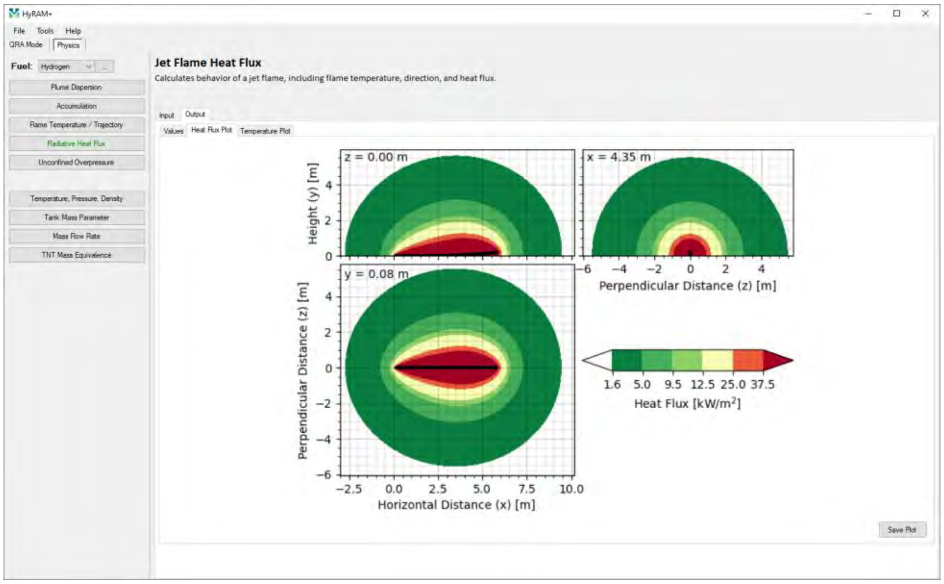

Figure A-32: Scenario 4 & 5 (1% leak) Heat Flux Output Traceability Figure

A.6.2. Bauwens Overpressure

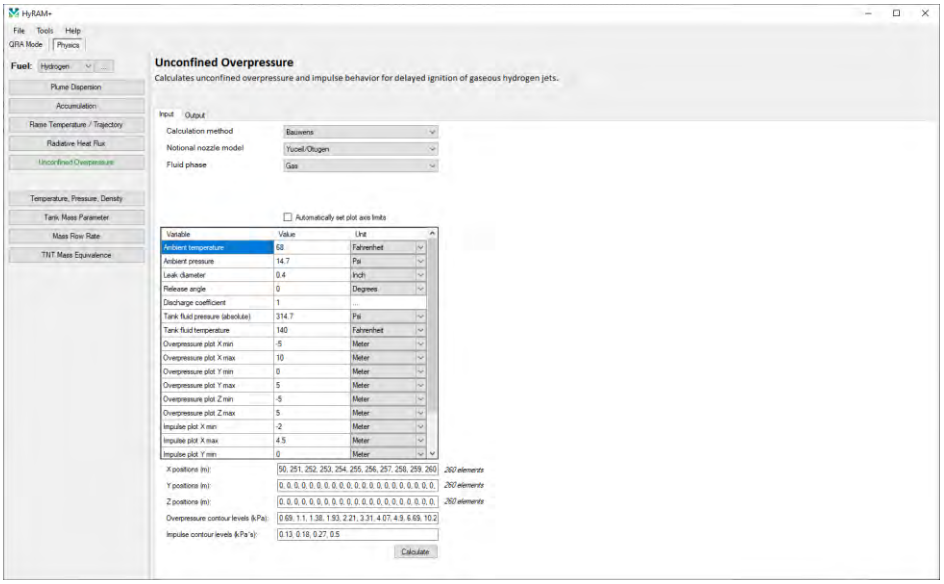

Figure A-33: Scenario 4 & 5 (1% leak) Bauwens Overpressure Input Traceability Figure

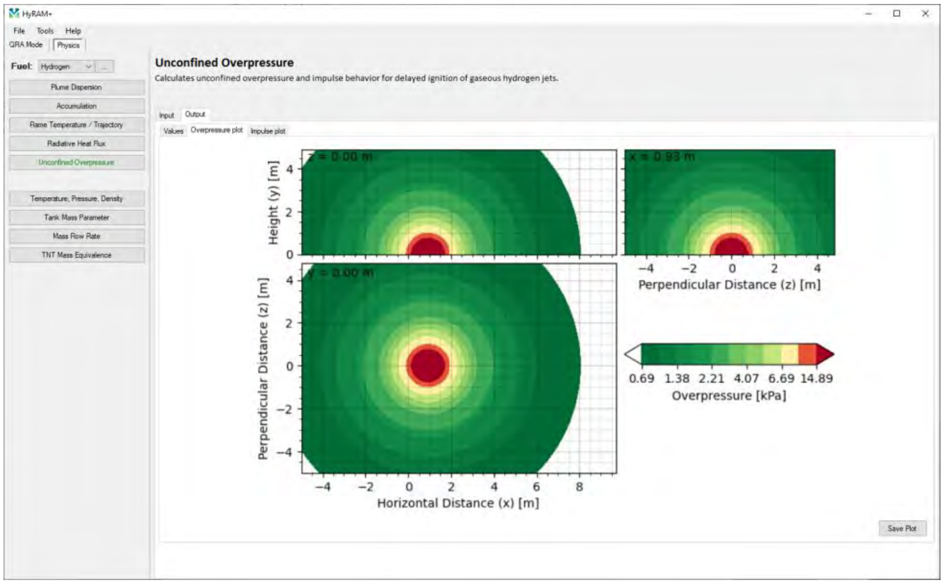

Figure A-34: Scenario 4 & 5 (1% leak) Bauwens Overpressure Output Traceability Figure

A.6.3. TNT Equivalence Overpressure

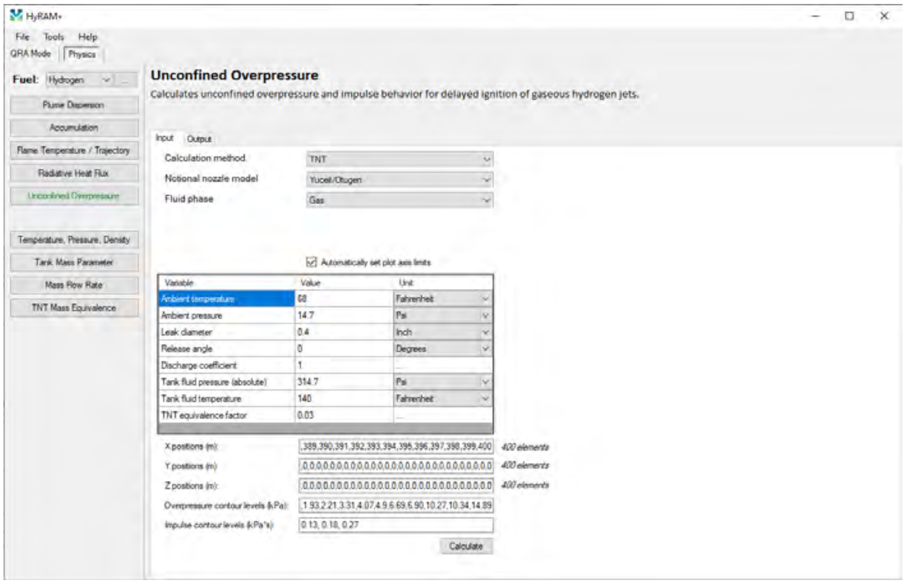

Figure A-35: Scenario 4 & 5 (1% leak) TNT Overpressure Input Traceability Figure

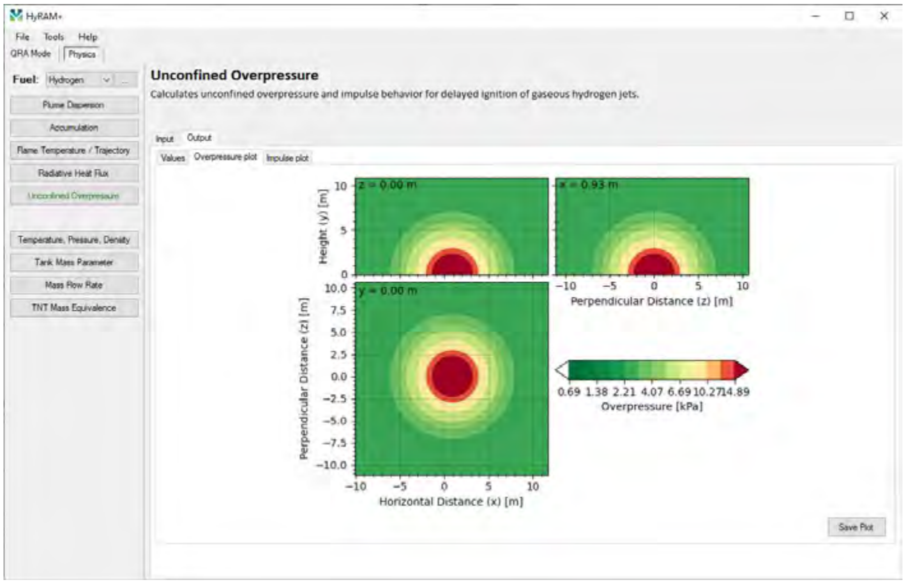

Figure A-36: Scenario 4 & 5 (1% leak) TNT Overpressure Output Traceability Figure

A.7. Scenario 6: 100% Leak Area

A.7.1. Heat Flux

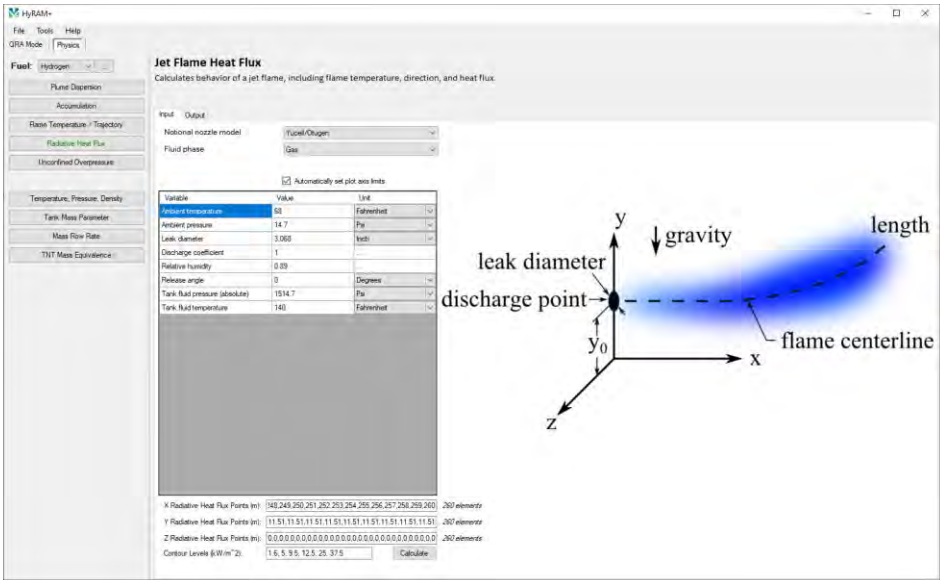

Figure A-37: Scenario 6 (100% leak) Heat Flux Input Traceability Figure

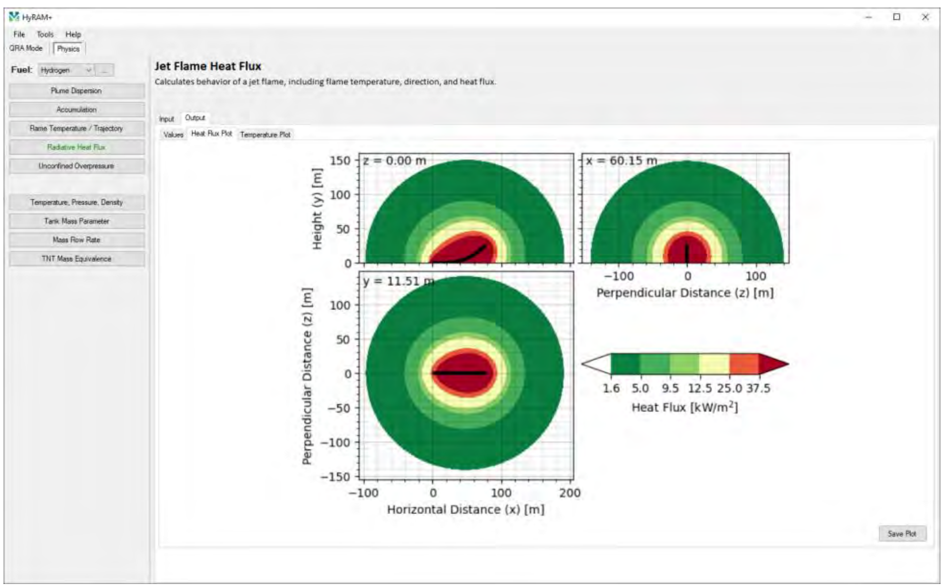

Figure A-38: Scenario 6 (100% leak) Heat Flux Output Traceability Figure

A.7.2. *Bauwens Overpressure*

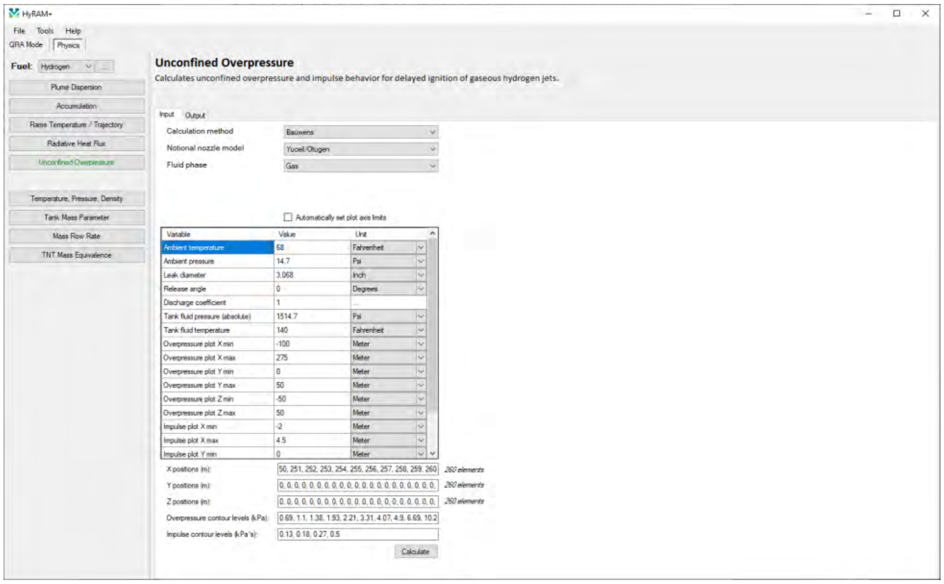

Figure A-39: Scenario 6 (100% leak) Bauwens Overpressure Input Traceability Figure

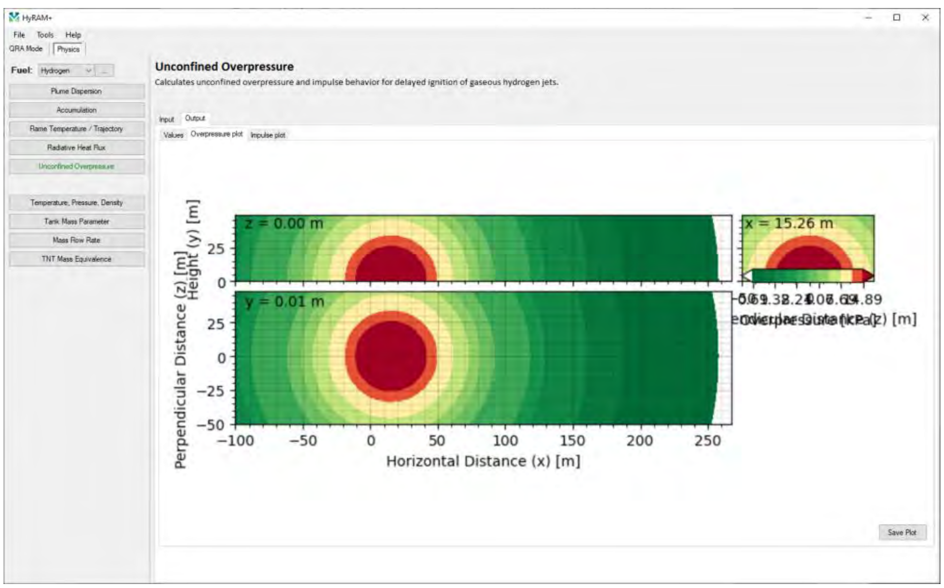

Figure A-40: Scenario 6 (100% leak) Bauwens Overpressure Output Traceability Figure

A.7.3. TNT Equivalence Overpressure

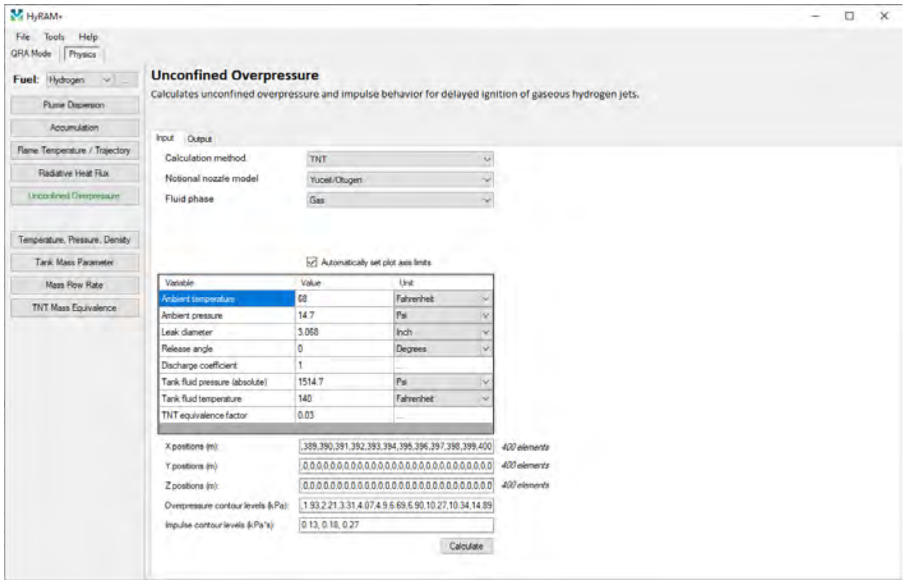

Figure A-41: Scenario 6 (100% leak) TNT Overpressure Input Traceability Figure

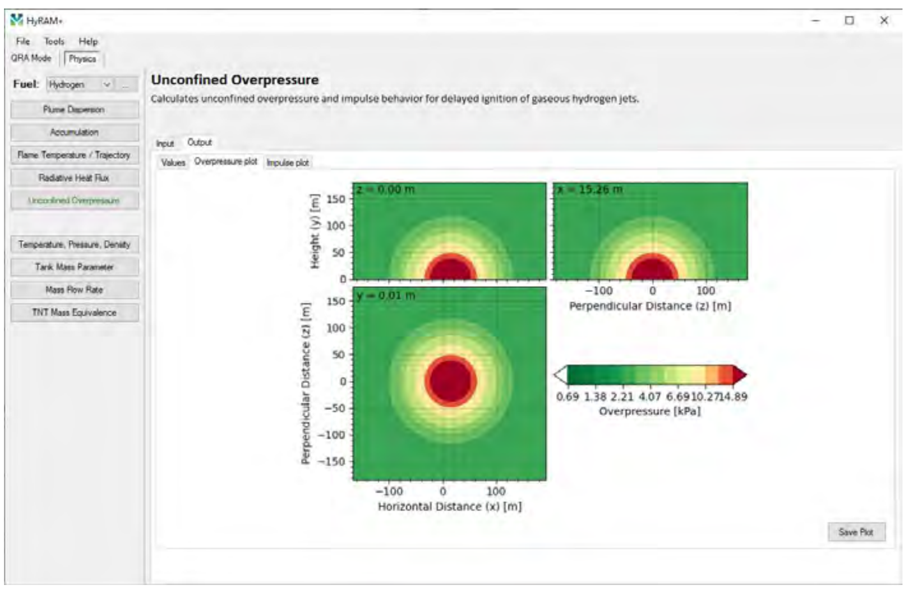

Figure A-42: Scenario 6 (100% leak) TNT Overpressure Output Traceability Figure

A.8. Scenario 6: 10% Leak Area

A.8.1. Heat Flux

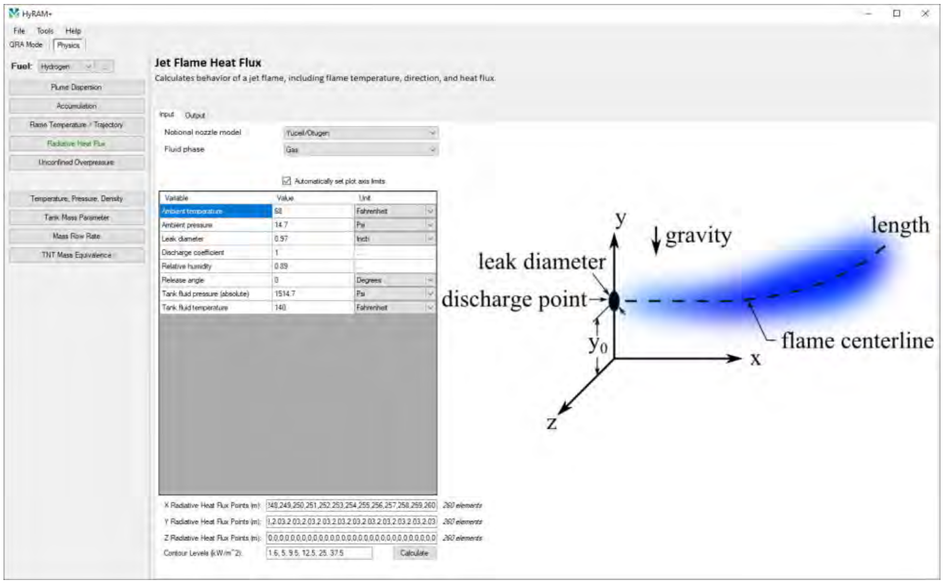

Figure A-43: Scenario 6 (10% leak) Heat Flux Input Traceability Figure

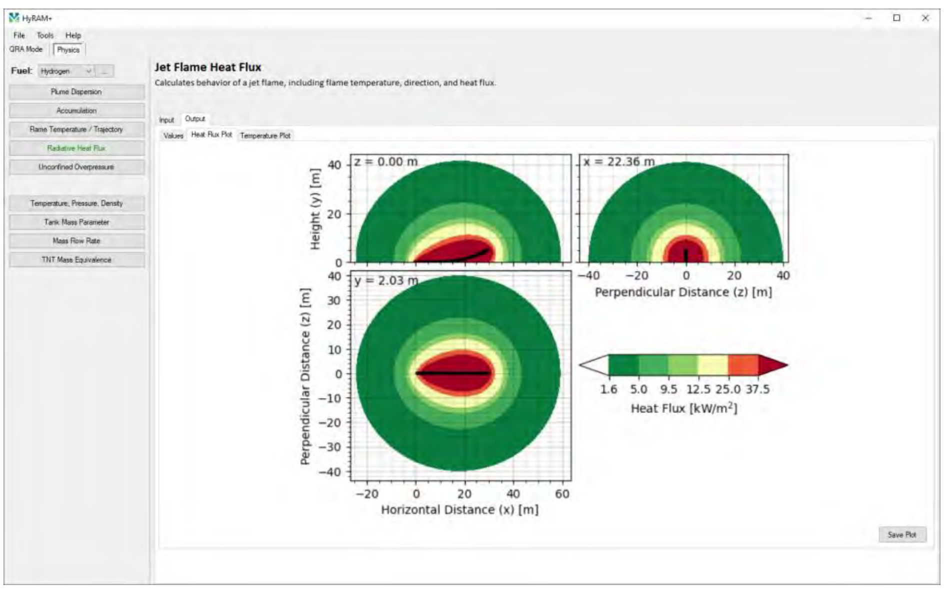

Figure A-44: Scenario 6 (10% leak) Heat Flux Output Traceability Figure

A.8.2. *Bauwens Overpressure*

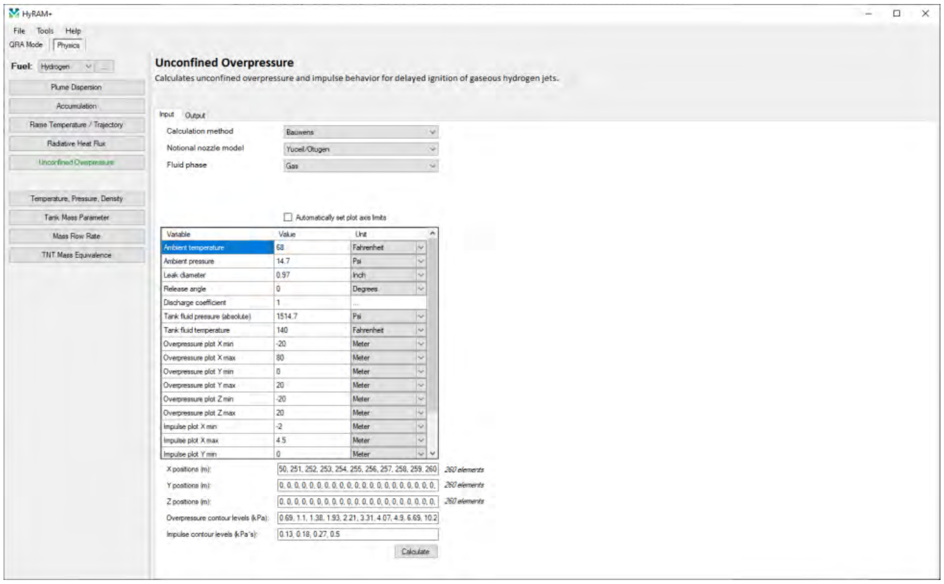

Figure A-45: Scenario 6 (10% leak) Bauwens Overpressure Input Traceability Figure

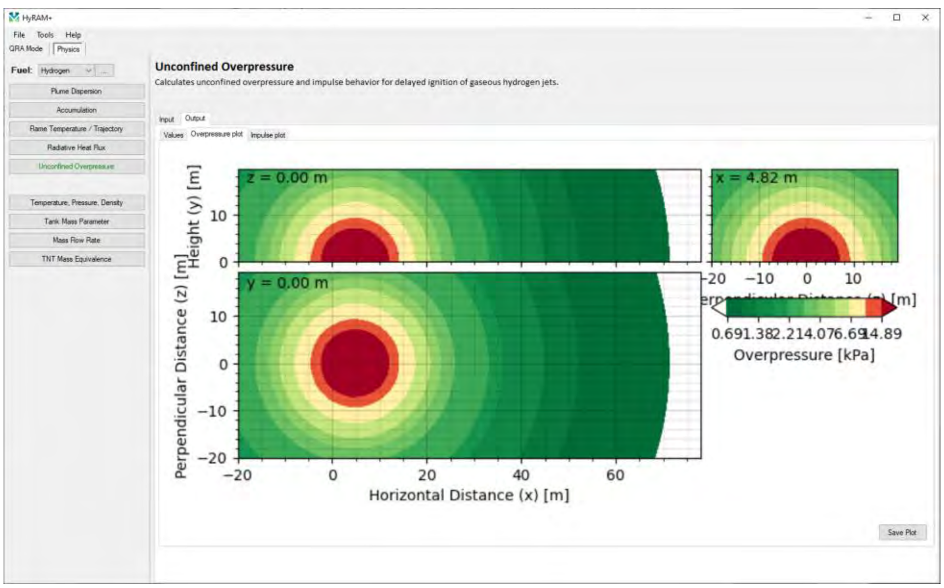

Figure A-46: Scenario 6 (10% leak) Bauwens Overpressure Output Traceability Figure

A.8.3. TNT Equivalence Overpressure

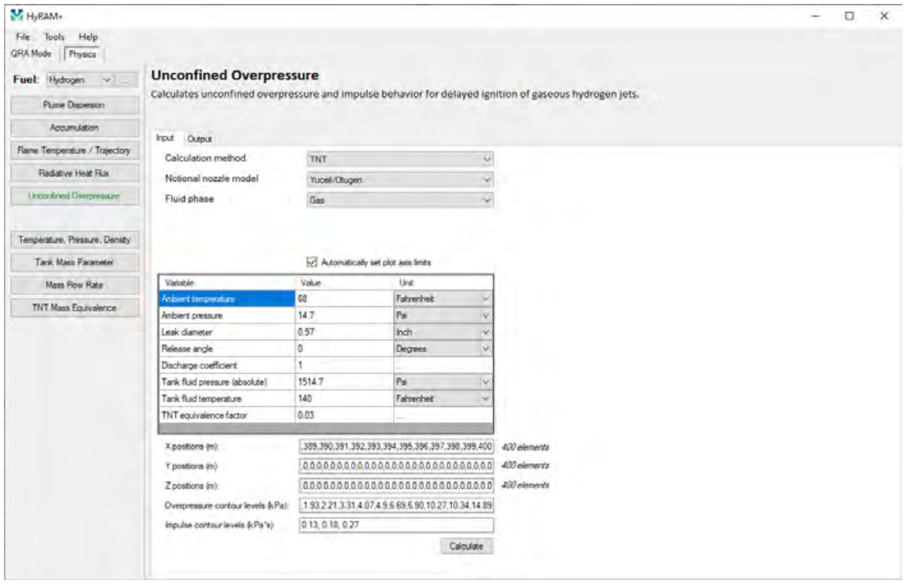

Figure A-47: Scenario 6 (10% leak) TNT Overpressure Input Traceability Figure

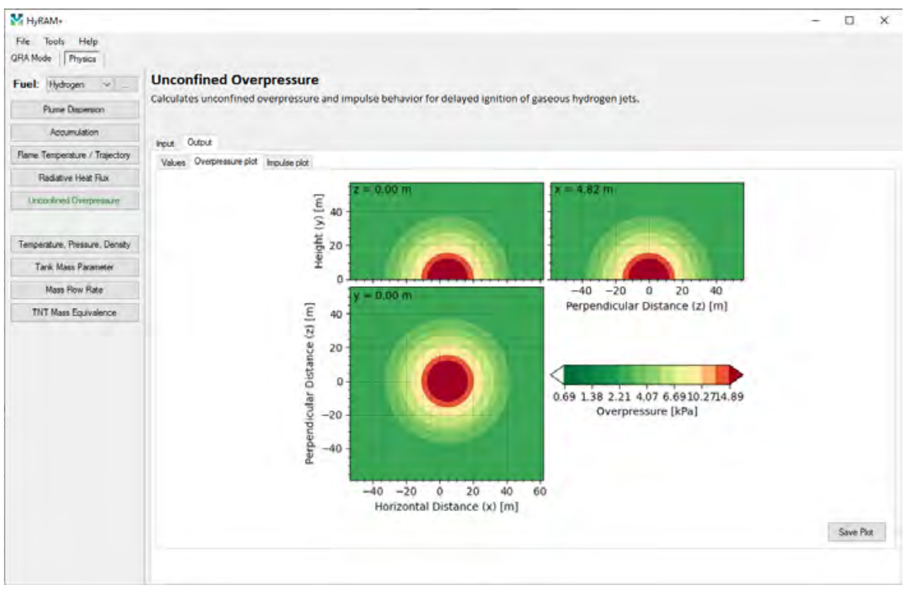

Figure A-48: Scenario 6 (10% leak) TNT Overpressure Output Traceability Figure

A.9. Scenario 6: 1% Leak Area

A.9.1. Heat Flux

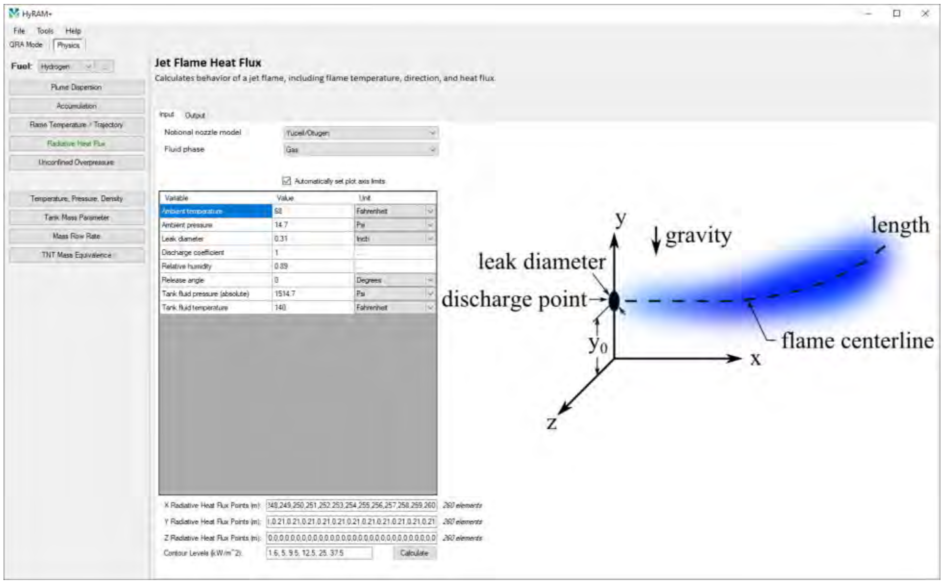

Figure A-49: Scenario 6 (1% leak) Heat Flux Input Traceability Figure

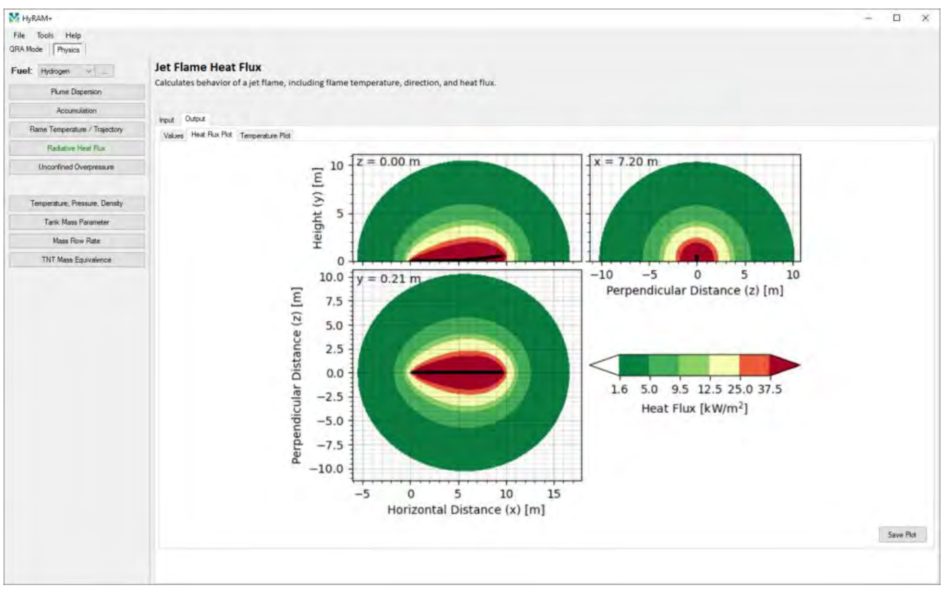

Figure A-50: Scenario 6 (1% leak) Heat Flux Output Traceability Figure

A.9.2. Bauwens Overpressure

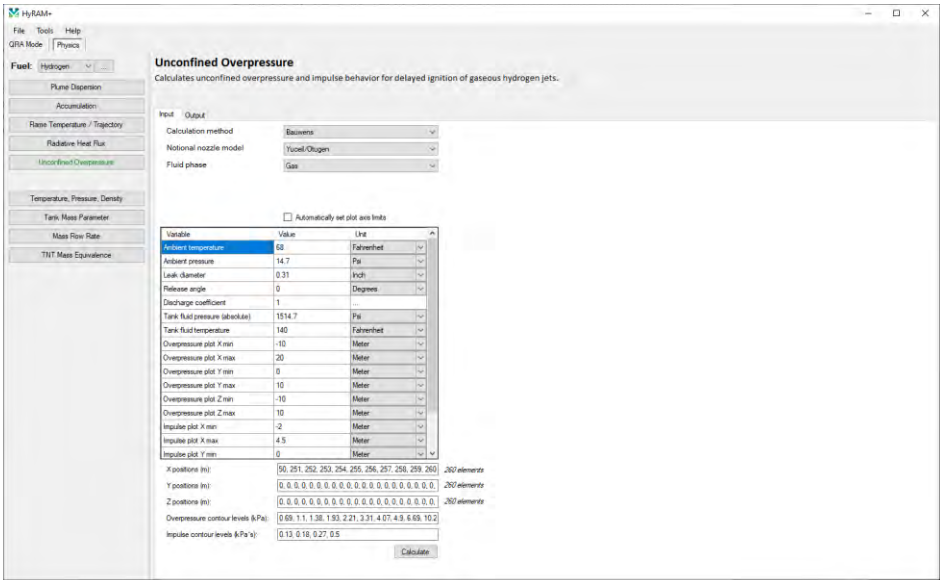

Figure A-51: Scenario 6 (1% leak) Bauwens Overpressure Input Traceability Figure

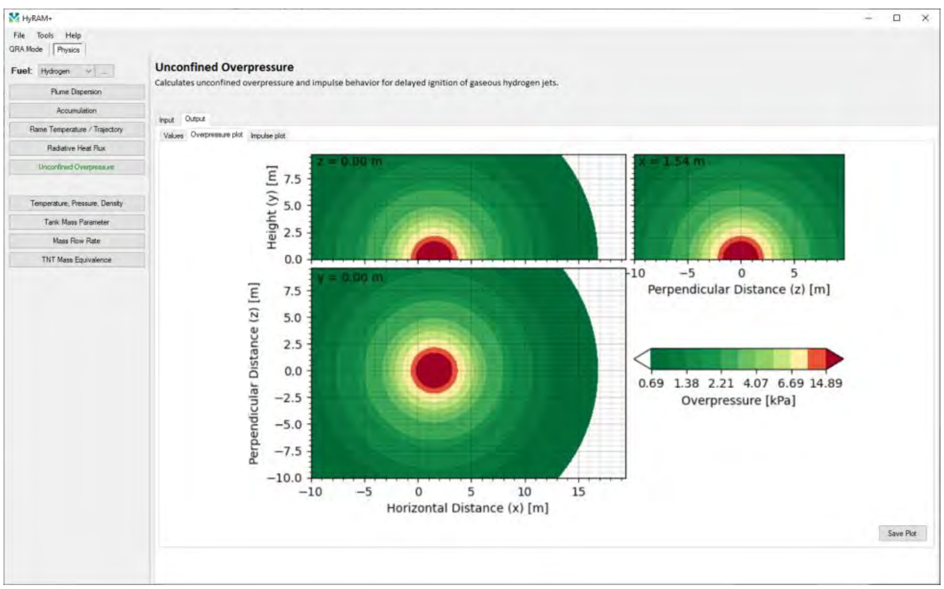

Figure A-52: Scenario 6 (1% leak) Bauwens Overpressure Output Traceability Figure

A.9.3. TNT Equivalence Overpressure

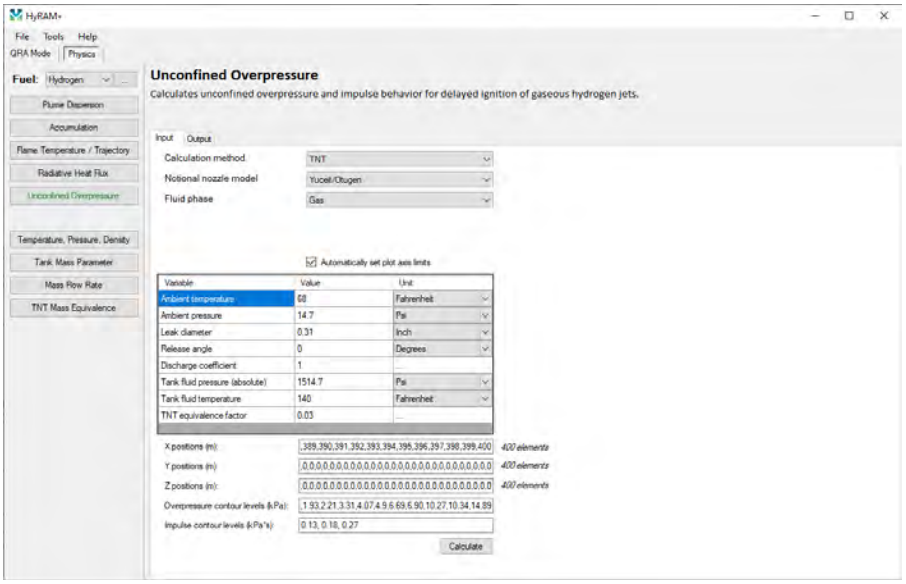

Figure A-53: Scenario 6 (1% leak) TNT Overpressure Input Traceability Figure

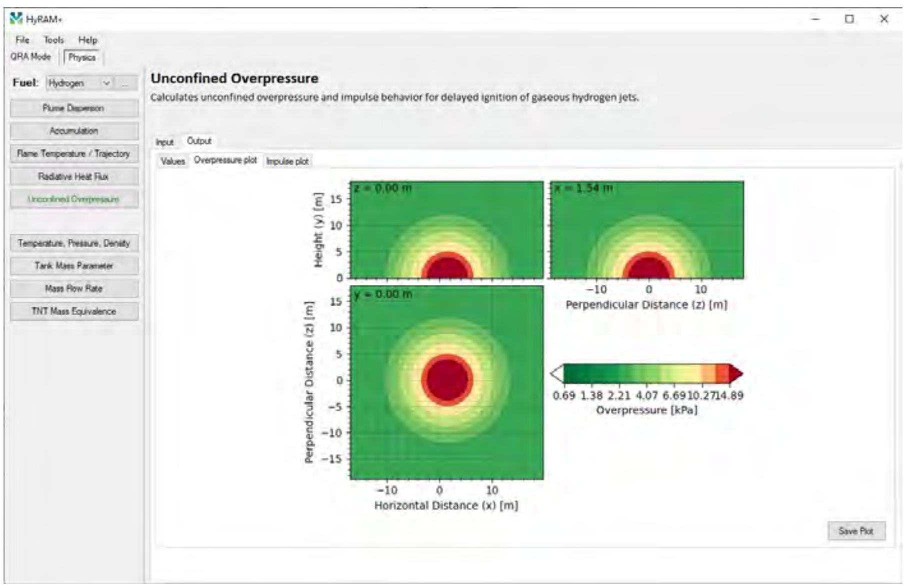

Figure A-54: Scenario 6 (1% leak) TNT Overpressure Output Traceability Figure

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