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HyRAM V2.0 User Guide

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ABSTRACT

Hydrogen Risk Assessment Models (HyRAM) is a software toolkit that provides a basis for quantitative risk assessment and consequence modeling for hydrogen infrastructure and transportation systems. HyRAM integrates validated, analytical models of hydrogen behavior, statistics, and a standardized QRA approach to generate useful, repeatable data for the safety analysis of various hydrogen systems. HyRAM is a software developed by Sandia National Laboratories for the U.S. Department of Energy. This document demonstrates how to use HyRAM to recreate a hydrogen system and obtain relevant data regarding potential risk. Specific examples are utilized throughout this document, providing detailed tutorials of HyRAM features with respect to hydrogen system safety analysis and risk assessment.

ACKNOWLEDGEMENTS

This user guide is heavily based upon the work completed in the HyRAM V1.0 User Guide SAND2016-3385 by Katrina M. Groth, Hannah R. Zumwalt, and Andrew J. Clark, and the HyRAM V1.1 User Guide SAND2018-0749 updated by Ethan A. Sena, Brian D. Ehrhart, and Alice B. Muna of Sandia National Laboratories. The current authors altered the document to correspond with revisions made to the HyRAM software over time.

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ACRONYMS

ASV	Auto Shutoff Valve
AIR	Average Individual Risk
BC	Break-away Coupling
CFD	Computational Fluid Dynamics
DOE	Department of Energy
ESD	Event Sequence Diagram
FAR	Fatal Accident Rate
FT	Fault Tree
FCTO	Fuel Cell Technologies Office
HV	Hydrogen / Manual Valve
HyRAM	Hydrogen Risk Assessment Models
NFPA	National Fire Protection Association
OD	Outer Diameter
P&ID	Piping and Instrumentation Diagram
PLL	Potential Loss of Life
PRV	Pressure Release Valve
QRA	Quantitative Risk Assessment
SRV1	Safety Release Valve 1
TNT	Trinitrotoluene
U.S.	United States of America

1. INTRODUCTION

1.1. What is HyRAM?

Hydrogen Risk Assessment Models (HyRAM) is a software toolkit that integrates data and methods relevant to assessing hydrogen safety for a variety of storage applications, including fueling stations. The HyRAM toolkit uses deterministic and probabilistic models for quantifying accident scenarios, predicting physical effects, and characterizing the impact of hydrogen hazards, including thermal effects from jet fires and thermal pressure effects from deflagration (i.e. how combustion spreads or "moves" throughout a fluid). HyRAM Version 2.0 incorporates all the features of previous version, including generic gaseous probabilities for equipment failures for nine types of components*, and probabilistic models for the impact of heat flux on humans and structures, with computationally and experimentally validated models of various aspects of gaseous hydrogen release and flame physics. Version 2.0 also includes additional capabilities, including the addition of two extra components for different applications and the ability to customize portions of the risk analysis.

HyRAM is software developed by Sandia National Laboratories for the U.S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy's Fuel Cell Technologies Office (FCTO).

1.2. Purpose of this Guide

This document provides examples of how to use HyRAM to conduct analysis of an indoor gaseous hydrogen forklift fueling facility. This document will guide users through the software and how to enter and edit certain inputs that are specific to the user-defined facility. Descriptions of the methodology and models contained in HyRAM are provided in [1].

This User's Guide is intended to capture the main features of HyRAM version 2.0 (any HyRAM version numbered as 2.0.X). This user guide was created with HyRAM version 2.0.0 and was based upon the HyRAM V1.1 User Guide [2]. Due to ongoing software development activities, newer versions of HyRAM may have differences from this guide.

It is not the intent of this Guide to provide an explanation as to the limitations and reference for each model. That information can be found in the HyRAM Technical Reference Manual [1], found at http://hyram.sandia.gov.

1.3. Requirements

HyRAM is a research software tool under active development at Sandia National Laboratories for the U. S. Department of Energy (DOE), Office of Energy Efficiency and Renewable Energy's Fuel Cell Technologies Office. HyRAM version 2.0 is available as a free, executable download from http://hyram.sandia.gov and its code is open source.

HyRAM was designed to be installed on any 64-bit Intel-compatible computer running Microsoft Windows.

* Further information regarding these models is available in the HyRAM Technical Reference Manual

The intended users for HyRAM are experienced safety professionals and researchers who are familiar with the modeling assumptions, limitations, and interpretation of Quantitative Risk Assessment (QRA) and consequence models.

2. BASIC FUNCTIONS

2.1. Save/Load Workspace

The Save/Load Workspace button can be found in the **File**[†] menu at the top left corner of the program window, as shown in Figure 1. The Save Workspace button functions as a "Save As" button. To save a workspace, click the Save Workspace option. The Engineering Toolkit input will not be saved or loaded with workspaces. Comments may be added to a workspace by typing in the text box in the Save Workspace window. To load a workspace that has been previously saved, click the Load Workspace option. To reset HyRAM to its default values and settings, the user must click File, then Exit, to close the program. After the user reopens the program, HyRAM will reset itself with default values and settings.

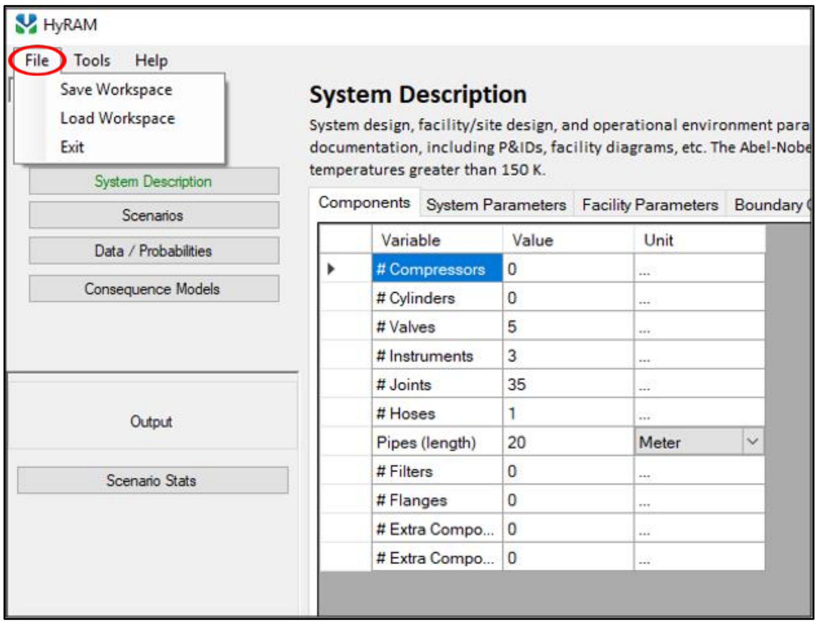


Figure 1: Save/Load Workspace

2.2. Changing Units

HyRAM contains a built-in unit conversion function. For variables with a unit, the unit must be selected before inputting a value. If a value is entered before a unit, when a different unit is selected, the software will convert the entered value into the new value corresponding to the selected unit. To change units for a variable, find the drop-down bar in the unit column, click on the **Arrow** next to the bar; this will reveal a **List of Possible Units**. Click on a new unit to select it, then click on a box within the input table to apply the unit conversion as shown in Figure 2.

[†] Colored text throughout this document corresponds to respectively colored indicators on associated figures to better illustrate HyRAM functionality and denote its features

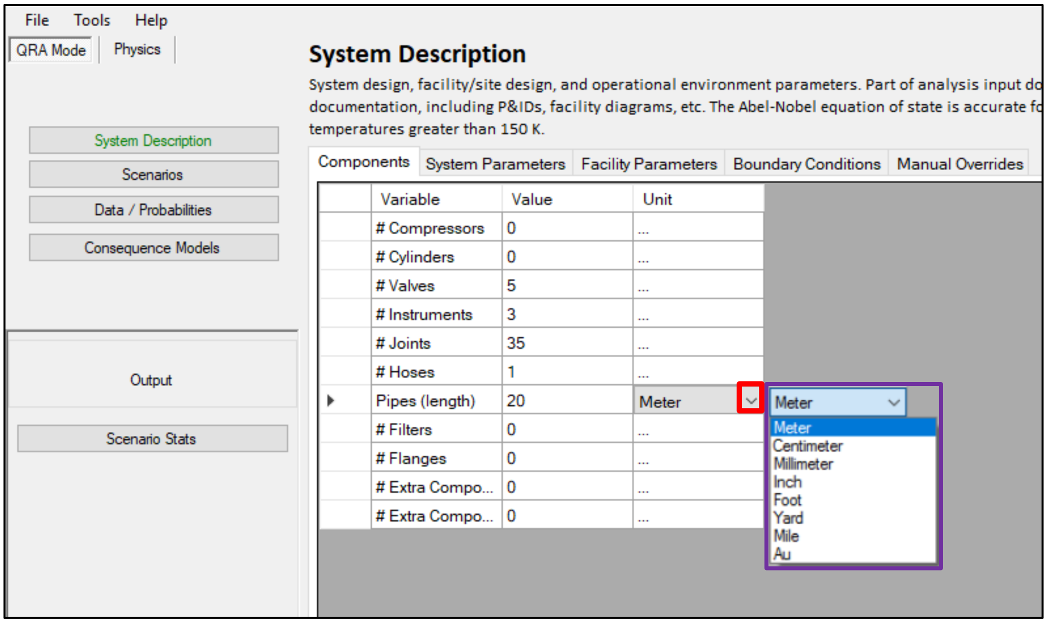


Figure 2: Changing Units

2.2.1. *Engineering Toolkit*

The user can also utilize the Engineering Toolkit under **Tools**, shown in Figure 3, to determine some parameters of a given system.

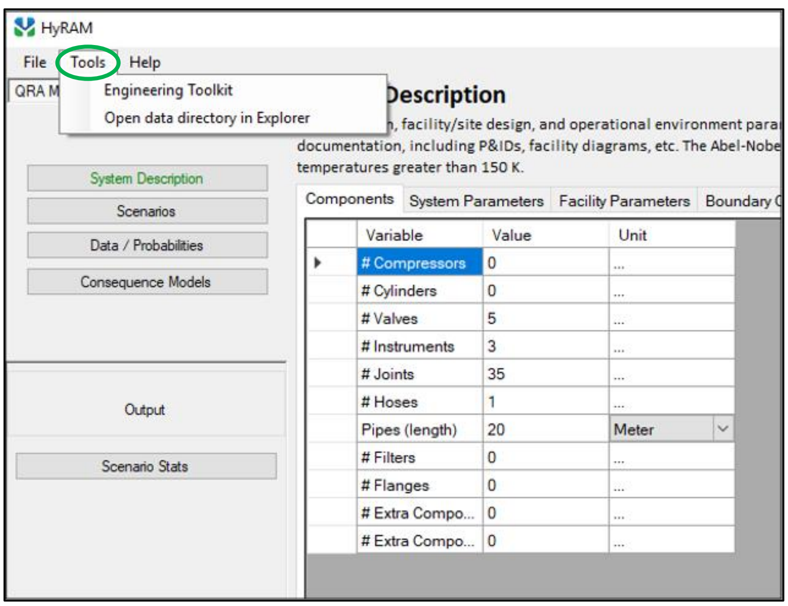


Figure 3: Engineering Toolkit Location

The Engineering Toolkit has four tabs to determine various quantities: Temperature, Pressure and Density; Tank Mass; Mass Flow Rate; and TNT (i.e. trinitrotoluene) Mass Equivalence. In the Temperature, Pressure and Density tab, the user enters two known quantities to determine an unknown quantity. When the user selects which parameter to calculate, the parameter will be "grayed-out" and no value can be entered in the corresponding box. In Figure 4, the density is chosen under **Calculate**. The **Temperature** is 300 K and the **Pressure** is 250 bar. With these two values entered, the **Calculate Density** button can be clicked to determine the density; in this case, the **Calculated Density** is 0.0175 g/cm^3.

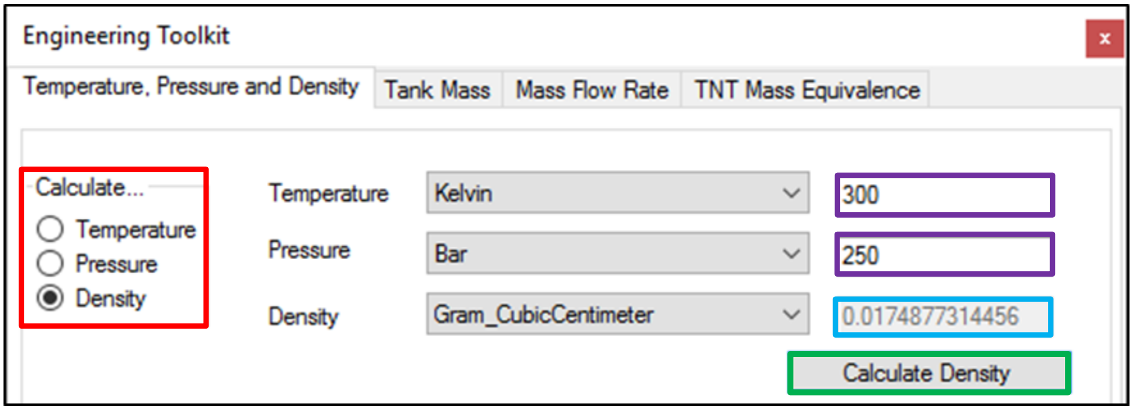


Figure 4: Example Calculation for Temperature, Pressure and Density Tab

The Tank Mass tab determines the mass of hydrogen inside a given tank. The user supplies inputs for the **Temperature**, **Pressure**, and **Volume**. In Figure 5, the temperature is 300 K, the pressure is 250 bar and the volume is 50 L. Once all the inputs are provided, the user can click **Calculate Mass**; in this example, the **Calculated Mass** is 0.874 kg.

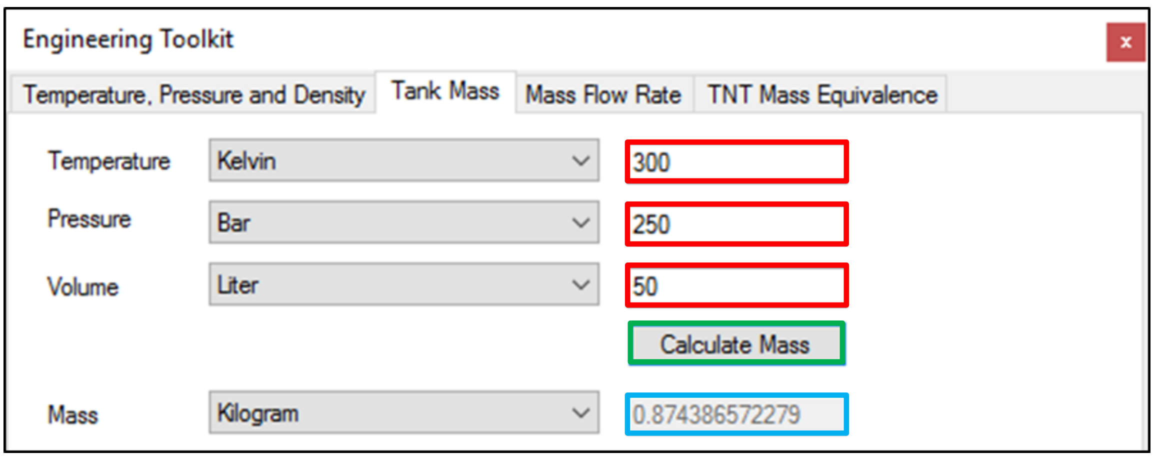


Figure 5: Example Calculation for Hydrogen Mass in Tank Mass Tab

The Mass Flow Rate tab is used to determine mass flow rates for either a steady or blowdown type of release. In addition to inputting the **Temperature**, **Pressure** and **Volume** as shown in Figure 6, the user also inputs the **Orifice Diameter** (i.e., the release diameter). The user must also select the **Release Type** before clicking the **Calculate Mass** button. Figure 6 illustrates a blowdown example for a 1 mm orifice diameter release.

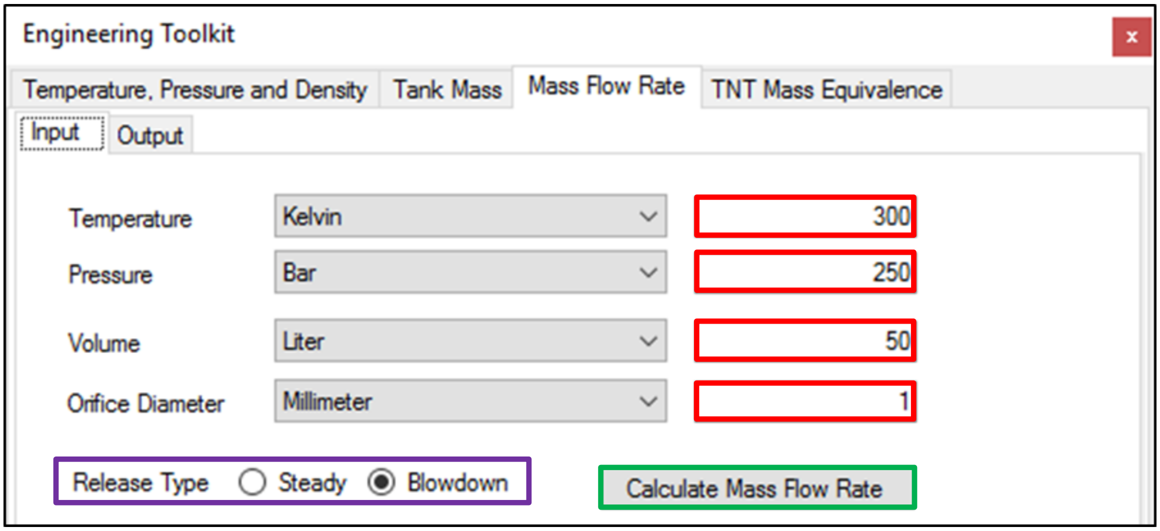


Figure 6: Example Input for Mass Flow Rate Tab

After the user clicks the **Calculate Mass Flow Rate** button, as shown in Figure 6, the screen will change to the Output tab. The Output tab is shown in Figure 7, with the **Time to Empty (seconds)** equal to 480.8 seconds. The user may also save an image of the generated plot by clicking **Save Plot**.

Note: Selecting a Steady Release Type will not produce a plot for the output.

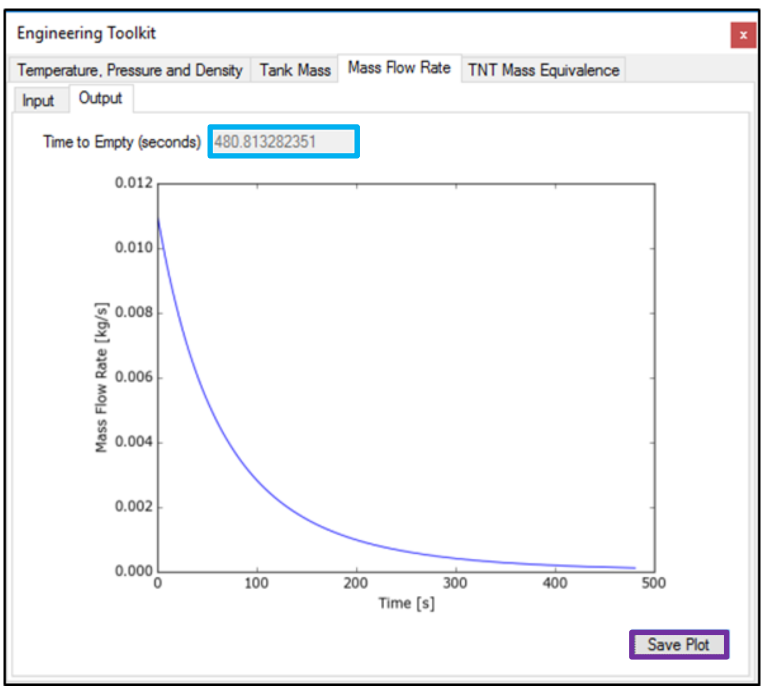


Figure 7: Mass Flow Rate Output Tab

The amount of energy released by combusting a specific mass of hydrogen can be compared to the amount of energy released in an explosion of TNT. The mass of TNT required to release the same amount of energy as a mass of hydrogen can be calculated using the TNT Mass Equivalence Tab in the Engineering Toolkit. In Figure 8, the **Flammable Vapor Release Mass** is 1 kg, **Explosive Energy Yield** is 100%, and **Net Heat of Combustion** is 118,830 kJ/kg. These input values yield an **Equivalent TNT Mass** of 26.41 kg. After the user inputs the required values, the Equivalent TNT Mass will automatically be calculated and displayed in a “grayed-out” box.

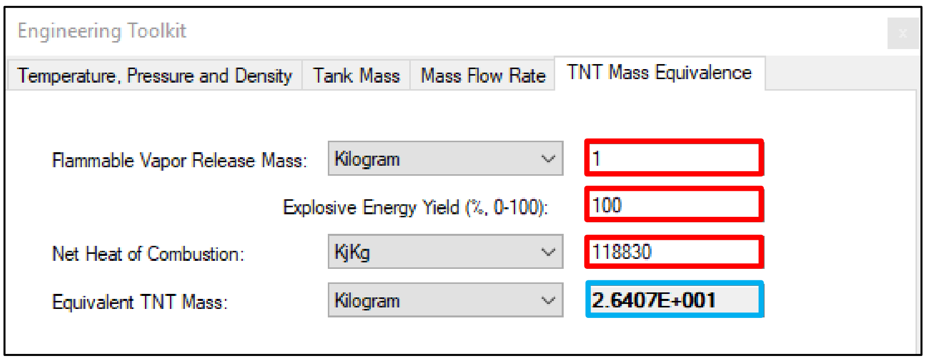


Figure 8: Example Calculation for TNT Mass Equivalence Tab

2.3. Sorting

All inputs are pre-organized. To change the rank or sorting of a column, click on the **Title Box** of the column, as in Figure 9. This will change the rank to numerical or alphabetical depending on the column input. Clicking the title box again will reverse the sort order.

Note: Sorting is not enabled for all columns.

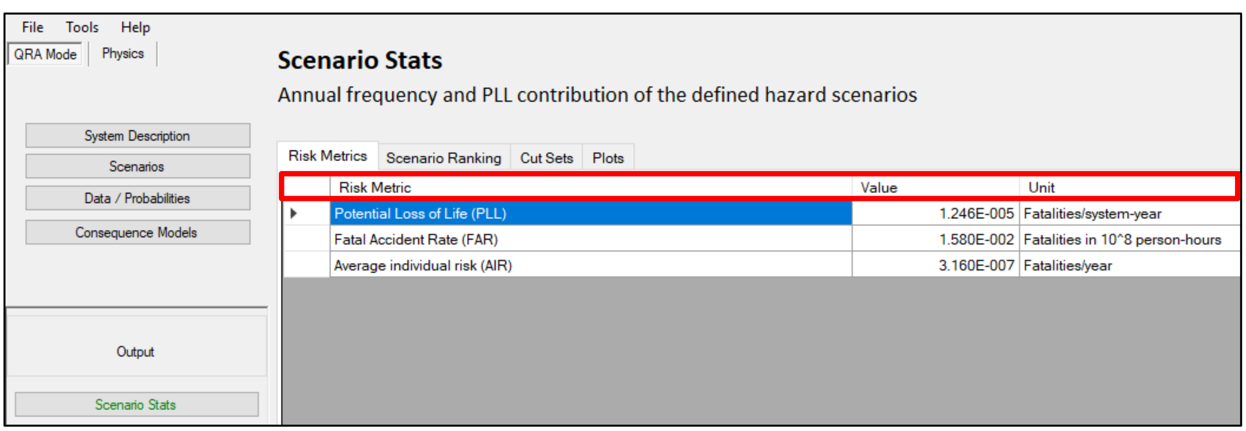


Figure 9: Sorting of Scenario Stats Risk Metrics

2.4. Copying Tables to Paste into Other Programs

HyRAM tables may be copied into external programs such as Microsoft Word and Excel. To do so, select the desired cells of the table and press Ctrl+C. Tables may be pasted into external programs using Ctrl+V or pasting options defined by the external program.

3. GENERIC INDOOR FUELING SYSTEM EXAMPLE

For this document, inputs are based on a generic indoor fueling system and the National Fire Protection Association (NFPA) Hydrogen Technologies Code (NFPA 2) requirements and industry practices. The example installation is based off the generic indoor fueling system for hydrogen-powered forklifts further documented in [1] and [3].

The system is a hydrogen dispenser located within a warehouse facility. The facility is a free-standing industrial frame structure. Interior dimensions are: 100 m (length) × 100 m (width) × 7.62 m (height). It is assumed that are 50 employees in the warehouse at any time and personnel each work 2,000 hours per year. In this example, most workers are located within 50 m of the dispenser due to building design. The vehicle fleet contains 150 vehicles (e.g., forklifts within the warehouse facility) that are operated 24 hours/day and 350 days/year. Each vehicle holds 1 kg of hydrogen and is refueled once per day.

The dispenser delivers gaseous hydrogen at 35 MPa. The dispenser operates for up to 5 minutes per fueling event, and the internal hydrogen temperature is 15°C. All piping in the storage system has an outer diameter (OD) of 3/8", wall thickness of 0.065", and the material is ASTM A269 seamless 316 stainless steel piping. The orifice diameter within the piping is 3.25 mm. The facility temperature is 15°C and pressure is atmospheric (0.101325 MPa). Figure 10 illustrates the Piping and Instrumentation Diagram (P&ID) for the generic dispenser. The part count only includes components inside the building and on the main process line: one hose, 20 m of piping, five valves (ASV2, HV1, BC1, SRV1, and N1), three instruments, and 35 joints. The system also contains additional components (not pictured; within the Dispenser Appliance Boundary): two cylinders, two valves, two instruments, eight joints, 10 m of piping, and three filters. In total, the system has two cylinders, seven valves, five instruments, 43 joints, one hose, 30 m of piping, and three filters.

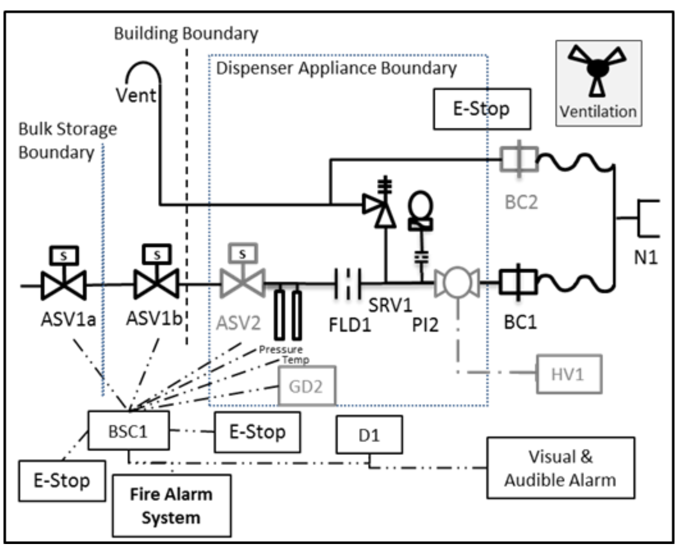


Figure 10: P&ID for the generic dispenser used in this example [3]

4. QRA MODE—INPUT

4.1. System Description

The System Description window, depicted in Figure 11, contains five tabs (Components, System Parameters, Facility Parameters, Boundary Conditions and Manual Overrides) which enable the user to input design specifications for the system.

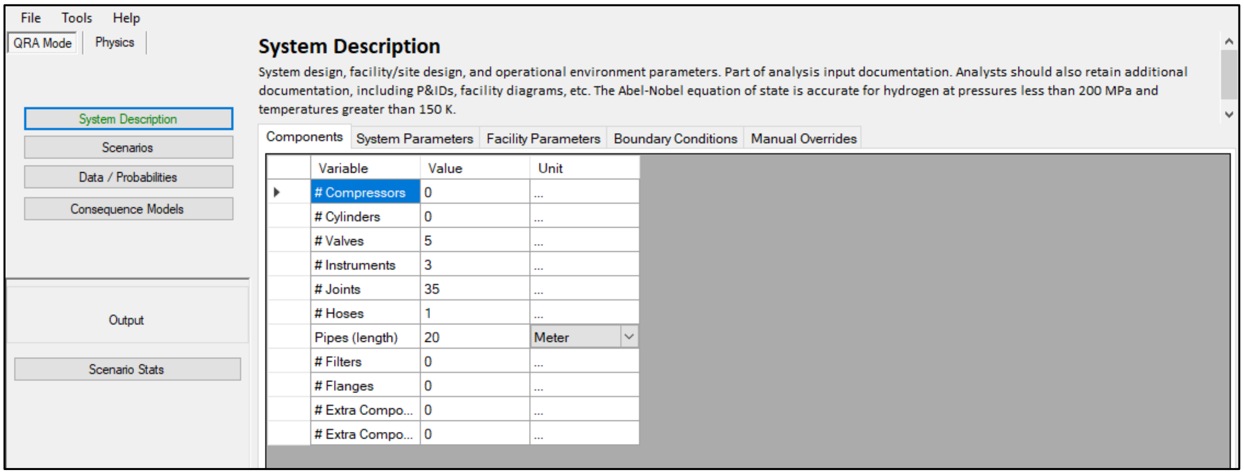


Figure 11: QRA Mode System Description Window

4.1.1. Components

The Components tab contains user input for nine types of components commonly seen in hydrogen applications and two extra component inputs for a different type of system. For example, liquid stations could include a pump and thus that analysis would use one of the extra component inputs. The user should refer to a P&ID for the proper number of components. The Components **Input**, based on the preceding example, is portrayed in Figure 12.

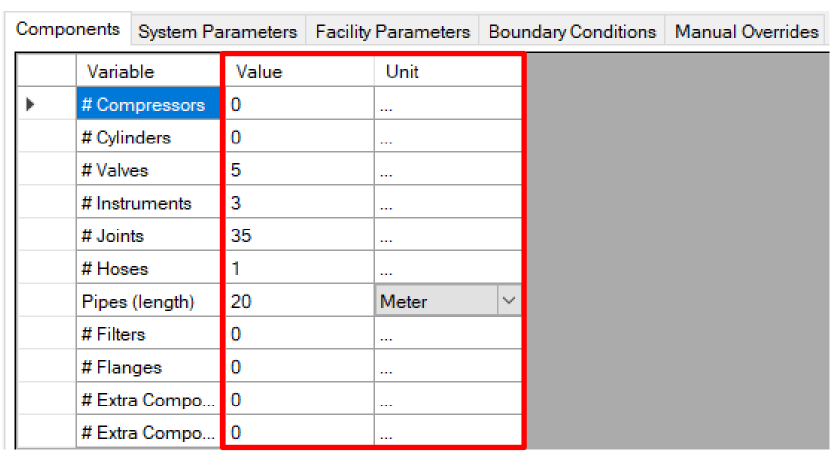


Figure 12: Components Input Window

4.1.2. System Parameters

The System Parameters tab contains Piping and Vehicle input. This information can be found in the P&ID and the description of the facility.

4.1.2.1. Piping

The Piping tab contains inputs for pipe dimensions of the system and the operating conditions (both internal to the system and in the surrounding external environment). This information is used in calculations for release sizes and characteristics. Based on the preceding example, the Piping tab **Input** is shown by Figure 13.

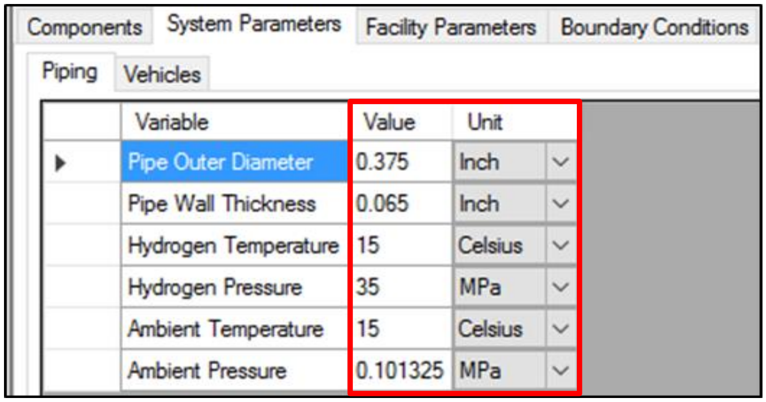


Figure 13: Piping Input

4.1.2.2. Vehicles

The Vehicles tab contains inputs that establish the use conditions of the station. Users input the Number of Vehicles, the number of times a vehicle is fueled per day (Number of Fuelings Per Vehicle Day), and the number of operating days of the vehicles (Number of Vehicle Operating Days per Year). HyRAM calculates the annual demands as the product of those three inputs. Based on the preceding example, Vehicles **Input** is depicted by Figure 14.

Note: The annual number of demands is used in the calculation of the frequency of releases from elements contained in a Fault Tree (FT) (i.e. a diagram that presents theoretical scenarios on which a component fails, and what events that might lead to). If the user decides to not use this FT, the user should input zero for one of the inputs. If the user puts zero for any variable, the code will result with an annual demand of zero. This implies that the "100% Release FT" will not be used. For example: if the user inputs zero on "Number of Vehicles", the code will produce an "Annual Demands (calculated)" of zero. The manual override (see Section 4.1.5) for "100% H2 Release (accidents and shutdown failures)" will also override this.

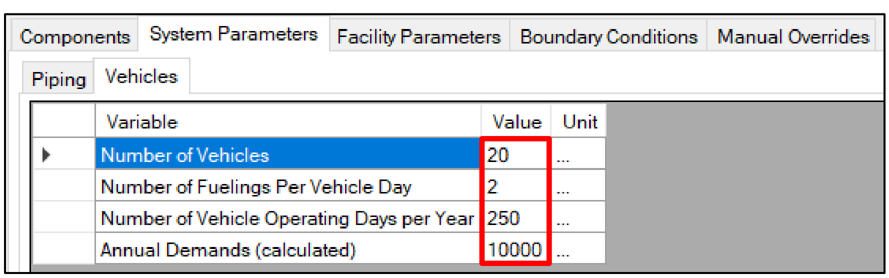


Figure 14: Vehicles Input

4.1.3. Facility Parameters

The Facility Parameters tab contains the Facility and Occupants tabs.

4.1.3.1. Facility

The Facility tab contains measurements for the entire facility, as shown in Figure 15. Based on the preceding example, Facility **Input** would be as shown:

Note: In HyRAM 2.0, the input values for Width and Length will not affect risk calculations. Future HyRAM versions may use these numbers to assess further risk characteristics. For now, they are only used to make the plot to positioning occupants (see Section 0).

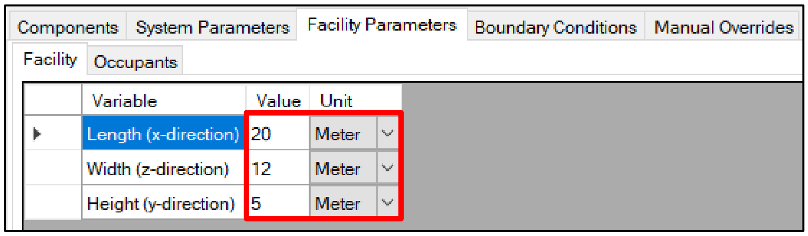


Figure 15: Facility Input

4.1.3.2. Occupants

The Occupants tab contains input details for number of persons on site (e.g., exposed employees) and a function to randomly distribute workers based on a uniform or normal distribution, or defines a specific location using the deterministic distribution. These distributions are used to determine personnel locations (i.e., the distance from the system for use in harm calculations).

Several scenarios can be defined for personnel. For each scenario, the user defines the Number of Occupants (i.e., the number of personnel) and provides a description of the scenario in the Description field. The user can then choose between the Normal, Uniform, or Deterministic Location **Distribution Types for each of the X, Y, and Z coordinate values**. If the user selects a Normal or Uniform Distribution Type, the user will need to enter coordinate values for Location Distribution **Parameters A and B**. If the user selects the Deterministic Distribution Type, only coordinate values for Location Distribution Parameter A are required. The units (Location Parameter Unit) correspond to the distribution parameters. The Exposed Hours Per Year for a single target is also assigned by the user. To delete a row in the Occupants tab, the user must click on the **Arrow** (see Figure 16) next to the row to highlight the entire row, and then press the keyboard Delete button. To add a row in the Occupants tab, the user must enter in a new value in the last row for **Number of Occupants** and press Enter on the keyboard, then a new row will be created.

When selecting the Normal Location Distribution Type, Location Distribution Parameter A corresponds to the mean (μ) and Location Distribution Parameter B corresponds to the standard deviation (σ). For the Uniform distribution, Location Distribution Parameter A and Location Distribution Parameter B correspond to the minimum (a) and maximum (b) values, respectively. Deterministic distribution corresponds to a constant value for the location and is entered in Location Distribution Parameter A. Distributions are applied with respect to the hydrogen system; that is, the hydrogen system is at the origin of the coordinate space (0, 0, 0), which effectively occurs at the lower left corner of a Cartesian coordinate system (in a top-view of the facility).

Worker positions relative to the storage system could be randomly assigned by sampling from a normal distribution. For the example case [3], the 50 workers are assumed to be within 50 m of the storage system. The authors translate this assumption into a normal distribution centered at the dispenser (μ = 0 m) and a standard deviation of 50/3 =16.67 m (μ = 0 m, σ = 16.67 m). The authors recommend using the shortest dispenser-to-wall distance and dividing by three since three standard deviations account for 99.7% of the possible positions. Based on the preceding example, the Occupants tab **Input** is shown by Figure 16.

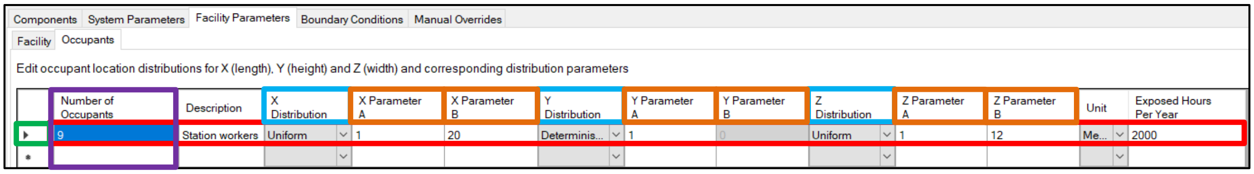


Figure 16: Example Input for Occupants Tab

4.1.4. Boundary Conditions

The Boundary Conditions tab inputs are used to generate positions of targets. Likewise, the location distributions (from the System Description, Facility Parameters, Occupants tab) are used to generate positions. However, all generated positions must be some minimum distance away from the leak; this is the **Exclusion Radius** (in meters). Additionally, the pseudo-random number generator requires a "seed" from which to generate positions; the user is given the ability to set whatever **Random Seed** value they wish; this will help generate reproducible results from session to session. Figure 17 shows the default Boundary Conditions input used for this example.

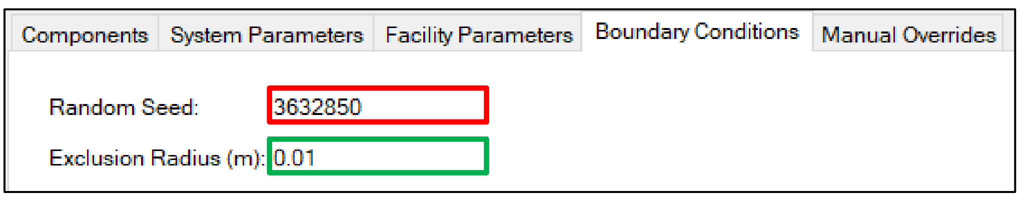


Figure 17: Boundary Conditions Input

4.1.5. Manual Overrides

There are six different Manual Overrides available for the user in HyRAM: one for each leak size and one for Gas Detection and Isolation Credit (the probability of successful release detection and isolation before ignition). While following the ESD (Event Sequence Diagram; see Section 4.2.1) on HyRAM, the **Gas Detection** and Isolation Credit feature works by establishing an amount of probability that the leak will be isolated and detected. For example, if the user inputs a credit of 0.9, then HyRAM runs by assigning a hydrogen leak occurs, then there is a 90% chance that it is detected and isolated. This means that there is a 10% chance said detection and isolation does not happen, therefore the rest of the ESD (ignition branches) will be considered. This gives the user an option to override it to any number, like zero (i.e. no gas detection or isolation whatsoever).

For each of the five leak sizes (0.01%, 0.1%, 1%, 10%, 100%), there is an associated Fault Tree (FT; see Section 4.2) based on the equipment around the user-described facility and how likely said leak size will occur. If the user wants to specify another FT with different leak frequencies, HyRAM gives the option to "customize" the FT. The Manual Overrides tab lets the user determine an annual leak frequency (e.g. for a 1% leak size, there is a 0.003% leaks/year), giving way to a customized FT. It is important to note that HyRAM does not exactly substitute the default FTs for a user-defined one, rather HyRAM lets the user by-pass the default FT to give way to tailored, user-specific FTs results.

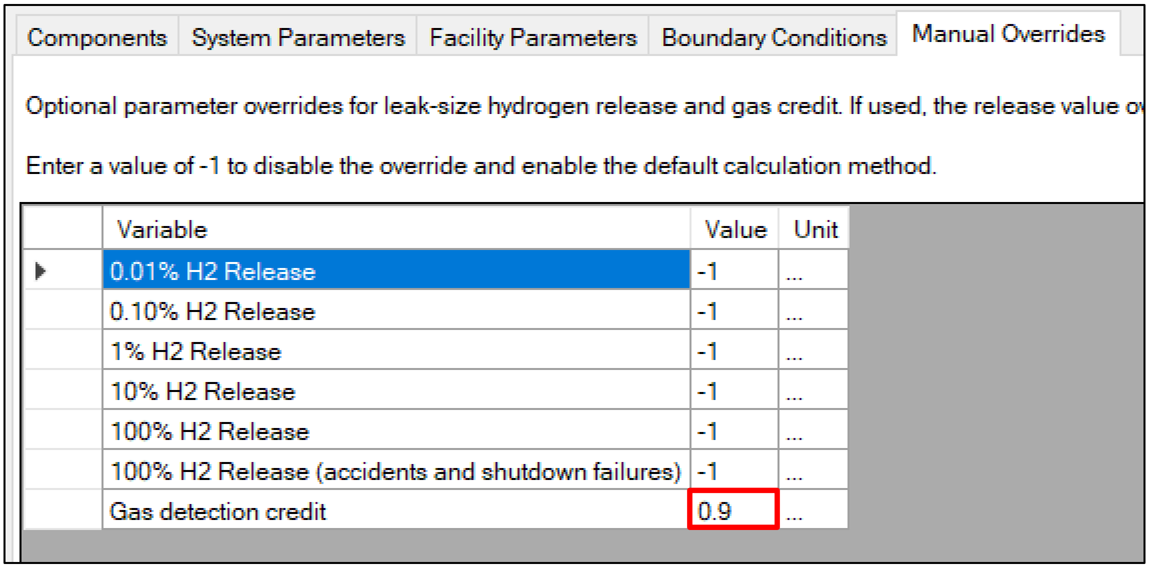


Figure 18: Manual Overrides Input Tab

4.2. Scenarios

The Scenarios window contains Event Sequence Diagrams (ESDs), which model the hydrogen release scenarios, and Fault Trees (FTs), which model causes of hydrogen releases.

Note: The ESDs and FTs could not be modified in HyRAM 1.1 – in 2.0, however, the user can now input a customized FT result and customizable values for the ESD.

4.2.1. Event Sequence Diagrams

The Event Sequence Diagrams, or Event Tree, tab illustrates the scenarios that could occur after a hydrogen release, depending on the success of detection/isolation and the time of ignition.

There are three possible outcomes that may result if a hydrogen release is not detected and isolated: jet fires, explosions, and unignited releases. If hydrogen is not ignited (either due to successful detection/isolation of the release or due to lack of ignition), there are no risk-significant consequences considered.[‡] When a high-pressure release of hydrogen is immediately ignited near the source, the result is a classic turbulent-jet flame. If hydrogen is not immediately ignited, hydrogen can accumulate. If the accumulated hydrogen is subsequently ignited (delayed ignition), the result is an explosion.

The Event Sequence Diagram coded in HyRAM models these scenarios. The user may input a value (between 0.0 and 1.0) for gas detection credit, as shown in Section 4.1.5. This value is the probabilistically associated with the ESD event *yes/true* (upper branch) for a single node "Leak

[‡] Asphyxiation, hypoxia, or frostbite are not considered because there is a higher chance that an ignition would happen instead of these events. For these accidents to happen, there needs to be an estimated amount of hydrogen for it to occur. Yet, the chance of an incident occurring by hydrogen's high flammability is much more likely to happen. For example, for hypoxia to occur, there must be an estimated concentration of about 50% of hydrogen per volume in air. However, hydrogen's upper flammability limit is 75% and its lower flammability limit is 4%. Both occurrences overlap each other, but hydrogen can be flammable since 4% concentration per volume. So, in the amount of time for the concentration of hydrogen to reach ~50% in air (for hypoxia to occur), there is already plenty of chance for an ignition (instant or delayed) to happen.

detected and isolated" (illustrated as two nodes in Figure 19, but treated as a single node in the HyRAM logic). If the user has separate probabilities for leak (release) detected and leak (release) isolated, simply multiply the two probabilities together and enter this product into the gas detection credit input.

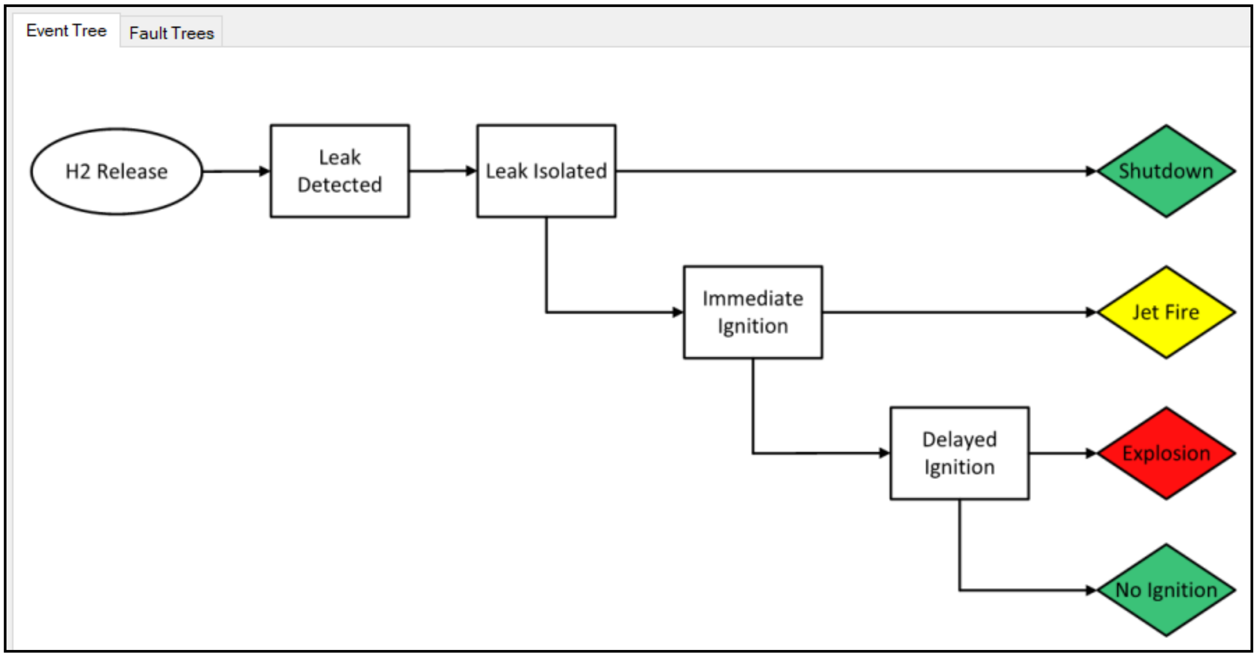


Figure 19: Event Sequence Diagram showing the scenarios coded in HyRAM

4.2.2. Fault Trees

Each leak size has an associated FT, on which the top event probability from the FTs is defined according to the user-selected FT (i.e. leak size scenario and number of pieces of equipment / components). But, the specific case where the leak is a 100% size, there is an additional sub-FT where other accidental failures for a dispenser are considered. If the user does not want to include this sub-FT or any other FT on their analysis, then input zero as per Section 4.1.2.2. If the result of another FT for a different application is known, that value can be inputted as per Section 4.1.2.2. Any one of the FTs can be overridden using the "Manual Override" tab.

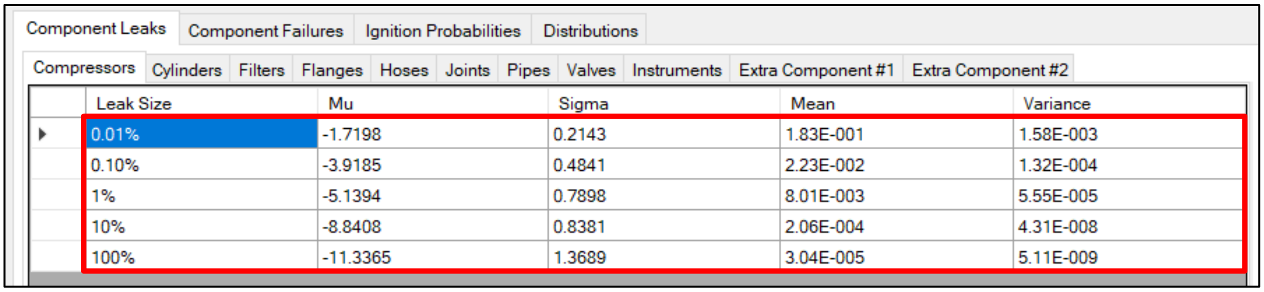
4.3. Data/Probabilities

The Data/Probabilities window contains the data for Component Leaks, Component Failures, and Ignition Probabilities.

4.3.1. Component Leaks

The Component Leaks tab contains assumptions about the frequency of leaks of five size categories for nine types of components used in gaseous hydrogen systems. The size categories are percentages (0.01%, 0.1%, 1%, 10%, and 100%) of the pipe area which is calculated from the user input described in Section 4.1.2.1.

HyRAM contains default values for the gaseous leak frequencies from each type of component. These frequencies were assembled from generic data from offshore oil, process chemical, and nuclear power industries and documented in [4]. The values in HyRAM are encoded as parameters of a lognormal distribution (*mu* and *sigma*). HyRAM automatically calculates the mean and variance from a given mu and sigma. Users may modify a component's leak probabilities by entering new values for mu and sigma. Figure 20 portrays the default Component Leaks **values** for Compressors.



Component Leaks | Component Failures | Ignition Probabilities | Distributions

Compressors | Cylinders | Filters | Flanges | Hoses | Joints | Pipes | Valves | Instruments | Extra Component #1 | Extra Component #2

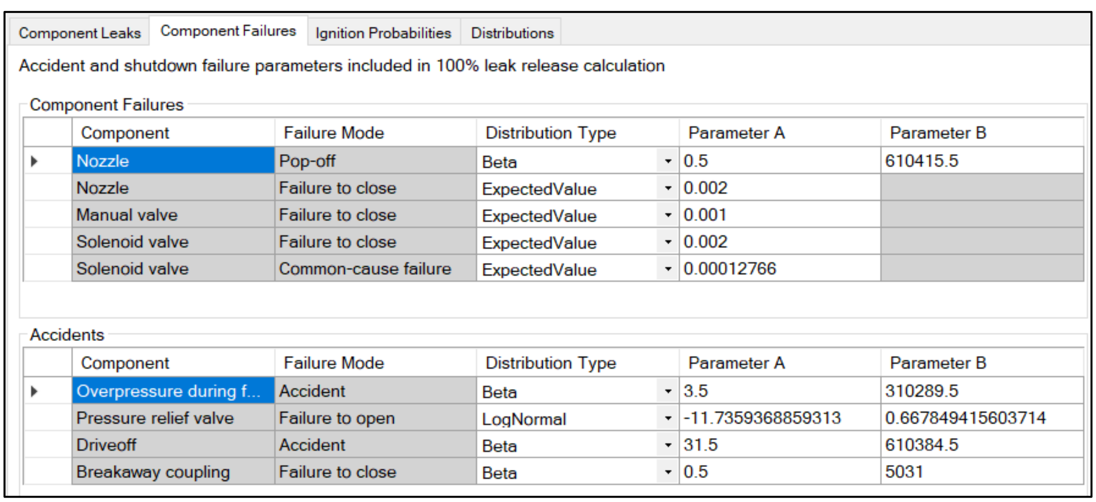
Leak Size	Mu	Sigma	Mean	Variance
0.01%	-1.7198	0.2143	1.83E-001	1.58E-003
0.10%	-3.9185	0.4841	2.23E-002	1.32E-004
1%	-5.1394	0.7898	8.01E-003	5.55E-005
10%	-8.8408	0.8381	2.06E-004	4.31E-008
100%	-11.3365	1.3689	3.04E-005	5.11E-009

Figure 20: Component Leaks Frequencies Input for Compressors

4.3.2. Component Failures

The Component Failures tab, depicted by Figure 21, contains generic hydrogen data about the likelihood of (non-leak) failure mechanisms of specific components, and about the likelihood of different accident-related events such as drive-offs (i.e. the event where the user "drives away" with the refueling station's nozzle still connected to the vehicle). It is important to note that the user can edit the Component Failures input values. These values are used in the calculation of the frequency of releases along with the vehicle demands as described in Section 4.1.2.2. Also, pressure relief valve (PRV) is the same as safety release valve 1 (SRV1) in Figure 10.

Note: For each different leak size there is a specific FT. But there is an additional FT for a 100% leak size which involves other accidental scenarios involving the system's dispenser. This section of the FT is emphasized because it involves not only a leak, but the possibility of a component failure and human error. It is important to include human error in the analysis because the dispenser is the part of the fueling station which involves the most frequent and direct interaction with the user.



Component Leaks | Component Failures | Ignition Probabilities | Distributions

Accident and shutdown failure parameters included in 100% leak release calculation

Component Failures

Component	Failure Mode	Distribution Type	Parameter A	Parameter B
Nozzle	Pop-off	Beta	0.5	610415.5
Nozzle	Failure to close	ExpectedValue	0.002	
Manual valve	Failure to close	ExpectedValue	0.001	
Solenoid valve	Failure to close	ExpectedValue	0.002	
Solenoid valve	Common-cause failure	ExpectedValue	0.00012766	

Accidents

Component	Failure Mode	Distribution Type	Parameter A	Parameter B
Overpressure during f...	Accident	Beta	3.5	310289.5
Pressure relief valve	Failure to open	LogNormal	-11.7359368859313	0.667849415603714
Driveoff	Accident	Beta	31.5	610384.5
Breakaway coupling	Failure to close	Beta	0.5	5031

Figure 21: Component Failures Input Window

4.3.3. *Ignition Probabilities*

The Ignition Probabilities tab is portrayed by Figure 22 and contains ignition probabilities associated with different release flow rate thresholds. The probabilities are associated with two ignition event classes: either that the gas ignites immediately (leading to a jet fire) or ignites with a delay (leading to an explosion).

The default input is based on published values for probabilities of hydrogen ignition cited in [4]. Users may input different values for **Immediate** and/or **Delayed Ignition Probabilities** for any of the defined release rates. Users may also add new release rate categories and remove the current categories.

To add a new **Ignition Flow Rate Threshold**, enter the value in the **kg/s box** and click the **Add** button. The addition of a new release rate requires the new input of ignition probabilities. To delete an Ignition Flow Rate Threshold, click on the value you want to delete in the Ignition Flow Rate Threshold box and click the **Delete** button.

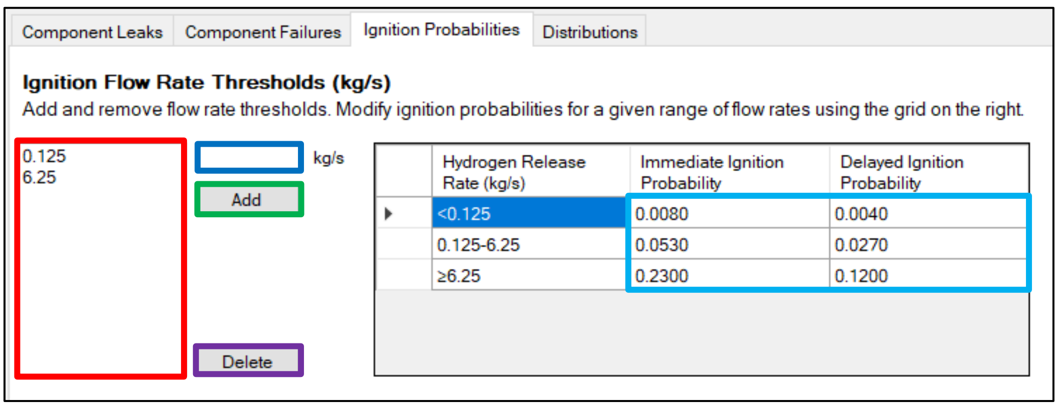
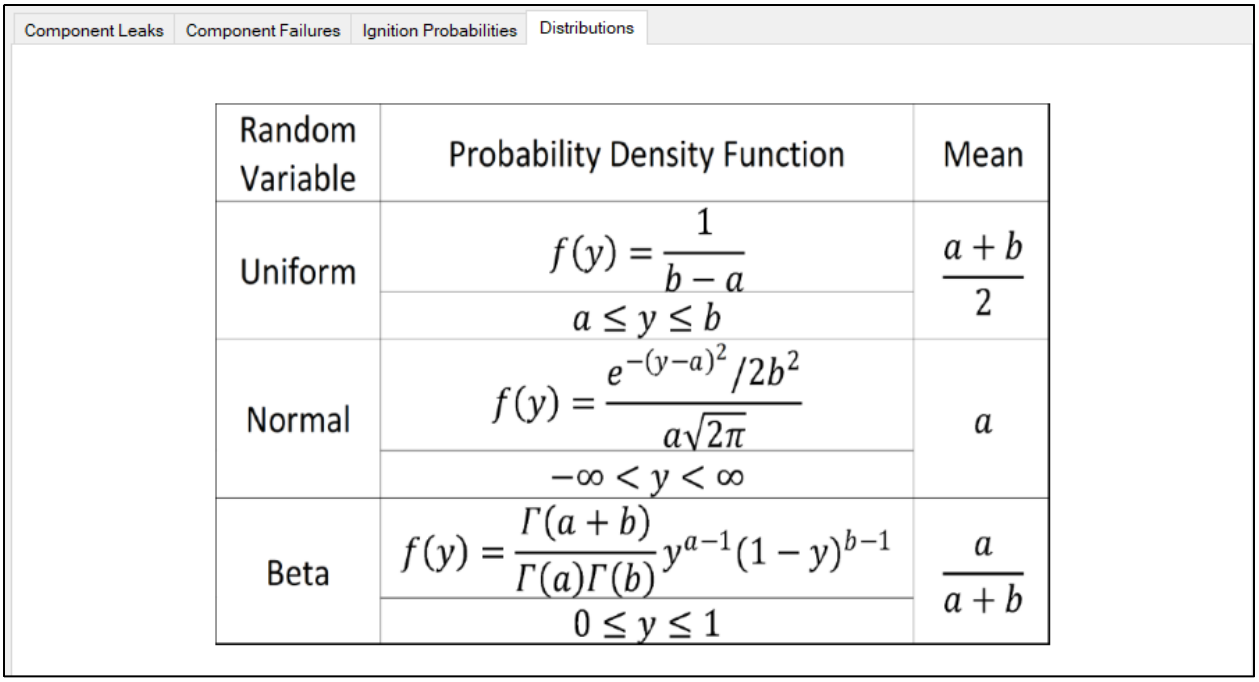


Figure 22: Ignition Probabilities Input

4.3.4. *Distributions*

The Distributions tab shows helpful information regarding how HyRAM understands each type of distribution available for the user. Each type can be described by a Random Variable with its Probability Density Function and Mean (shown in Figure 23**: Distributions Reference Tab**). This tab is included in the HyRAM GUI to provide the user with an explanation so that the user can select which is more appropriate for the user's analysis.



Random Variable	Probability Density Function	Mean
Uniform	$f(y) = \frac{1}{b-a}$ $a \leq y \leq b$	$\frac{a+b}{2}$
Normal	$f(y) = \frac{e^{-(y-a)^2}/2b^2}{a\sqrt{2\pi}}$ $-\infty < y < \infty$	a
Beta	$f(y) = \frac{\Gamma(a+b)}{\Gamma(a)\Gamma(b)} y^{a-1}(1-y)^{b-1}$ $0 \leq y \leq 1$	$\frac{a}{a+b}$

Figure 23: Distributions Reference Tab

4.4. Consequence Models

The Consequence Models window contains a selection of models used to calculate the physical effects of ignited releases and the probability of harm from a known physical effect.

4.4.1. Physical Consequence Models

The Physical Consequence Models tab contains input parameters for the Notional Nozzle Model, Deflagration Model, and Radiative Source Model as shown in Figure 24.

The default selections for physical effect models are the **Yuceil / Otugen** notional nozzle model, **Multiple radiation sources, integrated** radiative source model, and **Bauwens / Ekoto** deflagration model. The default options can be changed by selecting another option from the dropdown menus. Description of the different physical consequence models can be found in [1].

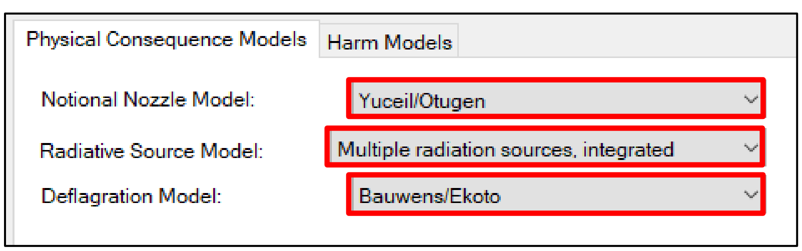


Figure 24: Physical Consequence Models Input

The Deflagration Model has two options: Bauwens / Ekoto and Computational Fluid Dynamics (CFD). The CFD model requires an **Input** of Peak Overpressure (the default units are Pa) and Impulse (always in units of pressure·seconds: Pa·sec for the default pressure units) for the five release (leak) size categories, depicted in Figure 25.

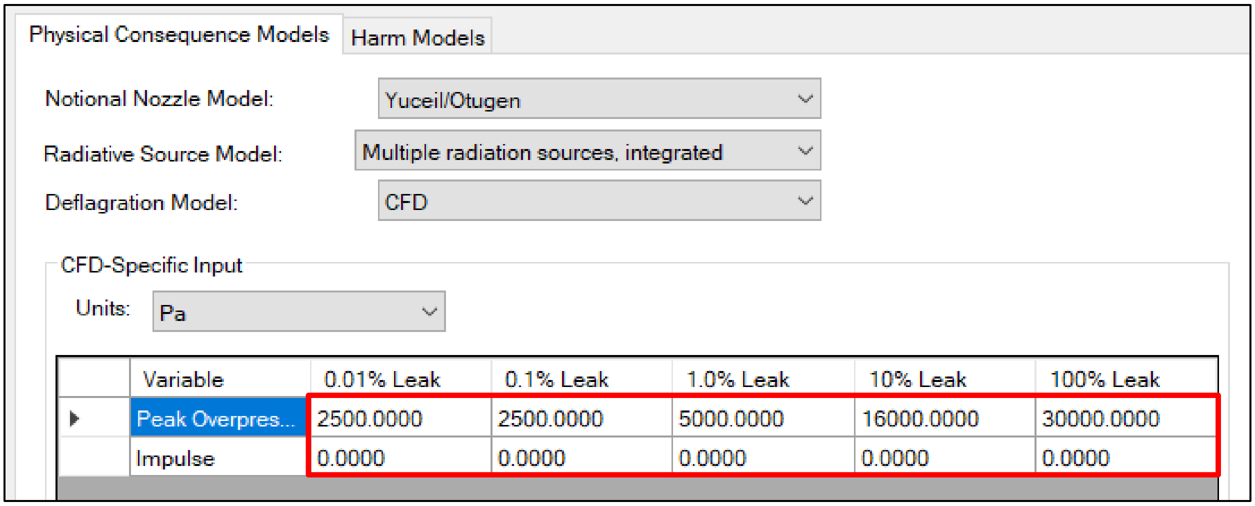


Figure 25: Physical Consequence CFD Model Input

4.4.2. Harm Models

The Harm Models tab, shown by Figure 26, contains the **Thermal Probit Model** and the **Overpressure Probit Model**. Users may select the preferred probit models by clicking the drop-down menu next to the model name. Input values for the **Thermal Exposure Time** can also be entered in the Thermal Probit section.

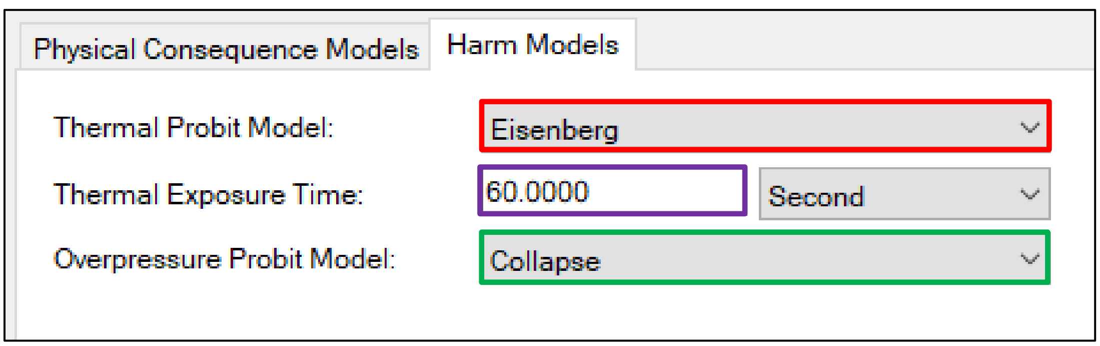


Figure 26: Harm Model Selection Window

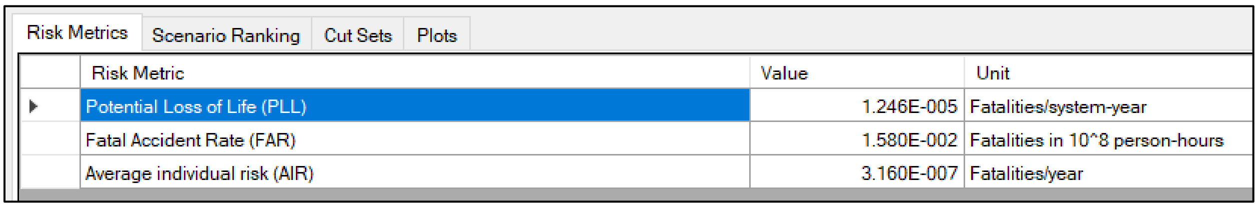
5. QRA MODE—OUTPUT

5.1. Scenario Stats

The Scenario Stats window output provides a single sheet divided into two sections: Risk Metrics, and the three tabs: Scenario Ranking, Cut Sets, and Plots, which are collectively called Importance Measures.

5.1.1. Risk Metrics

The Risk Metrics window contains the results of the calculated risk in terms of Potential Loss of Life (PLL), Fatal Accident Rate (FAR), and Average Individual Risk (AIR). Details of the risk metric calculations can be found in [1]. Based on preceding example, the Risk Metric output is portrayed by Figure *27*:



Risk Metric	Value	Unit
Potential Loss of Life (PLL)	1.246E-005	Fatalities/system-year
Fatal Accident Rate (FAR)	1.580E-002	Fatalities in 10^8 person-hours
Average individual risk (AIR)	3.160E-007	Fatalities/year

Figure 27: Risk Metrics Output

5.1.2. Scenario Ranking

The Scenario Ranking tab contains the end state types, frequencies, and potential loss of life (PLL) contribution for all release sizes. By default, the results are sorted by release size. These results can be sorted by any of the headings by clicking on the heading name (it is recommended to sort by Avg. Events/Year or by PLL Contribution). Based on the preceding example, Figure 28 shows the Scenario Ranking output tab.

Risk Metrics | Scenario Ranking | Cut Sets | Plots

	Scenario	End State Type	Avg. Events/Year	Branch Line Probability	PLL Contribution
▸	000.01% Release	Shutdown	0.0313728769	90.00000000%	0.00000000%
	000.01% Release	Jet fire	0.0000278870	0.08000000%	0.00000000%
	000.01% Release	Explosion	0.0000138320	0.03968000%	0.00000000%
	000.01% Release	No ignition	0.0034441563	9.88032000%	0.00000000%
	000.10% Release	Shutdown	0.0045062884	90.00000000%	0.00000000%
	000.10% Release	Jet fire	0.0000040056	0.08000000%	0.00000000%
	000.10% Release	Explosion	0.0000019868	0.03968000%	0.00000000%
	000.10% Release	No ignition	0.0004947064	9.88032000%	0.00000000%
	001.00% Release	Shutdown	0.0013532555	90.00000000%	0.00000000%
	001.00% Release	Jet fire	0.0000012029	0.08000000%	0.00000000%
	001.00% Release	Explosion	0.0000005966	0.03968000%	0.00000000%
	001.00% Release	No ignition	0.0001485622	9.88032000%	0.00000000%
	010.00% Release	Shutdown	0.0010615847	90.00000000%	0.00000000%
	010.00% Release	Jet fire	0.0000009436	0.08000000%	0.00000000%
	010.00% Release	Explosion	0.0000004680	0.03968000%	0.00000000%
	010.00% Release	No ignition	0.0001165422	9.88032000%	0.00000000%
	100.00% Release	Shutdown	0.0006921875	90.00000000%	0.00000000%
	100.00% Release	Jet fire	0.0000040762	0.53000000%	100.00000000%
	100.00% Release	Explosion	0.0000019665	0.25569000%	0.00000000%
	100.00% Release	No ignition	0.0000708670	9.21431000%	0.00000000%

Figure 28: Scenario Ranking Output

5.1.3. Cut Sets

The Cut Sets tabs, shown in Figure 29, represent the expected frequency of failure for each system component. Specifically, a Cut Set is the influence a component failure will have on a particular, potential leak size. This calculation takes into account the expected leak frequency for each leak size for each possible system component and weights these leak frequencies by the number of those specific components in the system. These calculations can tell the user which component is more likely to contribute to a leak of a particular size. This can provide insight to decision-makers on whether to limit the usage of particular components to minimize leaks.

Risk Metrics | Scenario Ranking | Cut Sets | Plots

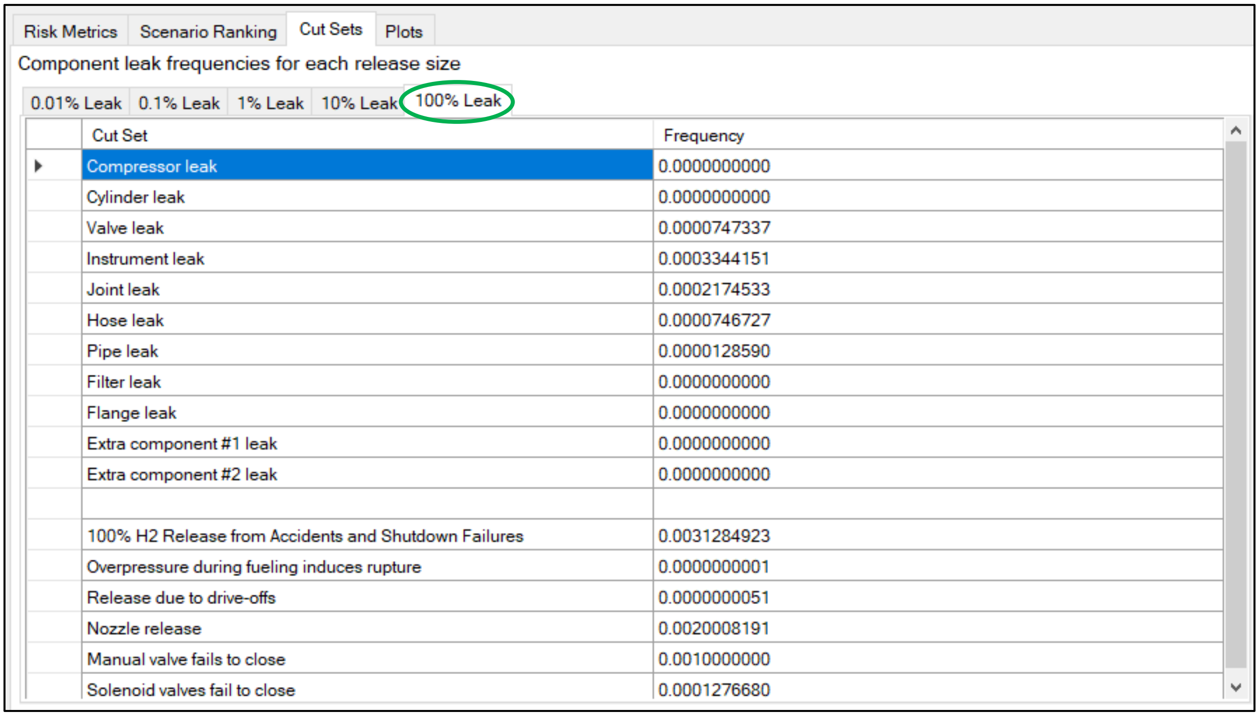
Component leak frequencies for each release size

0.01% Leak | 0.1% Leak | 1% Leak | 10% Leak | 100% Leak

	Cut Set	Frequency
▸	Compressor leak	0.0000000000
	Cylinder leak	0.0000000000
	Valve leak	0.0285747400
	Instrument leak	0.0024944924
	Joint leak	0.0024662988
	Hose leak	0.0011475404
	Pipe leak	0.0001756806
	Filter leak	0.0000000000
	Flange leak	0.0000000000
	Extra component #1 leak	0.0000000000
	Extra component #2 leak	0.0000000000

Figure 29: Cut Sets Output Tab

Make note that the Cut Sets tabs for a 100% leak size has more information as an output due to its expanded FT.



Risk Metrics | Scenario Ranking | Cut Sets | Plots

Component leak frequencies for each release size

0.01% Leak | 0.1% Leak | 1% Leak | 10% Leak | 100% Leak

Cut Set	Frequency
Compressor leak	0.0000000000
Cylinder leak	0.0000000000
Valve leak	0.0000747337
Instrument leak	0.0003344151
Joint leak	0.0002174533
Hose leak	0.0000746727
Pipe leak	0.0000128590
Filter leak	0.0000000000
Flange leak	0.0000000000
Extra component #1 leak	0.0000000000
Extra component #2 leak	0.0000000000
100% H2 Release from Accidents and Shutdown Failures	0.0031284923
Overpressure during fueling induces rupture	0.0000000001
Release due to drive-offs	0.0000000051
Nozzle release	0.0020008191
Manual valve fails to close	0.0010000000
Solenoid valves fail to close	0.0001276680

Figure 30. Cut Sets 100% Leak Size Output Tab.

5.1.4. *Plots*

Plots tab generates visual representations of the Radiative Heat Flux that system occupants may experience while in the presence of varying hydrogen leak sizes. The Radiative Heat Flux sustained by the occupants may serve as an indication of potential harm associated with the scenario. The parameters of the generated plots can be altered through the HyRAM QRA mode inputs. The facility in the following example uses the parameters set in the previous input examples with length and width facility dimensions of 100 meters, however, the Occupants tab was altered to demonstrate the Plots tab functionality. The Occupants tab within Facility Parameters of the System Description will allow the user to set the plot locations of facility occupants relative to a hydrogen leak.

In Figure 31, there are 9 occupants in the facility with Uniform X Location Distribution A and B Parameters set to 1 and 20 meters, respectively, to represent the length at which the occupants may be in the plot. The width that the facility occupants may be located is represented by the Uniform Z Location Distribution A and B Parameters set to 1 and 12 meters (see Section 4.1.3.2). The height from the ground at which the facility occupants would experience heat flux, relative to the hydrogen leak, was set at a Deterministic Y Location Distribution A Parameter of 1 meter. The time that occupants are exposed to a potential hydrogen leak per year was set to 2000 hours. After the user clicks on Scenario Stats to generate data, they have the option to choose plots with varying hydrogen leak diameter sizes. In this example, the leak size is 0.062 mm:

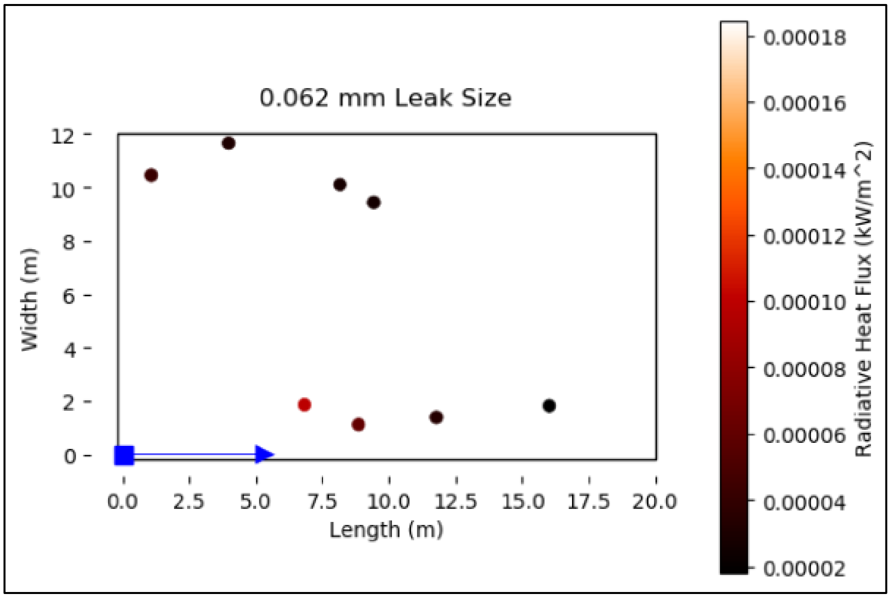


Figure 31: Plots Tab Output

The blue square in the corner of the generated facility plot represents the 0.062 mm hydrogen leak while the blue line on the bottom, x-axis, is the jet centerline of the hydrogen leak. The dots represent locations of the 9 facility occupants and respective dot colors indicate the radiative heat flux (in kW/m^2) that those facility occupants would experience relative to their locations to the hydrogen leak.

Note: In Figure 31: Plots Tab Output, there seems to be only eight dots, even though there are 9 occupants. This is because one of the dots is white, as in the occupant is experiencing high heat flux. Resulting in a dot being “camouflaged” with the background.

6. PHYSICS MODE

The physics models are intended to be stand-alone hydrogen behavior consequence models. Running models in physics mode does not impact the QRA mode models. At present, the physics models are all for gaseous hydrogen, but Sandia is looking to expand to liquid consequence models in the near future.

6.1. Gas Plume Dispersion

The Gas Plume Dispersion window contains variables that calculate the characteristics of a gaseous hydrogen plume. Before clicking the Calculate button located at the bottom right of the window, the user should input values in the Plot Properties, Standard, and Advanced tabs.

6.1.1. Gas Plume Dispersion Input

The Gas Plume Dispersion Input tab, depicted by Figure 32, contains the characteristics of the output plot for the gaseous hydrogen plume. The user can alter the Plot Title, as well as distinct environment and physical conditions **Inputs** to generate the appropriate plume characteristics.

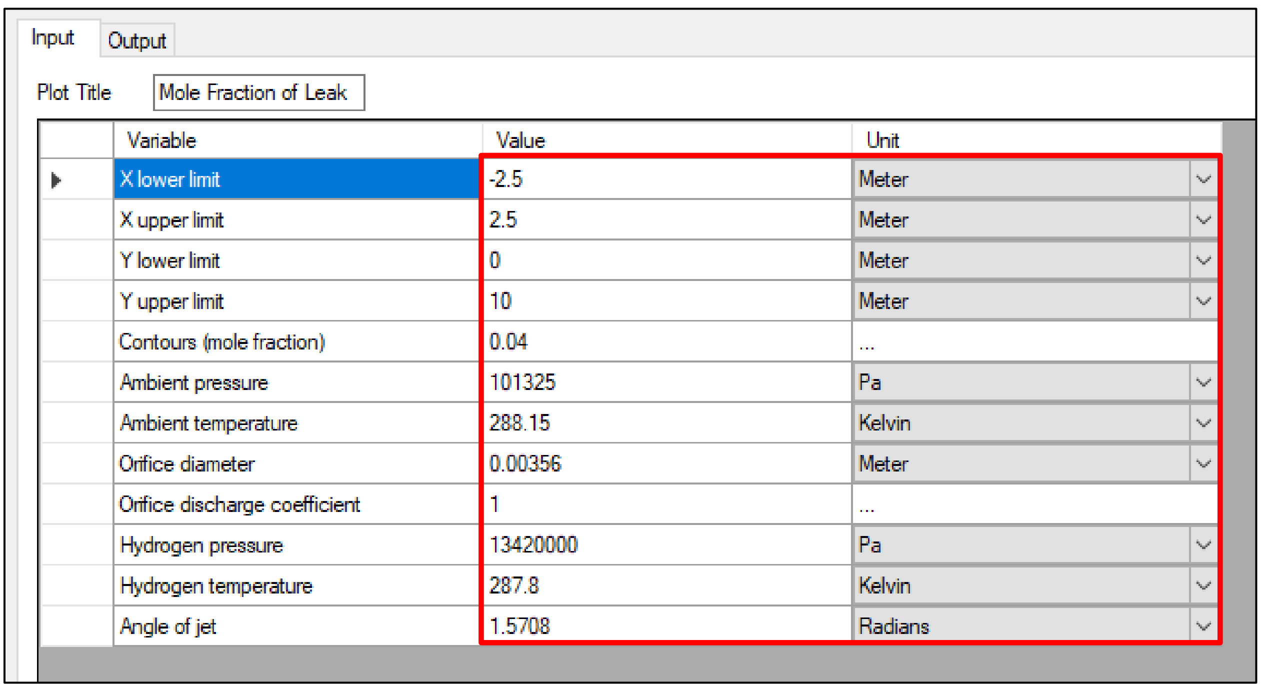


Figure 32: Plot Properties Input

To generate the Output plot, click the Calculate button located at the bottom right of the window.

6.1.2. Gas Plume Dispersion Output

Figure 33 shows the Gas Plume Dispersion Output based on the preceding example.

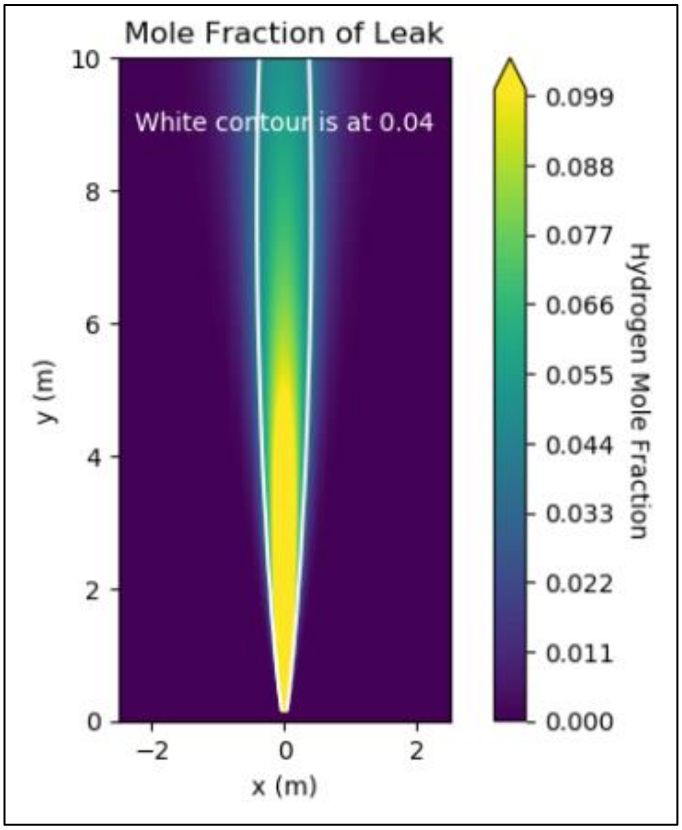


Figure 33: Gas Plume Dispersion Output

If the user wishes to save the output, click the Save Plot button located at the bottom right of the window.

6.2. Overpressure

6.2.1. Indoor Release Parameters

The Indoor Release Parameters tab contains measurements to calculate the accumulation of the storage system following an indoor release. The default window for the Indoor Release Parameters tab is shown below. A general sketch is provided to the right of the variable inputs to help the user visualize the enclosure and identify the variables related to the enclosure and the release. Once the user has entered all **Inputs** and selected the desired Output Options (see Section 6.2.2), then the user must click the **Calculate** button to produce the Overpressure Output, as shown in Figure 34.

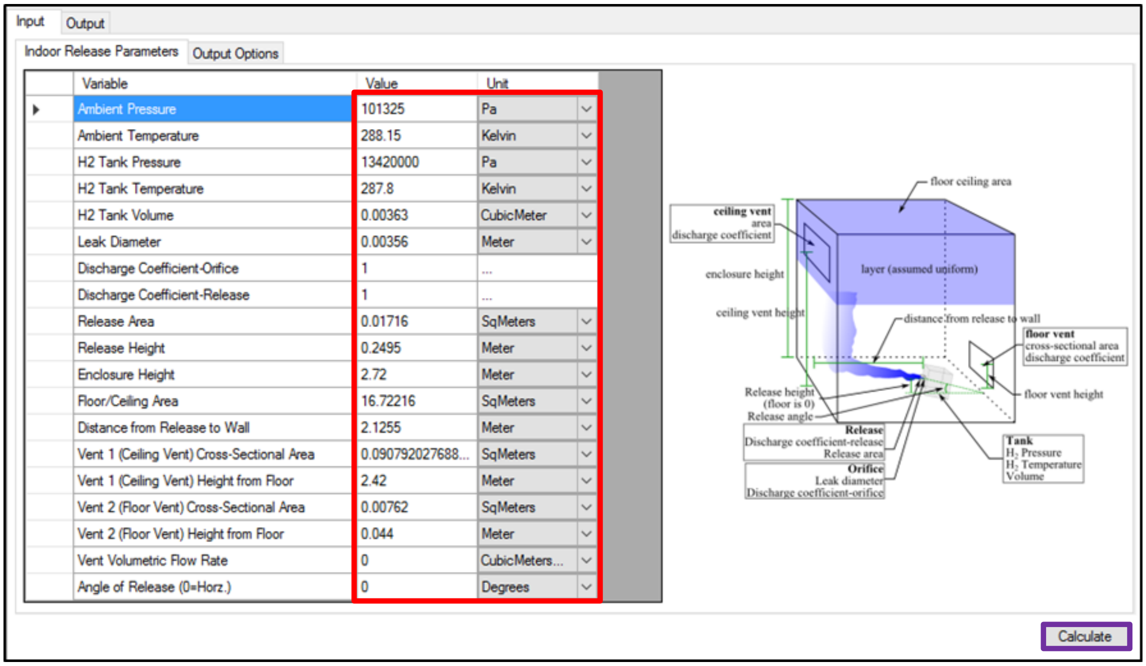


Figure 34: Indoor Release Parameters Input

6.2.2. *Output Options*

The Output Options tab, portrayed by Figure 35, allows the user to specify **Times** for calculating pressure, specify the **Maximum Time** for overpressure data generation, specify **Pressures** to be drawn across the plot with a horizontal line, and place dots where **Pressure** and **Time** intersect. After providing input parameters, the user must click **Calculate** (as shown in Figure 34) in the bottom right corner of the input window to produce the output.

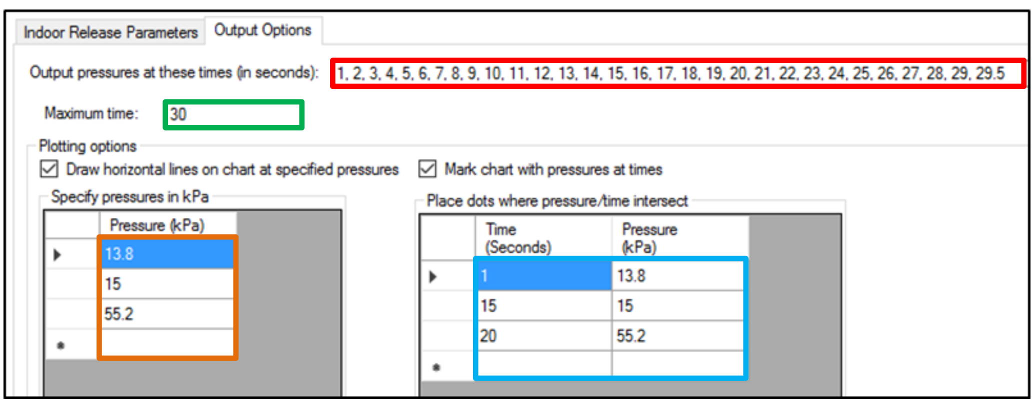


Figure 35: Output Options Input

6.2.3. *Overpressure Output*

The Output tab contains a Pressure plot, Flammable Mass plot, Layer plot, and Data table for those plots. Based on the default inputs, the Pressure plot is shown by Figure 36.

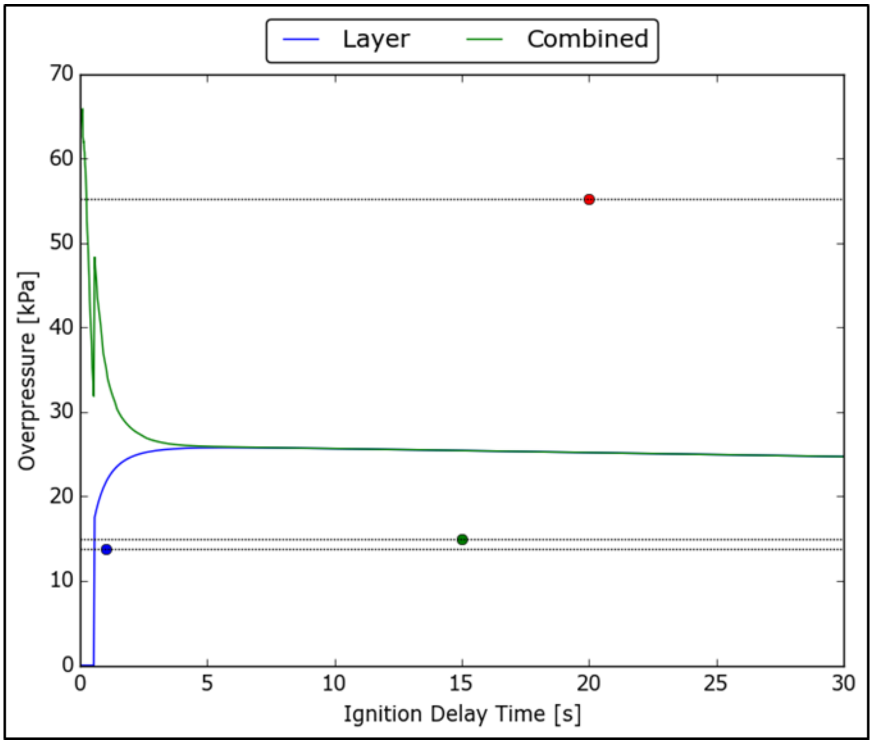


Figure 36: Overpressure Output Pressure Plot

In the Overpressure plot, the Layer line represents the overpressure that would develop if the accumulated layer were ignited. The Combined plot line represents the overpressure that would develop if both the layer and the gas plume were to be ignited. The pressures specified in Section 6.2.2 (13.8 kPa, 15 kPa, and 55.2 kPa) are also shown on this plot. If the user wishes to save the output, click the Save Plot button located at the bottom right of the window.

Figure 37 shows the Flammable mass plot based on default inputs.

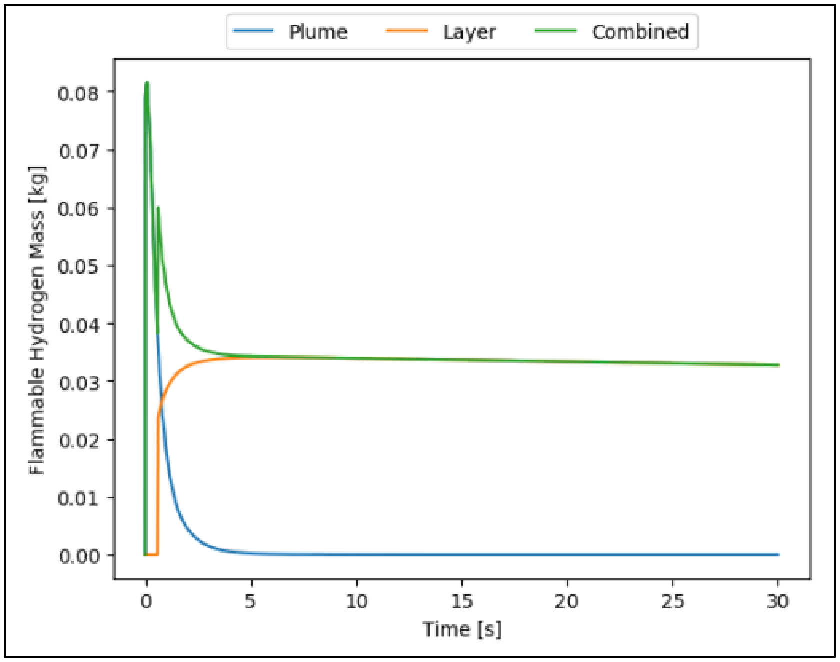


Figure 37: Overpressure Output Flammable Mass Plot

The Flammable Mass Plot shows the amount of hydrogen that exists in a flammable concentration over the time-period of interest. This includes both the accumulated layer as well as the plume from the leak; also plotted is the combined flammable mass that combines the flammable masses from both the layer and the plume.

Figure 38 shows the Layer plot based on the default inputs.

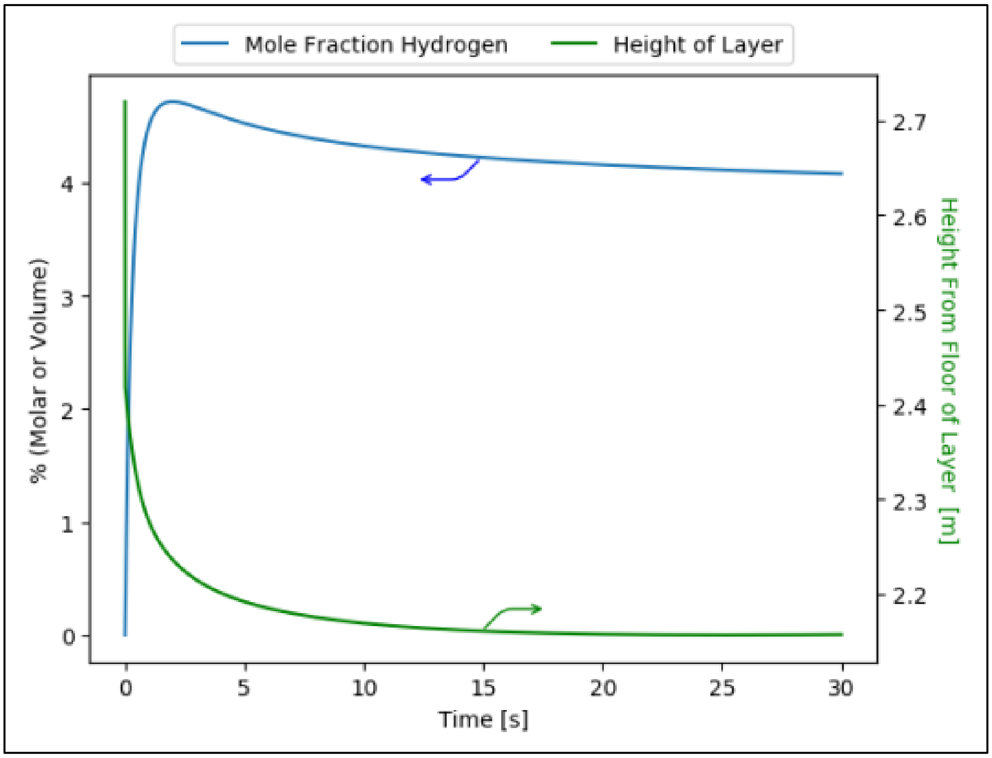


Figure 38: Overpressure Output Layer Plot

The Height of Layer represents the height of the hydrogen layer that develops above the floor. At 30 seconds, the hydrogen layer height is about 2.175 m above the floor and extends to the top of the enclosure. The hydrogen mole fraction of this layer is represented by the left vertical axis % (Molar or Volume). At 30 seconds, the hydrogen mole fraction is about 4%. It is assumed that at any point in space within the hydrogen layer, the hydrogen mole fraction is represented by % (Molar or Volume); i.e., the hydrogen mole fraction from 2.175 m to 2.72 m (height of enclosure) is 4% at 30 seconds.

Furthermore, in the Pressure plot (Figure 36), overpressure is non-zero from 0 seconds to 30 seconds. Comparing this time range to the Layer plot above, we see that the hydrogen mole fraction is greater than or equal to the lower flammable limit of hydrogen (χ_{H_2}= 0.04) in this timeframe. To save the output, the user must click the Save Plot button located at the bottom right of the window.

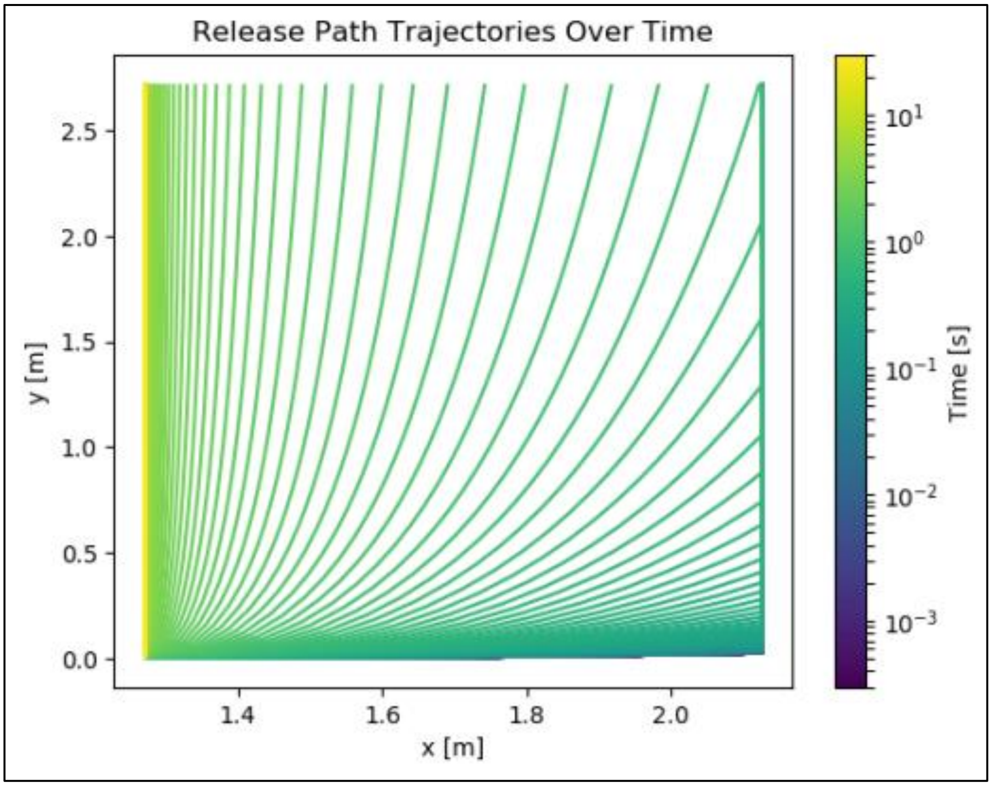


Figure 39: Overpressure Output Trajectory Plot

The Trajectory plot shows the hydrogen leak jet plume's travel trajectories over time, dark blue indicating moments early in the blowdown, and yellow later on in the duration. User-defined parameters (see Figure 34: Indoor Release Parameters Input) will influence how the jet plume will behave, specifically whether the plume will be momentum-dominant or buoyancy-dominant, and how the transition occurs on the interval of time as the hydrogen depletes from the tank.

Figure 40 shows the Data tab output based on default inputs.

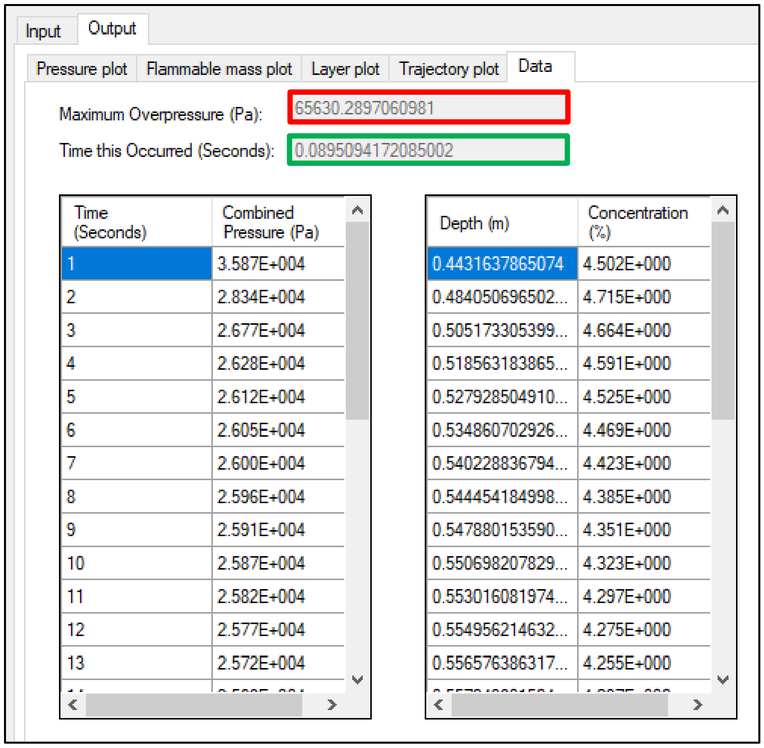


Figure 40: Overpressure Output Data

The units for Pressure and Time are Pa and seconds, respectively. The pressure data in the first table represents the overpressure of the combined plot in Figure 36. The concentration data in the second table represents the % (Molar or Volume) amounts given in the Layer Plot. In addition to the tabulated data, the **Maximum Overpressure (Pa)** and **Time this Occurred (Seconds)** are provided in the Data tab, as shown in Figure 40.

6.3. Jet Flame

Jet Flame contains two windows: Flame Temperature/Trajectory and Radiative Heat Flux.

6.3.1. Flame Temperature/Trajectory

The Flame Temperature/Trajectory window contains the variables that calculate behavior of a jet flame, including flame temperature, direction, and heat flux. A hydrogen system in a warehouse has been modeled with flame and trajectory results based on the Notional Nozzle Model **Yuceil / Otugen** with **Input** parameters shown in Figure 41.

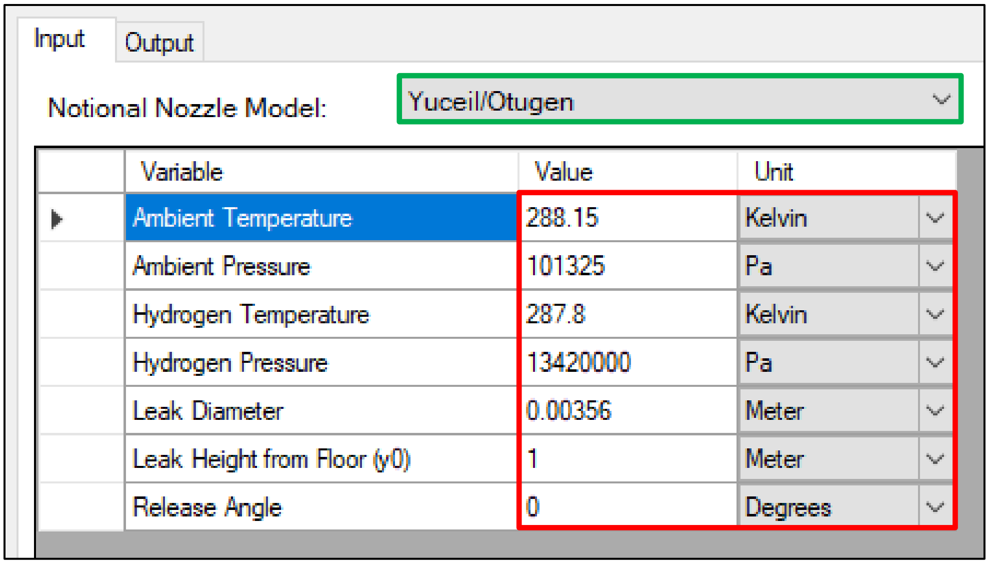


Figure 41: Flame Temperature/Trajectory Input

To generate the Output plot, the user must click the Calculate button located at the bottom right of the window. Based on the preceding example, the Flame Temperature/Trajectory output is shown by Figure 42.

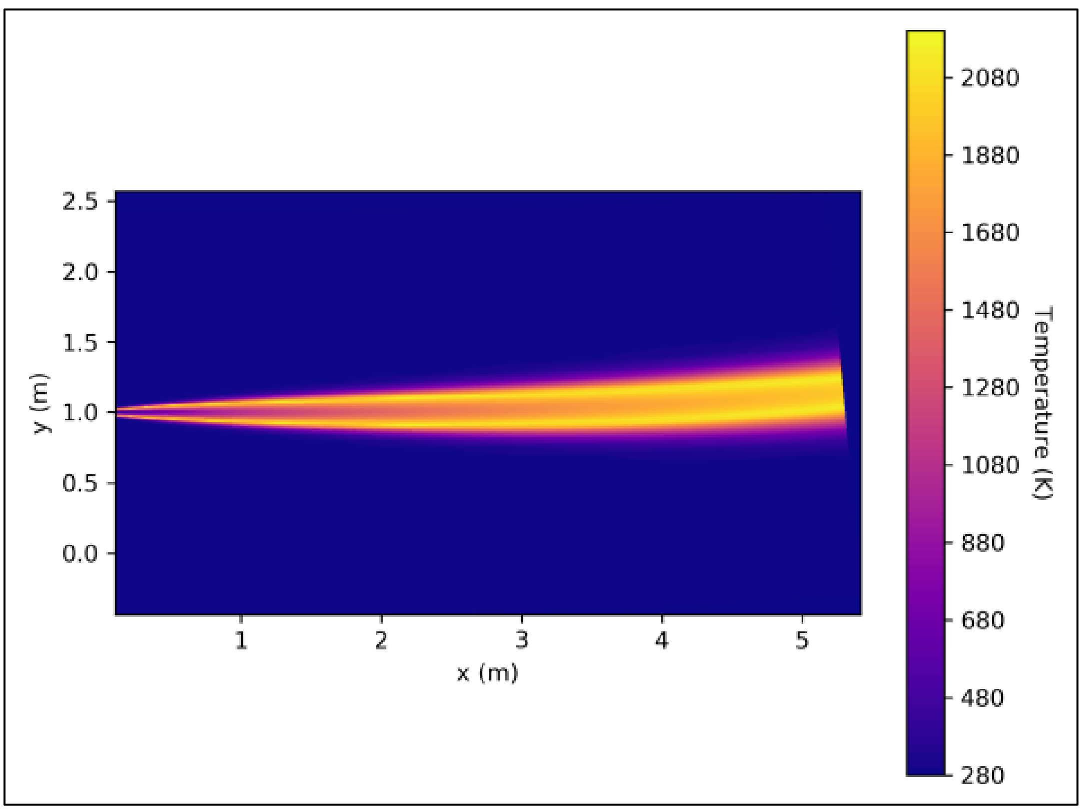


Figure 42: Flame Temperature/Trajectory Output

If the user wishes to save the output, click the Save Plot button located at the bottom right of the window.

6.3.2. Radiative Heat Flux

The Radiative Heat Flux window contains the variables that calculate radiative heat flux values, the respective plot, and the temperature plot.

The user can specify both **Notional Nozzle** and **Radiative Source Models**, provide **Input Parameters**, and determine the coordinates where the radiative heat flux is calculated by entering values in **X Radiative Heat Flux Points (m)**, **Y Radiative Heat Flux Points (m)**, and **Z Radiative Heat Flux Points (m)**. For reference, a general sketch of the jet flame is provided to the right of the variable inputs to help the user visualize the coordinate system with respect to the flame and identify the variables related to the jet flame. The user also specifies the desired radiative heat flux **Contour Levels (kW/m^2)** corresponding to desired harm criteria to be plotted. Based on the preceding example, with the default relative humidity of 0.89 and Radiative Heat Flux Points, the Radiative Heat Flux Input is displayed in Figure 43.

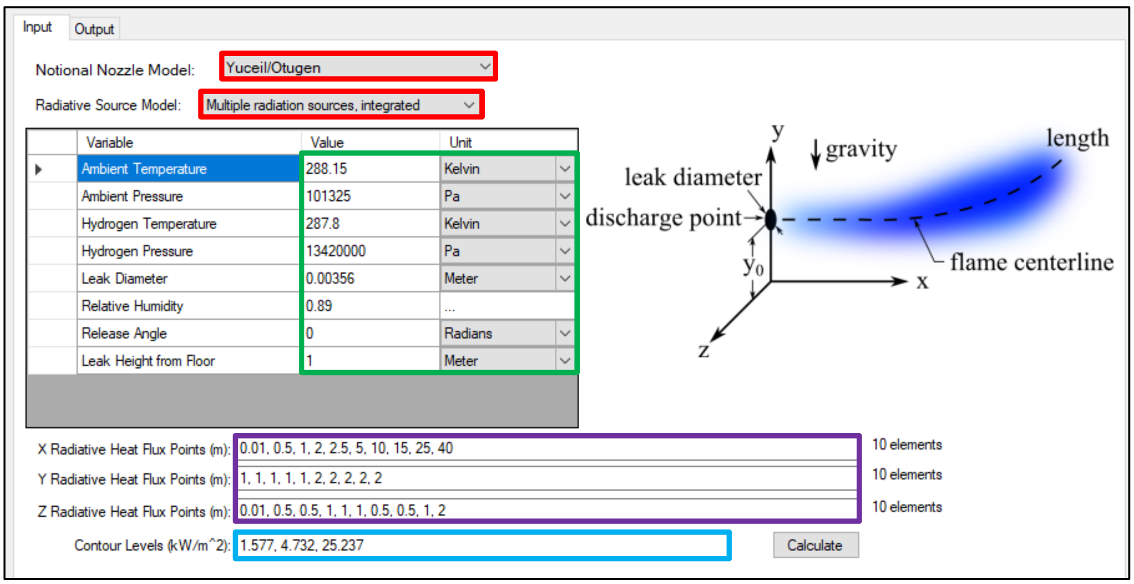
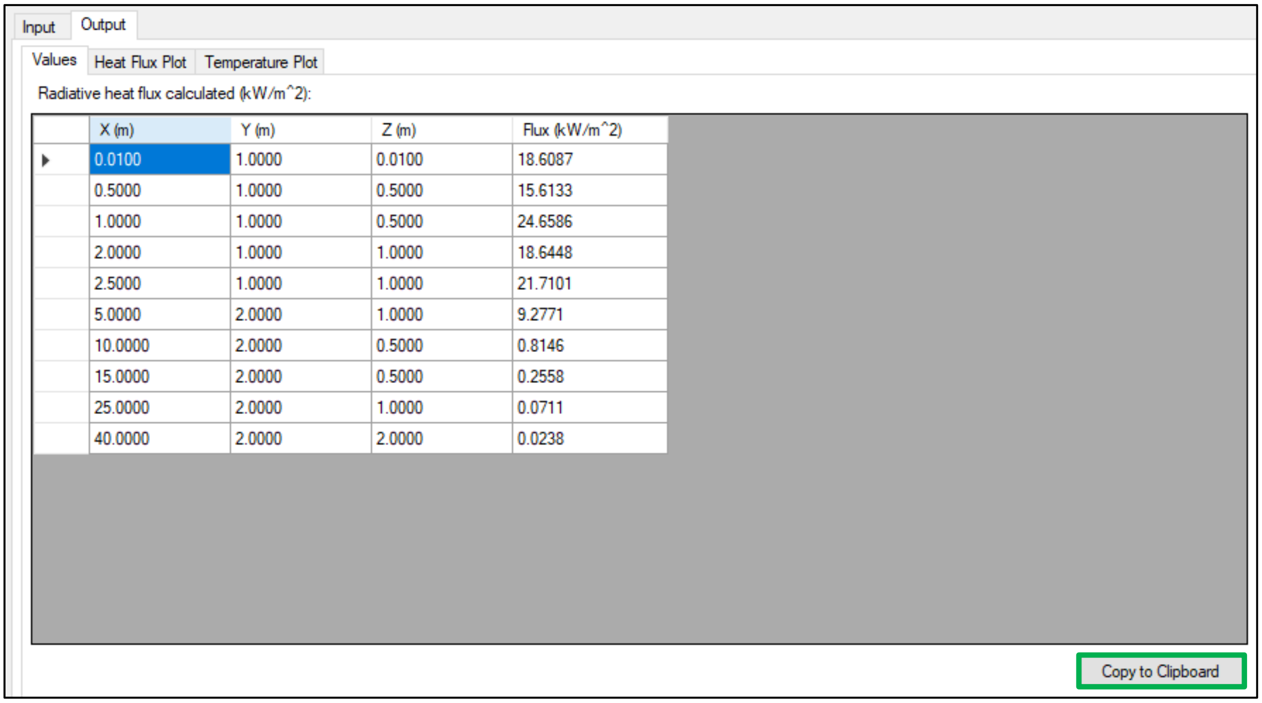


Figure 43: Radiative Heat Flux Input

Based on the preceding example, the Radiative Heat Flux output values are shown by Figure 44.



Input | Output

Values | Heat Flux Plot | Temperature Plot

Radiative heat flux calculated (kW/m^2):

X (m)	Y (m)	Z (m)	Flux (kW/m^2)
0.0100	1.0000	0.0100	18.6087
0.5000	1.0000	0.5000	15.6133
1.0000	1.0000	0.5000	24.6586
2.0000	1.0000	1.0000	18.6448
2.5000	1.0000	1.0000	21.7101
5.0000	2.0000	1.0000	9.2771
10.0000	2.0000	0.5000	0.8146
15.0000	2.0000	0.5000	0.2558
25.0000	2.0000	1.0000	0.0711
40.0000	2.0000	2.0000	0.0238

Copy to Clipboard

Figure 44: Radiative Heat Flux Values Output

The table provides the radiative heat flux calculated at the user specified positions (see Figure 43). By clicking the **Copy to Clipboard** button, the table is copied and can be pasted into another program, such as Microsoft Excel. The Radiative Heat Flux Plot output is depicted in Figure 45.

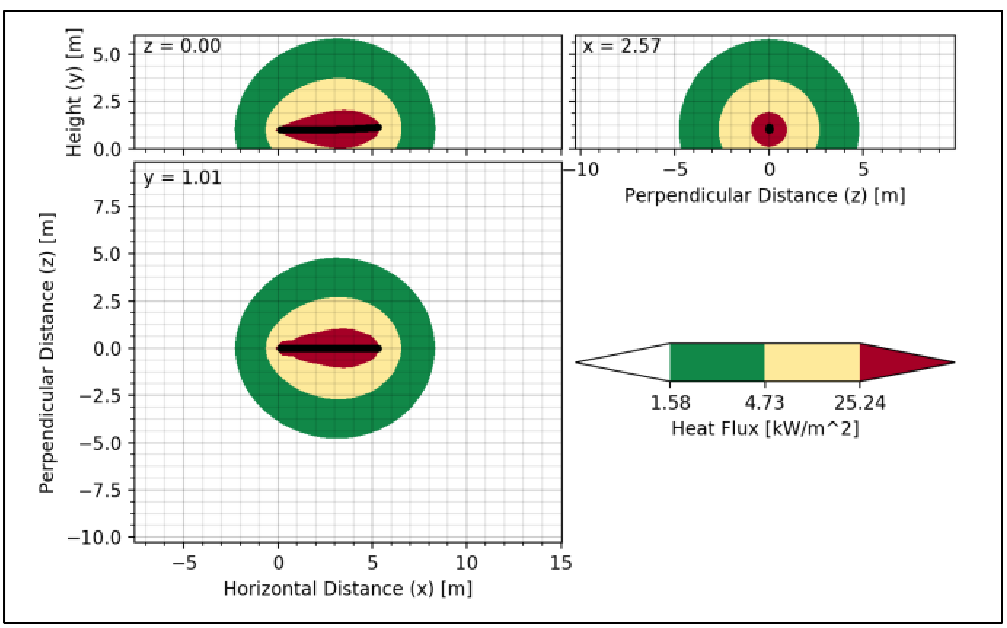


Figure 45: Radiative Heat Flux Plot

Presented in Figure 45 are three radiative heat flux 2-D plots that corresponds to the jet flame: a side view (top left), a front view (top right), a top view (bottom left), and a legend. The images show surfaces at which radiative heat flux is greater than or equal to the user specified contour levels (see Figure 43). To save the output, the user must click the Save Plot button located at the bottom right of the window.

The Radiative Heat Flux Temperature Plot output is shown by Figure 46.

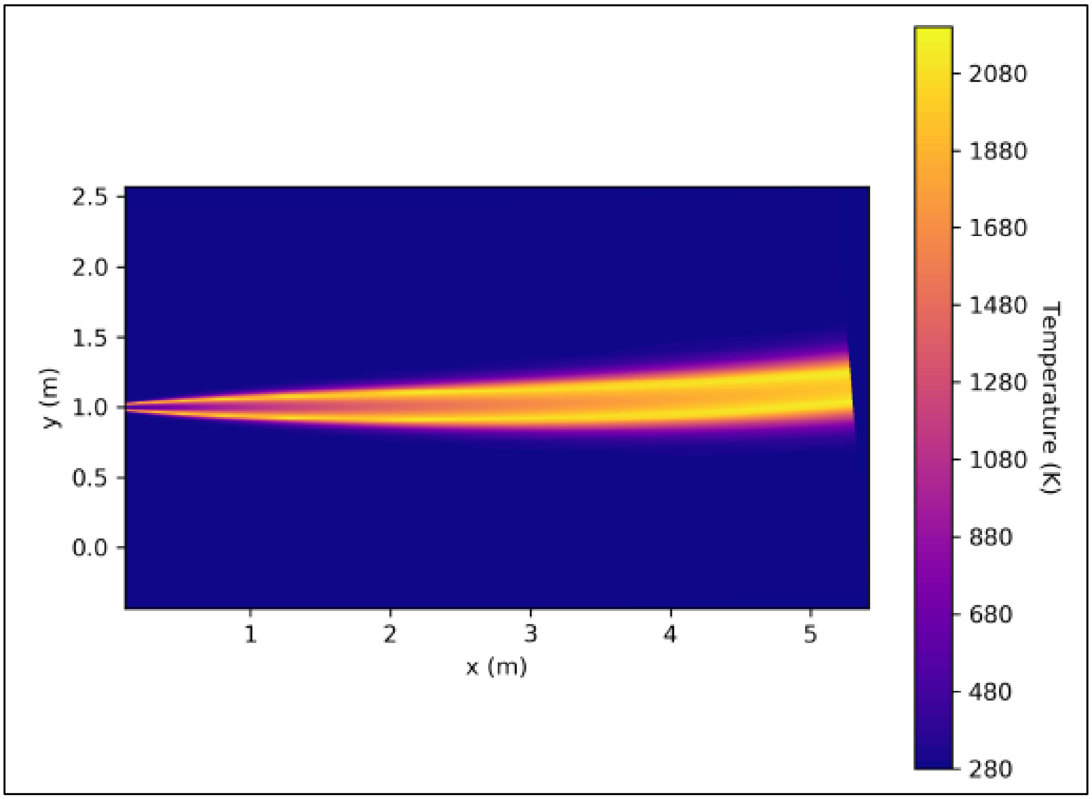


Figure 46: Radiative Heat Flux Temperature Plot

7. REFERENCES

1. Groth KM, Hecht ES, Reynolds JT, Blaylock ML, Carrier EE. Methodology for assessing the safety of Hydrogen Systems: HyRAM 1.1 Technical Reference Manual. Albuquerque, NM: Sandia National Laboratories, 2017 March. Report No.: SAND2017-2998.
2. Groth KM, Zumwalt HR, Clark AJ. HyRAM V1.0 User Guide. Albuquerque, NM: Sandia National Laboratories, 2016 March. Report No.: SAND2016-3385.
3. Groth KM, LaChance JL, Harris AP. Early-Stage Quantitative Risk Assessment to Support Development of Codes and Standard Requirements for Indoor Fueling of Hydrogen Vehicles. Albuquerque, NM: Sandia National Laboratories, 2012 November. Report No.: SAND2012-10150.
4. LaChance J, Houf W, Middleton B, Fluer L. Analyses to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards. Sandia National Laboratories, 2009 March. Report No.: SAND2009-0874.

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