HyRAM V1.0 User Guide

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Abbreviations

AIR	Average Individual Risk
CFD	Computational Fluid Dynamics
ESD	Event Sequence Diagram
FAR	Fatal Accident Rate
FCTO	Fuel Cell Technologies Office
FT	Fault Tree
HyRAM	Hydrogen Risk Assessment Models
NFPA	National Fire Protection Association
P&ID	Piping and Instrumentation Diagram
PLL	Potential Loss of Life
QRA	Quantitative Risk Assessment

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1. INTRODUCTION

1.1. What is HyRAM?

Hydrogen Risk Assessment Models (HyRAM) is a prototype software toolkit that integrates data and methods relevant to assessing the safety of hydrogen fueling and storage infrastructure. The HyRAM toolkit integrates 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. HyRAM version 1.0 incorporates generic 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.

HyRAM is a software prototype being developed by Sandia National Laboratories for the U.S. Department of Energy's (DOE) Fuel Cell Technologies Office (FCTO).

1.2. Purpose of this Guide

This document provides an example of how to use HyRAM to conduct analysis of a 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. Description of the methodology and models contained in HyRAM is provided in [1].

This User's Guide is intended to capture the main features of HyRAM version 1.0 (any HyRAM version numbered as 1.0.X.XXX). This user guide was created with HyRAM 1.0.1.798. Due to ongoing software development activities, newer versions of HyRAM may have differences from this guide.

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, Fuel Cell Technologies Office. HyRAM 1.0 is available as a free executable download from hyram.sandia.gov. After download users must also request a free product registration key via email.

HyRAM was designed to be installed on any 32-or-64-bit Intel-compatible computer with more than 4GB/RAM and 4GB free persistent storage (hard drive space), running Microsoft Windows 98 or later.

The intended users are experienced safety professionals and researchers who are familiar with the modeling assumptions, limitations, and interpretation of QRA and consequence models.

1.4. HyRAM License Terms

2. BASIC FUNCTIONS

2.1. Save/Load Workspace

The Save/Load Workspace can be found in the File menu at the top left corner of the program window. The Save Workspace button functions as a “Save As” button. To save a workspace and the resulting data, click the Save Workspace option. To load a workspace that has been previously saved, click the Load Workspace option.

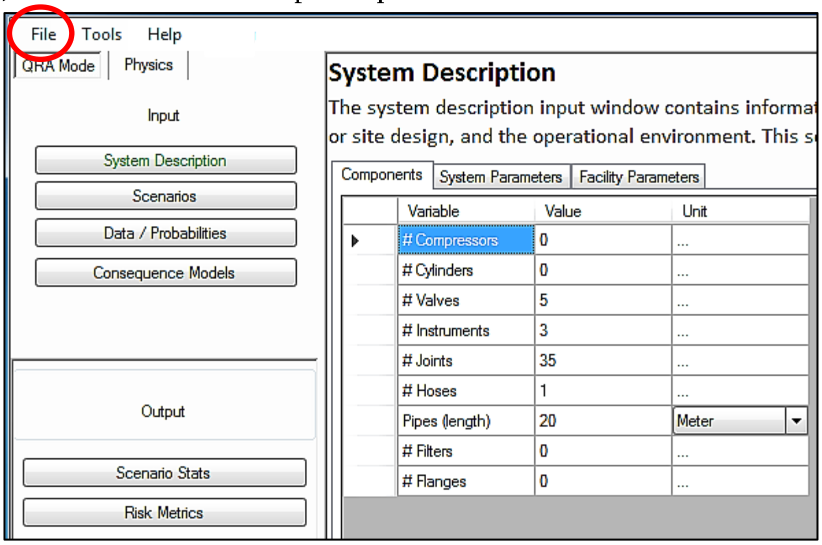


Figure 1 - Save/Load Workspace

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.

2.2.1. Engineering Toolkit

The user can also utilize the Engineering Toolkit under Tools to determine some parameters of a given system. Other tabs are available under Tools as will be discussed in the following sections.

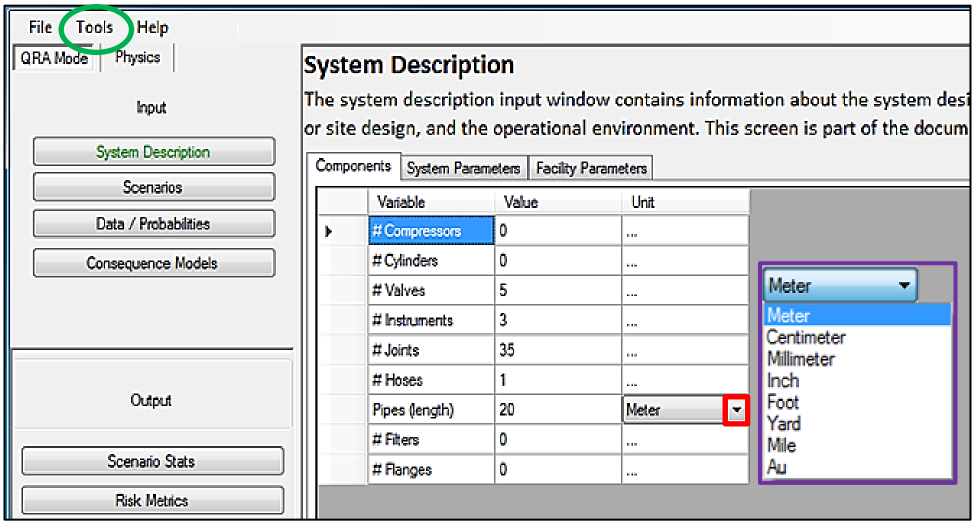


Figure 2 - Changing Units

The Engineering Toolkit has three tabs to determine various quantities: Temperature, Pressure and Density; Tank Mass; and Mass Flow Rate. 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 the following example, 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.

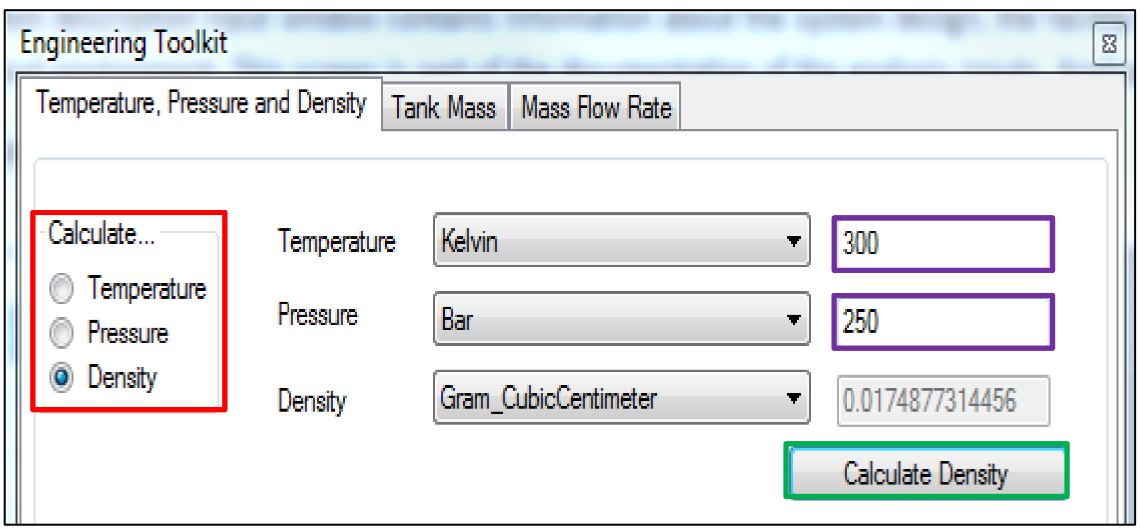


Figure 3 - Example calculation for Temperature, Pressure and Density tab.

The Tank Mass tab determines the mass of hydrogen inside a given tank. The user supplies inputs for the Temperature, Pressure, and Volume. In the example below, 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.

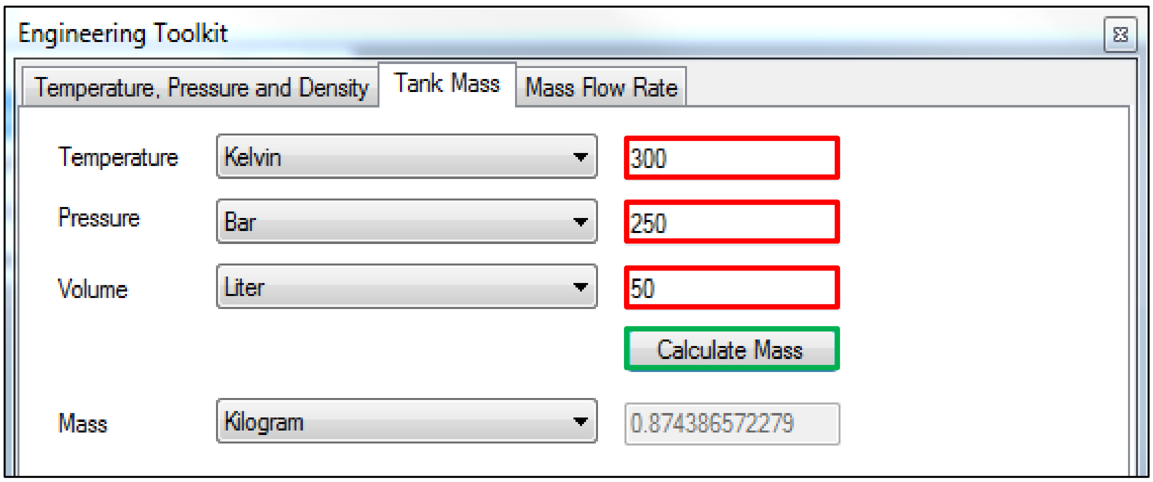


Figure 4 - Example calculation for hydrogen mass in Tank Mass tab.

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 4, 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 Flow Rate button. In the following example, the orifice diameter is 1 mm and the release type is a blowdown, in addition to the values provided in Figure 4.

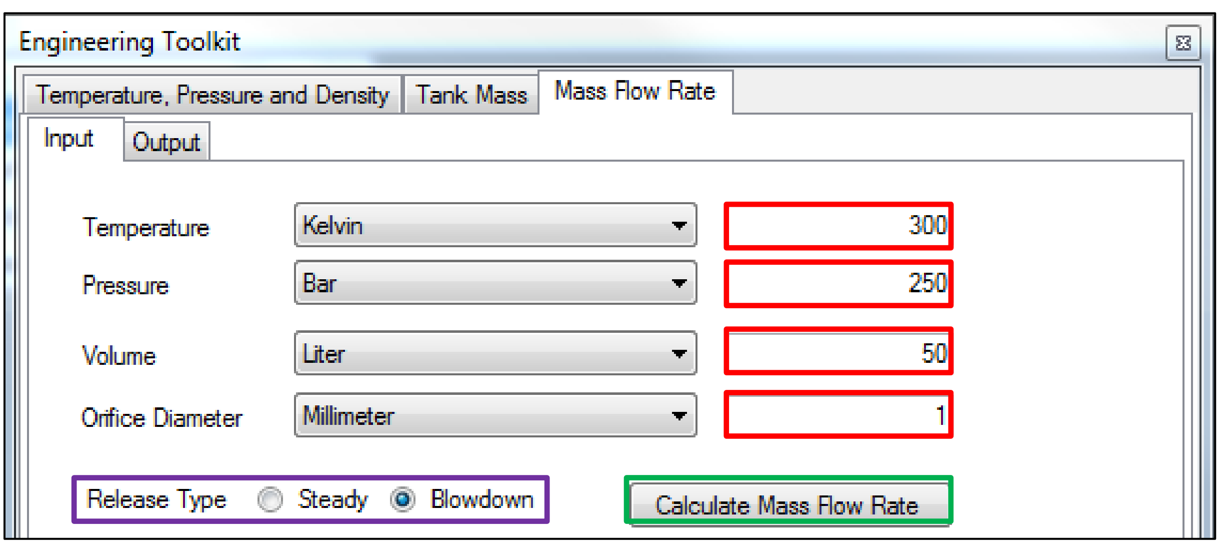


Figure 5 - Example Input for Mass Flow Rate tab.

When the user clicks Calculate Mass Flow Rate button, the screen will change to the output tab. The Output tab is shown below, with the Time to Empty (seconds) equal to 480.8 seconds. The user may also select to save an image of the plot by clicking Save Plot.

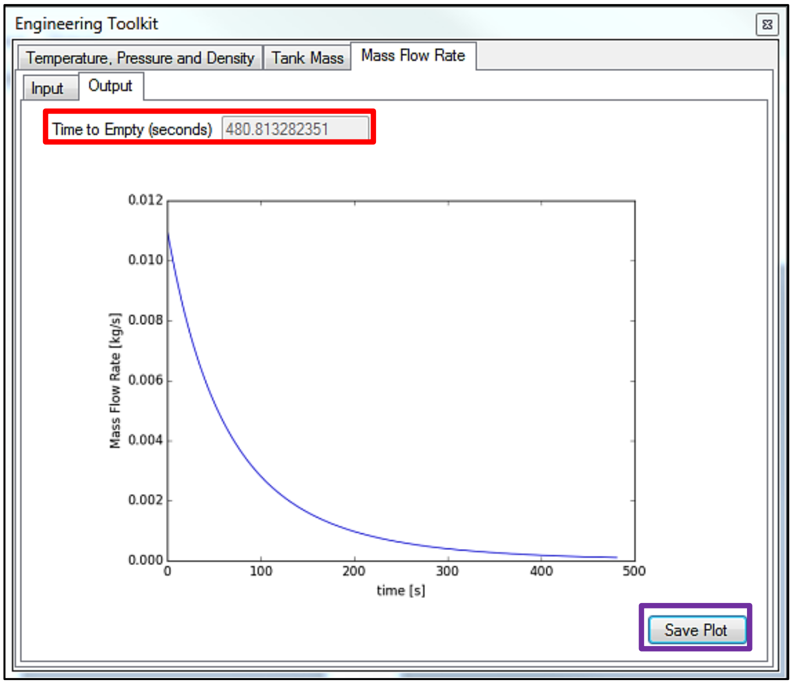


Figure 6 - Mass Flow Rate Output tab.

2.2.2. Reset All Defaults and Inputs to Zero

Warning: This feature is not yet active (in HyRAM version 1.0.1.798).

2.2.3. QRA Master Input Editor

Quantitative Risk Assessment (QRA) Master Input Editor tab provides the user with a quick view of the System Description inputs. The user can edit any of the values in this window and the changes will be reflected in the System Description tabs. Refer to Section 4.1 for further information on these tabs and variables.

Note: Because the System Description tab is a "loaded" window, the user will have to move away from this tab for the changes to be visible. For example, after changing inputs in the QRA Master Input Editor, close the window, click on the Scenarios tab, and then go back to System Description tab to see the changes made in the QRA Master Input Editor.

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. 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.

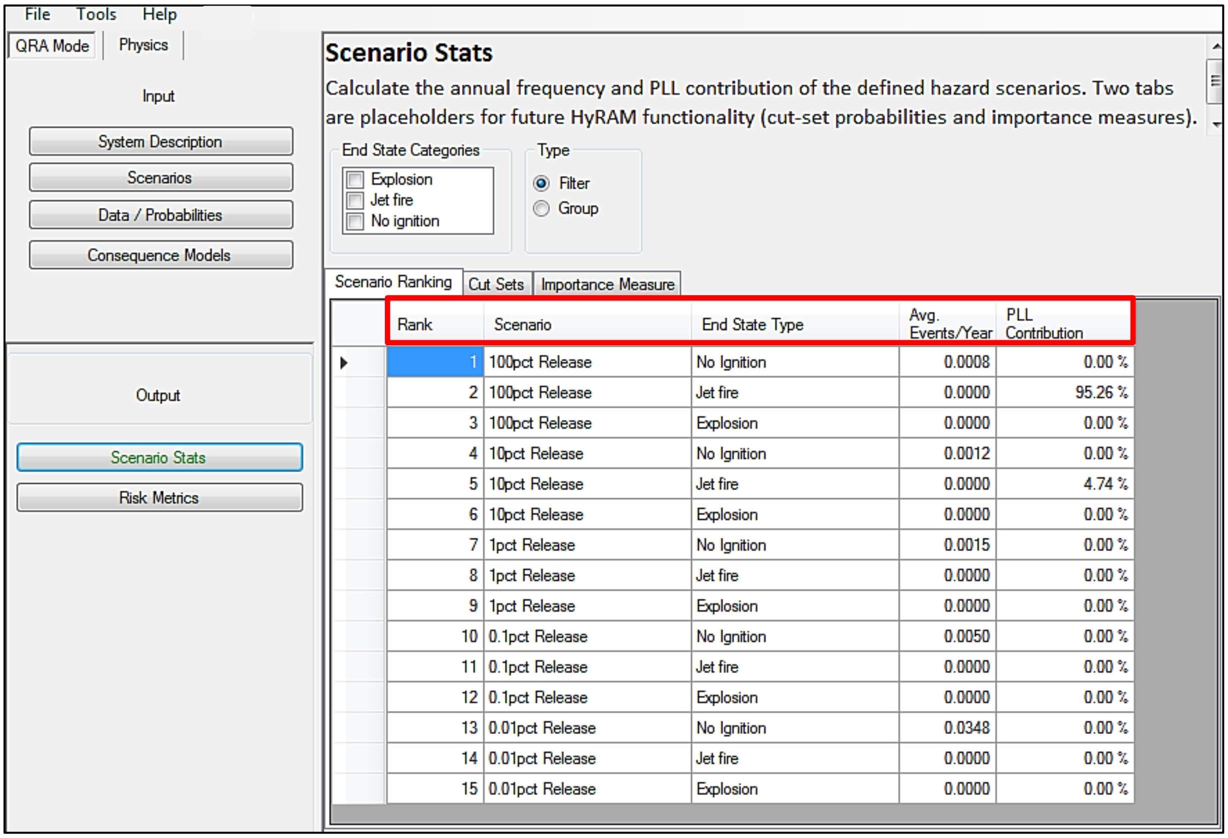


Figure 7 - Sorting

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 all of the 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, the inputs are based off of a generic indoor fueling system that was designed with the National Fire Protection Association's (NFPA) requirements for hydrogen systems (NFPA 2) and industry practices. The example installation is based off of the generic indoor fueling system 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). There are 50 employees in the warehouse at any time. Personnel each work 2,000 hours per year. In this example, most workers are located within 50 m of the dispenser due building design. The vehicle fleet contains 150 vehicles 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 ASTMA269 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 8 contains 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.

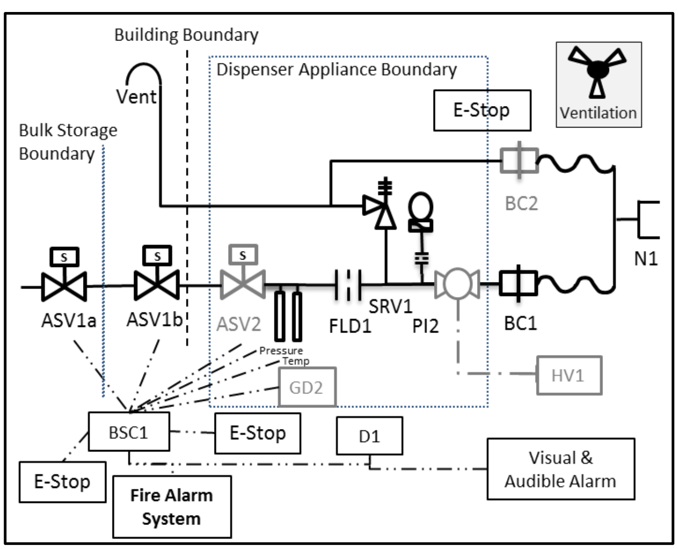


Figure 8 - P&ID for the generic dispenser used in this example [3].

4. QRA MODE – INPUT

4.1. System Description

The System Description window contains three tabs (Components, System Parameters, and Facility Parameters) which enable the user to input design specifications for the system.

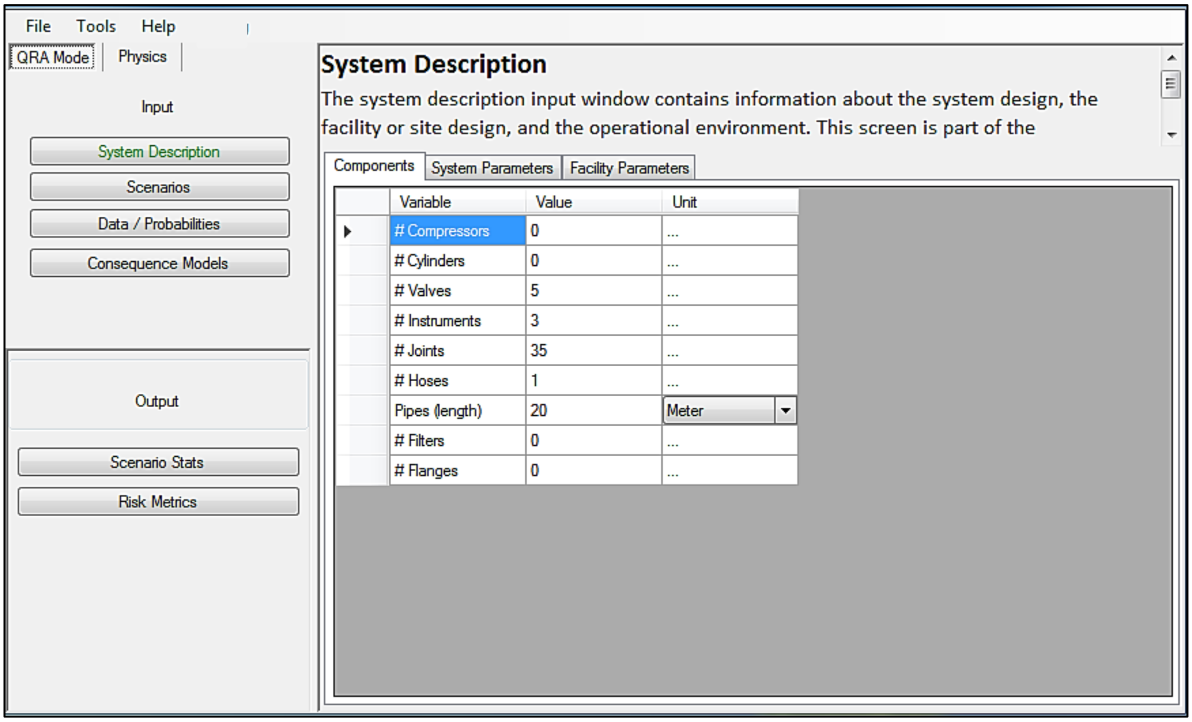
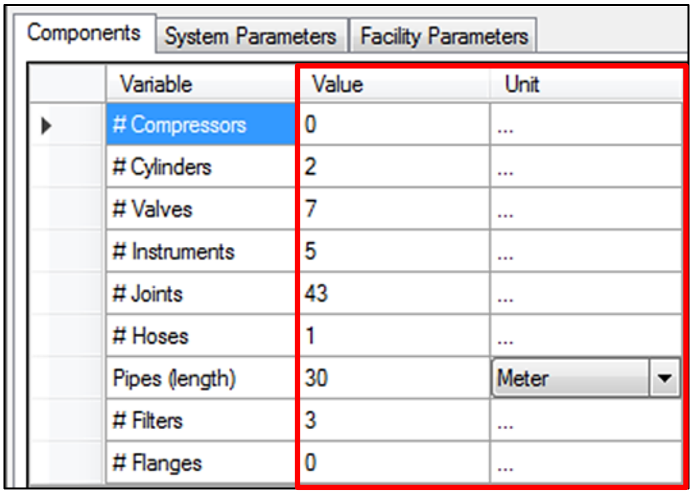


Figure 9 - System Description window

4.1.1. Components

The Components tab contains user input for nine types of components commonly seen in hydrogen applications. The user should refer to a P&ID for the proper number of components. Based on the preceding example, the Components input would be:



Components | System Parameters | Facility Parameters

Variable	Value	Unit
# Compressors	0	...
# Cylinders	2	...
# Valves	7	...
# Instruments	5	...
# Joints	43	...
# Hoses	1	...
Pipes (length)	30	Meter
# Filters	3	...
# Flanges	0	...

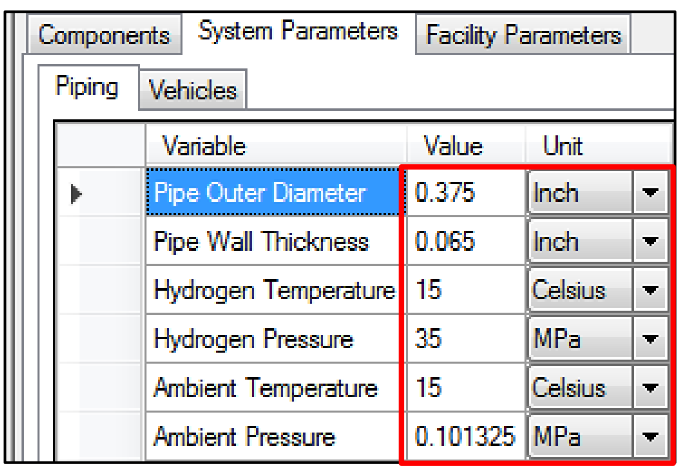
Figure 10 - Components input window

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 would be:



Components | System Parameters | Facility Parameters

Piping | Vehicles

Variable	Value	Unit
Pipe Outer Diameter	0.375	Inch
Pipe Wall Thickness	0.065	Inch
Hydrogen Temperature	15	Celsius
Hydrogen Pressure	35	MPa
Ambient Temperature	15	Celsius
Ambient Pressure	0.101325	MPa

Figure 11 - 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 (# Vehicles), the number of times a vehicle is fueled per day (nFuelingsPerVehicleDay), and the number of operating days of the vehicles (nVehicleOperatingDays). HyRAM calculates the annual demands as the product of those three inputs. Based on the preceding example, Vehicles input would be:

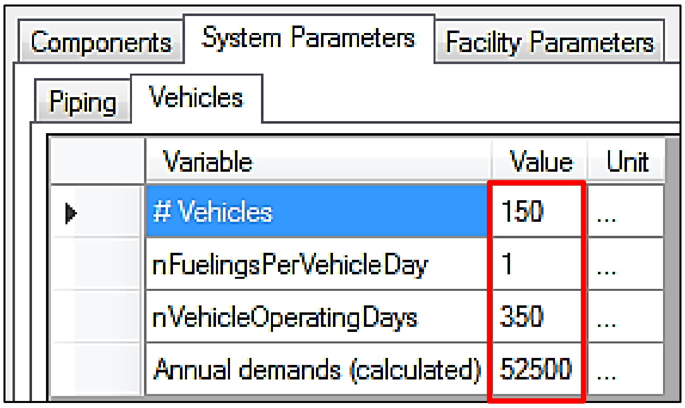


Figure 12 - Vehicles input

Note: The annual number of demands is used in the calculation of the frequency of releases from elements contained in the Fault Tree (FT). If a FT is not used, the user should input 0 for one of the inputs.

4.1.3. Facility Parameters

The Facility Parameters tab contains Facility, Occupants, and Enclosure tabs.

4.1.3.1. Facility

Warning: This input is not yet used in any calculations (in HyRAM version 1.0.1.798). User input is for documentation only.

The Facility tab contains measurements for the entire facility. Based on the preceding example, Facility input would be:

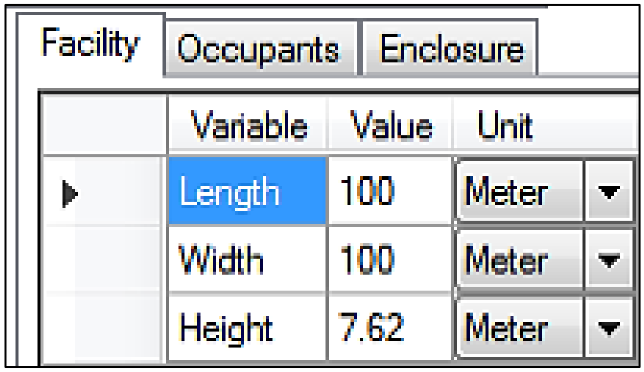


Figure 13 - Facility input

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 define 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 Targets (i.e., the number of personnel) and provides a description of the scenario in the Description field. If the user selects a Uniform or Normal distribution, the user will need to enter values for Location Distribution Parameter A and Location Distribution Parameter B. If the user selects the Deterministic distribution, only a value for Location Distribution Parameter A is 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. If the user chooses to delete a row in the Occupants tab, click on the arrow (see Figure 14) next to the row to highlight the entire row, and then click the Delete button on the keyboard.

When selecting the Normal distribution, 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) value, 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 regarded as the central location.

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 would be:

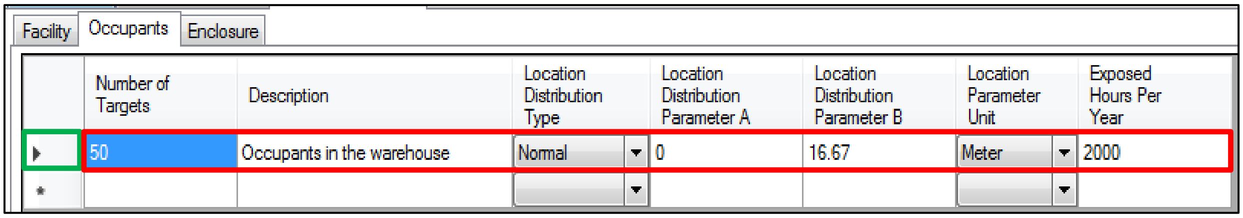


Figure 14 - Example input for Occupants tab

4.1.3.3. Enclosure

Warning: This input is not yet used in any calculations (in HyRAM version 1.0.1.798). User input is for documentation only.

The Enclosure tab contains information about an enclosure in the system that may exist in the system, such as a storage container being used to transport and hold the dispensing system. The user can choose to include/exclude the enclosure in the calculation by checking/unchecking the Use and Define Enclosure check box.

The following input is based on a standard ISO container. The container holds the dispensing system and measures 12 m (length) × 2.5 m (width) × 3 m (height). There is one ceiling vent, measuring 0.1 m^2. The ceiling vent is located 2.5 m above the ground. There is one floor vent, measuring 0.1 m^2. The floor vent is located 0.05 m above the ground. A release from the dispensing system measures 1 m high and occurs 1.5 m from the nearest wall. The Wind Velocity represents the mechanical venting speed and is set to 0 m/s for the ceiling and floor vents.

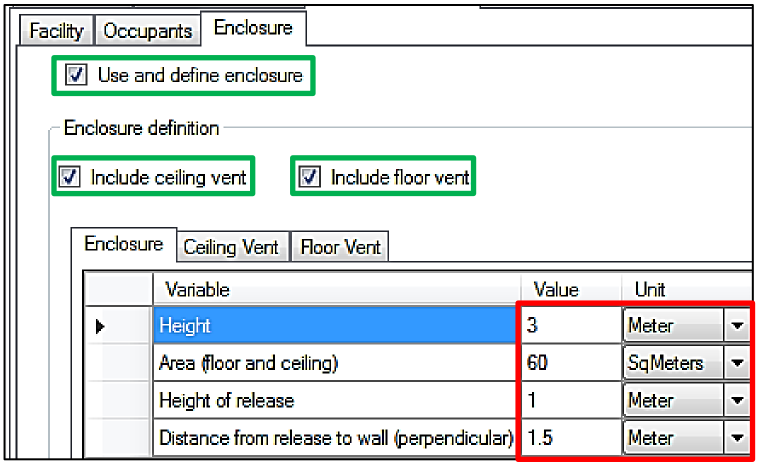


Figure 15 - Enclosure input

The user may also choose to include a ceiling vent (Figure 16) and/or a floor vent (Figure 17) for the enclosure by checking/unchecking the respective check boxes.

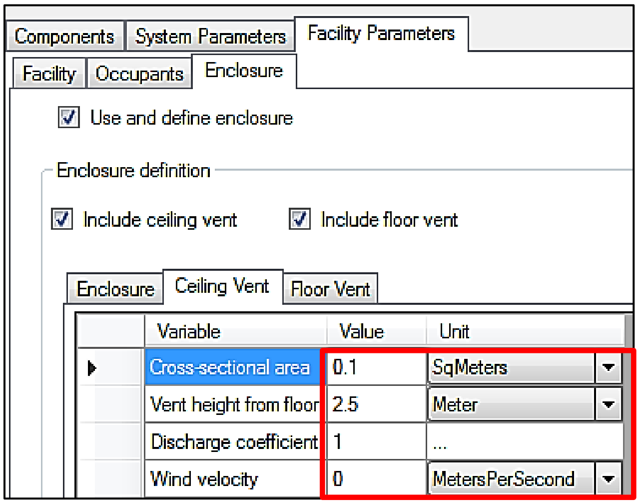


Figure 16 - Ceiling Vent input

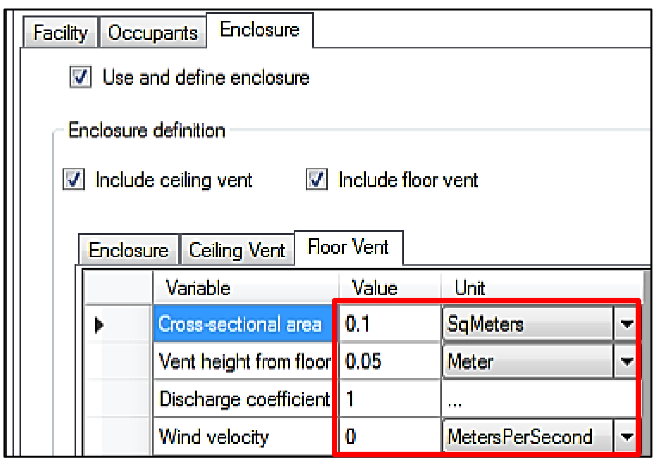


Figure 17 - Floor Vent input

Note: The variables in the Enclosure tab and the Overpressure tab in Physics Mode are not yet linked (in HyRAM version 1.0.1.798). In a future version of HyRAM the inputs on these two screens will share a variable set.

Note: The Ceiling Vent and Floor Vent are modeled such that they are on the walls *near* the ceiling and floor. In other words, the vents are not embedded in the ceiling and floor but in the side walls.

4.2. Scenarios

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

Note: The ESDs and FTs cannot be modified in HyRAM 1.0 – modifiable ESDs and FTs will be introduced in HyRAM 2.0.

4.2.1. Event Sequence Diagrams

The Event Sequence Diagrams 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. 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 and flame detection credit (the probability of successful release detection and isolation before ignition). This value is the probability associated with the ESD event *yes/true* (upper branch) for a single node "Leak detected and isolated" (illustrated as two nodes in Figure 18, 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.

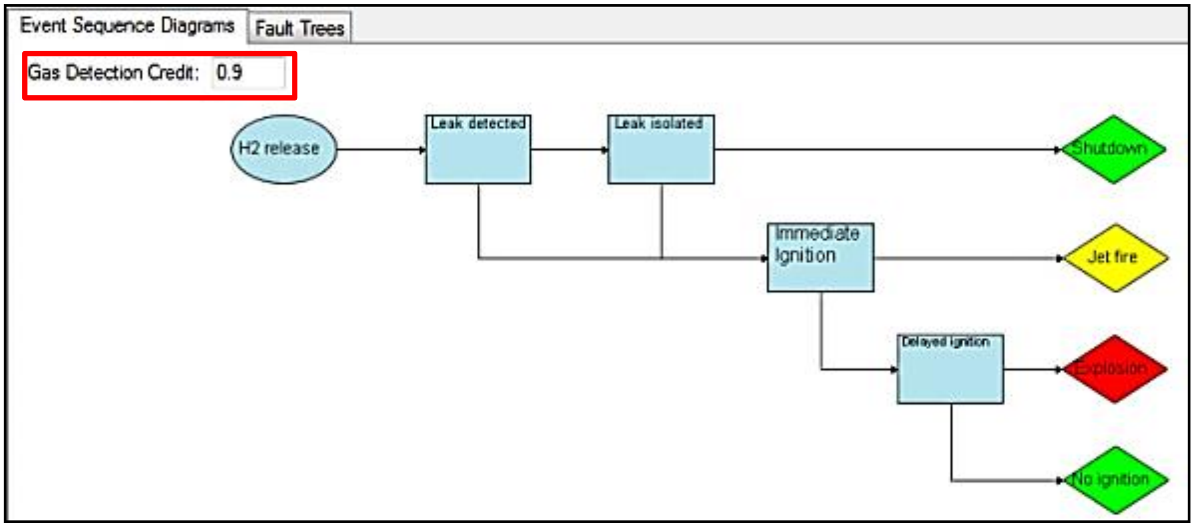


Figure 18 - Event Sequence Diagram showing the scenarios coded in HyRAM.

4.2.2. Fault Trees

The top event probability from these FTs (5.5e-9 failures/demand) is hard-coded into HyRAM: this value is multiplied by the annual number of demands from Section 4.1.2.2, and the resulting product is added to the frequency of 100% releases. To remove the FT from the calculation, the user should enter 0 in one of the inputs in Section 4.1.2.2. The model images contained on this tab are used only to illustrate the future concept of the FT feature for HyRAM 2.0.

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 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 leak frequency 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.

The default Component Leaks for Compressors is:

Component Leaks | Component Failures | Ignition Probabilities

Compressors | Cylinders | Filters | Flanges | Hoses | Joints | Pipes | Valves | Instruments

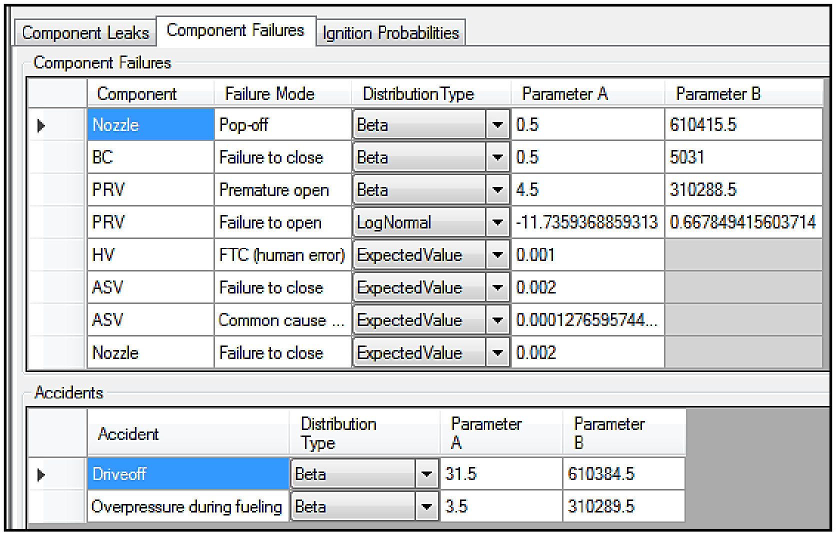
	Leak Size	Mu	Sigma	Mean	Variance
▶	0.01%	-1.7198	0.2143	1.83e-001	1.58e-003
	0.10%	-3.9185	0.4841	2.23e-002	1.32e-004
	1.00%	-5.1394	0.7898	8.01e-003	5.55e-005
	10.00%	-8.8408	0.8381	2.06e-004	4.31e-008
	100.00%	-11.3365	1.3689	3.04e-005	5.11e-009

Figure 19 - Component Leak frequencies input for Compressors

4.3.2. Component Failures

Warning: This input is not yet used in any calculations (in HyRAM version 1.0.1.798). User input is for documentation only.

The Component Failures tab will contain 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.



Component Leaks | Component Failures | Ignition Probabilities

Component Failures

Component	Failure Mode	Distribution Type	Parameter A	Parameter B
Nozzle	Pop-off	Beta	0.5	610415.5
BC	Failure to close	Beta	0.5	5031
PRV	Premature open	Beta	4.5	310288.5
PRV	Failure to open	LogNormal	-11.7359368859313	0.667849415603714
HV	FTC (human error)	ExpectedValue	0.001	
ASV	Failure to close	ExpectedValue	0.002	
ASV	Common cause ...	ExpectedValue	0.0001276595744...	
Nozzle	Failure to close	ExpectedValue	0.002	

Accidents

Accident	Distribution Type	Parameter A	Parameter B
Driveoff	Beta	31.5	610384.5
Overpressure during fueling	Beta	3.5	310289.5

Figure 20 - Component Failures input window concept

4.3.3. Ignition Probabilities

The Ignition Probabilities tab 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 Selected button.

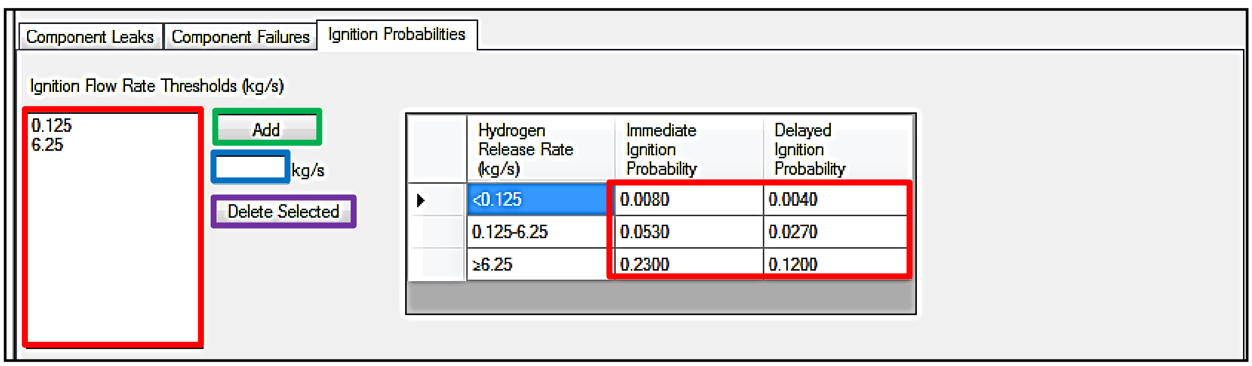


Figure 21 - Ignition Probabilities input

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 the Notional Nozzle Model, Flame Radiation Model, and Overpressure Model.

The default selections for physical effect models are the Birch2 notional nozzle model, Houf/Schefer (straight flame) flame radiation model, and Bauwens/Ekoto overpressure model. The default options can be changed by selecting another option from the dropdown menu. Description of the different physical consequence models can be found in [1].

Warning: Only the Birch2 Notional Nozzle Model is active in QRA mode in HyRAM version 1.0.1.798. Selecting one of the other notional nozzle models will generate an error message when the user attempts to calculate the Scenario Stats and Risk Metrics.

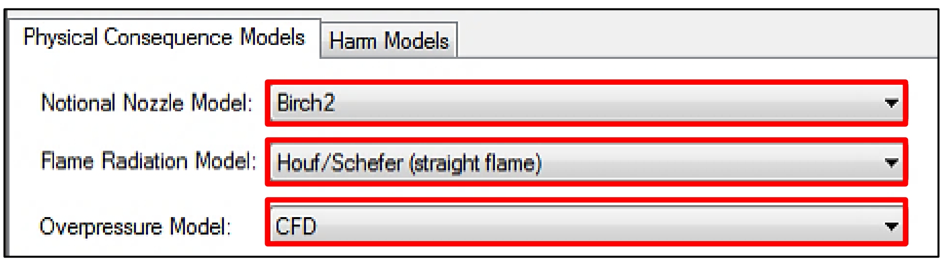


Figure 22 - Physical Consequence Models input

The Overpressure Model has two options: Bauwens/Ekoto and Computational Fluid Dynamics (CFD). The CFD model requires an input of peak overpressure (P_s; the default units are Pa) and impulse (always in Pa/sec) for the five release (leak) size categories.

Warning: Bauwens/Ekoto Overpressure Model is not active in QRA mode in HyRAM version 1.0.1.798. It will soon be linked to the overpressure model in physics mode.

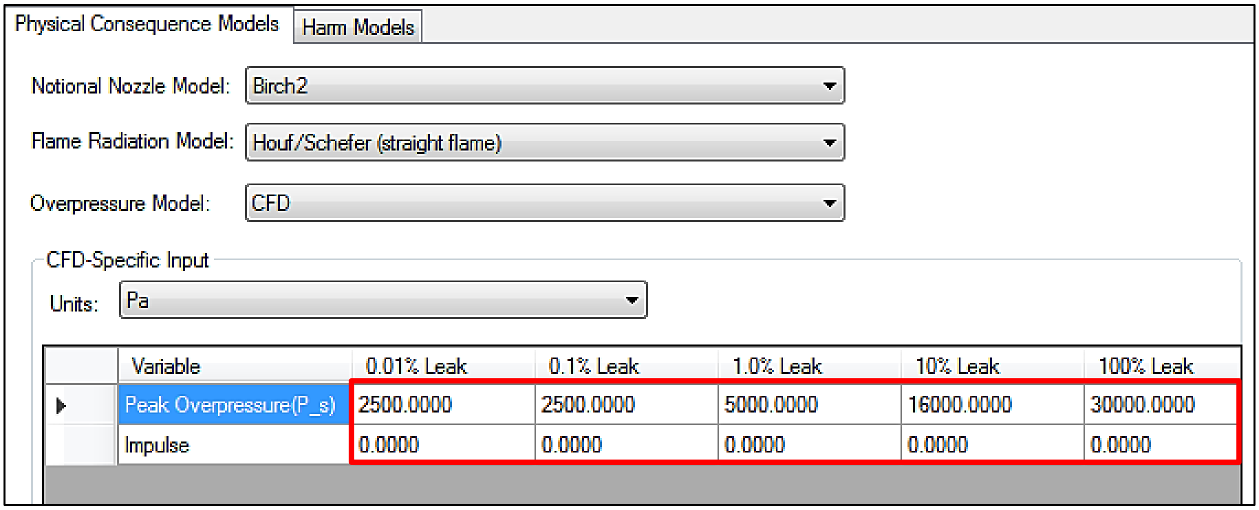


Figure 23 - Physical Consequence CFD model input

4.4.2. Harm Models

The Harm Models tab contains the Thermal Probit Model and the Overpressure Probit Model. Users may select the preferred probit models by clicking the drop-down next to the model name.

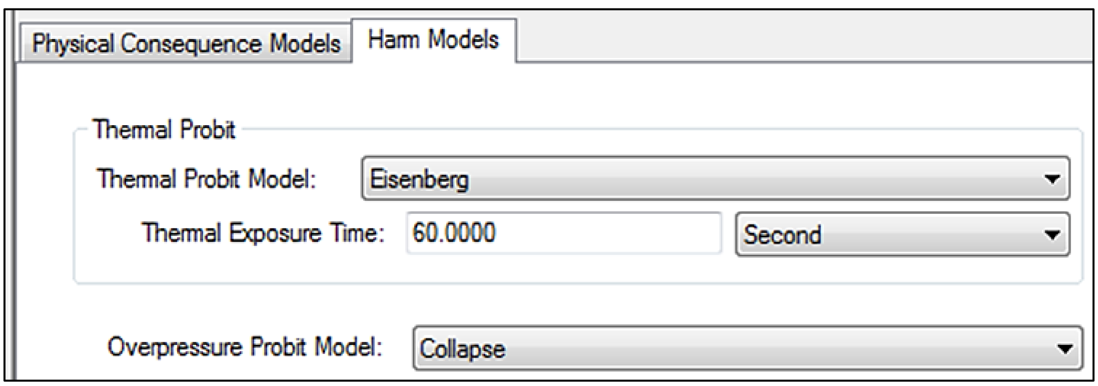


Figure 24 - Harm model selection window

5. QRA MODE – OUTPUT

5.1. Scenario Stats

The Scenario Stats window is divided into three sections: Scenario Ranking, Cut Sets, and Importance Measures.

5.1.1. Scenario Ranking

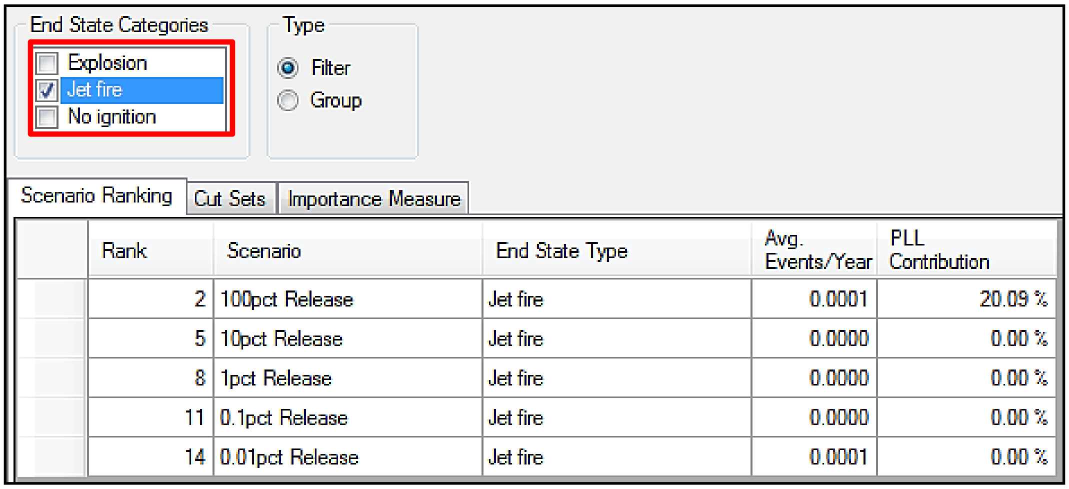
The Scenario Ranking tab contains the end state types, frequencies, and potential loss of life (PLL) contribution for all release sizes. By default, the results are sorted by release size. These results can be sorted by any of the headings by clicking on the heading name (we recommend sorting by Avg. Events/Year or by PLL). Based on the preceding example, the Scenario Ranking output would be:

Scenario Ranking | Cut Sets | Importance Measure

Rank	Scenario	End State Type	Avg. Events/Year	PLL Contribution
1	100pct Release	No Ignition	0.0217	0.00 %
2	100pct Release	Jet fire	0.0001	99.60 %
3	100pct Release	Explosion	0.0001	0.00 %
4	10pct Release	No Ignition	0.0223	0.00 %
5	10pct Release	Jet fire	0.0000	0.40 %
6	10pct Release	Explosion	0.0000	0.00 %
7	1pct Release	No Ignition	0.0452	0.00 %
8	1pct Release	Jet fire	0.0000	0.00 %
9	1pct Release	Explosion	0.0000	0.00 %
10	0.1pct Release	No Ignition	0.0550	0.00 %
11	0.1pct Release	Jet fire	0.0000	0.00 %
12	0.1pct Release	Explosion	0.0000	0.00 %
13	0.01pct Release	No Ignition	0.1616	0.00 %
14	0.01pct Release	Jet fire	0.0001	0.00 %
15	0.01pct Release	Explosion	0.0001	0.00 %

Figure 25 - Scenario Ranking Output

The filter option allows users to view the Scenario results tab for an individual end state type. To filer the results, click which end state type(s) you would like to have isolated in the End State Categories box. The grouping option is not currently enabled.



Rank	Scenario	End State Type	Avg. Events/Year	PLL Contribution
2	100pct Release	Jet fire	0.0001	20.09 %
5	10pct Release	Jet fire	0.0000	0.00 %
8	1pct Release	Jet fire	0.0000	0.00 %
11	0.1pct Release	Jet fire	0.0000	0.00 %
14	0.01pct Release	Jet fire	0.0001	0.00 %

Figure 26 - Scenario results filtered to show only jet fire end states

5.1.2. Cut Sets

The Cut Sets tab is currently inactive – no results are generated in version 1.0.1.798. The same output is displayed regardless of user-defined inputs or the system being modeled by the user.

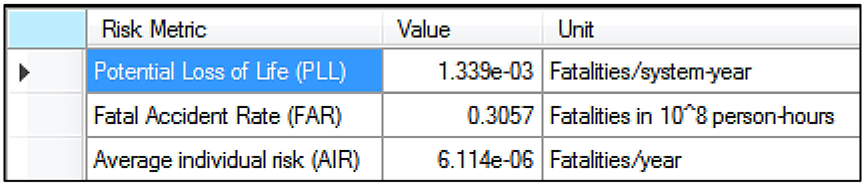
5.1.3. Importance Measure

The Importance Measure tab is currently inactive only – no results are generated in version 1.0.1.798. The same output is displayed regardless of user-defined inputs or the system being modeled by the user.

5.2. 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 would be:



Risk Metric	Value	Unit
Potential Loss of Life (PLL)	1.339e-03	Fatalities/system-year
Fatal Accident Rate (FAR)	0.3057	Fatalities in 10^8 person-hours
Average individual risk (AIR)	6.114e-06	Fatalities/year

Figure 27 - Risk Metrics Output

6. PHYSICS MODE

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. Plot Properties

The Plot Properties tab contains the characteristics of the output plot for the gaseous hydrogen plume.

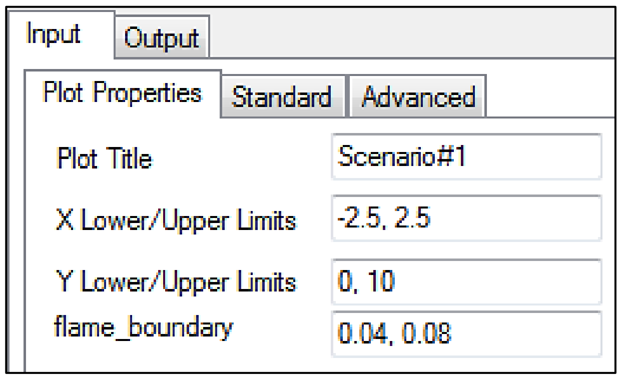


Figure 28 - Plot Properties input

6.1.2. Standard

The Standard input tab contains the standard physical variables that will affect the gaseous hydrogen plume.

The orifice diameter (diameter of the release) is 3.25 mm. Based on the preceding example, the Standard input would be:

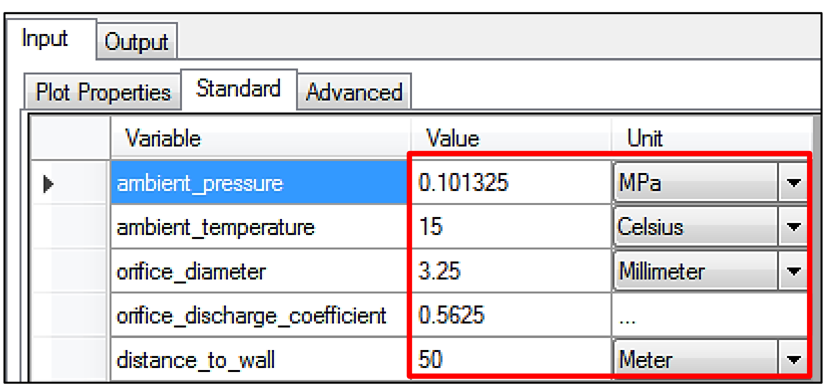


Figure 29 - Standard input

6.1.3. Advanced

The Advanced tab contains the advanced physical variables that will affect the gaseous hydrogen plume.

Based on the preceding example, the Advanced input would be:

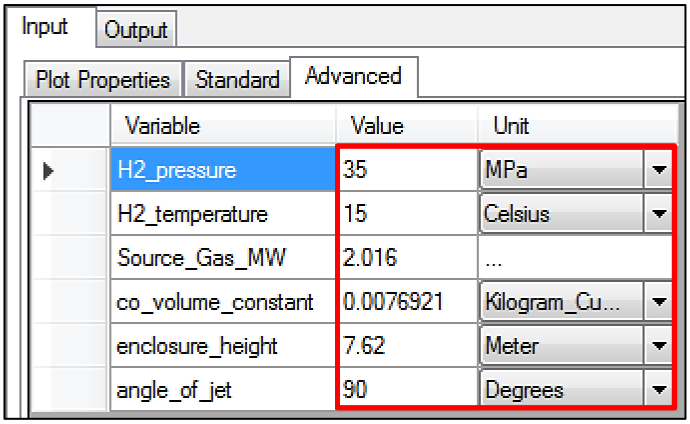


Figure 30 - Advanced input

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

Note: Variable co_volume_constant and Source_Gas_MW should not be changed. These constants are valid for hydrogen and are only included as placeholders for future versions where gases other than hydrogen are to be simulated.

6.1.4. Gas Plume Dispersion Output

Based on the preceding example, the Gas Plume Dispersion Output would be:

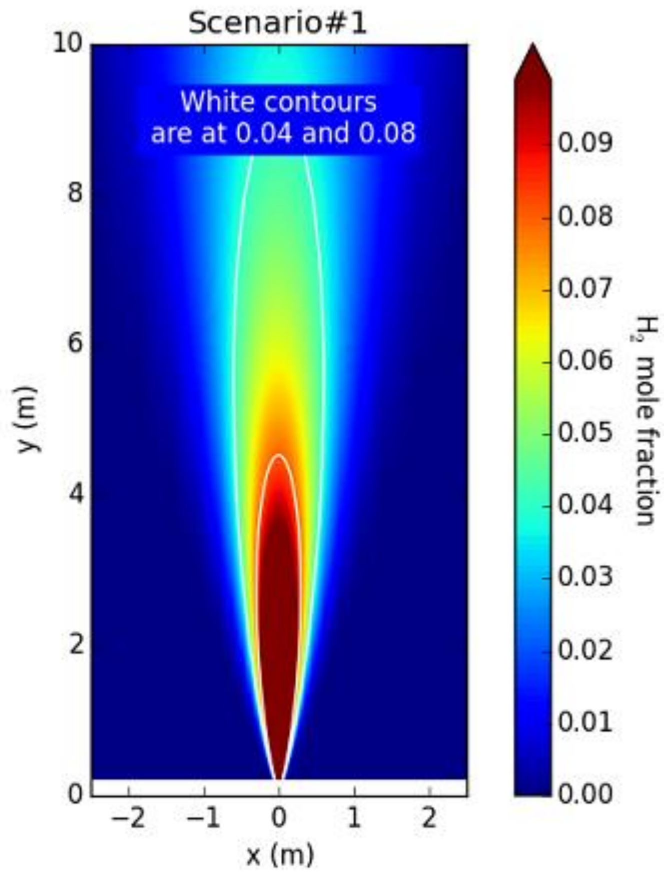


Figure 31 - Gas Plume Dispersion output

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 overpressure 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 clicks the Calculate button to produce the Overpressure Output.

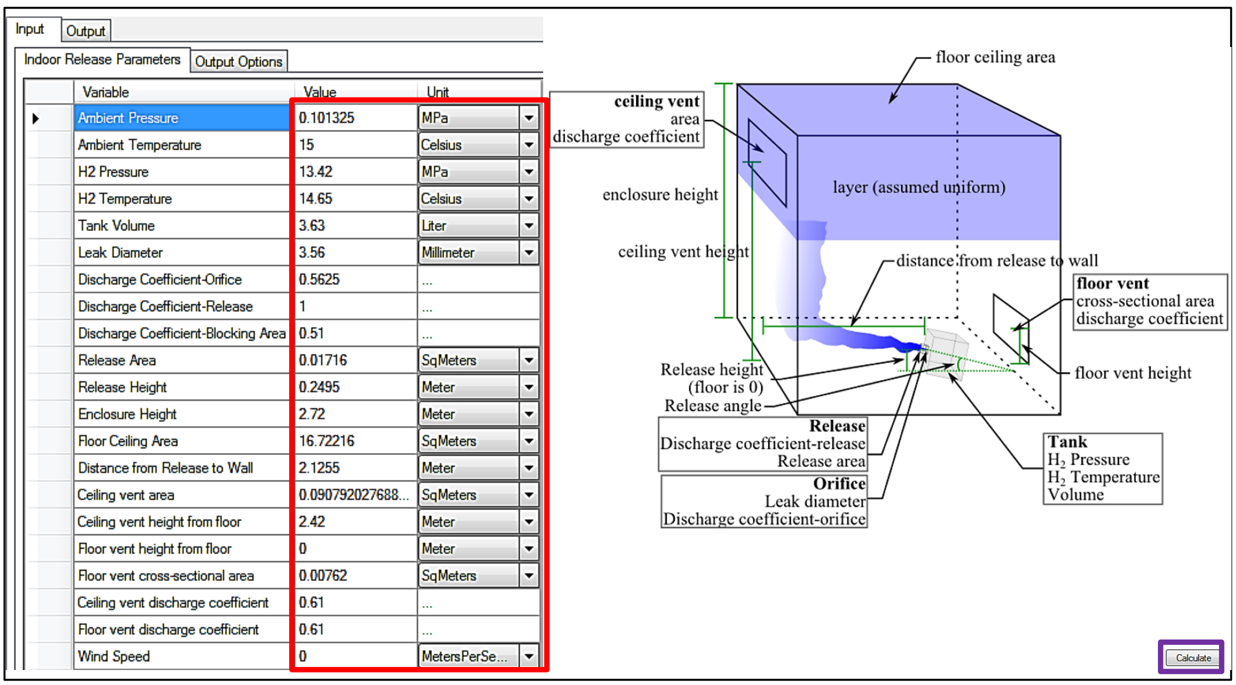


Figure 32 - Indoor Release Parameters input

6.2.2. Output Options

The Output Options tab allows the user to specify times for calculating pressure (less than 30 seconds), specify pressures to be drawn across the plot with a horizontal line, and place dots where pressure and time intersect.

Note: User must return to the Indoor Release Parameters tab and click Calculate in Figure 32 to produce the Output.

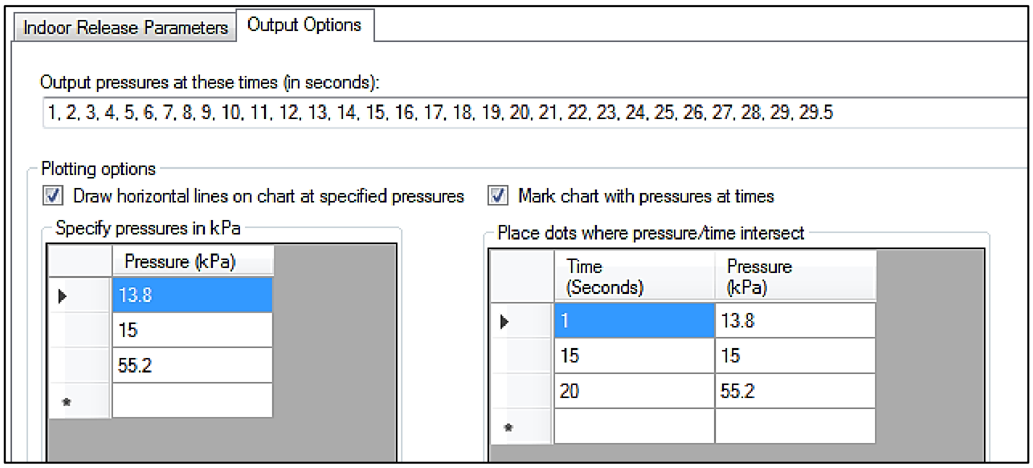


Figure 33 - Output Options input

6.2.3. Overpressure Output

The Output tab contains a Pressure plot, Layer plot, and data table for those plots.

Based on the default inputs, the Pressure plot would be:

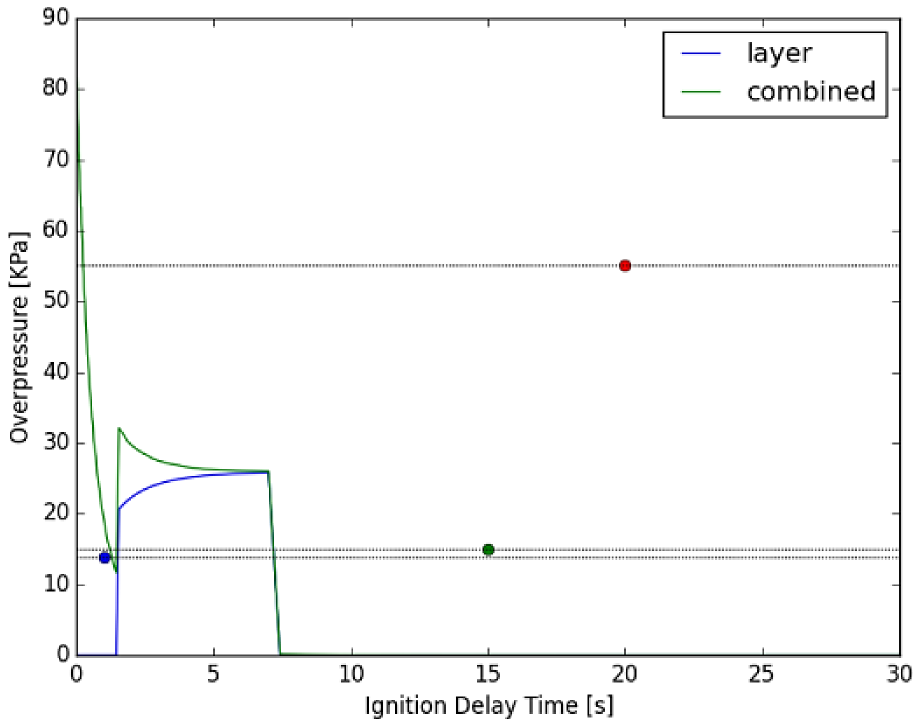


Figure 34 - Overpressure Output Pressure Plot

In the Overpressure plot, the layer plot represents the overpressure that would develop if the layer were ignited. The combined plot represents the overpressure that would develop if the layer plus 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.

Based on the default inputs, the Layer plot would be:

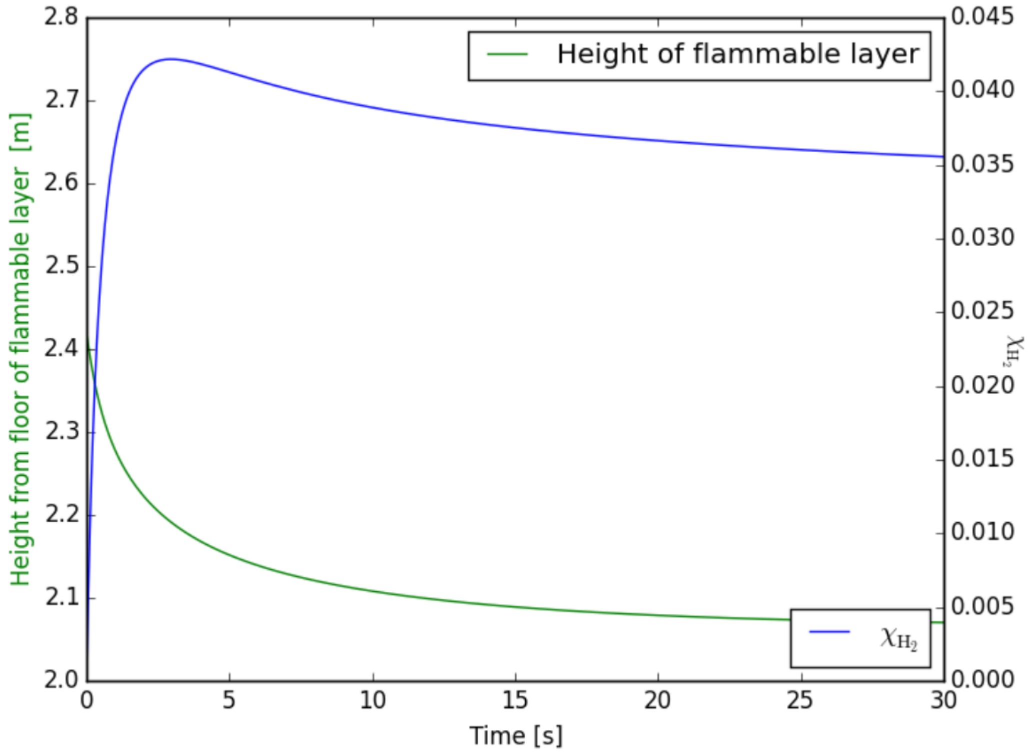


Figure 35 - Overpressure Output Layer Plot

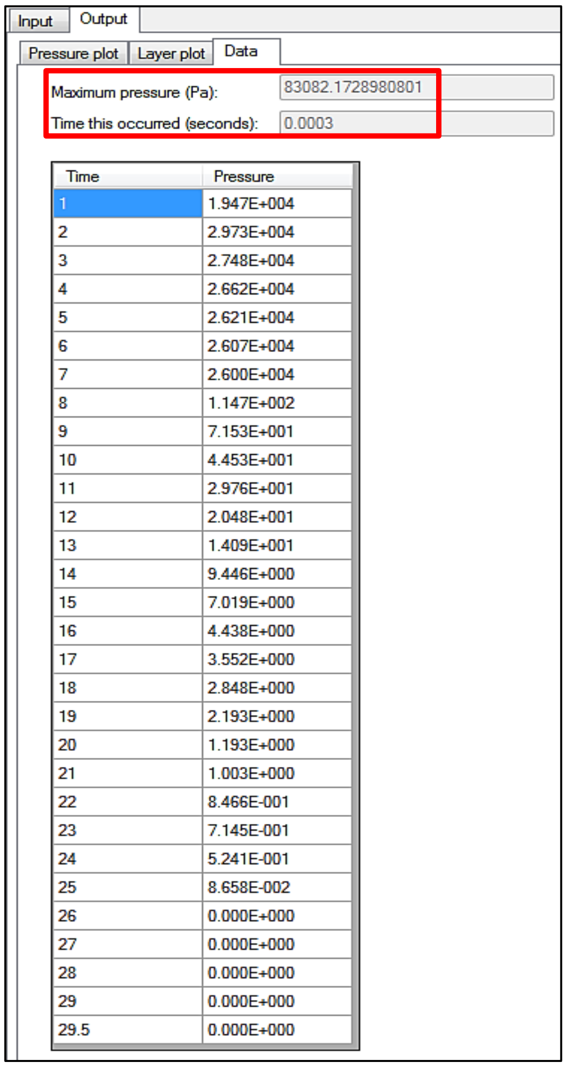
The Height of flammable layer represents the height of the hydrogen layer that develops above the floor. At 30 seconds, the hydrogen layer height is about 2.1 m above the floor and extends to the top of the enclosure. The hydrogen mole fraction of this layer is represented by χ_{H_2}. At 30 seconds, the hydrogen mole fraction is about 0.035. It is assumed that at any point in space within the hydrogen layer, the hydrogen mole fraction is represented by χ_{H_2}; i.e., the hydrogen mole fraction from 2.1 m to 2.72 m (height of enclosure) is 0.035 at 30 seconds.

Furthermore, in the Pressure plot (Figure 34), overpressure is non-zero from about 2 seconds to 7 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.

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

Note: HyRAM (version 1.0.1.798) incorrectly list the hydrogen layer as the Height of flammable layer. The hydrogen layer can only be regarded as the flammable layer when the mole fraction is between 0.04 and 0.75. This label will be corrected in subsequent versions.

Based on the default inputs, the Data tab would output:



Time	Pressure
1	1.947E+004
2	2.973E+004
3	2.748E+004
4	2.662E+004
5	2.621E+004
6	2.607E+004
7	2.600E+004
8	1.147E+002
9	7.153E+001
10	4.453E+001
11	2.976E+001
12	2.048E+001
13	1.409E+001
14	9.446E+000
15	7.019E+000
16	4.438E+000
17	3.552E+000
18	2.848E+000
19	2.193E+000
20	1.193E+000
21	1.003E+000
22	8.466E-001
23	7.145E-001
24	5.241E-001
25	8.658E-002
26	0.000E+000
27	0.000E+000
28	0.000E+000
29	0.000E+000
29.5	0.000E+000

Figure 36 - Overpressure Output Data.

The units for Time and Pressure are seconds and kPa, respectively. The pressure data in the table represents the overpressure of the combined plot in Figure 34. In addition to the tabulated data, the Maximum pressure (Pa) and Time this occurred (seconds) are also provided in the Data tab.

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.

The hydrogen system is located in a warehouse that has a relative humidity of 0.89. The flame and trajectory results are based on the Notional Nozzle Model Birch2.

The input window would look like the following:

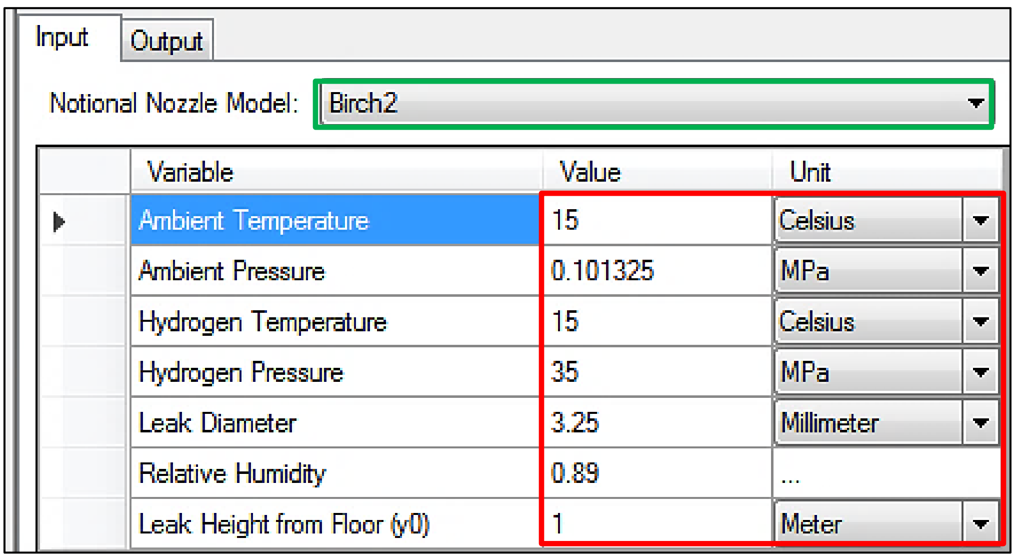


Figure 37 - Flame Temperature / Trajectory input

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

Based on the preceding example/input, the Flame Temperature/Trajectory output would be:

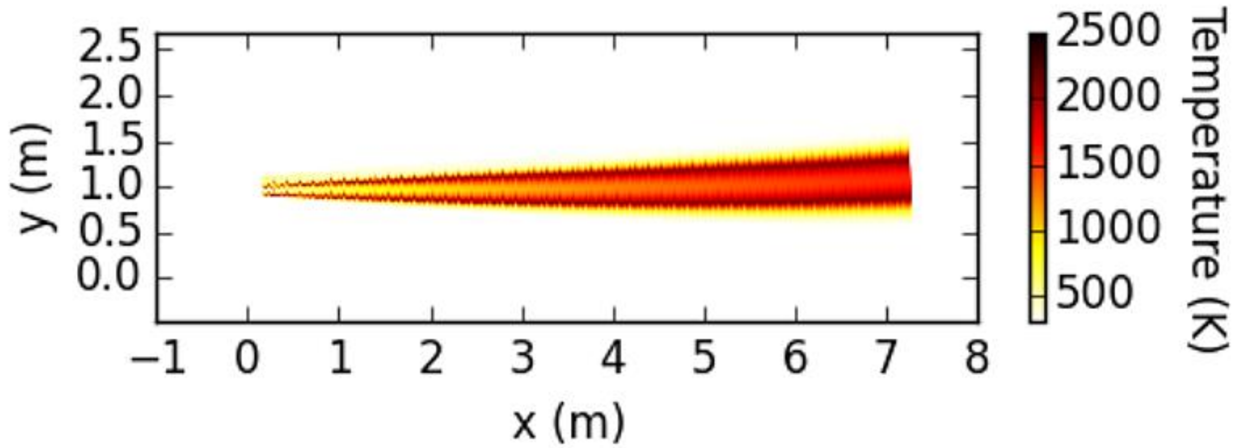


Figure 38 - Flame Temperature / Trajectory output

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 the heat flux plot.

The user specifies 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, the Radiative Heat Flux input would be:

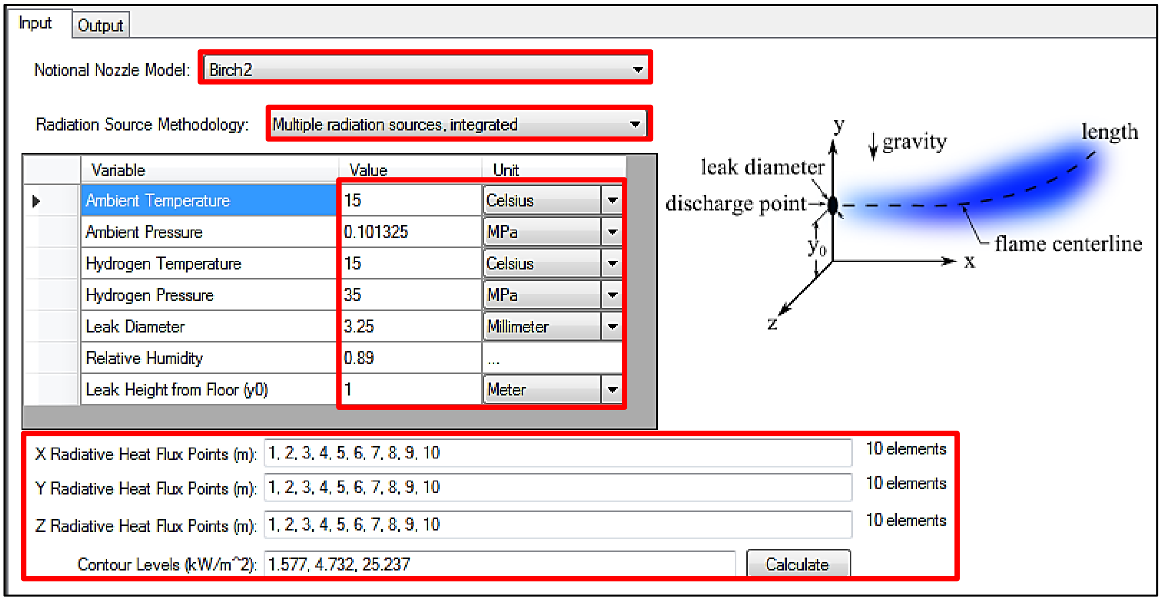
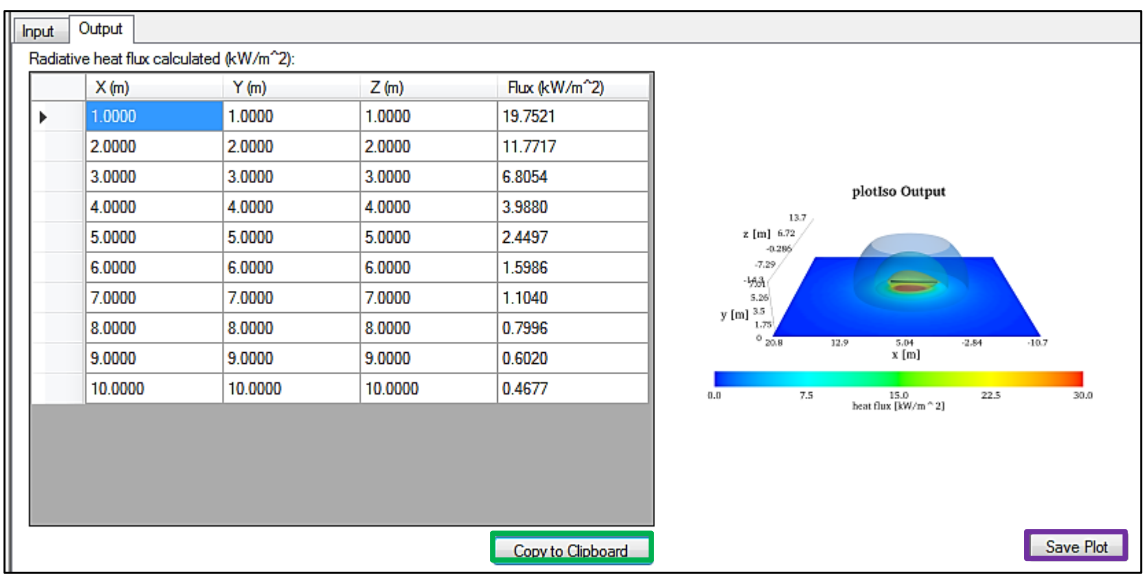


Figure 39 - Radiative Heat Flux input

Based on the preceding example, the Radiative Heat Flux output would be:



X (m)	Y (m)	Z (m)	Flux (kW/m^2)
1.0000	1.0000	1.0000	19.7521
2.0000	2.0000	2.0000	11.7717
3.0000	3.0000	3.0000	6.8054
4.0000	4.0000	4.0000	3.9880
5.0000	5.0000	5.0000	2.4497
6.0000	6.0000	6.0000	1.5986
7.0000	7.0000	7.0000	1.1040
8.0000	8.0000	8.0000	0.7996
9.0000	9.0000	9.0000	0.6020
10.0000	10.0000	10.0000	0.4677

Figure 40 - Radiative Heat Flux output

The table provides the radiative heat flux calculated at the user specified positions (see Figure 39). By clicking the Copy to Clipboard button, the table is copied and can be pasted into another program, such as Microsoft Excel.

The “plotIso Output” is a visual representation of the radiative heat flux. The image shows a plot of the 3-D isometric surfaces at which radiative heat flux is greater than or equal to the user specified contour levels (see Figure 39). If the user wishes to save the output, click the Save Plot button located at the bottom right of the window.

7. SUMMARY OF HyRAM INPUT AND OUTPUT

7.1. QRA Mode Input

7.1.1. System Description Input

The System Description window contains information about the system itself, such as the components, system parameters, and facility parameters. All inputs from System Description tab are listed in Table 1.

Table 1 - Summary of System Description Input

HyRAM Input Screen	HyRAM Input Parameter	Example User Input Values
Components	Compressors	1
	Cylinders	3
	Valves	34
	Instruments	11
	Joints	10
	Hoses	2
	Pipes (length in meters)	3
	Filters	3
	Flanges	0
System Parameters- Piping	Pipe OD	1.7145 cm
	Pipe wall thickness	0.23114 cm
	Hydrogen Temperature	15°C
	Hydrogen Pressure	1034 bar
	Ambient Temperature	15°C
	Ambient Pressure	1.01325 bar
System Parameters - Vehicles	Number of Vehicles	50
	# Fuelings Per Vehicle Day	1
	Vehicle Operating Days	360
	Annual demands (calculated from categories above)	18,000
Facility Parameters- Facility	Length	100 m
	Width	100 m
	Height	7.62 m
Occupants	Number of Targets	50 occupants in the warehouse
	Location Distribution Type	Normal
	Location Distribution Parameter A	0 m
	Location Distribution Parameter B	16.67 m
	Exposed Hours Per Year	2000

7.1.2. Scenarios

The Scenarios window contains different scenarios and outcomes displayed as event sequence diagrams and fault trees. In the current version of HyRAM, these defaults cannot be modified.

7.1.3. Data/Probabilities

The Data/Probabilities window contains the probability of occurrence of the events (e.g., component leaks, component failures, and ignition). Users may modify the ignition probabilities and the component leak frequencies. Note that the component leak frequency values are modified by changing the mu and sigma values from which the mean and variance are calculated.

Table 2 - Summary of component leak frequency data.

Component	Leak size	Mu	Sigma	Mean (Calculated)	Variance (Calculated)
Compressors	0.01%	-1.72	0.21	1.83e-1	1.58e-3
	0.1%	-3.92	0.48	2.23e-2	1.32e-4
	1%	-5.14	0.79	8.01e-3	5.55e-5
	10%	-8.84	0.84	2.06e-4	4.31e-8
	100%	-11.34	1.37	3.04e-5	5.11e-9
Cylinders	0.01%	-13.84	0.62	1.18e-6	6.46e-13
	0.1%	-14.00	0.61	9.98e-7	4.43e-13
	1%	-14.40	0.62	6.80e-7	2.19e-13
	10%	-14.96	0.63	3.90e-7	7.36e-14
	100%	-15.60	0.67	2.09e-7	2.47e-14
Filters	0.01%	-5.25	1.98	3.77e-2	7.18e-2
	0.1%	-5.29	1.52	1.60e-2	2.30e-3
	1%	-5.34	1.48	1.44e-2	1.64e-3
	10%	-5.38	0.89	6.87e-3	5.67e-5
	100%	-5.43	0.95	6.94e-3	7.16e-5
Flanges	0.01%	-3.92	1.66	7.86e-2	9.13e-2
	0.1%	-6.12	1.25	4.82e-3	8.84e-5
	1%	-8.33	2.20	2.72e-3	9.41e-4
	10%	-10.54	0.83	3.74e-5	1.41e-9
	100%	-12.75	1.83	1.55e-5	6.53e-9
Hoses	0.01%	-6.81	0.27	1.15e-3	9.82e-8
	0.1%	-8.64	0.55	2.06e-4	1.51e-8
	1%	-8.77	0.54	1.79e-4	1.11e-8
	10%	-8.89	0.55	1.60e-4	8.92e-9
	100%	-9.86	0.85	7.47e-5	5.82e-9
Joints	0.01%	-9.57	0.16	7.05e-5	1.35e-10
	0.1%	-12.83	0.76	3.56e-6	9.84e-12
	1%	-11.87	0.48	7.80e-6	1.54e-11
	10%	-12.02	0.53	6.96e-6	1.57e-11
	100%	-12.15	0.57	6.21e-6	1.45e-11
Pipes	0.01%	-11.86	0.66	8.78e-6	4.16e-11
	0.1%	-12.53	0.69	4.57e-6	1.26e-11
	1%	-13.87	1.13	1.80e-6	8.27e-12
	10%	-14.58	1.16	9.12e-7	2.33e-12
	100%	-15.73	1.71	6.43e-7	7.39e-12
Valves	0.01%	-5.18	0.17	5.71e-3	9.90e-7
	0.1%	-7.27	0.40	7.50e-4	9.67e-8
	1%	-9.68	0.96	9.92e-5	1.49e-8

	10%	-10.32	0.68	4.13e-5	9.86e-10
	100%	-12.00	1.33	1.49e-5	1.09e-9
Instruments	0.01%	-7.32	0.68	8.31e-4	4.00e-7
	0.1%	-8.50	0.79	2.78e-4	6.80e-8
	1%	-9.06	0.90	1.73e-4	3.68e-8
	10%	-9.17	1.07	1.84e-4	7.18e-8
	100%	-10.20	1.48	1.11e-4	9.85e-8

Table 3 - Summary of ignition probabilities

Hydrogen Release Rate (kg/s)	Immediate Ignition Probability	Delayed Ignition Probability
< 0.125	0.008	0.004
0.125 – 6.25	0.053	0.027
> 6.25	0.230	0.120

7.1.4. Consequence Models

The Consequence Models window contains selectors for the different models used to calculate physical effects of ignited releases and the probability of harm from a known physical effect. All inputs from the Consequence Models tab are listed in Table 4.

Table 4 - Summary Consequence Models Input

HyRAM Input Screen	HyRAM Input Parameter	Example User Input Values
Consequence Models - Physical Consequence	Notional Nozzle	Birch2
	Flame Radiation Model	Ekoto/Houf (curved flame)
	Overpressure Model	CFD P_s = [0,0,0,0,0] Impulse = [0,0,0,0,0]
Model Parameters - Harm	Thermal Probit	Tsao
	Thermal Exposure	60 s
	Overpressure Probit	Lung Eisenberg

7.2. QRA Mode Output

7.2.1. Risk Metrics

The Risk Metrics window calculates risk in terms of FAR, PLL, and AIR, shown in Table 5.

Table 5 - Summary Risk Metric

Risk metric	Value	Unit
Potential Loss of Life (PLL)	1.339e-03	Fatalities/system-year
Fatal Accident Rate (FAR)/100M exposed hours	0.3057	Fatalities in 10^8 person-hours
Average individual risk (AIR)	6.114e-06	Fatalities/year

7.2.2. Scenario Stats

The Scenario Stats window displays the probabilities of risk scenarios and calculates frequencies of accident scenarios, cut-set probabilities, and importance measures shown in Table 6. (Only scenario ranking is active in current version. Cut sets and important measures are placeholders for future versions).

Table 6 - Summary Scenario Stats

Rank	Scenario	End State Type	Avg. Events/Year	PLL Contribution
1	100pct Release	No Ignition	0.0217	0.00 %
2	100pct Release	Jet fire	0.0001	99.60 %
3	100pct Release	Explosion	0.0001	0.00 %
4	10pct Release	No Ignition	0.0223	0.00 %
5	10pct Release	Jet fire	0.0000	0.40 %
6	10pct Release	Explosion	0.0000	0.00 %
7	1pct Release	No Ignition	0.0452	0.00 %
8	1pct Release	Jet fire	0.0000	0.00 %
9	1pct Release	Explosion	0.0000	0.00 %
10	0.1pct Release	No Ignition	0.0550	0.00 %
11	0.1pct Release	Jet fire	0.0000	0.00 %
12	0.1pct Release	Explosion	0.0000	0.00 %
13	0.01pct Release	No Ignition	0.1616	0.00 %
14	0.01pct Release	Jet fire	0.0000	0.00 %
15	0.01pct Release	Explosion	0.0000	0.00 %

7.3. Physics Input

7.3.1. Gas Plume Dispersion Input

The Gas Plume Dispersion tab uses the inputs in Table 7 to determine the dispersion of hydrogen from a release.

Table 7 - Summary of Gas Plume Dispersion input

HyRAM Input Parameter	Example input value
X Lower/Upper Limits	-2.5, 2.5
Y Lower/Upper Limits	0, 10
Flame Boundary Contours	0.04, 0.08
Ambient Pressure	0.101325 MPa
Ambient Temperature	15°C
Orifice Diameter	3.25 mm
Orifice Discharge	0.5625
Distance to wall	50 m
Hydrogen Pressure	35 MPa
Hydrogen Temperature	15°C
Enclosure Height	7.62 m
Angle of Jet	90°

7.3.2. Overpressure Input

The Overpressure tab calculates overpressure and layering (accumulation) behavior for gaseous hydrogen in an enclosure.

Table 8 - Summary of Overpressure input

HyRAM Input Parameter	Example Input Value
Ambient Pressure	0.101325 MPa
Ambient Temperature	15°C
H2 Pressure	13.42 MPa
H2 Temperature	14.65°C
Tank Volume	3.63 L
Leak Diameter	3.56 mm
Discharge Coefficient-Orifice	0.5625
Discharge Coefficient-Release	1
Discharge Coefficient-Blocking Area	0.51
Release Area	0.01716 m^2

Release Height	0.2495 m
Enclosure Height	2.72 m
Floor Ceiling Area	16.72216 m^2
Distance from Release to Wall	2.1255 m
Ceiling vent area	0.090792 m^2
Ceiling vent height from floor	2.42 m
Floor vent height from floor	0 m
Floor vent cross-sectional area	0.00762 m^2
Ceiling vent discharge coefficient	0.61
Floor vent discharge coefficient	0.61
Wind speed	0 m/s

7.3.3. Jet Flame Input

The Jet Flame tab calculates the behavior of a jet flame, including flame temperature, direction and heat flux.

Table 9 - Summary of Jet Flame inputs

HyRAM Input Parameter	**Example input value**
Notional Nozzle Model	Birch2
Radiation Source Methodology	Multiple radiation sources, integrated
Ambient Temperature	15°C
Ambient Pressure	0.101325 MPa
Hydrogen Temperature	15°C
Hydrogen Pressure	35 MPa
Leak Diameter	3.25 mm
Relative Humidity	0.89
Leak Height from Ground	1 m
X radiative heat flux points (m) (Flame centerline)	1,2,3,4,5,6,7,8,9,10
Y radiative heat flux points (m) (Vertical)	1,2,3,4,5,6,7,8,9,10
Z radiative heat flux points (m) (Perpendicular to flame)	1,2,3,4,5,6,7,8,9,10

7.4. Physics Mode Outputs

7.4.1. Gas Plume Dispersion Output Window

The Gas Plume Dispersion Output is provided in Figure 41 below. Figure 41 shows the hydrogen mole fraction of the gas plume propagating from the release.

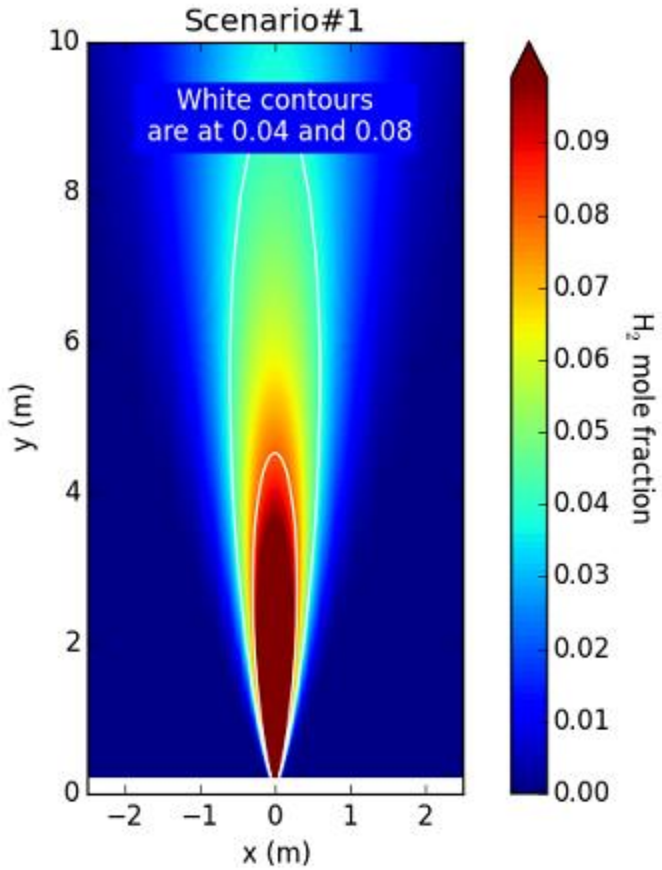


Figure 41 - Gas Plume Dispersion output

7.4.2. Overpressure Output Windows

The Overpressure Output windows are shown in Figure 42 and Figure 43. The Overpressure Output data is provided in Table 10. In Figure 42, the layer overpressure plot and combined (layer plus gas plume dispersing from release location) overpressure plot are a function of the ignition delay time. Figure 43 shows the height from the floor of the hydrogen layer and the uniform hydrogen mole fraction of that layer over time.

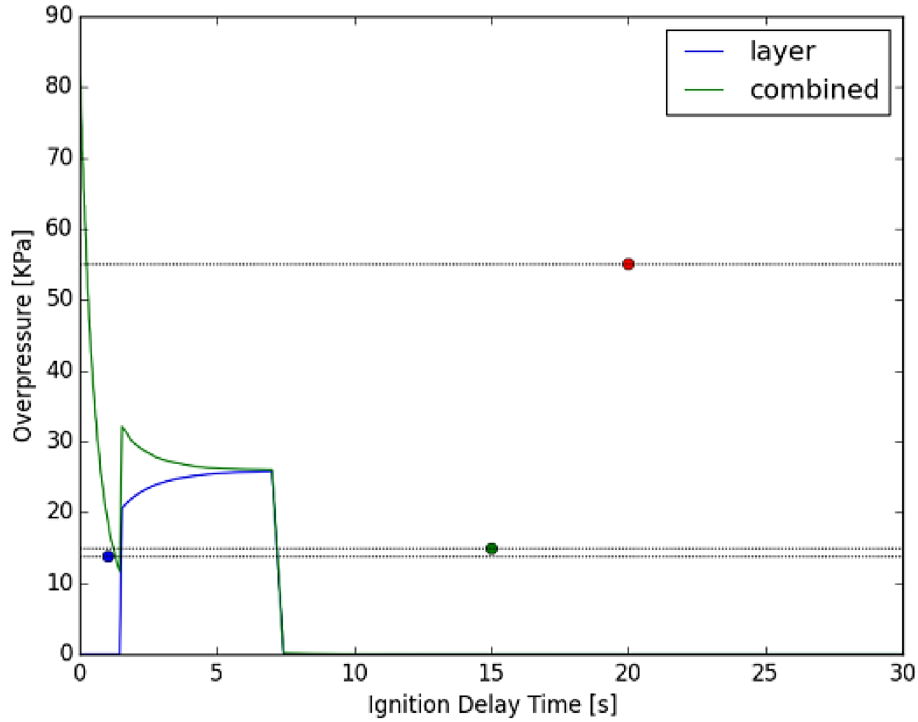


Figure 42 - Overpressure Output Pressure plot

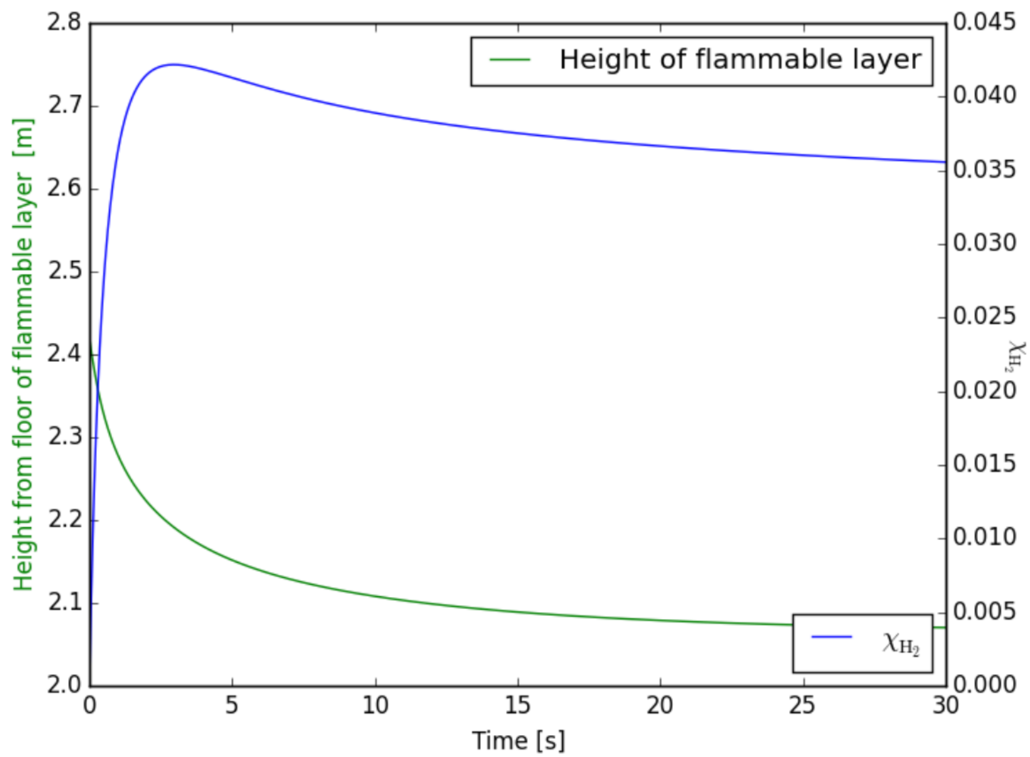


Figure 43 - Overpressure Output Layer plot

Table 10 - Overpressure Output data

Time (seconds)	Overpressure (kPa)
1	1.947e+04
2	2.973e+04
3	2.748e+04
4	2.662e+04
5	2.621e+04
6	2.607e+04
7	2.600e+04
8	1.147e+02
9	7.153e+01
10	4.453e+01
11	2.976e+01
12	2.048e+01
13	1.409e+01
14	9.446e+00
15	7.019e+00
16	4.438e+00
17	3.552e+00
18	2.848e+00
19	2.193e+00
20	1.193e+00
21	1.003e+00
22	8.466e-01
23	7.145e-01
24	5.241e-01
25	8.658e-02
26	0.000e+00
27	0.000e+00
28	0.000e+00
29	0.000e+00
29.5	0.000e+00

7.4.3. Jet Flame Output Windows

Flame Temperature/Trajectory outputs Figure 44 illustrating the flame temperature (K) at position (x, y):

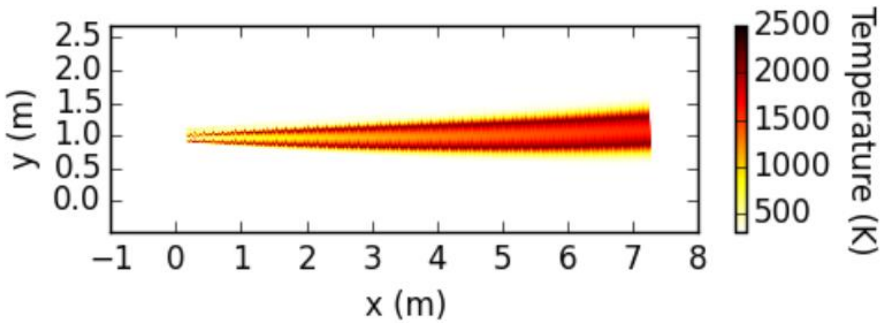


Figure 44 - Summary Flame Temperature / Trajectory output

Radiative Heat Flux outputs radiative heat flux (kW/m^2) at position [X, Y, Z] and Figure 45 illustrating three dimensional contours of where the radiative heat flux reaches three specific values: 1.577 kW/m^2 (no harm for long exposures) 4.732 kW/m^2, (pain after 20 seconds; possible first degree burn) and 25.237 kW/m^2 (100% lethality from a 60 second exposure):

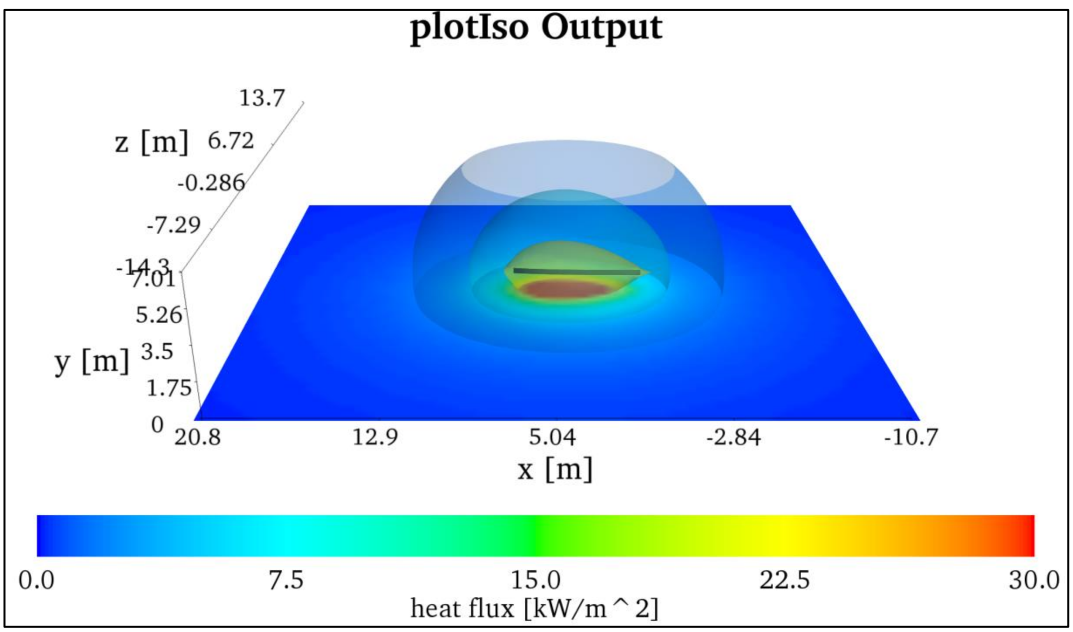


Figure 45 - Summary of Radiative Heat Flux output

Table 11 - Summary of Radiative Heat Flux data

X (m)	Y (m)	Z (m)	Flux (kW/m^2)
1	1	1	20.1951
2	2	2	11.8862
3	3	3	6.8602
4	4	4	4.0163
5	5	5	2.4640
6	6	6	1.6060
7	7	7	1.1080
8	8	8	0.8020
9	9	9	0.6035
10	10	10	0.4686

8. REFERENCES

[1] K. M. Groth, E. S. Hecht, and J. T. Reynolds (2015), *Methodology for assessing the safety of Hydrogen Systems: HyRAM 1.0 technical reference manual.* SAND2015-10216, Sandia National Laboratories, Albuquerque, NM, November.

[2] K. M. Groth, J. L. LaChance and A. P. Harris (2013). "Design-stage QRA for indoor vehicular hydrogen fueling systems;" *Proceedings of the European Society for Reliability Annual Meeting (ESREL 2013)*, Amsterdam, September 29 - October 2.

[3] K. M. Groth, J. L. LaChance and A. P. Harris (2012). *Early-Stage Quantitative Risk Assessment to Support Development of Codes and Standard Requirements for Indoor Fueling of Hydrogen Vehicles*. SAND2012-10150, Sandia National Laboratories, Albuquerque, NM November.

[4] J. LaChance, W. Houf, B. Middleton and L. Fluer (2009), *Analyses to Support Development of Risk-Informed Separation Distances for Hydrogen Codes and Standards*. SAND2009-0874, Sandia National Laboratories, Albuquerque, NM March.