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## Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) Version 5.1 Technical Reference Manual

Updated by: Brian D. Ehrhart, Ethan S. Hecht, and Benjamin B. Schroeder

Previous Contributors (chronological): Katrina M. Groth, Ethan S. Hecht, John T. Reynolds, Myra L. Blaylock, Erin E. Carrier, and Brian D. Ehrhart

Prepared by  
Sandia National Laboratories  
Albuquerque, New Mexico 87185  
Livermore, California 94550

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## **ABSTRACT**

The HyRAM+ software toolkit provides a basis for conducting quantitative risk assessment and consequence modeling for hydrogen, natural gas, and autogas systems. HyRAM+ is designed to facilitate the use of state-of-the-art models to conduct robust, repeatable assessments of safety, hazards, and risk. HyRAM+ integrates deterministic and probabilistic models for quantifying leak sizes and rates, predicting physical effects, characterizing hazards (thermal effects from jet fires, overpressure effects from delayed ignition), and assessing impacts on people. HyRAM+ is developed at Sandia National Laboratories to support the development and revision of national and international codes and standards, and to provide developed models in a publicly-accessible toolkit usable by all stakeholders.

This document provides a description of the methodology and models contained in HyRAM+ version 5.1. The most significant changes for HyRAM+ version 5.1 from HyRAM+ version 5.0 are updated default leak frequency values for propane, new default component counts for different fuel types, and an improved fuel specification view in the graphical user interface.

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## ACKNOWLEDGEMENTS

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## ACRONYMS AND TERMS

**AIR** average individual risk

**DOE** U.S. Department of Energy

**EERE** Office of Energy Efficiency and Renewable Energy

**ESD** event sequence diagram

**FAR** fatal accident rate

**FTC** failure to close

**FTO** failure to open

**HFTO** Hydrogen and Fuel Cell Technologies Office

**HSE** U.K. Health and Safety Executive

**HyRAM** Hydrogen Risk Assessment Models

**HyRAM+** Hydrogen Plus Other Alternative Fuels Risk Assessment Models

**MW** molecular weight

**NFPA** National Fire Protection Association

**PHMSA** Pipeline and Hazardous Materials Safety Administration

**PLL** potential loss of life

**PRD** pressure relief device

**QRA** quantitative risk assessment

**SI** International System of Units

**TNO** Netherlands Organisation for Applied Scientific Research

**TNT** trinitrotoluene

**VTO** Vehicle Technologies Office

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# **1. INTRODUCTION**

## **1.1. About HyRAM+ and This Report**

Hydrogen Plus Other Alternative Fuels Risk Assessment Models (HyRAM+) is a software toolkit that integrates data and methods relevant to assessing the safety of the delivery, storage, and use infrastructure of hydrogen and other alternative fuels (i.e., natural gas and propane). The HyRAM+ risk assessment calculation incorporates generic probabilities for component failures for both compressed gaseous and liquefied fuels, as well as probabilistic models for the effect of heat flux and overpressure on humans. HyRAM+ also incorporates experimentally validated models of various aspects of release and flame behavior. The HyRAM+ toolkit can be used to support multiple types of analysis, including code and standards development, safety basis development, and facility safety planning.

This report provides technical documentation of the algorithms, models, and data incorporated in HyRAM+ version 5.1. HyRAM+ version 5.1 is a revised version of the software, and this report has a lot of similar content due to similarities between the previous versions of this software, as well as several versions of the previously named Hydrogen Risk Assessment Models (HyRAM) software. This report and the HyRAM+ software builds off of the models and implementations from those earlier versions [1–7].

HyRAM+ is free and open source software: you can redistribute it and/or modify it under the terms of the GNU General Public License version 3, as published by the Free Software Foundation. This program is distributed in the hope that it will be useful, but WITHOUT ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or FITNESS FOR A PARTICULAR PURPOSE. See the GNU General Public License for more details (<https://www.gnu.org/licenses/gpl-3.0.html>).

## **1.2. Design Goals and Limitations**

HyRAM+ is designed to calculate multiple risk and harm/damage metrics from user-defined system configurations to provide insights for stakeholders in the safety, codes, and standards community [7–10]. HyRAM+ contains default inputs and fast-running, reduced-order models designed to facilitate comparison of different system designs and requirements. Reduced-order models use simplifying assumptions to approximate behavior much more quickly than more complex high-fidelity models. As such, the focus of HyRAM+ is on enabling systematic, defensible risk and consequence assessments for use in risk comparisons and sensitivity analyses, rather than a focus on absolute model accuracy.

Risk and safety assessment results should be used as part of a decision-making process, not as the sole basis for a decision. Safety and design decisions involve consideration of many factors and judgments; these factors include the safety assessments, the assumptions and limitations of safety assessments, the benefits of a technology, and public preferences. As such, HyRAM+ does not allow the user to specify an acceptability or tolerability criteria for risk or harm.

HyRAM+ is designed to enable defensible, repeatable calculations using documented algorithms. The algorithms, models, and data in HyRAM+ have been assembled from published, publicly available sources. The physics models contained in HyRAM+ have been validated against available experimental data [11–14]. Where model validation is lacking (e.g., for harm models), HyRAM+ often allows users to choose among different models. HyRAM+ includes default data for component leak frequencies, which are in most cases specific to the fuel. HyRAM+ also includes documented, expert-assigned probabilities for ignition. HyRAM+ is designed to allow users to replace the default parameters (e.g., leak frequency distribution parameters for every component) and assumptions with system-specific information when such information is available to the user.

### **1.3. Summary of HyRAM+ Outputs**

The quantitative risk assessment (QRA) mode in HyRAM+ can be used to calculate risk metrics which are commonly used to evaluate fatality risk in multiple industries [7–10], as well as other incident frequency information:

- Fatal Accident Rate (FAR), the expected number of fatalities in 100 million exposed hours
- Average Individual Risk (AIR), the expected number of fatalities per year per exposed individual
- Potential Loss of Life (PLL), the expected number of fatalities per system-year
- Expected number of releases per system-year (unignited and ignited cases)
- Expected number of jet fires per system-year (immediate ignition cases)
- Expected number of overpressures per system-year (delayed ignition cases)

The physics mode of HyRAM+ can be used to calculate multiple physical effects associated with hydrogen, methane, propane, and blends, including:

- Concentration for an unignited plume
- Jet flame temperature and trajectory
- Jet flame radiative heat flux
- Time histories of concentration, flammable mass, and overpressure due to accumulation and delayed ignition in an enclosure
- Overpressure from the delayed ignition of a jet/plume

## 1.4. Summary of Changes Made

HyRAM+ is an open source software, meaning that changes to the code can be observed directly<sup>1</sup>. However, a summary of major changes to the models is included here for ease of reference.

The most significant changes for HyRAM+ version 5.1 from HyRAM+ version 5.0 are updated default leak frequency values for propane, new default component counts for different fuel types, and an improved fuel specification view in the graphical user interface.

Other changes include:

- Added ability to output streamline and  $x$ -/ $y$ -distances to mole fractions for an unignited plume
- Added carbon monoxide as a potential fuel in the Python backend
- Added validation test suite for hydrogen physics based on the SAND2021-5811 report [11]
- Fixed a bug that was not allowing heat flux contours to be changed using the graphical user interface
- Bauwens/Dorofeev unconfined overpressure model now calculates limited, finite overpressure value very close to overpressure-origin to avoid division-by-zero
- Simplified graphical user interface forms
- Added flammability limits as optional input to the Physics overpressure calculation
- Added flammable mass (detonable mass for Bauwens model) as an output to the Physics API overpressure calculation
- Calculation of Planck mean absorption coefficient (used in radiant fraction calculation) is now automatic based on the fuel
- Removed default random seed value for QRA in Python, so that a new value will be used for each run
- Improved QRA calculation speed by avoiding re-doing redundant calculations

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<sup>1</sup>More detailed changes are given in the source code changelog: <https://github.com/sandialabs/hyram/blob/master/CHANGELOG.md>

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## 2. QUANTITATIVE RISK ASSESSMENT METHODOLOGY

In a QRA, multiple models are used together to provide a framework for reasoning about decision options, based on the input information used in those models. HyRAM+ includes a QRA mode, which provides calculations and models relevant to estimating the risk of systems for hydrogen and other alternative fuels. The consequences and fatality risk of jet flames and overpressures are estimated for different release sizes, each of which can be predicted to occur with different frequencies [7–10, 15]. These calculations use a subset of the models available in physics mode to estimate the release behavior (see Section 3).

### 2.1. Quantitative Risk Assessment Methodology Overview

Risk is characterized by a set of hazard exposure scenarios ( $i$ ), the consequences ( $c_i$ ) associated with each scenario, and the probability of occurrence ( $p_i$ ) of these consequences. One commonly used general expression for calculating risk is shown in Equation 1 [6, 15].

$$\text{Risk} = \sum_i (p_i \times c_i) \quad (1)$$

In a QRA, the consequences are expressed in terms of an observable quantity, such as number of fatalities or repair cost in a specific period of time. In HyRAM+, the number of fatalities is used as the safety metric of interest. The general expression shown in Equation 1 shows risk as a product of probability; depending on the application, risk may be characterized using either probability or frequency. The rest of this section will describe the specific implementation for risk calculations in HyRAM+.

### 2.2. Risk Metrics Calculations

There are multiple metrics used to express the fatality risk for a system under consideration. One such metric is the Potential Loss of Life (PLL), which expresses the expected number of fatalities per system-year. The PLL calculation is shown in Equation 2, where  $n$  is one of the possible safety-significant scenarios (described in Section 2.3),  $f_n$  is the frequency of that accident scenario  $n$  (described in Sections 2.3 and 2.4), and  $c_n$  is the expected number of fatalities for accident scenario  $n$  (described in Section 2.5) [7, 10].

$$\text{PLL} = \sum_n (f_n \times c_n) \quad (2)$$

Another risk metric related to the PLL is the Fatal Accident Rate (FAR), which is the expected number of fatalities in a group, per 100 million exposed hours. The FAR for a particular facility can be calculated using the PLL and the population of the facility [10]. The FAR is calculated using Equation 3, where  $N_{pop}$  is the average number of personnel in the facility, and dividing by 8760 converts from years to hours (24 hours per day and 365 days per year) [7, 15].

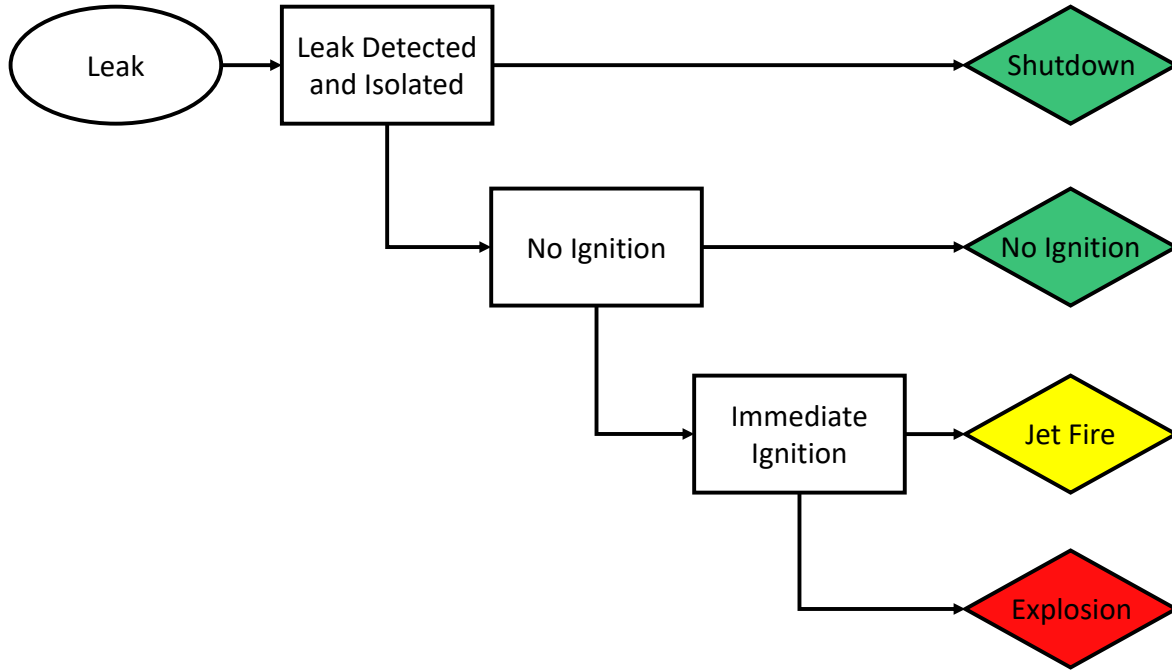
$$FAR = \frac{PLL \times 10^8}{\text{Exposed hours}} = \frac{PLL \times 10^8}{N_{pop} \times 8760} \quad (3)$$

The third metric used in HyRAM+ is the Average Individual Risk (AIR), which expresses the average number of fatalities per year per exposed individual. It is based on the number of hours the average occupant spends at the facility [10]. The AIR is calculated using Equation 4, where  $H$  is the annual number of hours the individual spends in the facility (e.g., 2000 hours for full-time worker) [7, 15].

$$AIR = H \times FAR \times 10^{-8} \quad (4)$$

### 2.3. Scenario Models

A release of a flammable fuel could lead to several different physical consequences and associated hazards. For continuous releases of a fuel, the physical consequences are unignited releases, jet fires (thermal effects), flash fires or fireballs (deflagration of accumulated gas dominated by thermal effects), and explosions (deflagration or detonation of accumulated gas dominated by overpressure effects) [7, 9, 10]. Currently, HyRAM+ calculates harm from thermal effects of jet fires (for immediate ignition) and overpressure (for delayed ignition). A release of a liquid fuel (e.g., liquid hydrogen or liquid natural gas) may also form a pool on the ground, but this is currently not considered in HyRAM+, nor are the thermal effects from the cold temperatures of these liquid fuels. These scenarios are modeled using an event sequence diagram (ESD) for release of a flammable fuel (see Figure 2-1).



**Figure 2-1: Event sequence diagram used by HyRAM+ for flammable gas releases [5].**

The ESD is implemented in HyRAM+ using Equations 5–8 where  $f_{\text{Release}}$  is the annual frequency of a release (see Section 2.4),  $p_{\text{Isolated}}$  is the probability of release (leak) detection and isolation before ignition (see Section 2.3.1),  $p_{\text{Immed. Ignite}}$  is the probability of immediate ignition (see Section 2.3.2), and  $p_{\text{Delayed Ignite}}$  is the probability of delayed ignition (see Section 2.3.2) [5].

$$f_{\text{Isolated}} = f_{\text{Release}} \times p_{\text{Isolated}} \quad (5)$$

$$f_{\text{Unignited}} = f_{\text{Release}} \times (1 - p_{\text{Isolated}}) \times (1 - p_{\text{Immed. Ignite}} - p_{\text{Delayed Ignite}}) \quad (6)$$

$$f_{\text{Jetfire}} = f_{\text{Release}} \times (1 - p_{\text{Isolated}}) \times p_{\text{Immed. Ignite}} \quad (7)$$

$$f_{\text{Explosion}} = f_{\text{Release}} \times (1 - p_{\text{Isolated}}) \times p_{\text{Delayed Ignite}} \quad (8)$$

These equations are defined differently than is typically seen for an ESD, in which each top level event (split) in the ESD is defined with a probability and complementary probability. These equations are written in this way to utilize immediate and delayed ignition probabilities that are each defined as conditional to a leak occurring (see Section 2.3.2). Thus, there are three possible ignition outcomes, and so a top level event was added to the ESD for immediate vs. delayed ignition for ease of viewing, even if the equations are written so that the ignition probabilities in Section 2.3.2 can be used directly.

### 2.3.1. Default Detection and Isolation Probability

The default value for successful detection and isolation of a release ( $p_{\text{Isolate}}$ ) is 0.9 [7]. This value incorporates many considerations on detection and isolation including: ventilation, sensor placement, leak location, and the ability of the sensor and isolation valve to operate successfully on demand.

**Note:** This value can vary significantly based on a particular system setup, and so the user/analyst needs to carefully consider the particulars of the system being assessed and decide if this default value is appropriate.

### 2.3.2. Default Ignition Probabilities

The default ignition probabilities are a function of release rate and are given in Table 2-1 [16]. It should be noted that both the immediate and delayed ignition probabilities are both relative to a release rate; the delayed ignition probability is not conditional upon the immediate ignition having not occurred. The total probability of ignition is the immediate and delayed ignition probabilities added together.

**Table 2-1: Default ignition probabilities for different fuels.**

| (a) Hydrogen        |                                |         | (b) Methane and Propane |                                |         |
|---------------------|--------------------------------|---------|-------------------------|--------------------------------|---------|
| Release Rate (kg/s) | Ignition Probability Immediate | Delayed | Release Rate (kg/s)     | Ignition Probability Immediate | Delayed |
| <0.125              | 0.008                          | 0.004   | <1                      | 0.007                          | 0.003   |
| 0.125–6.25          | 0.053                          | 0.027   | 1–50                    | 0.047                          | 0.023   |
| >6.25               | 0.230                          | 0.120   | >50                     | 0.200                          | 0.100   |

## 2.4. Frequency of a Release

HyRAM+ estimates the annual frequency of a release for release sizes of 0.01%, 0.1%, 1%, 10%, or 100% of pipe flow area [7–10]. These release sizes are relative to the pipe flow area ( $A$ ) as shown in Equation 9, where  $C_d$  is the discharge coefficient, and  $d$  is the inner diameter of the pipe. The leak sizes are all relative to the size of the interconnecting piping, so leaks from all components are assumed to be the same size.

$$A = \frac{\pi}{4} C_d d^2 \quad (9)$$

The annual frequency of a release for each of the four smallest release sizes ( $f_{\text{Release},k}$ ,  $k = 0.01\%$ ,  $0.1\%$ ,  $1\%$ , and  $10\%$ ) is only due to the annual frequency of random leaks ( $f_{\text{Random Releases},k}$ , see Section 2.4.1), as shown in Equation 10 [7, 15].

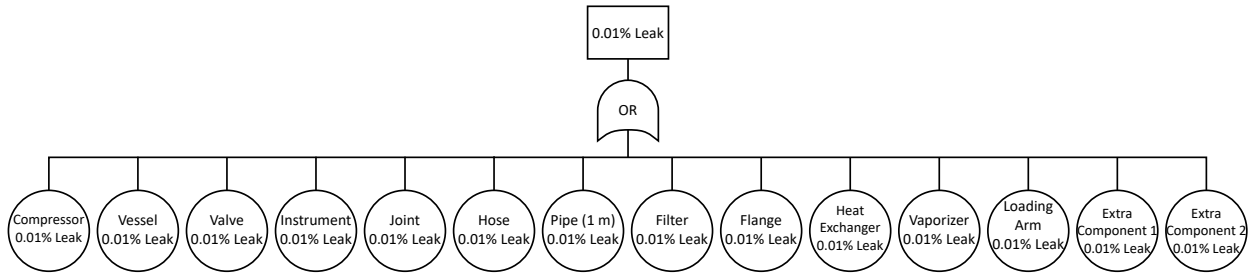
$$f_{\text{Release},k} = f_{\text{Random Releases},k} \quad (10)$$

The annual frequency of the largest release size (100%) is due to both random leaks (see Section 2.4.1) and other releases (i.e., dispenser failures, see Section 2.4.4), as shown in Equation 11 [7].

$$f_{\text{Release}, k=100\%} = f_{\text{Random Releases}, k=100\%} + f_{\text{Other Releases}} \quad (11)$$

### 2.4.1. Frequency of Random Leaks

The annual frequency of random leaks is obtained for each release size using a fault tree [5]. As an example, the fault tree for random leaks for leak size 0.01% is shown in Figure 2-2. The fault trees for random leaks for all other leak sizes are analogous per leak size.



**Figure 2-2: Fault tree for random leaks of size 0.01% from components.**

These fault trees are implemented in HyRAM+ to combine individual component leak frequencies into an overall system leak frequency for each leak size. The annual frequency of random leaks ( $f_{\text{Random Releases},k}$ ) is calculated using Equation 12 for each release of size  $k$  by combining the individual component leak frequencies for all the components in the system of interest, where  $N_{\text{Component}_i}$  is the number of components of each type and  $f_{\text{Leak}_{i,k}}$  is the leak frequency of size  $k$  for component  $i$  (see Section 2.4.3) [7]. This implementation assumes that the causes in the fault tree (leaks) are mutually exclusive; this is because a hydrogen leak in a system can result in a shutdown of the system itself, thereby precluding other releases<sup>2</sup>.

$$f_{\text{Random Releases},k} = \sum_i N_{\text{Component}_i} \times f_{\text{Leak}_{i,k}} \quad (12)$$

The component types are Vessels (Cylinders/Tanks), Compressors, Flanges, Hoses, Joints, Pipes<sup>3</sup>, Valves, Filters, Instruments, Heat Exchangers, Loading Arms, Vaporizers, Extra Component #1,

<sup>2</sup>While simultaneous releases are still possible, depending on how quickly a system shutdown can occur, treating the events as mutually exclusive will lead to a higher (and therefore more conservative) leak frequency compared to treating leak events as independent.

<sup>3</sup>The "Pipes" component type is per-meter of pipe; so if a system has 15 m worth of piping, then the "number" of components for that type is 15. By contrast, the "Hoses" component type is specified as per-hose, not per-length.

and Extra Component #2. Some of these components are only used for gaseous fuels (e.g., Compressors), while some are only used for liquid fuels (e.g., Vaporizers), although all are available as inputs for either gaseous or liquid fuels [3].

#### 2.4.2. Default Component Counts

Default component count values are meant to ease exploration of the tool and should be modified by users to represent their system of interest. Default component counts were informed by systems found in the literature. Users' systems may not contain all types of components supported by HyRAM+ due to either that component type not being relevant to the fuel type or the system design simply not including the component type; both of which were true for the reference literature systems. The default component count values are shown in Table 2-2.

**Table 2-2: Default component counts for different fuels types.**

| Component       | Gaseous Hydrogen | Liquid Hydrogen | Gaseous Methane | Liquid Methane | Propane |
|-----------------|------------------|-----------------|-----------------|----------------|---------|
| Compressors     | 1*               | -               | 1*              | -              | 1*      |
| Vessels         | 2                | 1               | 2               | 1              | 1       |
| Filters         | 3                | -               | 3               | -              | 2       |
| Flanges         | -                | 8               | -               | 8              | 8       |
| Hoses           | 1                | 1*              | 1               | 1*             | 1*      |
| Joints          | 43               | -               | 43              | -              | -       |
| Pipes           | 30               | 30*             | 30              | 30*            | 30*     |
| Valves          | 7                | 44              | 7               | 44             | 44      |
| Instruments     | 5                | -               | 5               | -              | -       |
| Heat Exchangers | -                | -               | 1*              | 1*             | -       |

\* indicates alteration to values specified in referenced system

Gaseous hydrogen component counts are based upon the complete fork lift fueling system specified in Groth et al. [15] with a compressor added based on the judgment that this would be necessary for the system. Component counts for liquid hydrogen systems come from a liquid hydrogen bulk supply system specified within CGA P-28 2014 [17], but a hose and increased length of pipe were included based on engineering judgment. Gaseous methane and blends utilize the gaseous hydrogen component counts, while liquid methane and propane use the liquid hydrogen component counts. Whenever a component type leak frequency is not specified for a fuel type, which may be due to lack of data, then the default component count for that component is zero. A heat exchanger was added to the gaseous and liquid methane component counts due to leak frequencies for that component being available for those fuels and a compressor was similarly added for propane. Deviations from the reference literature systems are indicated in Table 2-2 by a \*.

### 2.4.3. Default Component Leak Frequencies

In HyRAM+, the annual frequency of a random leak ( $f_{\text{Leak},i,k}$ ) for component  $i$  and leak size  $k$  is assumed to be distributed as a lognormal distribution with parameters  $\mu$  and  $\sigma$ , as noted in Equation 13 [7–10, 15].

$$f_{\text{Leak},i,k} \sim \text{Lognormal}(\mu, \sigma^2) \quad (13)$$

The geometric mean (which is equal to the median for lognormal distributions) values are used in the frequency calculations in HyRAM+ as a metric of central-tendency for the distribution<sup>4</sup> [5]. The geometric mean is calculated using Equation 14.

$$\text{median} = e^{\mu} \quad (14)$$

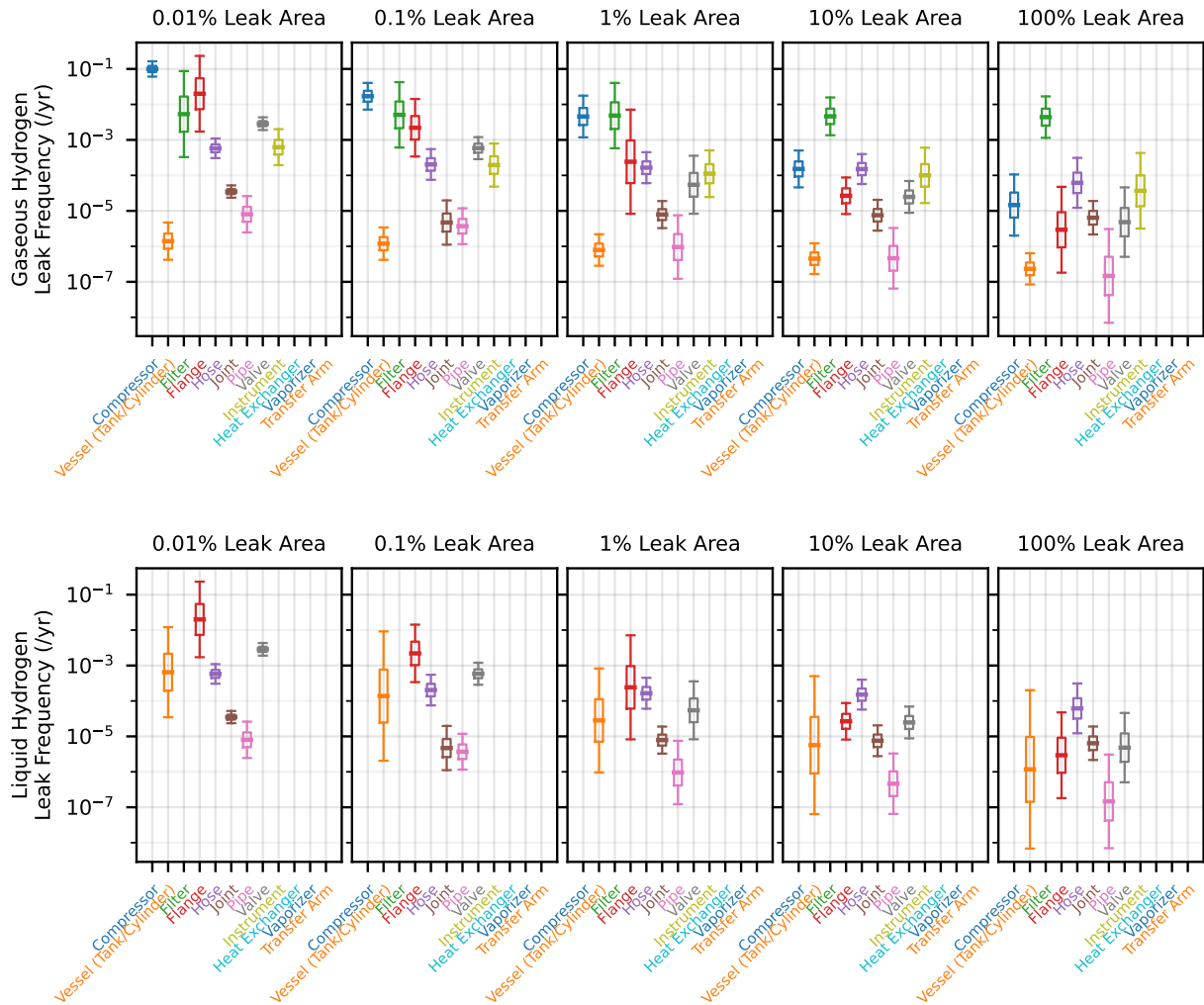
The default values for compressed hydrogen are based on generic system leak frequencies and data from compressed hydrogen systems developed by LaChance et al. [18] and updated by both Groth et al. [15] and Glover et al. [19]. For liquid hydrogen, leak frequencies were determined using gaseous hydrogen and liquefied natural gas data as outlined by Brooks et al. [20]. For compressed methane, values from the analysis by Brooks et al. are used [21]. For liquid methane, the analysis described by Mulcahy et al. [22] was used. For propane, values were estimated by Brooks and Ehrhart [23] based on generic and liquid propane gas data. The  $\mu$  and  $\sigma$  parameters were obtained from fitted distributions based on the reported distribution results from each of the original sources [3]. The default leak frequency distributions for each component are shown in Figures 2-3–2-5, and the default parameters and median values for the distributions are listed in Table 2-3.

There are two extra components: Extra Component #1 and Extra Component #2 which might not fall into the other component type categories [5]. The intention is that users can specify a custom leak frequency distribution for these components while still keeping the leak frequency distributions for the other components. These are meant to be set by the user.

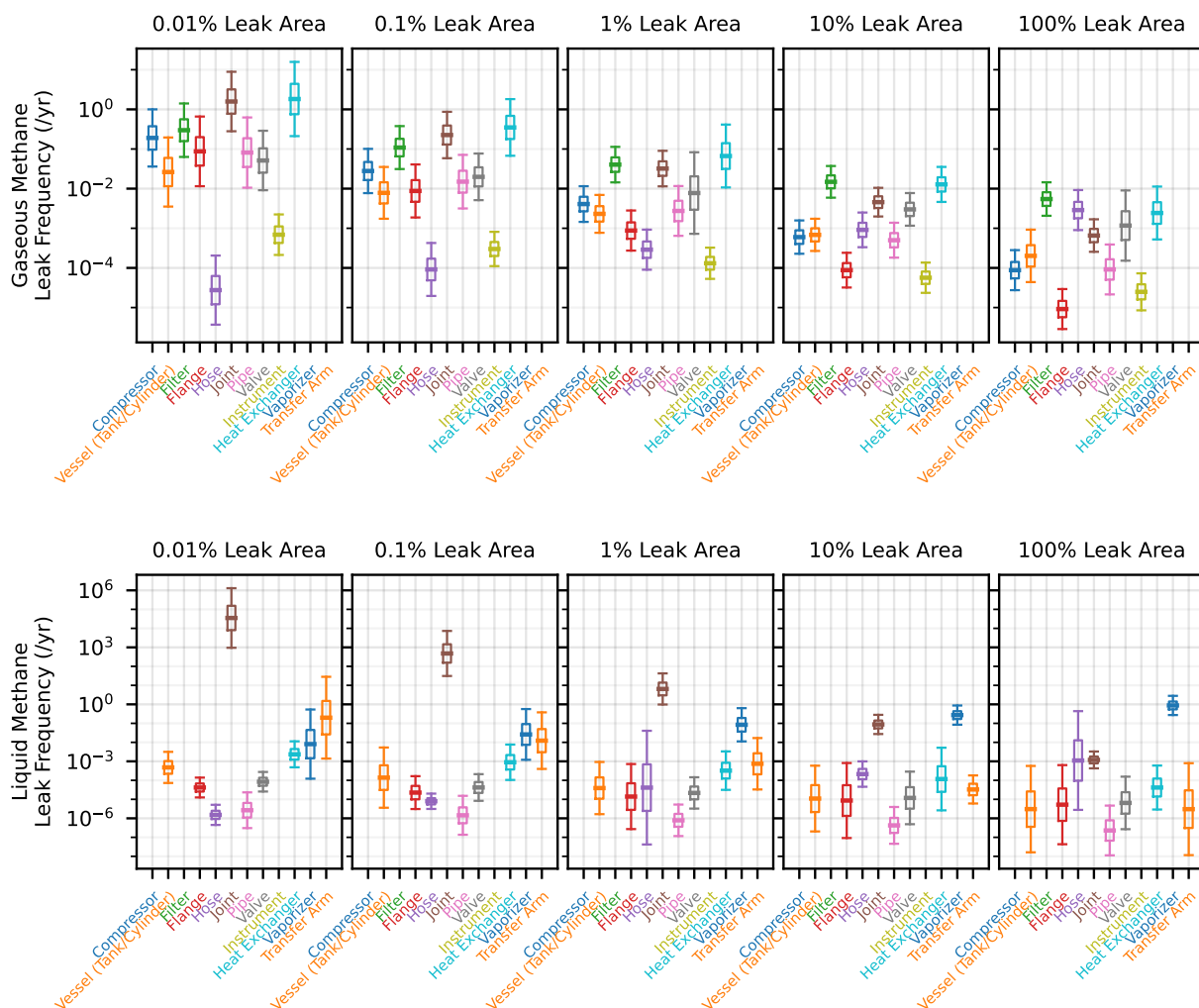
For each component for which there is no data for a specific fuel, the mean and median leak frequencies are set to infinity, with  $\mu$  and  $\sigma$  set to 999 to achieve this effect [3]. If a user has data for these components for a specific fuel, they can be updated. If a user does not have specific information for these components for the specific fuel of interest, leak frequency distribution parameters for another fuel or another component could be used as a proxy. By making the default median frequency infinity, the risk metric will result in a value of infinity if one of these components is included in the system without leak frequency data, thereby alerting the user.

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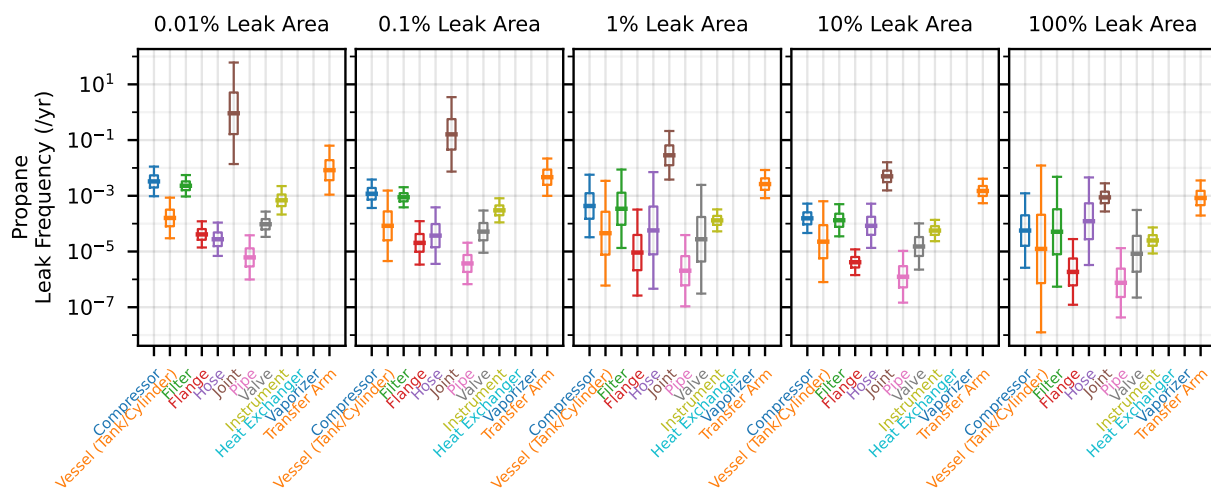
<sup>4</sup>Currently, only the geometric mean (median) leak frequency is used in risk calculations; future versions of HyRAM+ may use additional information from the lognormal distribution in uncertainty propagation.



**Figure 2-3: Box and whisker plots of gaseous hydrogen (top) and liquid hydrogen (bottom) leak frequencies for the different components and each leak size. The thick central line is the median leak frequency, the boxes show the 25<sup>th</sup> and 75<sup>th</sup> percentiles of the distribution and the whiskers show the 5<sup>th</sup> and 95<sup>th</sup> percentiles.**



**Figure 2-4: Box and whisker plots of gaseous methane (top) and liquid methane (bottom) leak frequencies for the different components and each leak size. The thick central line is the median leak frequency, the boxes show the 25<sup>th</sup> and 75<sup>th</sup> percentiles of the distribution and the whiskers show the 5<sup>th</sup> and 95<sup>th</sup> percentiles.**



**Figure 2-5: Box and whisker plot of propane (same default values for both gaseous and liquid) leak frequencies for the different components and each leak size. The thick central line is the median leak frequency, the boxes show the 25<sup>th</sup> and 75<sup>th</sup> percentiles of the distribution and the whiskers show the 5<sup>th</sup> and 95<sup>th</sup> percentiles.**

**Table 2-3: Default parameters for frequency of random leaks for individual components.**

| Component              | Leak Size | Gaseous Hydrogen |          |                      | Liquid Hydrogen |          |                      | Gaseous Methane |          |                      | Liquid Methane |          |                      | Propane |          |                      |
|------------------------|-----------|------------------|----------|----------------------|-----------------|----------|----------------------|-----------------|----------|----------------------|----------------|----------|----------------------|---------|----------|----------------------|
|                        |           | $\mu$            | $\sigma$ | median               | $\mu$           | $\sigma$ | median               | $\mu$           | $\sigma$ | median               | $\mu$          | $\sigma$ | median               | $\mu$   | $\sigma$ | median               |
| Compressor             | 0.01%     | -2.3             | 0.3      | $1.0 \times 10^{-1}$ | 999             | 999      | $\infty$             | -1.7            | 1.0      | $1.9 \times 10^{-1}$ | 999            | 999      | $\infty$             | -5.7    | 0.7      | $3.3 \times 10^{-3}$ |
|                        | 0.1%      | -4.1             | 0.5      | $1.7 \times 10^{-2}$ | 999             | 999      | $\infty$             | -3.6            | 0.8      | $2.8 \times 10^{-2}$ | 999            | 999      | $\infty$             | -6.7    | 0.7      | $1.2 \times 10^{-3}$ |
|                        | 1%        | -5.4             | 0.8      | $4.6 \times 10^{-3}$ | 999             | 999      | $\infty$             | -5.5            | 0.6      | $4.1 \times 10^{-3}$ | 999            | 999      | $\infty$             | -7.8    | 1.6      | $4.3 \times 10^{-4}$ |
|                        | 10%       | -8.8             | 0.7      | $1.5 \times 10^{-4}$ | 999             | 999      | $\infty$             | -7.4            | 0.6      | $6.0 \times 10^{-4}$ | 999            | 999      | $\infty$             | -8.8    | 0.7      | $1.6 \times 10^{-4}$ |
|                        | 100%      | -11.1            | 1.2      | $1.5 \times 10^{-5}$ | 999             | 999      | $\infty$             | -9.3            | 0.7      | $8.8 \times 10^{-5}$ | 999            | 999      | $\infty$             | -9.8    | 1.9      | $5.7 \times 10^{-5}$ |
| Vessel (Tank/Cylinder) | 0.01%     | -13.5            | 0.7      | $1.4 \times 10^{-6}$ | -7.3            | 1.8      | $6.5 \times 10^{-4}$ | -3.6            | 1.2      | $2.6 \times 10^{-2}$ | -7.6           | 1.1      | $4.8 \times 10^{-4}$ | -8.7    | 1.0      | $1.6 \times 10^{-4}$ |
|                        | 0.1%      | -13.6            | 0.6      | $1.2 \times 10^{-6}$ | -8.9            | 2.6      | $1.4 \times 10^{-4}$ | -4.8            | 0.9      | $7.8 \times 10^{-3}$ | -8.9           | 2.2      | $1.4 \times 10^{-4}$ | -9.4    | 1.8      | $8.4 \times 10^{-5}$ |
|                        | 1%        | -14.1            | 0.6      | $7.9 \times 10^{-7}$ | -10.5           | 2.1      | $2.8 \times 10^{-5}$ | -6.1            | 0.7      | $2.3 \times 10^{-3}$ | -10.1          | 1.9      | $3.9 \times 10^{-5}$ | -10.0   | 2.6      | $4.5 \times 10^{-5}$ |
|                        | 10%       | -14.6            | 0.6      | $4.5 \times 10^{-7}$ | -12.1           | 2.7      | $5.7 \times 10^{-6}$ | -7.3            | 0.6      | $6.8 \times 10^{-4}$ | -11.4          | 2.4      | $1.1 \times 10^{-5}$ | -10.7   | 2.0      | $2.3 \times 10^{-5}$ |
|                        | 100%      | -15.3            | 0.6      | $2.3 \times 10^{-7}$ | -13.7           | 3.1      | $1.2 \times 10^{-6}$ | -8.5            | 0.9      | $2.0 \times 10^{-4}$ | -12.7          | 3.2      | $3.1 \times 10^{-6}$ | -11.3   | 4.2      | $1.2 \times 10^{-5}$ |
| Filter                 | 0.01%     | -5.2             | 1.7      | $5.3 \times 10^{-3}$ | 999             | 999      | $\infty$             | -1.2            | 0.9      | $3.0 \times 10^{-1}$ | 999            | 999      | $\infty$             | -6.1    | 0.5      | $2.3 \times 10^{-3}$ |
|                        | 0.1%      | -5.3             | 1.3      | $5.1 \times 10^{-3}$ | 999             | 999      | $\infty$             | -2.2            | 0.8      | $1.1 \times 10^{-1}$ | 999            | 999      | $\infty$             | -7.0    | 0.5      | $8.8 \times 10^{-4}$ |
|                        | 1%        | -5.3             | 1.3      | $4.8 \times 10^{-3}$ | 999             | 999      | $\infty$             | -3.2            | 0.6      | $4.0 \times 10^{-2}$ | 999            | 999      | $\infty$             | -8.0    | 2.0      | $3.4 \times 10^{-4}$ |
|                        | 10%       | -5.4             | 0.7      | $4.6 \times 10^{-3}$ | 999             | 999      | $\infty$             | -4.2            | 0.6      | $1.5 \times 10^{-2}$ | 999            | 999      | $\infty$             | -8.9    | 0.8      | $1.3 \times 10^{-4}$ |
|                        | 100%      | -5.4             | 0.8      | $4.4 \times 10^{-3}$ | 999             | 999      | $\infty$             | -5.2            | 0.6      | $5.5 \times 10^{-3}$ | 999            | 999      | $\infty$             | -9.9    | 2.8      | $5.1 \times 10^{-5}$ |
| Flange                 | 0.01%     | -3.9             | 1.5      | $2.0 \times 10^{-2}$ | -3.9            | 1.5      | $2.0 \times 10^{-2}$ | -2.4            | 1.2      | $8.7 \times 10^{-2}$ | -10.1          | 0.7      | $4.2 \times 10^{-5}$ | -10.1   | 0.7      | $4.1 \times 10^{-5}$ |
|                        | 0.1%      | -6.1             | 1.1      | $2.2 \times 10^{-3}$ | -6.1            | 1.1      | $2.2 \times 10^{-3}$ | -4.7            | 0.9      | $8.7 \times 10^{-3}$ | -10.7          | 1.2      | $2.3 \times 10^{-5}$ | -10.8   | 1.1      | $2.0 \times 10^{-5}$ |
|                        | 1%        | -8.3             | 2.1      | $2.4 \times 10^{-4}$ | -8.3            | 2.1      | $2.4 \times 10^{-4}$ | -7.0            | 0.7      | $8.8 \times 10^{-4}$ | -11.2          | 2.4      | $1.4 \times 10^{-5}$ | -11.6   | 2.2      | $9.2 \times 10^{-6}$ |
|                        | 10%       | -10.5            | 0.7      | $2.7 \times 10^{-5}$ | -10.5           | 0.7      | $2.7 \times 10^{-5}$ | -9.3            | 0.6      | $8.8 \times 10^{-5}$ | -11.7          | 2.8      | $8.6 \times 10^{-6}$ | -12.4   | 0.6      | $4.1 \times 10^{-6}$ |
|                        | 100%      | -12.7            | 1.7      | $2.9 \times 10^{-6}$ | -12.7           | 1.7      | $2.9 \times 10^{-6}$ | -11.6           | 0.7      | $9.2 \times 10^{-6}$ | -12.2          | 2.9      | $5.2 \times 10^{-6}$ | -13.2   | 1.6      | $1.9 \times 10^{-6}$ |
| Hose                   | 0.01%     | -7.5             | 0.4      | $5.8 \times 10^{-4}$ | -7.5            | 0.4      | $5.8 \times 10^{-4}$ | -10.5           | 1.2      | $2.8 \times 10^{-5}$ | -13.4          | 0.7      | $1.5 \times 10^{-6}$ | -10.5   | 0.8      | $2.8 \times 10^{-5}$ |
|                        | 0.1%      | -8.5             | 0.6      | $2.0 \times 10^{-4}$ | -8.5            | 0.6      | $2.0 \times 10^{-4}$ | -9.3            | 0.9      | $9.1 \times 10^{-5}$ | -11.7          | 0.6      | $7.9 \times 10^{-6}$ | -10.2   | 1.4      | $3.7 \times 10^{-5}$ |
|                        | 1%        | -8.7             | 0.6      | $1.6 \times 10^{-4}$ | -8.7            | 0.6      | $1.6 \times 10^{-4}$ | -8.2            | 0.7      | $2.9 \times 10^{-4}$ | -10.1          | 4.2      | $4.1 \times 10^{-5}$ | -9.8    | 2.9      | $5.7 \times 10^{-5}$ |
|                        | 10%       | -8.8             | 0.6      | $1.5 \times 10^{-4}$ | -8.8            | 0.6      | $1.5 \times 10^{-4}$ | -7.0            | 0.6      | $9.1 \times 10^{-4}$ | -8.5           | 0.9      | $2.1 \times 10^{-4}$ | -9.4    | 1.1      | $8.4 \times 10^{-5}$ |
|                        | 100%      | -9.7             | 1.0      | $6.2 \times 10^{-5}$ | -9.7            | 1.0      | $6.2 \times 10^{-5}$ | -5.8            | 0.7      | $2.9 \times 10^{-3}$ | -6.8           | 3.6      | $1.1 \times 10^{-3}$ | -9.0    | 2.2      | $1.2 \times 10^{-4}$ |
| Joint                  | 0.01%     | -10.3            | 0.2      | $3.5 \times 10^{-5}$ | -10.3           | 0.2      | $3.5 \times 10^{-5}$ | 0.5             | 1.1      | $1.6 \times 10^0$    | 10.5           | 2.2      | $3.5 \times 10^4$    | -0.1    | 2.5      | $9.2 \times 10^{-1}$ |
|                        | 0.1%      | -12.3            | 0.9      | $4.7 \times 10^{-6}$ | -12.3           | 0.9      | $4.7 \times 10^{-6}$ | -1.5            | 0.8      | $2.3 \times 10^{-1}$ | 6.2            | 1.7      | $4.8 \times 10^2$    | -1.8    | 1.9      | $1.6 \times 10^{-1}$ |
|                        | 1%        | -11.8            | 0.5      | $7.9 \times 10^{-6}$ | -11.8           | 0.5      | $7.9 \times 10^{-6}$ | -3.4            | 0.6      | $3.2 \times 10^{-2}$ | 1.9            | 1.1      | $6.5 \times 10^0$    | -3.6    | 1.2      | $2.8 \times 10^{-2}$ |
|                        | 10%       | -11.8            | 0.6      | $7.5 \times 10^{-6}$ | -11.8           | 0.6      | $7.5 \times 10^{-6}$ | -5.4            | 0.5      | $4.6 \times 10^{-3}$ | -2.4           | 0.7      | $8.8 \times 10^{-2}$ | -5.3    | 0.7      | $5.0 \times 10^{-3}$ |
|                        | 100%      | -12.0            | 0.7      | $6.4 \times 10^{-6}$ | -12.0           | 0.7      | $6.4 \times 10^{-6}$ | -7.3            | 0.6      | $6.6 \times 10^{-4}$ | -6.7           | 0.6      | $1.2 \times 10^{-3}$ | -7.0    | 0.7      | $8.8 \times 10^{-4}$ |
| Pipe                   | 0.01%     | -11.7            | 0.7      | $8.0 \times 10^{-6}$ | -11.7           | 0.7      | $8.0 \times 10^{-6}$ | -2.5            | 1.2      | $8.1 \times 10^{-2}$ | -12.8          | 1.3      | $2.7 \times 10^{-6}$ | -12.0   | 1.1      | $6.1 \times 10^{-6}$ |
|                        | 0.1%      | -12.5            | 0.7      | $3.7 \times 10^{-6}$ | -12.5           | 0.7      | $3.7 \times 10^{-6}$ | -4.2            | 0.9      | $1.5 \times 10^{-2}$ | -13.4          | 1.4      | $1.4 \times 10^{-6}$ | -12.5   | 1.0      | $3.7 \times 10^{-6}$ |
|                        | 1%        | -13.9            | 1.3      | $9.6 \times 10^{-7}$ | -13.9           | 1.3      | $9.6 \times 10^{-7}$ | -5.9            | 0.9      | $2.7 \times 10^{-3}$ | -14.1          | 1.2      | $7.9 \times 10^{-7}$ | -13.1   | 1.8      | $2.0 \times 10^{-6}$ |
|                        | 10%       | -14.6            | 1.2      | $4.6 \times 10^{-7}$ | -14.6           | 1.2      | $4.6 \times 10^{-7}$ | -7.6            | 0.6      | $5.0 \times 10^{-4}$ | -14.7          | 1.4      | $4.2 \times 10^{-7}$ | -13.6   | 1.3      | $1.2 \times 10^{-6}$ |
|                        | 100%      | -15.7            | 1.8      | $1.5 \times 10^{-7}$ | -15.7           | 1.8      | $1.5 \times 10^{-7}$ | -9.3            | 0.9      | $9.1 \times 10^{-5}$ | -15.3          | 1.8      | $2.3 \times 10^{-7}$ | -14.1   | 1.7      | $7.5 \times 10^{-7}$ |
| Valve                  | 0.01%     | -5.9             | 0.2      | $2.9 \times 10^{-3}$ | -5.9            | 0.2      | $2.9 \times 10^{-3}$ | -3.0            | 1.1      | $5.1 \times 10^{-2}$ | -9.4           | 0.7      | $8.4 \times 10^{-5}$ | -9.3    | 0.6      | $9.5 \times 10^{-5}$ |
|                        | 0.1%      | -7.4             | 0.4      | $5.9 \times 10^{-4}$ | -7.4            | 0.4      | $5.9 \times 10^{-4}$ | -3.9            | 0.8      | $2.0 \times 10^{-2}$ | -10.1          | 1.0      | $4.2 \times 10^{-5}$ | -9.9    | 1.1      | $5.2 \times 10^{-5}$ |
|                        | 1%        | -9.8             | 1.1      | $5.4 \times 10^{-5}$ | -9.8            | 1.1      | $5.4 \times 10^{-5}$ | -4.9            | 1.4      | $7.8 \times 10^{-3}$ | -10.7          | 1.2      | $2.2 \times 10^{-5}$ | -10.5   | 2.7      | $2.8 \times 10^{-5}$ |
|                        | 10%       | -10.6            | 0.6      | $2.5 \times 10^{-5}$ | -10.6           | 0.6      | $2.5 \times 10^{-5}$ | -5.8            | 0.6      | $3.0 \times 10^{-3}$ | -11.3          | 1.9      | $1.2 \times 10^{-5}$ | -11.1   | 1.2      | $1.5 \times 10^{-5}$ |
|                        | 100%      | -12.2            | 1.4      | $4.8 \times 10^{-6}$ | -12.2           | 1.4      | $4.8 \times 10^{-6}$ | -6.8            | 1.2      | $1.2 \times 10^{-3}$ | -11.9          | 1.9      | $6.5 \times 10^{-6}$ | -11.7   | 2.2      | $8.3 \times 10^{-6}$ |
| Instrument             | 0.01%     | -7.4             | 0.7      | $6.2 \times 10^{-4}$ | 999             | 999      | $\infty$             | -7.3            | 0.7      | $6.9 \times 10^{-4}$ | 999            | 999      | $\infty$             | -7.3    | 0.7      | $6.9 \times 10^{-4}$ |
|                        | 0.1%      | -8.5             | 0.8      | $2.0 \times 10^{-4}$ | 999             | 999      | $\infty$             | -8.1            | 0.6      | $3.0 \times 10^{-4}$ | 999            | 999      | $\infty$             | -8.1    | 0.6      | $3.0 \times 10^{-4}$ |
|                        | 1%        | -9.1             | 0.9      | $1.1 \times 10^{-4}$ | 999             | 999      | $\infty$             | -8.9            | 0.6      | $1.3 \times 10^{-4}$ | 999            | 999      | $\infty$             | -8.9    | 0.6      | $1.3 \times 10^{-4}$ |
|                        | 10%       | -9.2             | 1.1      | $1.0 \times 10^{-4}$ | 999             | 999      | $\infty$             | -9.8            | 0.5      | $5.7 \times 10^{-5}$ | 999            | 999      | $\infty$             | -9.8    | 0.5      | $5.7 \times 10^{-5}$ |
|                        | 100%      | -10.2            | 1.5      | $3.7 \times 10^{-5}$ | 999             | 999      | $\infty$             | -10.6           | 0.7      | $2.5 \times 10^{-5}$ | 999            | 999      | $\infty$             | -10.6   | 0.7      | $2.5 \times 10^{-5}$ |
| Heat Exchanger         | 0.01%     | 999              | 999      | $\infty$             | 999             | 999      | $\infty$             | 0.6             | 1.3      | $1.8 \times 10^0$    | -6.1           | 1.0      | $2.3 \times 10^{-3}$ | 999     | 999      | $\infty$             |
|                        | 0.1%      | 999              | 999      | $\infty$             | 999             | 999      | $\infty$             | -1.1            | 1.0      | $3.5 \times 10^{-1}$ | -7.0           | 1.3      | $8.9 \times 10^{-4}$ | 999     | 999      | $\infty$             |
|                        | 1%        | 999              | 999      | $\infty$             | 999             | 999      | $\infty$             | -2.7            | 1.1      | $6.7 \times 10^{-2}$ | -8.0           | 1.4      | $3.2 \times 10^{-4}$ | 999     | 999      | $\infty$             |
|                        | 10%       | 999              | 999      | $\infty$             | 999             | 999      | $\infty$             | -4.4            | 0.6      | $1.3 \times 10^{-2}$ | -9.1           | 2.3      | $1.2 \times 10^{-4}$ | 999     | 999      | $\infty$             |
|                        | 100%      | 999              | 999      | $\infty$             | 999             | 999      | $\infty$             | -6.0            | 0.9      | $2.4 \times 10^{-3}$ | -10.1          | 1.6      | $4.2 \times 10^{-5}$ | 999     | 999      | $\infty$             |
| Vaporizer              | 0.01%     | 999              | 999      | $\infty$             | 999             | 999      | $\infty$             | 999             | 999      | $\infty$             | -4.8           | 2.5      | $8.1 \times 10^{-3}$ | 999     | 999      | $\infty$             |
|                        | 0.1%      | 999              | 999      | $\infty$             | 999             | 999      | $\infty$             | 999             | 999      | $\infty$             | -3.6           | 1.9      | $2.6 \times 10^{-2}$ | 999     | 999      | $\infty$             |
|                        | 1%        | 999              | 999      | $\infty$             | 999             | 999      | $\infty$             | 999             | 999      | $\infty$             | -2.5           | 1.2      | $8.4 \times 10^{-2}$ | 999     | 999      | $\infty$             |
|                        | 10%       | 999              | 999      | $\infty$             | 999             | 999      | $\infty$             | 999             | 999      | $\infty$             | -1.3           | 0.7      | $2.7 \times 10^{-1}$ | 999     | 999      | $\infty$             |
|                        | 100%      | 999              | 999      | $\infty$             | 999             | 999      | $\infty$             | 999             | 999      | $\infty$             | -0.1           | 0.7      | $8.8 \times 10^{-1}$ | 999     | 999      | $\infty$             |
| Transfer Arm           | 0.01%     | 999              | 999      | $\infty$             | 999             | 999      | $\infty$             | 999             | 999      | $\infty$             | -1.6           | 3.0      | $2.0 \times 10^{-1}$ | -4.8    | 1.2      | $8.3 \times 10^{-3}$ |
|                        | 0.1%      | 999              | 999      | $\infty$             | 999             | 999      | $\infty$             | 999             | 999      | $\infty$             | -4.4           | 2.1      | $1.2 \times 10^{-2}$ | -5.4    | 0.9      | $4.7 \times 10^{-3}$ |
|                        | 1%        | 999              | 999      | $\infty$             | 999             | 999      | $\infty$             | 999             | 999      | $\infty$             | -7.2           | 1.9      | $7.5 \times 10^{-4}$ | -5.9    | 0.7      | $2.6 \times 10^{-3}$ |
|                        | 10%       | 999              | 999      | $\infty$             | 999             | 999      | $\infty$             | 999             | 999      | $\infty$             | -10.3          | 1.0      | $3.3 \times 10^{-5}$ | -6.5    | 0.6      | $1.5 \times 10^{-3}$ |
|                        | 100%      | 999              | 999      | $\infty$             | 999             | 999      | $\infty$             | 999             | 999      | $\infty$             | -12.7          | 3.4      | $3.0 \times 10^{-6}$ | -7.1    | 0.9      | $8.3 \times 10^{-4}$ |

#### 2.4.4. Frequency of Dispenser Releases

The annual frequency of other releases ( $f_{\text{Other Releases}}$ ) deals with failures that can happen at a dispenser, rather than random leaks from individual components [5, 15]. The probability of an accident can be high for several reasons: fueling typically involves direct human interaction to operate the fueling dispenser, temporary connections rather than hard-plumbed lines, and inadvertently broken connections because the vehicle is not a permanent part of the system. On the other hand, releases from fueling can only occur when fueling occurs, and so different systems that involve different numbers of fueling events can be impacted by these releases to varying degrees. It is assumed that a dispenser failure would result in a large release of fuel, and so this frequency is only used in the largest (100%) leak size.

The annual frequency of other releases ( $f_{\text{Other Releases}}$ ) is calculated using Equation 15, in which  $f_{\text{Fueling Demands}}$  is the annual frequency of fueling demands (i.e., the number of times a dispenser is used to refuel a vehicle in a year) and  $p_{\text{Dispenser Releases}}$  is the probability of a release from a dispenser during fueling [5]. This implementation assumes that the causes in the fault tree are mutually exclusive; this is because a hydrogen leak in a system can result in a shutdown of the system itself, thereby precluding other releases<sup>5</sup>.

$$f_{\text{Other Releases}} = f_{\text{Fueling Demands}} \times p_{\text{Dispenser Releases}} \quad (15)$$

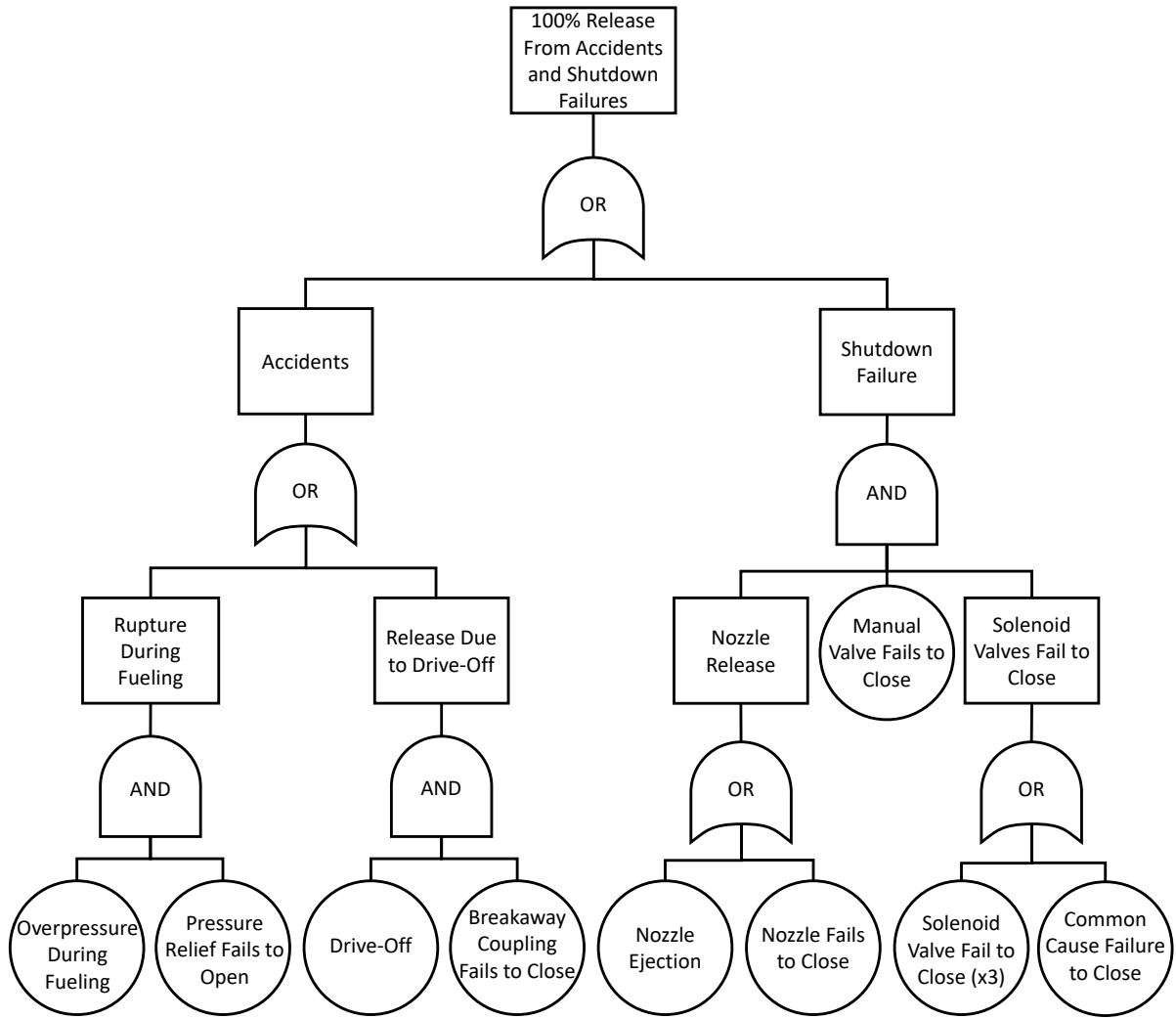
The annual frequency of fueling demands ( $f_{\text{Fueling Demands}}$ ) is given by Equation 16, where  $N_{\text{Vehicles}}$  is the number of vehicles at the facility,  $N_{\text{Fuelings per Day}}$  is the average number of times each vehicle is fueled per day, and  $N_{\text{Operating Days per Year}}$  is the number of operating days in a year [5].

$$f_{\text{Fueling Demands}} = N_{\text{Vehicles}} \times N_{\text{Fuelings per Day}} \times N_{\text{Operating Days per Year}} \quad (16)$$

Dispenser failures are categorized in HyRAM+ as Accidents (in which the vehicle tank overpressurizes or a drive-off occurs) or Shutdown Failures (in which the system fails to shut down after a release from the nozzle) [5]. The probability for these types of releases are estimated using a fault tree as shown in Figure 2-6.

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<sup>5</sup>While simultaneous releases are still possible, depending on how quickly a system shutdown can occur, treating the events as mutually exclusive will lead to a higher (and therefore more conservative) release probability compared to treating leak events as independent.



**Figure 2-6: Fault tree for Other Releases from a dispenser [5].**

The probability of a release from a dispenser during fueling ( $p_{\text{Dispenser Releases}}$ ) is given by Equation 17, where  $p_{\text{Accidents}}$  is the probability of an accident during fueling and  $p_{\text{Shutdown Failure}}$  is the probability of a shutdown failure during fueling [5].

$$p_{\text{Dispenser Releases}} = p_{\text{Accidents}} + p_{\text{Shutdown Failure}} \quad (17)$$

The probability of an accident during fueling ( $p_{\text{Accidents}}$ ) is given by Equation 18, where  $p_{\text{Rupture During Fueling}}$  is the probability of a rupture that occurs during fueling and  $p_{\text{Release Due to Drive-Off}}$  is the probability of a release occurring due to a vehicle drive-off [5].

$$p_{\text{Accidents}} = p_{\text{Rupture During Fueling}} + p_{\text{Release Due to Drive-Off}} \quad (18)$$

The probability of a rupture during fueling is given by Equation 19, in which  $p_{\text{Overpressure During Fueling}}$  is the probability of an overpressure occurring during fueling (e.g., the dispenser over-fills the vehicle tank) and  $p_{\text{PRD FTO}}$  is the probability of the dispenser pressure relief device failing to open on demand [5].

$$p_{\text{Rupture During Fueling}} = p_{\text{Overpressure During Fueling}} \times p_{\text{PRD FTO}} \quad (19)$$

The probability of a release occurring due to a vehicle drive-off ( $p_{\text{Release Due to DriveOff}}$ ) is given by Equation 20, where  $p_{\text{DriveOff}}$  is the probability of a vehicle driving off while still attached to the dispenser during fueling and  $p_{\text{Breakaway FTC}}$  is the probability of the breakaway coupling failing to close on demand [5].

$$p_{\text{Release Due to DriveOff}} = p_{\text{DriveOff}} \times p_{\text{Breakaway FTC}} \quad (20)$$

The probability of a shutdown failure during fueling ( $p_{\text{Shutdown Failure}}$ ) is given by Equation 21, where  $p_{\text{Nozzle Release}}$  is the probability of the dispensing nozzle releasing fuel,  $p_{\text{Manual Valve FTC}}$  is the probability of the manual shutoff valve failing to close on demand, and  $p_{\text{Solenoid Valves FTC}}$  is the probability of the automated solenoid valves on the dispenser failing to close on demand [5].

$$p_{\text{Shutdown Failure}} = p_{\text{Nozzle Release}} \times p_{\text{Manual Valve FTC}} \times p_{\text{Solenoid Valves FTC}} \quad (21)$$

The probability of the dispensing nozzle releasing fuel ( $p_{\text{Nozzle Release}}$ ) is given by Equation 22, in which  $p_{\text{Nozzle Ejection}}$  is the probability of the dispenser nozzle being ejected during fueling, and  $p_{\text{Nozzle FTC}}$  is the probability of the dispenser nozzle failing to close on demand [5].

$$p_{\text{Nozzle Release}} = p_{\text{Nozzle Ejection}} + p_{\text{Nozzle FTC}} \quad (22)$$

The probability of the automated solenoid valves on the dispenser failing to close on demand ( $p_{\text{Solenoid Valves FTC}}$ ) is given by Equation 23, where  $p_{\text{Solenoid Valve FTC}}$  is the probability of any one automated solenoid valve failing to close on demand and  $p_{\text{Common Cause FTC}}$  is the probability of something causing all of the solenoid valves to fail to close on demand (e.g., loss of connection to sensors) [5].

$$p_{\text{Solenoid Valves FTC}} = [p_{\text{Solenoid Valve FTC}}]^3 + p_{\text{Common Cause FTC}} \quad (23)$$

It should be noted that this fault tree implementation assumes that there are 3 solenoid valves and that all of them need to fail in order for fuel to be released; thus, the probability for any single valve failing is cubed.

The probabilities  $p_{\text{Overpressure During Fueling}}$ ,  $p_{\text{PRD FTO}}$ ,  $p_{\text{DriveOff}}$ ,  $p_{\text{Breakaway FTC}}$ ,  $p_{\text{Manual Valve FTC}}$ ,  $p_{\text{Nozzle Ejection}}$ ,  $p_{\text{Nozzle FTC}}$ ,  $p_{\text{Solenoid Valve FTC}}$ , and  $p_{\text{Common Cause FTC}}$  can each be specified as a specific expected value from 0.0 to 1.0, or can be specified as a probability distribution such as beta or lognormal distributions [5]. If a probability distribution is specified, the mean (or median

for a lognormal distribution) value will be calculated and used in the above calculations. Default values for these probabilities are given in Section 2.4.5.

Any of the probabilities in this section can be used to estimate an annual frequency of any of the events in question. This can be done by multiplying the probability for event of interest  $A$  ( $p_A$ ) by the annual number of fueling demands ( $f_{\text{Fueling Demands}}$ ), as shown in Equation 24 [5].

$$f_A = p_A \times f_{\text{Fueling Demands}} \quad (24)$$

#### 2.4.5. Default Dispenser Failure Probabilities

The default failure probabilities in HyRAM+ were estimated from generic data from the offshore oil, process chemical, and nuclear power industries as part of a risk assessment for indoor refueling of hydrogen-powered forklifts [15]. Table 2-4 shows the default probability distributions and parameters for various types of component failures and Table 2-5 shows the default accident occurrence probability distributions and parameters for different types of accidents that are described in Section 2.4.4.

**Table 2-4: Default probability distributions for component failure.**

| Component             | Failure Mode  | Distribution Type           | Parameters                       |
|-----------------------|---|-----------------------------|----------------------------------|
| Nozzle                | Pop-off   | Beta ( $\alpha, \beta$ )    | $\alpha = 0.5, \beta = 610415.5$ |
| Nozzle                | Failure to close                                    | Expected value              | 0.002                            |
| Breakaway coupling    | Failure to close                                    | Beta ( $\alpha, \beta$ )    | $\alpha = 0.5, \beta = 5031$     |
| Pressure relief valve | Failure to open                                     | Lognormal ( $\mu, \sigma$ ) | $\mu = -11.74, \sigma = 0.67$    |
| Manual valve          | Failure to close (human error)                      | Expected value              | 0.001                            |
| Solenoid valve        | Failure to close                                    | Expected value              | 0.002                            |
| Solenoid valves       | Common cause failure (3 valves, beta factor method) | Expected value              | $1.28 \times 10^{-4}$            |

**Table 2-5: Default probability distributions for accident occurrence.**

| Accident                    | Distribution Type        | Parameters                        |
|-----------------------------|--------------------------|-----------------------------------|
| Drive-off                   | Beta ( $\alpha, \beta$ ) | $\alpha = 31.5, \beta = 610384.5$ |
| Overpressure during fueling | Beta ( $\alpha, \beta$ ) | $\alpha = 3.5, \beta = 310289.5$  |

See Equation 14 for the calculation of the geometric mean (median) for a lognormal distribution. For a beta distribution with parameters  $\alpha$  and  $\beta$ , the arithmetic mean is calculated using

Equation 25<sup>6</sup>.

$$\text{mean} = \frac{\alpha}{\alpha + \beta} \quad (25)$$

The default number of vehicles that use the dispenser is 20, each with 2 fuelings per day, and the default number of vehicle operating days per year is 250. This results in 10000 annual fueling demands by default (see Equation 16).

## 2.5. Consequence Models

The consequences of a leak scenario ( $c_{\text{Scenario},k}$  for  $k = 0.01\%$ ,  $0.1\%$ ,  $1\%$ ,  $10\%$ , and  $100\%$ ) in HyRAM+ are the estimated numbers of fatalities from each of the  $j$  occupants of the facility (see Section 2.5.1), as calculated in Equation 26.

$$c_{\text{Scenario},k} = \sum_j c_{\text{Scenario},k,j} \quad (26)$$

The consequences for each of the leak scenarios are estimated by the probability of a fatality for each of the occupants in the facility, as described in the following sub-sections.

### 2.5.1. Facility Occupants

The harm and fatalities of interest in HyRAM+ are assumed to happen to facility occupants [5, 15]. General risk contours or risk at a specific location (such as a building or lot line) are not calculated explicitly. The risk for the entire facility is a summation of fatality risk for each of the user-specified occupant locations.

The occupant positions and number of occupants are defined by user input. For each dimension ( $x, y, z$ ) for each occupant, the user may assign a position deterministically or may specify a probability distribution. Probability distributions will be randomly sampled to assign the positions using user-specified inputs to a uniform or normal distribution. The occupant positions are all defined relative to the leak point; i.e., the leak occurs at the "origin" (0, 0, 0) and extends in the positive- $x$  direction, so the occupant positions ( $x, y, z$ ) are based on that point of reference. The  $x$  and  $z$  coordinates are horizontal to the ground, while the  $y$  coordinate is height above the ground. The occupant locations are only sampled (and locations assigned) once per QRA calculation; this means that if any occupant location dimensions are specified with a probability distribution, the resulting risk value may differ between calculation runs. Instead, if occupant locations are specified deterministically for all dimensions, then the same risk value result will occur for each calculation run. A user who wants to repeat a previously specified set of determined locations can

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<sup>6</sup>Currently, only the mean value from the beta distribution is used in risk calculations; future versions of HyRAM+ may use additional information from the probability distribution in uncertainty propagation.

either specify those locations deterministically or use the "random seed" input, which will cause the same values to be sampled from the probability distributions.

By default, HyRAM+ includes a set of 9 occupants that are meant to provide an example of workers within a station or facility. The locations of these default occupants are assumed to be distributed with a uniform distribution in the  $x$ -direction between 1–20 m, a constant height of 0 m (i.e., same height as the leak itself), and distributed with a uniform distribution in the  $z$ -direction between 1–12 m. These default occupants are assumed to have 2,000 exposed hours per occupant per year. The number, location specifications, and exposed hours for these default occupants can be edited by the user, and additional groups with occupants with separate number, locations, and exposed hours can be specified by the user as well.

### **2.5.2. Detection and Isolation Scenario Consequences**

The scenario in which a leak is safely detected and isolated is assumed to result in no fatalities for all of the occupant positions [15], as shown in Equation 27.

$$C_{\text{Isolated},k,j} = 0 \quad (27)$$

### **2.5.3. No Ignition Scenario Consequences**

The scenario in which a leak does not ignite is assumed to result in no fatalities for all of the occupant positions [15], as shown in Equation 28.

$$C_{\text{NoIgnition},k,j} = 0 \quad (28)$$

### **2.5.4. Jet Fire Scenario Consequences**

The consequences of a jet fire on facility occupants are calculated using Equation 29, in which  $p_{\text{fatal,jetfire},k,j}$  is the probability of a fatality from a jetfire for the leak size  $k$  and occupant position  $j$ .

$$C_{\text{Jetfire},k,j} = p_{\text{fatal,jetfire},k,j} \quad (29)$$

The probability of a fatality from a jetfire is described in Section 2.6, which uses physical effect modeling as described in Section 3. Specifically, the flame model described in Section 3.4.2 and multi-point radiative heat flux model described in Section 3.4.3 are used for this scenario. These models are coupled to the developing flow models described in Section 3.2. The heat flux calculation is performed at each of the occupant locations, and the resulting values are then used to estimate the probability of a fatality at each of the occupant locations using the fatality probits in Section 2.6.1.

### 2.5.5. Overpressure Scenario Consequences

The consequences of an explosion on facility occupants are calculated using Equation 30, in which  $p_{\text{fatal,explosion},k,j}$  is the probability of a fatality from an explosion for the leak size  $k$  and occupant position  $j$ .

$$C_{\text{Explosion},k,j} = p_{\text{fatal,explosion},k,j} \quad (30)$$

The probability of a fatality from an explosion is described in Section 2.6, which uses physical effect modeling as described in Section 3. The unconfined overpressure model described in Section 3.4.5 is used for this scenario. The overpressure calculation is performed at each of the occupant locations, and the resulting values are then used to estimate the probability of a fatality at each of the occupant locations using the fatality probits in Section 2.6.2.

## 2.6. Harm and Loss Models

Probit models are used in HyRAM+ to estimate the probability of a fatality for a given exposure [7–10, 15]. The probit model is a linear combination of predictors that model the inverse cumulative distribution function associated with the normal distribution [7, 15]. The probability of a fatality is given by Equation 31, which evaluates the standard normal cumulative distribution function ( $\Phi$ )<sup>7</sup> at the value established by the appropriate probit model ( $Y$ , see Sections 2.6.1 and 2.6.2) [7, 15].

$$p_{\text{fatal}} = F(Y|\mu = 5, \sigma = 1) = \Phi(Y - 5) \quad (31)$$

### 2.6.1. Thermal Harm

For thermal radiation, the harm level is a function of both the heat flux intensity and the duration of exposure. Harm from radiant heat fluxes is often expressed in terms of a thermal dose unit ( $V$ ) which combines the heat flux intensity ( $I$ , in  $\text{W}/\text{m}^2$ ) and exposure time ( $t$ , in seconds) using Equation 32 [7, 15]. The default thermal exposure time used in HyRAM+ is 30 s<sup>8</sup>, but users may modify this value. This default value was selected based on multiple literature sources that include the ability of a person to move away from a heat source [24, 25].

$$V = I^{(4/3)} \times t \quad (32)$$

Table 2-6 lists the thermal probit models that are encoded in HyRAM+ [7, 15]. The probability of a fatality is evaluated using the probit value resulting from the equations in Table 2-6 with Equation 31.

<sup>7</sup>The standard normal cumulative distribution function ( $\Phi(x)$ ) is the case in which the normal cumulative distribution function ( $F(x)$ ) has parameters of  $\mu = 0$  and  $\sigma = 1$ .

<sup>8</sup>The default value in HyRAM+ version 4.1 and earlier was 60 s [7, 15]

**Table 2-6: Probit models used to calculate fatality probability as a function of thermal dose (V).**

| Reference         | Fatality Model                       | Notes   |
|-------------------|--------------------------------------|---|
| Eisenberg [26]    | $Y = -38.48 + 2.56 \times \ln(V)$    | Based on population data from nuclear blasts at Hiroshima and Nagasaki (ultra-violet radiation)   |
| Tsao & Perry [27] | $Y = -36.38 + 2.56 \times \ln(V)$    | Eisenberg model, modified to account for infrared radiation   |
| TNO [24]          | $Y = -37.23 + 2.56 \times \ln(V)$    | Tsao and Perry model modified to account for clothing   |
| Lees [28]         | $Y = -29.02 + 1.99 \times \ln(0.5V)$ | Accounts for clothing, based on porcine skin experiments using ultraviolet source to determine skin damages. Uses burn mortality information. |

LaChance et al. [29] recommended using either the Eisenberg and the Tsao & Perry probit models for hydrogen-related applications. Therefore, the HyRAM+ default is the Eisenberg probit model for heat flux. This recommendation is based on the fact that hydrogen flames are less radiative than hydrocarbon flames, and so the Tsao & Perry probit model may overpredict due to the inclusion of infrared radiation. By contrast, the Tsao & Perry probit may be more relevant for hydrocarbon fuels like methane and propane. The TNO and Lees probit accounts for clothing, which may be appropriate for some situations, though may be less conservative than the probits that do not account for clothing.

Structures and equipment can also be damaged by exposure to radiant heat flux. Some typical heat flux values and exposure times for damage to structures and components were provided by LaChance et al. [29]. However, because the exposure times required for damage is long (>30 min), the fatality risk due to thermal radiation from fires on structures and equipment is not generally significant since personnel are able to evacuate the building before significant structural damage occurs [7, 15]. This is only noted because structural damage can cause physical harm (fatalities) to humans, which is the risk metric of interest within HyRAM+.

### **2.6.2. Overpressure Harm**

There are several probit models available in HyRAM+ to predict harm and loss from overpressures [7, 15]. These models generally differentiate between direct and indirect effects of pressure. Significant increases in pressure can cause direct damage to pressure-sensitive organs such as the lungs and ears. Indirect effects include the impact from fragments and debris generated by the overpressure event and collapse of structures. Large explosions can also carry a person some distance resulting in injury from collisions with structures or from the resulting violent movement.

The probit models for the effects of overpressures that are included in HyRAM+ are provided in Table 2-7 [7]. The probability of a fatality is evaluated using the probit value resulting from the

equations in Table 2-7 with Equation 31. In this context, the overpressure is defined as the pressure above ambient.

**Table 2-7: Probit models to calculate fatality probability from exposure to overpressures, where  $P_s$  is peak overpressure (Pa) and  $i$  is the impulse of the shock wave (Pa·s).**

| Reference                        | Fatality Model   |
|----------------------------------|--|
| Eisenberg - Lung hemorrhage [30] | $Y = -77.1 + 6.91 \ln(P_s)$                                |
| HSE - Lung hemorrhage [31, 32]   | $Y = 5.13 + 1.37 \ln(P_s 10^{-5})$                         |
| TNO - Head impact [24]           | $Y = 5 - 8.49 \ln[(2430/P_s) + 4.0 \times 10^8 / (P_s i)]$ |
| TNO - Structure collapse [24]    | $Y = 5 - 0.22 \ln[(40000/P_s)^{7.4} + (460/i)^{11.3}]$     |

LaChance et al. [29] recommended the use of the TNO probit models, and suggested that indirect effects from overpressure events represent the most important concern for people. The overpressures required to cause fatal lung damage are significantly higher than the values required to throw a person against obstacles or to generate missiles that can penetrate the skin. In addition, a person inside a structure would more likely be killed by the facility collapse than from lung damage [7, 15]. However, a person located outdoors would not be at risk of a structure collapse; for this reason, the HyRAM+ default is the TNO - Head Impact probit model for explosion/overpressure effects. It should be noted that some of the unconfined overpressure models in Section 3.4.5 only estimate peak overpressure, not impulse values, and so cannot be used with probit models that include an impulse term (i.e., the TNO models).

### 3. PHYSICS MODELS

HyRAM+ includes a physics mode, which provides models relevant to the behavior, hazards, and consequences of releases of the different fuels. Jet flames, concentration profiles for unignited jets/plumes, overpressure from the delayed ignition of a plume, and indoor accumulation with delayed ignition causing overpressure can all be investigated from the physics mode. A subset of these models is used in the QRA mode to calculate the consequences from a given release scenario, as described in Section 2.5. Several basic property calculations (e.g., the thermodynamic equation of state) are necessary to numerically simulate the release scenarios.

#### 3.1. Properties of the Fluids

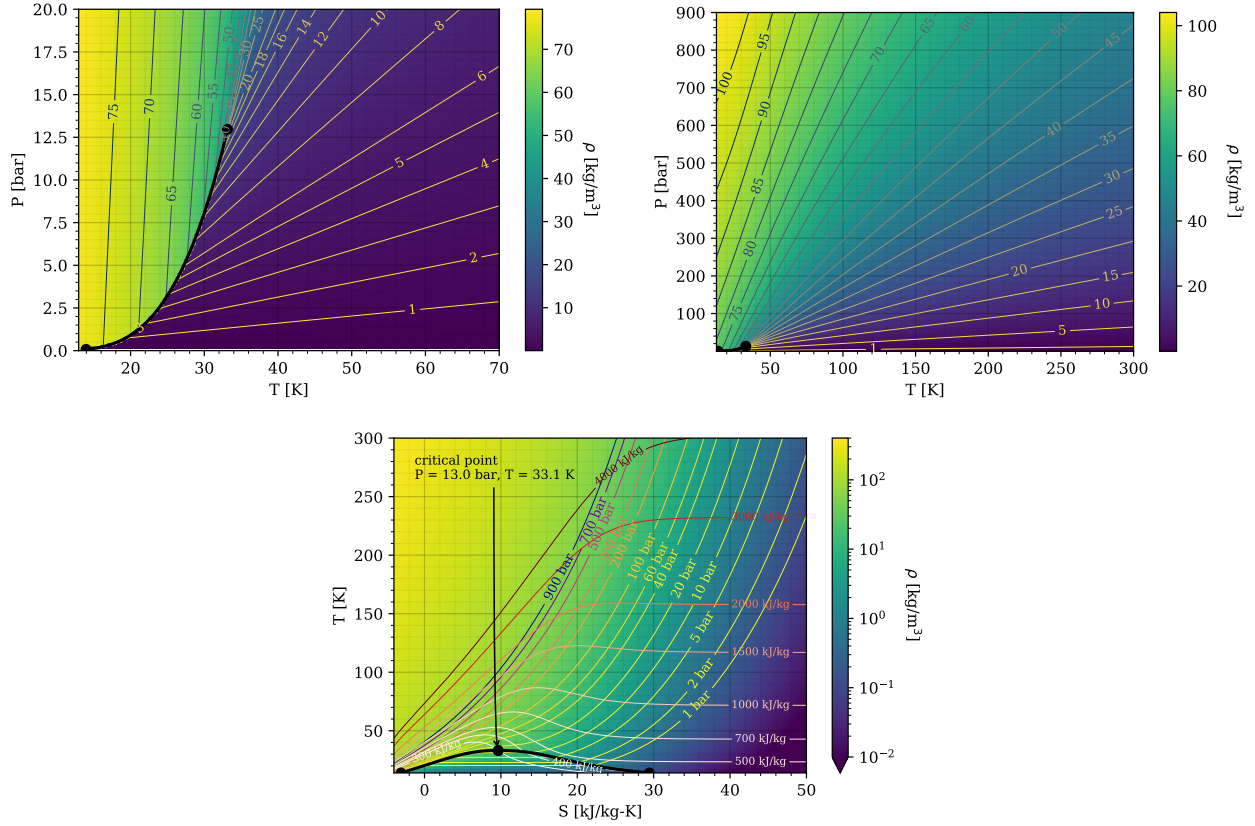
The formulations in this section describe the thermodynamic properties of unignited and ignited hydrogen, methane, propane, and blends, which are needed to calculate different aspects of dispersion and combustion. They are described here in detail, and then referred to in subsequent sections.

##### 3.1.1. Equation of State

**Description:** HyRAM+ utilizes the CoolProp library [33], called through its Python interface to perform several thermodynamic calculations. The property calculations are based on a Helmholtz energy function, and account for the real gas behavior at high pressures and at liquid (which can be cryogenic) temperatures, for liquids, gases, and two-phase mixtures. CoolProp [33] can be used to calculate the properties of hydrogen, methane, propane, air, or other fluids, including blends. For hydrogen, the relationships and energy functions are detailed in Leachman et al. [34], for methane, in Setzmann and Wagner [35], and for propane, in Lemmon et al. [36]. CoolProp handles blends following the work of Kunz et al. [37, 38] and Lemmon et al. [39–41]. The mixing parameters for the fluids available in the front-end of HyRAM+ are from Kunz et al. [37, 38]. These thermodynamic calculations are used to calculate leak rates and are used in mass, momentum, and energy balances in regions close to the leak point. As an example, for hydrogen, the relationships between pressure<sup>9</sup>, temperature, density, enthalpy, and entropy are plotted in Figure 3-1. In some regions of the models, the ideal gas equation of state is used, as described in other sections.

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<sup>9</sup>HyRAM+ calculation inputs use absolute pressure, not gauge pressure



**Figure 3-1: Graphical representations of state points, calculated using CoolProp [33] which uses the Leachman et al. [34] equation of state for hydrogen. Top plots show shading and iso-contours of density as a function of temperature and pressure. Bottom plot shows shading of density as a function of entropy and temperature, with iso-contours of pressure and enthalpy. The thick black line shows the liquid/two-phase/vapor boundary, and the black dots mark the triple point and critical points.**

**Applicability:** The fundamental equation of state described by Leachman et al. [34] is valid for hydrogen at pressures up to 2000 MPa and between 14 K and 1000 K. The equation of state for methane described by Setzmann and Wagner [35] is valid from 90 K to 620 K at pressures up to 1000 MPa. The relationships described by Lemmon et al. [36] are valid for propane from 85.5 K to 650 K and for pressures up to 1000 MPa. The most accurate range of validity for mixtures/blends is for temperatures from 90 K to 450 K and pressures up to 35 MPa, although limited data extends validity from 60 K to 700 K and up to 70 MPa [38]. Note that there is no check that the equation of state is being used within the stated validation limits and HyRAM+ can calculate outputs for temperatures and pressures outside the range of validity using the same equation of state.

### 3.1.2. Combustion

**Description:** HyRAM+ flame calculations are based on the work of Ekoto et al. [42] and rely on several underlying properties of burned fuel, namely the stoichiometric mixture fraction,  $f_s$ ,

the heat of combustion,  $\Delta H_c$ , along with the temperature, molecular weight and density of combustion products for a given mixture fraction.

**Assumptions:** Combustion is only assumed to occur in expanded fuel at atmospheric pressure. Because combustion occurs at ambient pressure, the ideal gas equation is used to calculate the density of the product mixture ( $\rho$ ) based on the molecular weight of the mixture ( $MW_{\text{mixture}}$ ), the temperature ( $T$ ), and the gas constant ( $R$ ):

$$\rho = \frac{P(MW_{\text{mixture}})}{RT}. \quad (33)$$

These combustion calculations assume that there are no losses, that the mixture is thermally perfect with the local enthalpy, and the pressure of the products is the same as the pressure of the reactants.

**Relationships:** It is assumed that there are fuels and inerts reacting with pure air, and complete combustion drives the products to water and carbon dioxide. For each mole of carbon as a reactant, 1 mole  $O_2$  is needed as a reactant and 1 mole of  $CO_2$  will be produced. For each mole of hydrogen as a reactant, 1/4 mole of  $O_2$  is needed as a reactant to produce 1/2 mole of  $H_2O$ . For each mole of oxygen in the reactants (for example, in  $CO_2$ ), 1/2 mole less of  $O_2$  is needed as a reactant. Therefore, the moles of oxygen needed as a reactant is

$$\nu_{O_2} = n_C + \frac{n_H}{4} - \frac{n_O}{2} \quad (34)$$

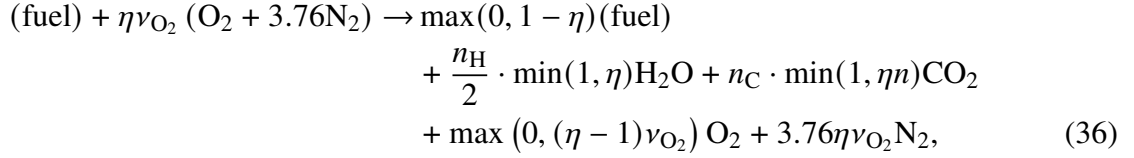
where  $n$  is the moles of each species (subscripts C - carbon, H - hydrogen, O - oxygen) in the fuel. For example, hydrogen ( $H_2$ ) has 2 moles of hydrogen and requires  $2/4 = 1/2$  mole of  $O_2$ , methane ( $CH_4$ ) has 4 moles of hydrogen and 1 mole of carbon and requires  $1 + 4/4 = 2$  moles of  $O_2$ , and propane ( $C_3H_8$ ) has 3 moles of carbon and 8 moles of hydrogen and therefore requires  $3 + 8/4 = 5$  moles of  $O_2$  for complete combustion. For blends, the moles of carbon, hydrogen, and oxygen are often non-integers.

During combustion, 242 kJ is released for every mole of gaseous water produced, and 394 kJ is released for every mole of carbon dioxide produced [43]. Therefore, when hydrogen is the fuel, the heat of combustion is 242 kJ/mol $H_2$  or 120 MJ/kg $H_2$  (using the lower heating value) [44, 45]. For methane and propane, the heats of combustion are 50 MJ/kg and 46.4 MJ/kg, respectively. The values can be calculated for other fuels in a similar manner. The heat of combustion from a blend is weighted based on the mass fraction of each reactant in the fuel.

From the moles of oxygen required for complete combustion (Eq. 34), the stoichiometric mixture fraction ( $f_s$ ), which is the same as the mass fraction of fuel, can be calculated as:

$$f_s = \frac{MW_{\text{fuel}}}{MW_{\text{fuel}} + \nu_{O_2}(MW_{O_2} + 3.76MW_{N_2})}. \quad (35)$$

The stoichiometric mixture fractions for hydrogen, methane, and propane are 0.02852, 0.05519, and 0.06034 respectively. If incomplete combustion occurs (a mixture fraction other than stoichiometric), there will be excess air or fuel as a reactant, with the stoichiometry given by



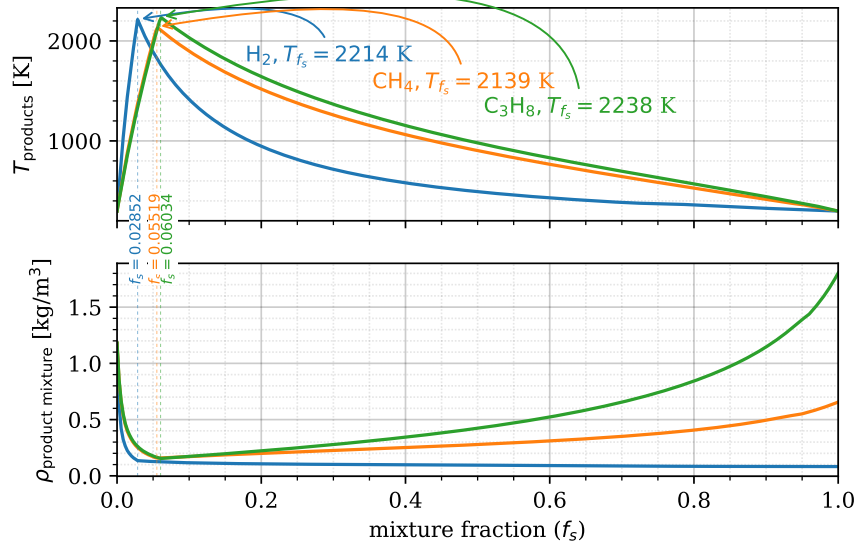
where  $\eta$ , which specifies the moles of air, can vary from 0 to  $\infty$ . In this case, the mixture fraction is equal to

$$f = Y_{\text{fuel}} + Y_{\text{H}_2\text{O}} \frac{\text{MW}_{\text{fuel}}}{\text{MW}_{\text{H}_2\text{O}}} + Y_{\text{CO}_2} \frac{\text{MW}_{\text{fuel}}}{\text{MW}_{\text{CO}_2}}, \quad (37)$$

where  $Y$  is the mass fraction of products. HyRAM+ uses CoolProp [33] to calculate the mass fraction weighted enthalpy ( $h$ ) of the fuel along with the enthalpy of  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ,  $\text{O}_2$ , and  $\text{N}_2$  as a function of temperature and then solves for the temperature of products assuming an isenthalpic reaction, i.e.,

$$\begin{aligned}
 \sum_{i=\text{fuel}, \text{O}_2, \text{N}_2} Y_{i,\text{reac}} h_{i,\text{reac}}(T_{\text{reac}}, P_{\text{reac}}) &= \sum_{i=\text{fuel}, \text{O}_2, \text{N}_2, \text{CO}_2, \text{H}_2\text{O}} Y_{i,\text{prod}} h_{i,\text{prod}}(T_{\text{prod}}, P_{\text{prod}}) \\
 &+ Y_{\text{H}_2\text{O},\text{prod}} \frac{\text{MW}_{\text{fuel}}}{(n_{\text{C}} + 1) \text{MW}_{\text{H}_2\text{O}}} \Delta H_c.
 \end{aligned} \quad (38)$$

The calculation of the adiabatic flame temperature ( $T_{ad}$ ) and density of the products of 298 K, 101,325 Pa pure fuels are shown in Figure 3-2.



**Figure 3-2: Temperature and density of products for the combustion of 298 K, 101,325 Pa fuels as a function of mixture fraction.**

**Applicability:** These combustion calculations are applicable in atmospheric pressure regions where heat losses are negligible.

### 3.2. Developing Flow

Several engineering models are used in HyRAM+ to develop boundary conditions for the integral models of jets/plumes and diffusion flames. These engineering models describe the flow through an orifice, how the fluid expands to atmospheric pressure (if necessary), how the fluid warms to a level that the equation of state is valid (if necessary), and finally how the flow develops into the Gaussian profiles that serve as the boundary conditions to the models described in Sections 3.3.1 and 3.4.2.

#### 3.2.1. Orifice Flow

HyRAM+ assumes that fluids flow isentropically through an orifice. CoolProp [33] is used to calculate the entropy ( $s_0$ ) and enthalpy ( $h_0$ ) of the fluid upstream of an orifice, using the specified pressure and temperature (or phase if a saturated vapor or saturated liquid is specified). CoolProp [33] is then used to calculate the enthalpy ( $h$ ) and density ( $\rho$ ) of a fluid at a given pressure with the same entropy as the upstream fluid ( $s_0$ ). An isenthalpic expansion requires

$$\frac{v^2}{2} + h = h_0 \quad (39)$$

which can be solved for the velocity,  $v$ , and the mass flux can be calculated as

$$\dot{m}'' = \rho v. \quad (40)$$

A maximum mass flux is sought between the ambient and upstream pressures [46–48] using a bounded solver. If the maximum mass flux occurs at atmospheric pressure, the flow is unchoked, while if the maximum mass flux is at a pressure above atmospheric, the flow is choked. In the case of choked flow, the velocity through the orifice will be the speed of sound for the given throat conditions. The choked flow speed of sound for gases is the same as that calculated by CoolProp [33], but this algorithm also works for two-phase and liquid flows through the throat, for which the speed of sound is ill-defined.

Orifices in HyRAM+ are assumed to be circular, characterized by their diameter,  $d$ , and a coefficient of discharge,  $C_d$ . When the velocity and density of the fluid at the orifice is known, the mass flow rate is calculated as:

$$\dot{m} = \frac{\pi}{4} d^2 \dot{m}'' C_d = \frac{\pi}{4} d^2 \rho v C_d. \quad (41)$$

#### 3.2.2. Notional Nozzles

Notional nozzles are used to calculate the effective diameter, velocity, and thermodynamic state after the complex shock structure of an under-expanded jet. In HyRAM+, a notional nozzle model is used if the pressure at the orifice is above atmospheric pressure. They are not necessarily a physical description of the phenomena, but a jet with the diameter, velocity and state (temperature and atmospheric pressure) of the notional nozzle would lead to the same dispersion characteristics

as the underexpanded jet. There are five different notional nozzle models in HyRAM+, with each model conserving mass between flow through the real orifice and flow through the notional nozzle. This means that

$$\rho_{\text{eff}} v_{\text{eff}} A_{\text{eff}} = \rho_{\text{throat}} v_{\text{throat}} A_{\text{throat}} C_D \quad (42)$$

where  $\rho$  is the density,  $v$  is the velocity,  $A$  is the cross-sectional area,  $C_D$  is the discharge coefficient, the subscript "throat" denotes the choke point (at the orifice, see Section 3.2.1), and the subscript "eff" denotes effective (after the shock structure and the pressure has returned to atmospheric).

The default notional nozzle model in HyRAM+ is based on the work of Yüceil and Ötügen [49]. In this case, mass (Equation 42), momentum, and energy are conserved. Conservation of momentum is written as

$$\rho_{\text{eff}} v_{\text{eff}}^2 A_{\text{eff}} = \rho_{\text{throat}} v_{\text{throat}}^2 A_{\text{throat}} C_D + A_{\text{throat}} (P_{\text{throat}} - P_{\text{ambient}}) \quad (43)$$

where  $P$  is the pressure. Simultaneous solution of Equations 42 and 43 yields a solution for the velocity at the notional nozzle

$$v_{\text{eff}} = v_{\text{throat}} C_D + \frac{P_{\text{throat}} - P_{\text{ambient}}}{\rho_{\text{throat}} v_{\text{throat}} C_D} \quad (44)$$

and the effective area of the notional nozzle

$$A_{\text{eff}} = \frac{\rho_{\text{throat}} v_{\text{throat}}^2 A_{\text{throat}} C_D^2}{\rho_{\text{eff}} (P_{\text{throat}} - P_{\text{ambient}} + \rho_{\text{throat}} v_{\text{throat}}^2 C_D^2)} \quad (45)$$

The effective area calculation in Equation 45 requires the effective density, which can be calculated using the conservation of energy (assuming isentropic expansion), where

$$\frac{v_{\text{eff}}^2}{2} + h(\rho_{\text{eff}}, P_{\text{ambient}}) = \frac{v_{\text{throat}}^2}{2} + h_{\text{throat}}. \quad (46)$$

CoolProp [33] is used to calculate the enthalpy and Equation 46 is iteratively solved to determine the effective density.

Alternative to using Equation 46, the second notional nozzle model follows the work of Birch et al. (1987) [50]. In this work, the effective density is calculated by assuming that the temperature of the notional nozzle is the same as the temperature of the stagnant gas, or

$$\rho_{\text{eff}} = \rho(T_0, P_{\text{ambient}}) \quad (47)$$

where  $T_0$  is the temperature of the stagnant gas (storage temperature) and CoolProp [33] is used to calculate the density.

Three other notional nozzle models do not conserve momentum (Equation 43), but rather assume that the notional nozzle velocity is at the speed of sound, as follows. The third notional nozzle model follows the work of Birch et al. (1984) [51]. For this model, it is assumed that the

temperature at the notional nozzle is the same as temperature of the stagnant gas, the density (see Equation 47) and velocity at the notional nozzle can be calculated

$$v_{\text{eff}} = a(T_0, P_{\text{ambient}}) \quad (48)$$

where  $a$  is the speed of sound, calculated using CoolProp [33]. The conservation of mass, Equation 42, along with Equations 47 and 48, can be used to specify the notional nozzle conditions.

Alternatively, Ewan and Moody [52] use the assumption that the temperature at the notional nozzle is the same as the temperature at the throat, or

$$\rho_{\text{eff}} = \rho(T_{\text{throat}}, P_{\text{ambient}}) \quad (49)$$

$$v_{\text{eff}} = a(T_{\text{throat}}, P_{\text{ambient}}). \quad (50)$$

Finally, Molkov et al. [53] specifies that mass and energy are conserved between the orifice and the notional nozzle and that the notional nozzle is at the speed of sound, i.e., Equation 42 along with the simultaneous solution of the equations,

$$\frac{v_{\text{eff}}^2}{2} + h(\rho_{\text{eff}}, P_{\text{ambient}}) = \frac{v_{\text{throat}}^2}{2} + h_{\text{throat}} \quad (51)$$

$$v_{\text{eff}} = a(\rho_{\text{eff}}, P_{\text{ambient}}) \quad (52)$$

where  $h$  and  $a$  are calculated using CoolProp [33].

To summarize, the 5 different notional nozzles available in HyRAM+ solve the equations:

- (default) Yüceil and Ötügen [49]: Equations 44, 45, and 46
- Birch et al. (1987) [50]: Equations 44, 45, and 47
- Birch et al. (1984) [51]: Equations 42, 47, and 48
- Ewan and Moody [52]: Equations 42, 49, and 50
- Molkov et al. [53]: Equations 42, 51, and 52

### 3.2.3. Initial Entrainment and Heating

The models in HyRAM+ are valid for hydrogen, methane, propane, and blends, including saturated vapor and saturated liquid releases. Specifically for cryogenic hydrogen, there are challenges calculating properties in regions of the flow where oxygen and nitrogen from the entrained air would condense due to the extremely low temperatures, as noted by Houf and Winters [54]. To account for this, conservation of mass, energy and momentum can be applied until the temperature of the mixture (still assumed to be a plug-flow) is above a specified temperature ( $T_{\text{min}}$ ). However, it should be noted that the default minimum temperature is 0 K, so initial entrainment and heating is currently unused in the GUI implementation and can only be used in the Python implementation. If the temperature of the notional nozzle (or at the orifice, if

the flow is unchoked) is below  $T_{min}$ , the state after initial entrainment and heating is specified as the fuel at  $T_{min}$ , and simultaneous solution to the momentum and energy balances yields the mass fraction of fuel ( $Y$ ) when the mixture has warmed to  $T_{min}$ , i.e.,

$$\dot{m}_{out} = \dot{m}_{in} + \frac{1-Y}{Y} \dot{m}_{in} \quad (53)$$

$$v_{out} = v_{in} \frac{\dot{m}_{in}}{\dot{m}_{out}} \quad (54)$$

$$h_{out} = (1-Y)h_{air}(T_{min}, P_{ambient}) + Yh_{H_2}(T_{min}, P_{ambient}) + \frac{v_{out}^2}{2} \quad (55)$$

$$\dot{m}_{out}h_{out} = \dot{m}_{in}h_{in} + (\dot{m}_{out} - \dot{m}_{in})h_{air}(T_{ambient}, P_{ambient}). \quad (56)$$

Once the mass fraction ( $Y$ ) is known, conservation of mass is used to yield the diameter of the plug flow at the end of the zone of initial entrainment and heating,

$$\rho_{out} = \frac{1}{\frac{1-Y}{\rho_{air}(T_{min}, P_{ambient})} + \frac{Y}{\rho_{H_2}(T_{min}, P_{ambient})}} \quad (57)$$

$$d_{out} = \sqrt{\frac{\pi \dot{m}_{out}}{4 \rho_{out} v_{out}}} \quad (58)$$

and the momentum driven entrainment rate (see Equation 80) is used to calculate the length of this zone,

$$S = \frac{(1-Y)(\dot{m}_{out} - \dot{m}_{in})}{\rho_{ambient}(T_{ambient}, P_{ambient})E_{mom}}. \quad (59)$$

### 3.2.4. Establishment of a Gaussian Profile

The flows described in Sections 3.2.1, 3.2.2, and 3.2.3 are all assumed to be plug flows, where the properties (e.g., velocity, density) are constant across the entire cross-section of the flow.

However, jets, plumes, or flames from a pure source are well-known to have Gaussian profiles of their properties (e.g., velocity, density, mixture fraction) in the downstream regions [42, 55]. The final model for developing flow describes the transition from plug flow to the Gaussian profile that is used as an input to a one-dimensional system of ordinary differential equations that describes unignited dispersion or a diffusion flame (see Sections 3.3.1 and 3.4.2). Following the work of Winters [56], the centerline velocity of the Gaussian flow is assumed to be equivalent to the plug flow velocity, the jet is characterized by a half-width,  $B$ , where the velocity drops to half of the center-line value, and a spreading ratio,  $\lambda$ , the ratio of density spreading relative to velocity. The center-line (denoted with a  $cl$  subscript) mass-fraction is related to  $\lambda$  via the relationship,

$$\frac{\lambda^2 + 1}{2\lambda^2} = \frac{Y_{cl} - Y_{ambient}}{Y_{plug} - Y_{ambient}}. \quad (60)$$

Then the center-line molecular weight can be calculated,

$$MW_{cl} = \frac{1}{Y_{cl}/MW_{fuel} + (1 - Y_{cl})/MW_{air}}. \quad (61)$$

The heat capacity of the fluid and ambient air are determined from CoolProp [33] and used to calculate the individual and mixture enthalpies as  $h = c_p \cdot T$ , where

$$c_{p,\text{plug}} = c_{p,\text{C}_n\text{H}_{2n+2}} Y_{\text{plug}} + c_{p,\text{air}} (1 - Y_{\text{plug}}), \quad (62)$$

$$c_{p,\text{cl}} = c_{p,\text{plug}} Y_{\text{cl}} + c_{p,\text{air}} (1 - Y_{\text{cl}}), \quad (63)$$

$$\frac{\lambda^2 + 1}{2\lambda^2} = \frac{h_{\text{cl}} - h_{\text{ambient}}}{h_{\text{plug}} - h_{\text{ambient}}}. \quad (64)$$

From these equations, the center-line temperature can be calculated, and the center-line density is calculated using the ideal gas equation of state, where

$$\rho_{\text{cl}} = \frac{\text{MW}_{\text{cl}} P}{RT_{\text{cl}}}. \quad (65)$$

The length of the developing flow region is taken from Abraham [57], where  $S/d = 6.2$ , which assumes that the Froude number (Equation 84) is greater than the square root of 40 for these high speed, low density jets.

### 3.3. Unignited Releases

#### 3.3.1. Gas Jet/Plume

For a jet or plume, HyRAM+ follows the one-dimensional model described by Houf and Winters [54]. While the model only considers one dimension, this dimension is along the streamline, and the jet/plume can curve due to buoyancy effects (or wind, although this aspect is not currently included). The reduction in dimension comes from the assumption that the mean profiles of the velocity ( $v$ ), density ( $\rho$ ), and product of density and mass fraction ( $Y$ ) of fuel are Gaussian, as

$$v = v_{\text{cl}} \exp\left(-\frac{r^2}{B^2}\right) \quad (66)$$

$$\rho = (\rho_{\text{cl}} - \rho_{\text{amb}}) \exp\left(-\frac{r^2}{\lambda^2 B^2}\right) + \rho_{\text{amb}} \quad (67)$$

$$\rho Y = \rho_{\text{cl}} Y_{\text{cl}} \exp\left(-\frac{r^2}{\lambda^2 B^2}\right) \quad (68)$$

where  $B$  is a characteristic half-width,  $\lambda$  is the ratio of density spreading relative to velocity, the subscript  $\text{cl}$  denotes the centerline, the subscript  $\text{amb}$  denotes ambient, and  $r$  is perpendicular to the stream-wise direction. Gravity acts in the negative  $y$ -direction, and the plume angle,  $\theta$  is relative to the  $x$ -axis (horizontal), as shown in Figure 3-3.

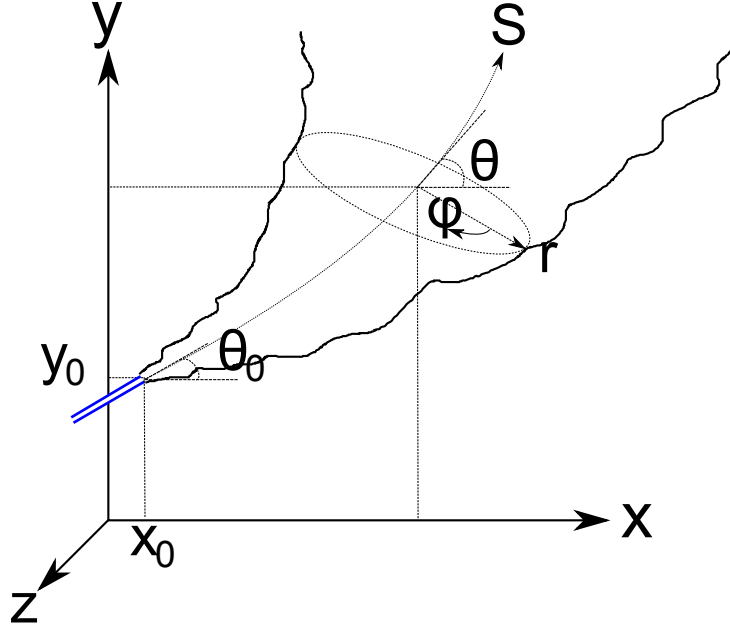


Figure 3-3: Sketch of plume model coordinates. Gravity acts in the negative  $y$ -direction.

The derivatives of the spatial dimensions are therefore

$$\frac{dx}{dS} = \cos \theta, \quad (69)$$

$$\frac{dy}{dS} = \sin \theta. \quad (70)$$

The conservation equations can be written as follows:

continuity:

$$\frac{d}{dS} \int_0^\infty (\rho v) 2\pi r dr = \rho_{amb} E, \quad (71)$$

$x$ -momentum:

$$\frac{d}{dS} \int_0^\infty (\rho v^2 \cos \theta) 2\pi r dr = 0, \quad (72)$$

$y$ -momentum:

$$\frac{d}{dS} \int_0^\infty (\rho v^2 \sin \theta) r dr = \int_0^\infty (\rho_{amb} - \rho) g r dr, \quad (73)$$

species continuity:

$$\frac{d}{dS} \int_0^\infty (\rho v Y) 2\pi r dr = 0, \quad (74)$$

energy:

$$\frac{d}{dS} \int_0^\infty \rho v \left( h + \frac{v^2}{2} - h_{amb} \right) 2\pi r dr = 0. \quad (75)$$

Similar to Houf and Winters [54], HyRAM+ assumes that  $h = c_p T$  and the ideal gas equation of state is used for these ambient pressure mixtures. The mixture molecular weight, heat capacity, and product of density and enthalpy all vary with respect to the radial coordinate (due to the fact that  $Y$  and  $\rho$  vary radially, see Equation 68) according to the following expressions:

$$MW = \frac{MW_{amb} MW_{fuel}}{Y(MW_{amb} - MW_{fuel}) + MW_{fuel}}, \quad (76)$$

$$c_p = Y(c_{p,fuel} - c_{p,amb}) + c_{p,amb}, \quad (77)$$

$$\rho h = \frac{P}{R} c_p MW. \quad (78)$$

The Gaussian profiles in Equations 66-68 are plugged into the governing equations, and with the exception of the energy equation can be integrated analytically. For the energy equation, Equation 75, the numeric integration to infinity is estimated by evaluation to  $5B$ . This results in a system of 7 first order differential equations where the independent variable is  $S$  and the dependent variables are  $v_{cl}$ ,  $B$ ,  $\rho_{cl}$ ,  $Y_{cl}$ ,  $\theta$ ,  $x$ , and  $y$ . This system of equations is integrated from the starting point to the distance desired using an explicit Runge-Kutta method of order (4)5.

The entrainment model follows Houf and Schefer [55], where there is a combination of momentum and buoyancy driven entrainment,

$$E = E_{mom} + E_{buoy}, \quad (79)$$

where

$$E_{mom} = 0.282 \left( \frac{\pi d_{exp}^2 \rho_{exp} v_{exp}^2}{4 \rho_\infty} \right)^{1/2}, \quad (80)$$

where the "exp" subscript denotes after the notional nozzle and zone of initial entrainment and heating (if used; see Sections 3.2.2 and 3.2.3), and

$$E_{buoy} = \frac{a}{Fr_l} (2\pi v_{cl} B) \sin \theta, \quad (81)$$

where the local Froude number,

$$Fr_l = \frac{v_{cl}^2}{gD(\rho_\infty - \rho_{cl})/\rho_{exit}}. \quad (82)$$

In these equations,  $a$  is empirically determined:

$$\begin{cases} a = 17.313 - 0.116665 Fr_{den} + 2.0771 \times 10^{-4} Fr_{den}^2, & Fr_{den} < 268 \\ a = 0.97, & Fr_{den} \geq 268, \end{cases} \quad (83)$$

with the densimetric Froude number

$$\text{Fr}_{\text{den}} = \frac{v_{\text{plug}}}{\sqrt{g d_{\text{plug}} |\rho_{\infty} - \rho_{\text{plug}}| / \rho_{\text{plug}}}}, \quad (84)$$

where the subscript “plug” denotes the plug flow at the exit of the orifice, notional nozzle, or zone of initial entrainment and heating, as applicable (see Sections 3.2.1, 3.2.2, and 3.2.3).

As the jet/plume becomes buoyancy-dominated (as opposed to momentum-dominated), the non-dimensional number

$$\alpha = \frac{E}{2\pi B v_{cl}} \quad (85)$$

will increase. When  $\alpha$  reaches the limiting value of  $\alpha = 0.082$ ,  $\alpha$  is held constant and the entrainment value becomes:

$$E = 2\pi\alpha B v_{cl} = 0.164\pi B v_{cl}. \quad (86)$$

### 3.3.2. *Tank Mass*

The mass of fuel in a storage container ( $m$ ) is calculated using the density of the fuel ( $\rho$ ) and fixed volume of the container ( $V$ ) using Equation 87. The density of the fuel ( $\rho$ ) is calculated using the specified temperature and pressure using the CoolProp library [33] as described in Section 3.1.1.

$$m = \rho V \quad (87)$$

### 3.3.3. *Tank Emptying*

In the case of a storage tank with a given volume, the transient process of the tank emptying (blowdown) can also be calculated by HyRAM+. In this case, energy and mass are conserved, following the work of Hosseini et al. [58]. The mass flow rate,  $\dot{m}$  is calculated as described in Section 3.2.1, whether the flow is choked or not. Energy is conserved in the tank volume, where

$$\frac{du}{dt} = \frac{\dot{m}(h - u) + q}{m}, \quad (88)$$

where  $u$  and  $h$  are the specific energy and specific enthalpy (J/kg), respectively, of the fuel in the tank (calculated using CoolProp [33]),  $m$  is the mass of fuel in the tank (kg, see Section 3.3.2), and  $q$  is the heat flow into the tank (J/s,  $q = 0$  if adiabatic). This equation and the equations describing the mass flow rate (which are functions of the pressure and temperature inside the tank) are integrated until the mass or pressure in the tank reaches the desired stopping point (e.g., the tank pressure reaches ambient).

### 3.3.4. Accumulation in Confined Areas/Enclosures

When a release occurs in an enclosure, a stratified mixture of fuel and air can accumulate. For hydrogen or methane, the accumulated mixture will be near the ceiling due to buoyancy.

The release inside an enclosure is assumed to come from some tank with a fixed volume. Therefore, the flow from the tank follows Section 3.3.3. At each point in time for the blowdown, the jet/plume is modeled as described in Section 3.3.1. When these releases occur indoors, the plumes could impinge on a wall. Currently, should this impingement happen, the trajectory of the jet/plume is modified such that the fuel will travel vertically upwards along the wall, rather than in the horizontal direction, with the same features (e.g., half-width, centerline velocity). Note that this deflection upwards will occur regardless of the fuel and is a poor assumption for heavier fuels such as propane.

Accumulation occurs following the model of Lowesmith et al. [59], where a layer forms along the ceiling. Conservation of mass requires that

$$\frac{dV_l}{dt} = Q_{in} - Q_{out}, \quad (89)$$

where  $V_l$  is the volume of gas in the layer, and  $Q$  is the volumetric flow rate, with subscript “in” referring to the flow rate of fuel and air entrained into the jet at the height of the layer, and “out” referring to flow out the ventilation. Species conservation requires that

$$\frac{d(\chi V_l)}{dt} = Q_{leak} - \chi Q_{out}, \quad (90)$$

where  $\chi$  is the mole or volume fraction of fuel in the layer and  $Q_{leak}$  is the leak rate of the fuel. Expanding the derivative and substituting Equation 89 yields

$$V_l \frac{d\chi}{dt} = Q_{leak} - \chi Q_{in}. \quad (91)$$

$Q_{in}$  is solved for by modeling a jet/plume within the enclosure to calculate the jet half-width ( $B$ ) and centerline velocity ( $v_{cl}$ ), as described in Section 3.3.1 at the height of the bottom of the layer. The volumetric flow rate ( $Q_{in}$ ) is calculated as:

$$Q_{in} = \pi B^2 v_{cl}. \quad (92)$$

Flows out of the enclosure are driven by buoyancy, and potentially wind or a fan. Buoyancy driven flow is calculated as

$$Q_b = C_d A_v \sqrt{g' H_l}, \quad (93)$$

where  $C_d$  is a coefficient of discharge,  $A_v$  is the area of the upper (outlet) vent,  $H_l$  is the height of the layer (between the bottom of the layer and the center-point of the outlet vent), and  $g'$  is reduced gravity:

$$g' = g \frac{\rho_{air} - \rho_l}{\rho_{air}}, \quad (94)$$

where  $g$  is the gravitational constant,  $\rho_l$  is the density of the layer, and  $\rho_{\text{air}}$  is the density of air (at the temperature and pressure of the enclosure). The density in the layer ( $\rho_l$ ) is calculated from the density of air ( $\rho_{\text{air}}$ ) and the density of the fuel ( $\rho_{\text{C}_n\text{H}_{2n+2}}$ ), both at the temperature and pressure of the enclosure, as:

$$\rho_l = \chi \rho_{\text{C}_n\text{H}_{2n+2}} + (1 - \chi) \rho_{\text{air}}. \quad (95)$$

Wind (or mechanical ventilation) is assumed to drive the flow at a rate of:

$$Q_w = \frac{C_d A_v U_w}{\sqrt{2}} = \frac{C_d Q_{\text{vent}}}{\sqrt{2}}, \quad (96)$$

where  $C_d$  is a coefficient of discharge,  $A_v$  is the area of the lower (inlet) vent,  $U_w$  is the velocity of the wind (or mechanical ventilation) through the lower (inlet) vent, and  $Q_{\text{vent}}$  is the volumetric flow rate through the lower (inlet) vent ( $Q_{\text{vent}} = A_v U_w$ ). Note that  $Q_{\text{vent}}$  is a user input.

The total flow out of the enclosure, accounting for buoyancy driven flow and flow from the vent, is calculated as

$$Q_{\text{out}} = Q_{\text{leak}} + \sqrt{Q_b^2 + Q_w^2}. \quad (97)$$

### 3.4. Ignited Releases

#### 3.4.1. Flame Correlations

As noted by Houf and Schefer [60], a non-dimensional flame length, defined as

$$L^* = \frac{L_{\text{vis}} f_s}{d_j \sqrt{\rho_j / \rho_{\text{amb}}}} \quad (98)$$

collapses onto a single curve for a range of fuels (hydrogen, methane, and propane), where  $L_{\text{vis}}$  is the visible flame length (from the orifice, including any liftoff distance),  $f_s$  is the mass fraction of fuel in a stoichiometric mixture of fuel and air (Equation 35), and  $d_j$ ,  $\rho_j$ , and  $\rho_{\text{amb}}$  are the orifice diameter, density of fuel at the orifice, and density of air, respectively. It is assumed that this curve will also be valid for blends. The curve is given by

$$L^* = \begin{cases} \frac{13.5 \text{Fr}^{2/5}}{(1+0.07 \text{Fr}^2)^{1/5}}, & \text{Fr} < 5, \\ 23, & \text{Fr} > 5, \end{cases} \quad (99)$$

which is a function of the Froude number (Fr), which is the ratio of buoyancy to momentum forces. The Froude number is defined as

$$\text{Fr} = \frac{u_j f_s^{3/2}}{\sqrt{g d_j (T_{\text{ad}} - T_{\text{amb}}) / T_{\text{amb}} \sqrt{\rho_j / \rho_{\text{amb}}}}}, \quad (100)$$

where  $g$  is the gravitational constant,  $u_j$  is the velocity of the jet at the orifice,  $T_{\text{ad}}$  is the adiabatic flame temperature (for a stoichiometric mixture, see section 3.1.2), and  $T_{\text{amb}}$  is the ambient temperature. The flame width is constant at  $W_f = 0.17 L_{\text{vis}}$  [61, 62].

The total emitted radiative power from a flame,  $S_{\text{rad}}$ , is related to the total energy in the flame by the radiant fraction,

$$S_{\text{rad}} = X_{\text{rad}} \dot{m}_{\text{fuel}} \Delta H_c, \quad (101)$$

where  $X_{\text{rad}}$  is the radiant fraction,  $\dot{m}_{\text{fuel}}$  is the mass flow rate of fuel, and  $\Delta H_c$  is the heat of combustion (120 MJ/kg for hydrogen, 50 MJ/kg for methane, and 46.4 MJ/kg for propane [44, 45]). The radiant fraction ( $X_{\text{rad}}$ ) varies with the flame residence time ( $\tau_f$ ); the relationship is [63]

$$X_{\text{rad}} = 9.45 \times 10^{-9} (\tau_f a_p T_{\text{ad}}^4)^{0.47}, \quad (102)$$

where  $a_p$  is the Planck-mean absorption coefficient for an optically thin flame. To calculate the absorption coefficient, the absorption coefficients of  $\text{H}_2\text{O}$  and  $\text{CO}_2$  are calculated at the adiabatic flame temperature from correlations given by Chmielewski and Gieras [64]. The total Planck-mean absorption coefficient is calculated by averaging the absorption coefficient for all of the products of combustion (only  $\text{H}_2\text{O}$  and  $\text{CO}_2$  are radiatively active), weighted by the stoichiometric mole fractions of the products. This results in absorption coefficients similar to those reported by Molina et al. [65] (approximately 0.2 for a hydrogen flame and 0.5 for a methane flame).

The flame residence time can be calculated as

$$\tau_f = \frac{\pi \rho_f W_f^2 L_{\text{vis}} f_s}{12 \dot{m}_{\text{fuel}}}, \quad (103)$$

where  $\rho_f$  is the flame density. The flame density is calculated as the density at the adiabatic flame temperature:

$$\rho_f = \frac{p_{\text{amb}} W_{\text{mix}}}{RT_{\text{ad}}}, \quad (104)$$

where  $p_{\text{amb}}$  is the ambient pressure,  $W_{\text{mix}}$  is the mean molecular weight of the stoichiometric products of combustion in air, and  $R$  is the universal gas constant.

The transmissivity, which can reduce the radiated heat flux is calculated to account for the absorption from water vapor and  $\text{CO}_2$ , using a correlation from Wayne [66]:

$$\begin{aligned} \tau = 1.006 - 0.001171 (\log_{10} X_{\text{H}_2\text{O}}) - 0.02368 (\log_{10} X_{\text{H}_2\text{O}})^2 \\ - 0.03188 (\log_{10} X_{\text{CO}_2}) + 0.001164 (\log_{10} X_{\text{CO}_2})^2, \end{aligned} \quad (105)$$

where  $X_{\text{H}_2\text{O}}$  and  $X_{\text{CO}_2}$  is proportional to the amount of water vapor or  $\text{CO}_2$  in the path (dimensionless). These values are calculated by:

$$X_{\text{CO}_2} = L \cdot \frac{273}{T} \cdot \frac{c_{\text{CO}_2}}{335}, \quad (106)$$

$$X_{\text{H}_2\text{O}} = R_H \cdot L \cdot S_{\text{mm}} \cdot \frac{2.88651 \times 10^2}{T}. \quad (107)$$

In these relationships,  $L$  is the path length (m) through which the radiative light must travel,  $T$  is the ambient temperature (K),  $c_{\text{CO}_2}$  is the concentration of  $\text{CO}_2$  in the atmosphere (ppm, assumed to be 400 ppm),  $R_H$  is the fractional relative humidity (ranges from 0–1), and  $S_{\text{mm}}$  is the saturated water vapor pressure (mm Hg), estimated by the relationship:

$$S_{\text{mm}} = \exp \left( 10.386 - \frac{5132}{T} \right). \quad (108)$$

### 3.4.2. Jet Flame with Buoyancy Correction

A similar model to the jet/plume model described in Section 3.3.1 is also used to describe a flame. The model is described by Ekoto et al. [42]. The major difference between the jet/plume model and the flame model is that rather than the mole fraction, the mixture fraction, shown in Equation 37, is a conserved scalar. Similar assumptions are made for Gaussian profiles of the velocity and mixture fraction:

$$v = v_{cl} \exp\left(-\frac{r^2}{B^2}\right), \quad (109)$$

$$f = f_{cl} \exp\left(-\frac{r^2}{\lambda^2 B^2}\right), \quad (110)$$

with the conservation equations written as

$x$ -centerline:

$$\frac{dx}{dS} = \cos \theta, \quad (111)$$

$y$ -centerline:

$$\frac{dy}{dS} = \sin \theta, \quad (112)$$

continuity:

$$\frac{d}{dS} 2\pi \int_0^\infty \rho v r dr = \rho_{amb} E, \quad (113)$$

$x$ -momentum:

$$\frac{d}{dS} 2\pi \int_0^\infty \rho v^2 \cos \theta r dr = \rho_{amb} E v_{wind}, \quad (114)$$

$y$ -momentum:

$$\frac{d}{dS} \int_0^\infty \rho v^2 \sin \theta r dr = \int_0^\infty (\rho_{amb} - \rho) g r dr, \quad (115)$$

mixture fraction:

$$\frac{d}{dS} 2\pi \int_0^\infty \rho V f r dr = 0. \quad (116)$$

Note that energy conservation is not included in this formulation, but rather the mixture is assumed to be thermally perfect, with combustion calculations shown in Section 3.1.2. These

calculations assume that the mixture is always in equilibrium (neglecting heat-losses), which results in a calculation of flame temperature and density as functions of mixture fraction similar to Figure 3-2 (with slight variations depending on the reactant temperature).

Equation 114 does not explicitly set the right-hand side of the  $x$ -momentum equation to 0, as is done in the unignited jet/plume model (Equation 72). While the Windows GUI version of HyRAM+ sets  $v_{\text{wind}} = 0$ , the Python backend enables specification of a cross-wind velocity,  $v_{\text{wind}}$ . The Gaussian profiles in Equations 109 and 110 are numerically evaluated out to  $5B$  (an estimate of  $\infty$ ), along with the radial profiles of the density (based off of the mixture fraction), which can be plugged into Equations 111–116 and numerically integrated. This results in a system of 6 first order differential equations where the independent variable is  $S$  and the dependent variables are  $v_{cl}$ ,  $B$ ,  $\theta$ ,  $f_{cl}$ ,  $x$ , and  $y$ . This system of equations is integrated from the starting point to the distance desired using an Adams/BDF method with automatic stiffness detection and switching. Typically, the integration distance is the visible flame length, calculated using the correlations in Equations 98 and 99.

Similar to the nonreacting jet, entrainment in the jet flame is modeled as the sum of momentum and buoyancy contributions (Equation 79). However, the contributions have modified empirical parameters and calculation methods. The momentum driven entrainment is calculated as

$$E_{mom} = 0.0342 \left( \frac{\pi d_{\text{exp}}^2}{4} \frac{\rho_{\text{exp}} v_{\text{exp}}^2}{\rho_{\infty}} \right)^{1/2}, \quad (117)$$

and buoyancy driven entrainment is calculated as

$$E_{buoy} = 2\pi\alpha_{buoy}g \sin\theta \frac{\int_0^{\infty} (\rho_{amb} - \rho) dr}{Bv_{cl}\rho_{exit}} \quad (118)$$

where  $\alpha_{buoy} = 5.75 \times 10^{-4}$  [42].

### 3.4.3. Radiation From a Curved Flame

The radiative heat flux from the buoyancy corrected, curved flame is calculated by a weighted multi-source model, similar to that described by Hankinson and Lowesmith [67]. The heat flux at a point along the flame is calculated as

$$q = \tau S_{\text{rad}} \frac{V_F}{A_f}, \quad (119)$$

where  $S_{\text{rad}}$  is calculated according to Equations 101–103,  $V_F$  is the view-factor, proportional to the heat flux transmitted to the observer,  $\tau$  is the transmissivity, calculated by Equation 105, and  $A_f$  is the surface area of the flame. Contributions to the total heat flux are broken up into many ( $N$ , generally 50) points along the length of the curved flame, and the weighted average proceeds as

$$\tau \frac{V_F}{A_f} = \sum_{i=1}^N \frac{w_i \cos \beta_i}{4\pi D_i^2} \tau_i, \quad (120)$$

where the emitter strength weighting parameter

$$w_i = \begin{cases} iw_1 & i \leq 0.75N \\ \left[ n - \frac{n-1}{N-n-1} (i - (n+1)) \right] w_1 & i > 0.75N, \end{cases} \quad (121)$$

with the constraint that  $1 \leq n \leq N$  and  $\sum_{i=1}^N w_i = 1$ . In these equations,  $D$  and  $\beta$  are the distance and angle, respectively between the observer and unit normal to the point emitter.

#### 3.4.4. Overpressure in Enclosures

If a confined mixture ignites, significant overpressures can develop within the enclosure or confinement area. Overpressure is calculated assuming that the cause of overpressure is the volume change on combustion pressurizing the enclosure. Within HyRAM+, the models described in Section 3.3.4 are used to calculate the volume of fuel within the layer and entire enclosure. It is assumed that all of the fuel within the flammability limits (in both the jet/plume and the accumulated layer) reacts, and the overpressure is calculated, following Bauwens and Dorofeev [68] as

$$\Delta p = p_0 \left( \left[ \left( \frac{V_T + V_{C_nH_{2n+2}}}{V_T} \right) \left( \frac{V_T + V_{stoich}(\sigma - 1)}{V_T} \right) \right]^\gamma - 1 \right), \quad (122)$$

where  $p_0$  is the initial pressure,  $V_T$  is the total volume of the enclosure,  $V_{C_nH_{2n+2}}$  is the expanded volume of pure fuel following the release,  $V_{stoich}$  is the volume of a stoichiometric mixture of the consumed fuel,  $\sigma$  is the expansion ratio of a stoichiometric fuel-air mixture, and  $\gamma$  is the specific heat ratio of air. The expanded volume is given by  $V_{C_nH_{2n+2}} = m_{C_nH_{2n+2}} / \rho_{C_nH_{2n+2}}$  where  $m_{C_nH_{2n+2}}$  is the mass of fuel consumed and  $\rho_{C_nH_{2n+2}}$  is the density of the fuel at ambient conditions.  $V_{stoich}$  is  $V_{C_nH_{2n+2}}$  divided by the stoichiometric mole fraction of fuel.

#### 3.4.5. Unconfined Overpressure

If an unconfined mixture ignites after a release has been flowing for some time, an overpressure can be observed as the initial mixture burns. In this context, the overpressure is defined as the pressure above ambient. HyRAM+ has three different methods for calculating the overpressure, each of which requires the calculations from an unconfined and unignited jet/plume as described in Section 3.3.1. Each method calculates an overpressure and possibly impulse as a function of distance,  $R$ . The origin for the overpressure/impulse (distance from which  $R$  is measured) is the point at which the fuel concentration is assumed to be halfway between the lower and upper flammability limits along the jet streamline. This is assumed to be a reasonable origin location, given the overpressure blast wave will originate from the flammable mixture<sup>10</sup>.

<sup>10</sup>This is also roughly consistent with the suggested ignition concentration by Jallais et al. [69] for hydrogen.

**BST** The Baker-Strehlow-Tang (BST) model is based on blast curves that relate overpressure and impulse to the Mach flame speed [70]. The flammable mass of fuel within the unignited jet/plume ( $m_{flam}$ ) is first found by volumetrically integrating the product of the mass fraction ( $Y$ ) and density ( $\rho$ ) of the jet/plume that is within the flammability limits ( $Y_{LFL}$ ,  $Y_{UFL}$ ) along the entire length of the jet/plume streamline coordinate ( $S$ ), or

$$m_{flam} = \int_{S=0}^{S=\infty} \left( \int_{rY=Y_{UFL}}^{rY=Y_{LFL}} \rho Y 2\pi r dr \right) dS. \quad (123)$$

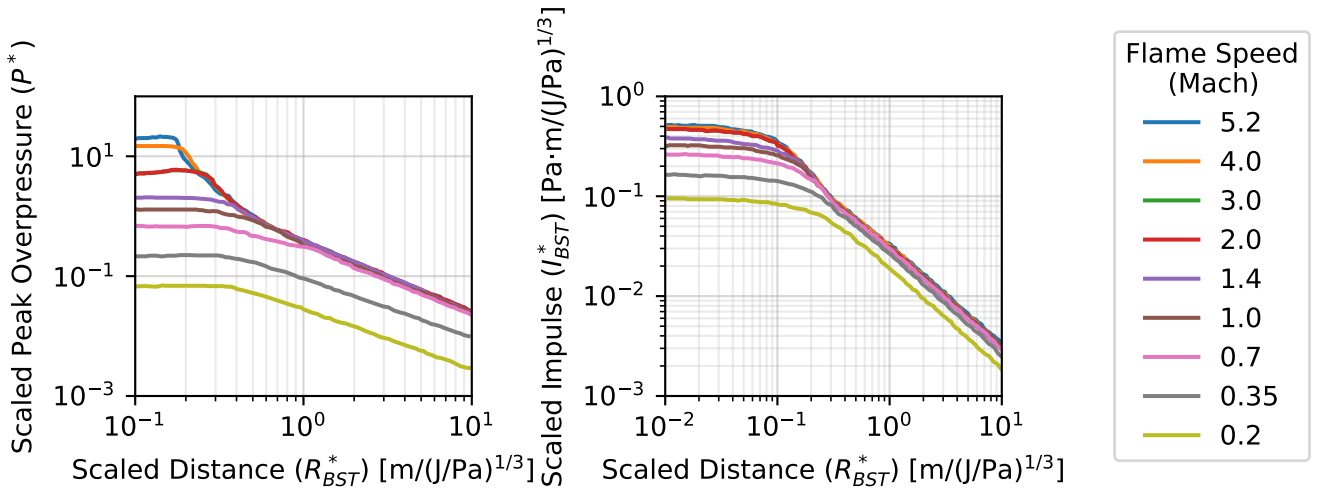
The energy within the unignited flammable mixture ( $E_{flam}$ ) is related to the flammable mass through the relationship

$$E_{flam} = k_{reflection} m_{flam} \Delta H_c \quad (124)$$

where  $k_{reflection}$  is a ground reflection factor (assumed to be 2) and  $\Delta H_c$  is the heat of combustion of the fuel [70]. The scaled distance is related to the energy through the relationship [70]

$$R_{BST}^* = \frac{R}{(E_{flam}/P_{ambient})^{1/3}}. \quad (125)$$

The scaled overpressure and impulse are related to the scaled distance, based on the Mach flame speed, as shown in Figure 3-4 [70]. The Mach flame speed selection is an important choice for BST model results, and can depend on the fuel being combusted, confinement and congestion of the flammable mixture, and other factors [70]. The default value in HyRAM+ for the Mach flame speed is 0.35<sup>11</sup>, based on overpressure observations for unconfined releases of hydrogen [69]; this value can be changed by the user.



**Figure 3-4: Mapping of scaled distance to scaled overpressure (left) and scaled impulse (right) for the BST unconfined overpressure model [3].**

<sup>11</sup>The default Mach flame speed value was 5.2 for HyRAM+ versions 4.0 and 4.1, which is used for detonations; however, experimental observations of unconfined deflagrations seem more applicable for these models.

The scaled overpressure ( $P^*$ ) is the peak overpressure ( $P_s$ ) relative to ambient pressure ( $P_{\text{ambient}}$ ),

$$P^* = P_s / P_{\text{ambient}}, \quad (126)$$

and the impulse ( $I$ ) is scaled by the flammable energy ( $E_{\text{flam}}$ ), ambient pressure ( $P_{\text{ambient}}$ ), and speed of sound for air ( $a_{\text{air}} = 340$  m/s) as

$$I_{\text{BST}}^* = \frac{I a_{\text{air}}}{(E_{\text{flam}} P_{\text{ambient}}^2)^{1/3}}. \quad (127)$$

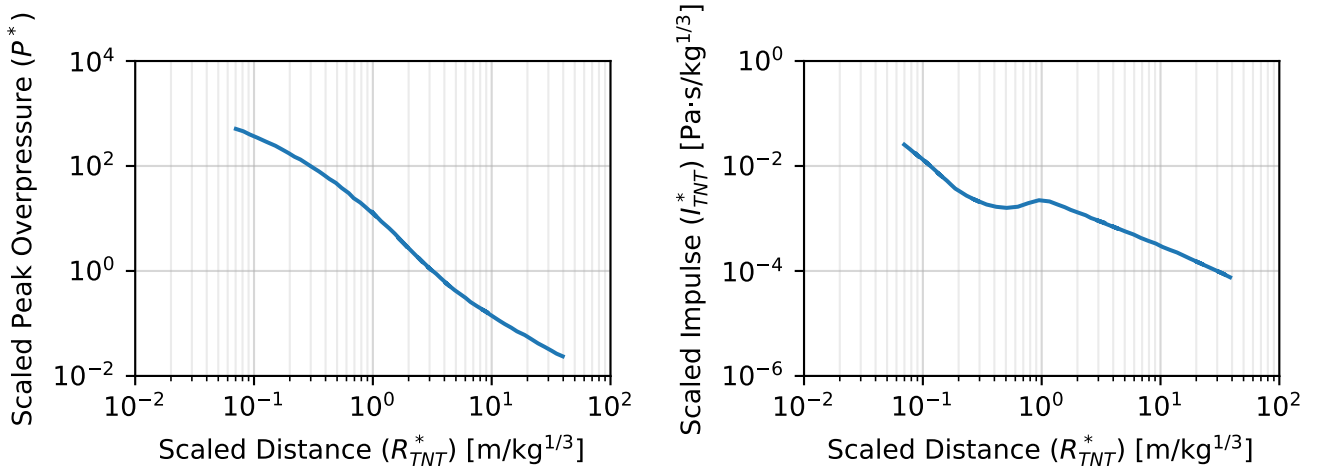
**TNT** The TNT equivalence method is based on finding the mass of TNT that contains the same energy as the fuel being combusted [70]. The flammable mass of fuel within the jet/plume ( $m_{\text{flam}}$ ) is found by volumetrically integrating the product of the mass fraction and density of the jet/plume that is within the flammability limits (see Equation 123). The flammable mass is scaled by an equivalence factor ( $F_{\text{equiv}}$ , 3% by default [70]), and the equivalent mass of TNT ( $m_{\text{TNTequiv}}$ ) is calculated as

$$m_{\text{TNTequiv}} = F_{\text{equiv}} \frac{m_{\text{flam}} \Delta H_c}{\Delta H_{c,\text{TNT}}}, \quad (128)$$

where  $\Delta H_{c,\text{TNT}} = 4.68$  MJ/kg is the equivalent specific blast energy of TNT<sup>12</sup>. The scaled distance ( $R_{\text{TNT}}^*$ ) is related to the equivalent mass of TNT ( $m_{\text{TNTequiv}}$ ) through the relationship

$$R_{\text{TNT}}^* = \frac{R}{m_{\text{TNTequiv}}^{1/3}}, \quad (129)$$

and the scaled overpressure ( $P^*$ ) and scaled impulse ( $I_{\text{TNT}}^*$ ) resulting from combustion are related to the scaled distance as shown by Figure 3-5.



**Figure 3-5: Mapping of scaled distance to scaled overpressure (left) and scaled impulse (right) for the TNT equivalence unconfined overpressure model [3].**

<sup>12</sup>Previous versions of HyRAM+ (e.g., [2]) had a separate Engineering Toolkit calculation that used a slightly different value for the TNT blast energy.

The scaled overpressure ( $P^*$ ) is the overpressure ( $P_s$ ) relative to ambient pressure (see Equation 126), and the impulse ( $I$ ) is scaled by the third root of the TNT mass ( $m_{\text{TNT}_{\text{equiv}}}$ ), or

$$I_{\text{TNT}}^* = \frac{I}{m_{\text{TNT}_{\text{equiv}}}^{1/3}}. \quad (130)$$

**Bauwens** The Bauwens method for unconfined overpressure calculation is based on the work of Bauwens and Dorfeev [71, 72]. In this method, the detonable mass within the unconfined jet/plume is calculated and then the overpressure is based on detonation of that mass of fuel. Due to the dependence of this model on detonation cell size, it has not been updated to work with mixtures/blends yet.

The detonation cell size ( $\lambda_{\text{det}}$ ) is calculated at each point in the jet/plume, based on the mass fraction field ( $Y$ , see section 3.3.1) and fits to data from the detonation database [73]. The fits to the data are based on a polynomial fit in log-log space [2]:

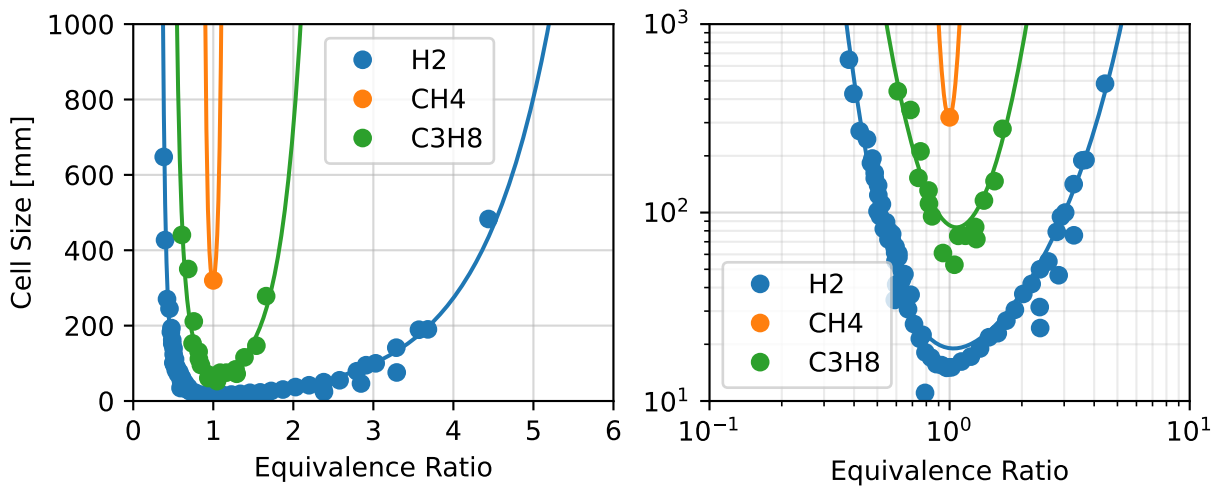
$$\ln \lambda_{\text{det}} = a + b \ln \phi + c (\ln \phi)^2 + d (\ln \phi)^3 + e (\ln \phi)^4, \quad (131)$$

where the parameters  $a$ – $e$  are given in Table 3-1.

**Table 3-1: Detonation cell size fitted parameters**

| Fuel                          | $a$        | $b$         | $c$          | $d$         | $e$        |
|-------------------------------|------------|-------------|--------------|-------------|------------|
| H <sub>2</sub>                | 2.94771698 | -0.16536739 | 2.2608031    | -1.18064551 | 0.45823461 |
| CH <sub>4</sub>               | 5.768321   | 1.13938677  | 113.36802963 | 0           | 0          |
| C <sub>3</sub> H <sub>8</sub> | 4.44856885 | -0.73108257 | 5.50526263   | 0           | 0          |

The fits and data for different fuels are shown in Figure 3-6.



**Figure 3-6: Detonation cell size data (points) from the detonation database [73] and fits to the data (lines) on a linear (left) and logarithmic (right) scale.**

Once the detonation cell size is calculated, the gradient in the radial direction of the detonation cell size ( $d\lambda_{det}/dr$ ) is found numerically. In addition, the number of cells that fit within the layer ( $n_{\lambda_{det}}$ ) is numerically calculated as

$$n_{\lambda_{det}} = \int_0^r \frac{dr}{\lambda_{det}(r)}. \quad (132)$$

Detonations are presumed to propagate in areas that are within the flammability limits, with a detonation cell size gradient less than 0.1 ( $d\lambda_{det}/dr < 0.1$ ), and where there are at least 5 cells within the layer ( $n_{\lambda_{det}} \geq 5$ ). The mass of fuel within the jet/plume that meets these constraints is calculated as the detonable mass ( $m_{det}$ ). In equation form,

$$m_{det} = \int_{S=0}^{\infty} \left( \int_{r=0}^{\infty} \rho Y 2\pi r dr \right) dS, \quad \text{where } Y_{lean} \leq Y \leq Y_{rich}, \quad d\lambda_{det}/dr < 0.1, \quad \text{and } n_{\lambda_{det}} \geq 5. \quad (133)$$

The dimensionless distance ( $R_{Bauwens}^*$ ) from the center of the detonable region is calculated as

$$R_{Bauwens}^* = R \left( \frac{P_{ambient}}{E_{det}} \right)^{1/3}, \quad (134)$$

where the energy of detonable fuel ( $E_{det}$ ) is calculated as

$$E_{det} = m_{det} \Delta H_c. \quad (135)$$

Finally, the scaled overpressure ( $P^*$ ) is calculated as

$$P^* = \frac{0.34}{(R^*)^{4/3}} + \frac{0.062}{(R^*)^2} + \frac{0.0033}{(R^*)^3}. \quad (136)$$

To prevent infinite overpressure calculation and division by zero errors, the scaled distance,  $R^*$ , is limited to a minimum value of 0.01 and any scaled distances less than that will use 0.01 in calculation of the scaled overpressure.

There is currently no calculation of impulse for this model. This means that the overpressure probit models in Section 2.6.2 that use impulse cannot be used with this model.

## 4. SUMMARY OF NUMERICAL METHODS

### 4.1. Python Calculation Methods

The Python modules in HyRAM+ utilize the NumPy and SciPy packages [74–76]. NumPy provides support for multi-dimensional arrays, mathematical functions of arrays, and some numerical linear algebra routines. SciPy provides a variety of numerical method routines including support for statistical distributions, numerical linear algebra, integration, interpolation, optimization, root-finding, ordinary differential equation solvers, and others. Plots in HyRAM+ are made using Matplotlib [77].

### 4.2. Leak Frequency Computations

Almost all of the computations for HyRAM+ are done in the Python code modules. However, the HyRAM+ QRA mode uses statistical distributions from Math.NET [78] for calculating the component release frequency mean and variance (see Section 2.4). This allows the leak frequency values to update quickly in the front-end without calling Python.

### 4.3. Unit Conversion

HyRAM+ enforces an immutable link between values and the units that define them. Input values are stored in the International System of Units (SI). Conversions are performed implicitly by the system. Therefore, the application is able to present data in units preferred by the user or more relevant in problem context, while being able to pass data to the Python calculation algorithms in the expected SI units. Table 4-1 contains the convertible units currently available in HyRAM+. Note that all pressure units are assumed to be absolute pressure, not gauge pressure.

**Table 4-1: HyRAM+ convertible units.**

| Unit Type            | Units Available  |
|----------------------|--|
| Distance             | m, cm, mm, in, ft, yd, mi, au  |
| Area                 | m <sup>2</sup> , cm <sup>2</sup> , mm <sup>2</sup> , ft <sup>2</sup> , in <sup>2</sup> , yd <sup>2</sup>   |
| Volume               | cm <sup>3</sup> , dm <sup>3</sup> , dam <sup>3</sup> , m <sup>3</sup> , km <sup>3</sup> , mm <sup>3</sup> , $\mu$ m <sup>3</sup> , ft <sup>3</sup> , in <sup>3</sup> , yd <sup>3</sup> , mi <sup>3</sup> , L, $\mu$ L, mL, dL, daL, kL, ML |
| Angle                | radians, degrees   |
| Energy               | J, kWh, BTU  |
| Time                 | s, ms, min, hr   |
| Pressure             | Pa, kPa, MPa, psi, atm, bar, J/m <sup>3</sup>  |
| Temperature          | Celsius, Fahrenheit, Kelvin  |
| Speed                | m/s  |
| Volumetric Flow Rate | m <sup>3</sup> /s  |

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