STANDARD FOR HYDROGEN VENT SYSTEMS

AIGA 135/26

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As part of a program of harmonization of industry standards, the Asia Industrial Gases Association (AIGA) has issued this publication AIGA 135, Standard for Hydrogen Vent Systems, jointly produced by members of the International Harmonisation Council and originally published by the Compressed Gas Association (CGA), CGA G-5.5, Standard for Hydrogen Vent Systems.

This publication is intended as an international harmonized standard for the worldwide use and application of all members of the Asia Industrial Gases Association (AIGA), Compressed Gas Association (CGA), European Industrial Gases Association (EIGA), and Japan Industrial and Medical Gases Association (JIMGA). Each association's technical content is identical, except for regional regulatory requirements and minor changes in formatting and spelling.

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Table of Contents **Page**

Figures

Tables

Appendices

Appendices Tables

Appendices Figures

1 Introduction

This publication provides information for personnel who design, install, and maintain hydrogen vent systems.

2 Scope

This publication provides design guidelines for hydrogen vent systems used in gaseous and liquid hydrogen systems and provides recommendations for safe operation of these vents. It begins at the discharge port of relief devices and other components (operational venting) that control the release of hydrogen and ends at the point where hydrogen concentration in the atmosphere is below the lower flammable limits.

This publication addresses vent system components after relief devices. Pressure relief devices (PRDs) are addressed by:

– CGA S-1.1, *Pressure Relief Device Standards–Part 1–Cylinders for Compressed Gases* [1]; [1]

– CGA S-1.2, *Pressure Relief Device Standards–Part 2–Portable Containers for Compressed Gases* [2];

– CGA S-1.3, *Pressure Relief Device Standards–Part 3–Stationary Storage Containers for Compressed Gases* [3];

– ISO 21013-1, *Cryogenic vessels — Pressure-relief accessories for cryogenic service, Part 1: Reclosable pressure-relief valves* [4];

– ISO 21013-2, *Cryogenic vessels — Pressure-relief accessories for cryogenic service, Part 2: Non-reclosable pressure-relief devices* [5]; and

– ISO 21013-3, *Cryogenic vessels — Pressure-relief accessories for cryogenic service, Part 3: Sizing and capacity determination* [6].

This publication addresses locating hydrogen vent systems. Siting of storage systems is addressed by locally recognized codes or standards, for example NFPA 2, *Hydrogen Technologies Code* [7].

3 Definitions

For the purpose of this publication, the following definitions apply.

3.1 Publication terminology

3.1.1 Shall

Indicates that the procedure is mandatory. It is used wherever the criterion for conformance to specific recommendations allows no deviation.

3.1.2 Should

Indicates that a procedure is recommended.

3.1.3 May

Indicates that the procedure is optional.

3.1.4 Will

Is used only to indicate the future, not a degree of requirement.

3.1.5 Can

Indicates a possibility or ability.

[1] References are shown by bracketed numbers and are listed in order of appearance in the reference section.

3.2 Technical definitions

3.2.1 Deflagration

Propagation of combustion at a velocity that is less than the speed of sound in the unreacted medium.

3.2.2 Detonation

Propagation of combustion at a velocity that is greater than the speed of sound in the unreacted medium.

3.2.3 Gaseous hydrogen storage system

System in which hydrogen is delivered, stored, and discharged in gaseous form to the user's piping.

NOTE—A gaseous hydrogen storage system includes stationary containers or transport containers used as stationary storage for temporary supply, pressure regulators, PRDs, manifolds, interconnecting piping, and controls. The system terminates where hydrogen at service pressure first enters the user supply line.

3.2.4 Liquid hydrogen storage system

System in which hydrogen is delivered and stored as a liquid and from which it is discharged in liquid or gaseous form to the user's piping.

NOTE—A liquid hydrogen storage system can include stationary or portable containers, pressure regulators, PRDs, manifolds, interconnecting piping, and controls as required. The system originates at the storage container fill connection and terminates where hydrogen at service pressure first enters the user supply line.

3.2.5 Operator

Entity responsible for the safe and reliable operation of the hydrogen system.

3.2.6 Vent system

Apparatus used for depressurizing or relieving gas from a system to a safe location. Vents can be used for normal discharge, abnormal discharge or emergency discharge as required. The vent stack is the part of the vent system routing the gas to the designed elevation with an outlet to direct the flow.

4 Properties of hydrogen

Hydrogen is a flammable gas. It is colorless, odorless, tasteless, and nontoxic. It is the lightest gas known, having a specific gravity of 0.0696 (air = 1.0) at standard conditions. Gaseous hydrogen is buoyant in air at normal temperatures. Hydrogen diffuses rapidly in air and through porous materials. Hydrogen burning in air has a pale blue flame that is nearly invisible.

4.1 Flammability

At atmospheric pressure, the ignition temperature of hydrogen-air mixtures has been reported to be as low as 932 °F (500 °C). The flammable limits of hydrogen-air mixtures depend on pressure, temperature, and water vapor content. At atmospheric pressure, the flammable range is approximately 4% to 75% by volume of hydrogen in air. Hydrogen-air mixtures are extremely easy to ignite requiring as little as 0.02 millijoules (mJ) ignition energy.

4.2 Temperature impact

Hydrogen has properties unlike most other compressed gases such as oxygen, nitrogen, and carbon dioxide when expanded from a higher to lower pressure. Hydrogen gas will increase in temperature approximately 10 °F (5.6 °C) when throttled from 2000 psi (13 790 kPa) to atmospheric pressure.[2] The temperature increase resulting from throttled expansion is a function of the starting temperature as well as initial and final pressures.

Hydrogen-air mixtures created from cryogenic hydrogen sources can behave in a neutrally buoyant manner. Considering temperature inversion and high velocity and high turbulence wind conditions, it is possible for cold hydrogen not to rise as rapidly as under normal conditions. See 4.5 for more information.

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[2] psi, bar, and kPa shall indicate gauge pressure unless otherwise noted as (psia; bar, abs; and kPa, abs) for absolute pressure or (psid; bar, dif; and kPa, dif) for differential pressure. All kPa values are rounded off per CGA P-11, *Guideline for Metric Practice in the Compressed Gas Industry* [8].

4.3 Diffusion and leakage

Hydrogen, due to its small molecular size, rapidly diffuses through porous materials, which can lead to leakage. It also dissolves in and diffuses through metals slowly at ambient temperatures and more rapidly at elevated temperatures and high pressures. It can leak out of a system that is gas-tight for air or other common gases at equivalent pressure. Closed manual valves, relief valve seats, or other control devices can leak hydrogen at a low rate that can result in a flammable atmosphere within the vent stack.

4.4 Asphyxiant

Hydrogen is nontoxic but can act as a simple asphyxiant by displacing the oxygen in air. Unconsciousness from breathing air in which hydrogen has displaced oxygen can occur without warning symptoms because hydrogen is colorless, odorless, and tasteless. Hydrogen is a flammability hazard at much lower concentrations than those at which it causes asphyxiation.

4.5 Liquid hydrogen

At atmospheric pressure and a temperature of –423 °F (–253 °C), hydrogen becomes a transparent liquid with a density only one-fourteenth that of water. All other gases, except helium, will condense and freeze at liquid hydrogen and cold gaseous hydrogen temperatures. Liquid hydrogen has a relatively high thermal coefficient of expansion and high compressibility compared with other cryogenic liquids.

Upon contact with the skin and other tissues, liquid hydrogen and the cold gas evolving from the liquid can produce severe frost burns that are similar to thermal burns. Eyes can be injured by exposure to the cold gas or by a brief splash of liquid. Contact between unprotected parts of the body and uninsulated piping or vessels containing liquid hydrogen can cause flesh to stick and tear when an attempt is made to remove it from the piping or vessel.

Liquid hydrogen and cold gaseous hydrogen flowing through uninsulated piping can cause the liquefaction of air on the outer surfaces. This condensed liquid air can boil off the nitrogen first and can form an oxygen-enriched atmosphere.

Condensed liquid air dripping from piping will chill vent stack piping and mounting brackets. The system shall be designed to prevent liquid air and low temperatures from migrating to segments of the system that cannot withstand these cold temperatures. Condensing air left on cold surfaces (insulated from ambient conditions) can solidify.

As hydrogen temperatures are reduced, the buoyance also reduces and for cryogenic release such mixtures will approach neutral buoyancy. Hydrogen at 80 K when mixed with dry air at 293 K to a 29% by volume mixture will result in a cloud that is approximately 229 K. This hydrogen/air cloud will be essentially neutrally buoyant in surrounding, unmixed, air.

4.6 Hydrogen effects on materials

Hydrogen is noncorrosive and nonreactive, but hydrogen service will generally reduce the mechanical properties of certain metals by embrittlement or extreme cold temperatures. Materials selection for hydrogen vent stacks should consider hydrogen damage mechanisms. For additional information, see AIGA 087, *Standard for Hydrogen Piping Systems at User Locations* and AIGA 136, *Safe Operation of Hydrogen, Carbon Monoxide, and Syngas Pipeline Systems* [9, 10].

5 Hydrogen vent system design

This section covers the following features of vent stacks:

– minimum height of a vent stack and the minimum separation distances from personnel, equipment, and other exposures to mitigate exposure to thermal radiation and other exposures (see 5.1);

– sizing and mechanical design of a vent stack including piping and components (see 5.2); and

– installation procedures including pipe connections, inspections, electrical grounding, and impact protection (see 5.3).

5.1 Determining height and location for vent stacks

Determining the release point for the hydrogen, the vent stack location and height, is a key consideration in the overall siting of hydrogen equipment. Such determinations shall be derived from flame and heat flux models that have been verified and are generally available for review by the authority having jurisdiction (AHJ).

Acceptable models include ensuring that vented gases do not pose a risk of flammability, explosion, or asphyxiation to personnel or the public. Here are some of the primary factors to consider:

- Gas dispersion—The height of the vent stack influences how gases disperse in the atmosphere. A taller vent stack can promote better dispersion of gases, reducing the concentration levels near the ground to below flammable or asphyxiation limits;
- Prevailing wind conditions—Local wind patterns and speeds should be considered to ensure that vented gases are carried away from sensitive areas. This can affect both the height and the orientation of the vent stack;
- Proximity to sensitive areas—Vent stack exits shall be located outdoors and away from personnel areas, ignition sources, air intakes, building openings, and overhangs. The required siting distances to minimize exposure risks influence the stack design and location;
- Emergency and operational scenarios—Consideration should be given to both normal operational conditions and potential emergency scenarios where the volume or type of gas being vented might change, influencing the required stack height for safety; and
- Local topography and building height—The surrounding topography and the height of nearby buildings can affect wind patterns and gas dispersion, potentially necessitating adjustments to the vent stack height and location.

Properly verified and documented models acceptable to the AHJ shall be used and the outputs of the model documented and be made available to the AHJ. An acceptable model is outlined in 5.1.1 – 5.1.4.

The models in 5.1.1 – 5.1.4 are based on thresholds acceptable in North America. Different models and heat flux thresholds may be required in other regions.

5.1.1 Determining the design mass flow for evaluation

The mass flow rates for evaluation shall be the largest of the following:

- the primary relief system requirement as determined by CGA S-1.2, CGA S-1.3, or ISO 21013-3 [2, 3, 6];
- automatic vent systems;
- other processes that are designed to be introduced to the vent stack; or
- any credible combinations mentioned previously.

5.1.2 Definition of thermal radiation regions

There are four defined radiation regions that are used to determine the design spacing and height for a vent stack to address thermal hazards to personnel and equipment, both on and offsite. These regions are defined by transitions at various heat flux levels, noting that the ultimate allowable radiation level is a function of the time of exposure or thermal dose measured in ($[kW/m^2]^{4/3}$) • s. The predominant radiation wavelength from a hydrogen flame is ultraviolet (UV) versus infrared (IR) from hydrocarbon flames. The result of this difference is that the impact to people is on average half that for UV versus IR allowing for a higher exposure threshold. More specifically the thermal dose for UV over IR is reduced [11].

Exposure regions specified in this publication should not be confused with the setback table groups in NFPA 2 [7]. The groupings in NFPA 2, while they align with these regions' heat fluxes, are based on unexpected leaks at grade versus intentional vent stack releases and the design basis of preventing harm to people [7]. As noted previously, the ultimate allowable radiation level is a function of exposure time and factors such as escape time, personnel mobility, training, elevated work areas, protective clothing, use of shielding, equipment proximity, and general public exposure should be considered when designing a vent system. Region two transitions above 4.7 kW/m^2 where extended exposure is not recommended for personnel should be escape only unless specialized training and protective clothing is provided. See locally recognized codes or standards such as NFPA 2112 and NFPA 1970 [12, 13]. Generally, no activity should be required in these regions when a fire is present at the vent stack.

The site design shall define a set of radii that are depicted in Figure 1. The design of the vent stack height shall be such that the radius and vertical distance to the release point satisfy the requirements of Tables 1 and 2 given the release condition. The following regions are used to synchronize with the anticipated release rates and their frequency. Note that should the vent system be sufficiently high, some of the radius may not exist.

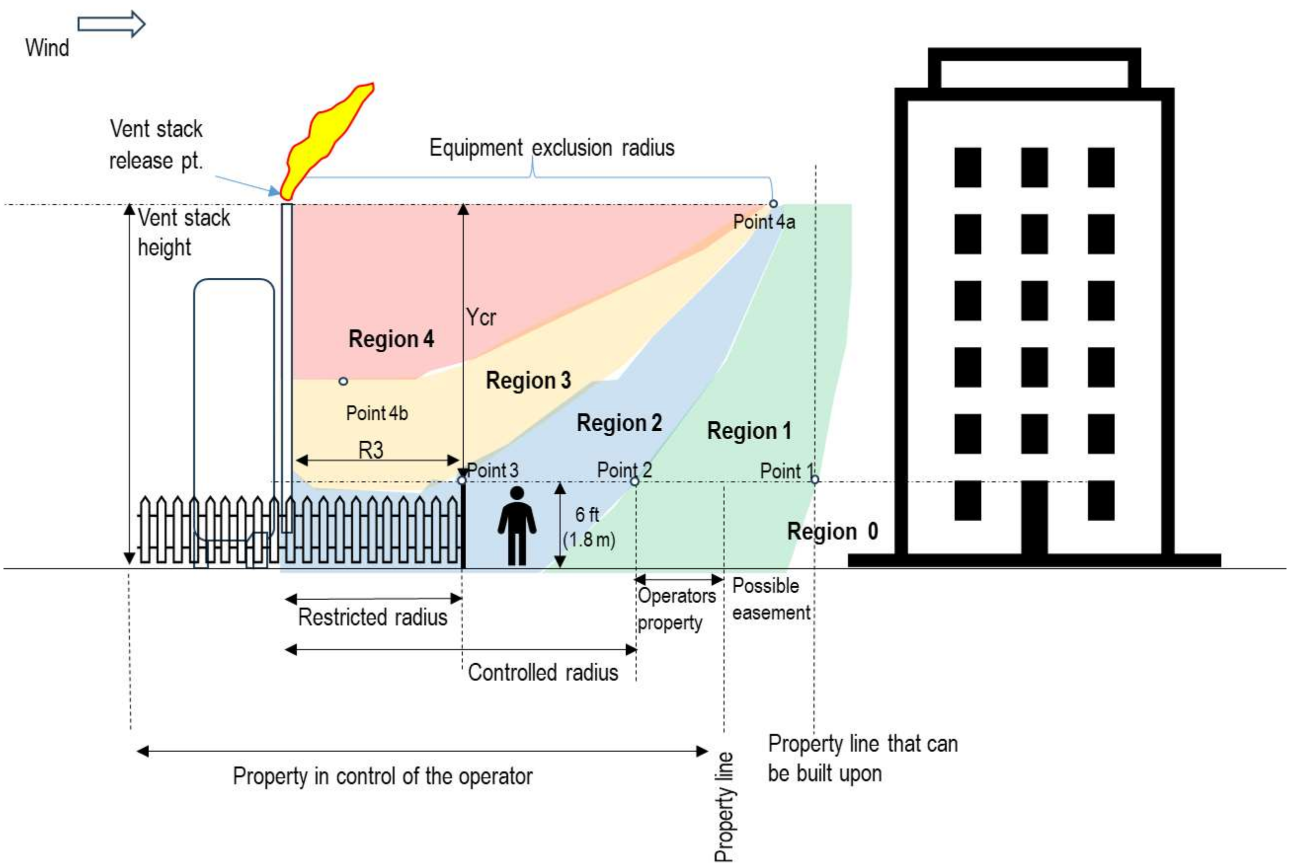

Figure 1—Heat flux radius map

Table 1—Example of thermal radiation zone recommendations for people

Region	Heat flux range (Btu/hr)/(ft^2) (kW/m^2)	Nominal exclusions	Personal protective equipment (PPE) for activities lasting less than 3 minutes	For activities lasting more than 3 minutes
0	≤ 500 (1.577)	No Restrictions	No requirements for PPE	No requirements for PPE
1	> 500 (1.577) and ≤ 1500 (4.732)	Requires surveillance and protection for non-ambulatory personnel.	No requirements for PPE	No requirements for PPE; operator should clear the area when a vent stack fire is present.
2 [1)]	> 1500 (4.732) and ≤ 3000 (9.46)	Personnel shall have a means of egress. Requires training and PPE.	Long sleeve/pant fire-resistant clothing [2)], hard hat, safety glasses, safety shoes, personal atmospheric monitor, hearing protection, gloves.	Long sleeve/pant fire-resistant clothing [2), 3)], hard hat, safety glasses, safety shoes, personal atmospheric monitor, hearing protection, gloves.
3	> 3000 (9.46) and ≤ 6340 (20)	Not for prolonged personnel exposure. Requires specialized training and PPE.	Long sleeve/pant fire-resistant clothing [2), 3)], hard hat, safety glasses, safety shoes, personal atmospheric monitor, hearing protection, gloves.	Exclusion region
4 [4)]	> 6340 (20)	Equipment exclusion	Exclusion region	Exclusion region

NOTES

1 Heat flux tolerance from hydrogen flames is higher for humans compared to the same heat flux from other hydrocarbons due to the predominantly UV wavelength of the heat.

2 See Sandia Report SAND2023-12548, Ehrhart, et al. [11]

1) Region 2 and higher shall be considered electrical Class 1/Division 2 Group B [7]. See NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas* [14].

2) Fire-resistant clothing shall meet the requirements of NFPA 2112 [12].

3) Persons who will be exposed for more than 3 minutes shall be trained in the use of firefighting gear (see NFPA 1970) and firefighting procedures [13].

4) Within 3 ft (1 m) from the vent stack release point in all directions shall be considered electrical Class 1/Division 1 Group B [7, 14].

Table 2—Example of zone and area requirements for equipment

Radius	Vertical distance from stack height ft (m)	Horizontal distance from stack ft (m)	Design heat flux (Btu/hr)/(ft^2) (kW/m^2)
No restrictions Beyond Figure 1, Point 1	No closer than 6 ft (1.8 m) above grade	Beyond property line that can be built upon	Region 0 ≤ 500 (1.577)
Monitored radius Between Figure 1, Points 1 and 2	No closer than 6 ft (1.8 m) above grade	Between controlled radius and property line that can be built upon	Region 1 > 500 (1.577) and ≤ 1500 (4.732)
Controlled radius Between Figure 1, Points 2 and 3	No closer than 6 ft (1.8 m) above grade	Between restricted radius and controlled radius and in no case beyond the property line	Region 2 > 1500 (4.732) and ≤ 3000 (9.46)
Restricted radius Between Figure 1, Point 3 and base of vent stack	No closer than 6 ft (1.8 m) above grade	Between base of vent stack and restricted radius	Region 3 > 3000 (9.46) and ≤ 6340 (20)
Equipment exclusion radius Between Figure 1, Points 4a and 4b and base of vent stack	No closer than 6 ft (1.8 m) above grade	0 to no further than the property line that can be built upon	Region 4 > 6340 (20)

NOTE—See Point 1, Point 2, and Point 3 in Figure 1 to define radius with respect to region at operator height.

5.1.2.1 Monitored radius

This radius should be under surveillance by the operator so they can take management actions to coordinate with stakeholders on potentials for releases. Such actions may include updating the design such that the radius classification changes, coordinating controlled releases for environmental conditions, instructing others to control entry to the radius. Unattended non-ambulatory persons shall not be permitted in the monitored radius.

5.1.2.2 Controlled radius

This radius shall be under the direct control of the operator. It should be indicated by means such as lines, signage, or temporary cones as in the case of an attended release. This radius should be able to be cleared by the operators at their discretion and accordingly not exceed the property in their control. Typical personal protective equipment (PPE) is recommended for this radius including long sleeves/pants during attended operational releases.

5.1.2.3 Restricted radius

This radius requires higher security with an obstruction like a fence or continuous monitoring by trained personnel at the restricted radius with direct visual line of sight. Entry into this radius shall be limited to personnel trained and with PPE consistent with the heat exposure predicted by the study. Working in the restricted region can require the use of protective clothing suited for firefighting instead of flash protection provided by flame-retardant clothing. It can also be necessary to impose restrictions on the time that personnel are allowed to work in the restricted region.

5.1.2.4 Equipment exclusion radius

This radius of high heat flux and potential transient flame impingement shall only include equipment specifically designed for such an environment. This radius shall not penetrate the other mentioned radii, nor shall it penetrate the vertical plane of the property line that can be built upon. Equipment, buildings, and locations of personnel on the neighbor’s side of the property lines shall be located outside of the equipment exclusion region.

5.1.3 Determining point of interest given a heat profile for study

The determination of the point of interest for a specified heat profile is described in this section. Figure 2 outlines the relationship of a given heat profile as described by critical flame geometry parameters. Figure 2 shows the point of interest on a heat profile, and this profile extends in all directions around the vent outlet. Appendix A specifies curve fit parameters as a function of the mass flow rate, the release condition, and the release diameter. Generalized parameter curve fits and their design basis are found in Appendix B.

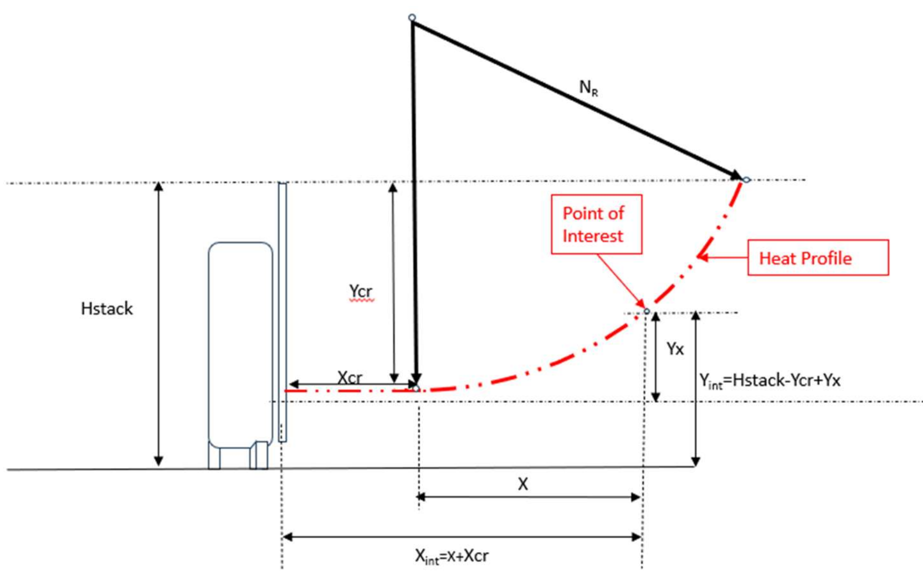

Figure 2—Heat flux parameter map

5.1.4 Determining Y_x for a given incremental spacing X

Positions on a given heat flux profile can be determined as depicted in Figure 3 where Y_x is calculated with the formula or by the graph.

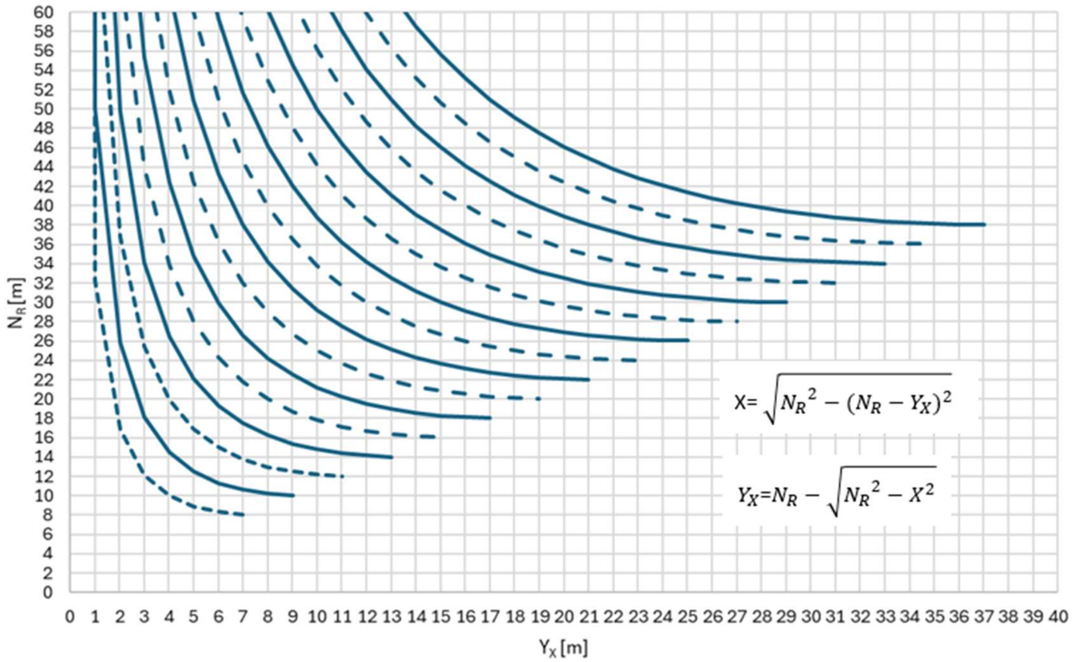

Figure 3—Y_x value (given N_R and X)

5.1.5 Heat

Vent stacks shall be located to prevent impingement exposure and lessen the effects of high temperature or thermal radiation exposure from the escaping plume to the supply system, personnel, and adjacent structures. The vent system for cold vapors or large flows of warm gas should be designed to discharge vertically upwards at a sufficient height from grade and with proper configuration and velocity to facilitate flow dispersion. Discharge of small warm gas flows may be directed laterally, if necessary. See 5.1 for details on determining height and location for vent stacks.

Flammable gas vent stacks shall be considered as potential ignition sources. It is preferred to gather all vent lines into a common vent stack when practical. When multiple vent stacks are used, the discharge of each vent stack should be located to minimize the potential for a cascading event.

5.1.6 Delayed ignition and overpressure

Impacts from hydrogen vapor cloud explosions (VCEs) on nearby receptors of interest (e.g., personnel, buildings, equipment) shall be evaluated as part of the design and sizing of hydrogen vent systems. For protecting people outdoors, it is expected that thermal hazards from flash fires and/or jet fires will be the dominant hazard. The heat flux provisions outlined in this publication provide for sufficient mitigations to satisfy overpressure considerations provided the following conditions are met:

- There are no occupiable building structures in Region 2 as shown in Figure 1;
- There are no congested or confined areas in Region 3 as shown in Figure 1; and
- Mass flowrates from the exit points do not exceed the choked flow limits provided in Appendix A or B.

Should the conditions previously mentioned not be satisfied, the explosion hazards associated with the delayed ignition of a vented hydrogen release, also called a free-jet, should be evaluated as a VCE. The primary factors that determine the blast load resulting from a hydrogen VCE are the size and mass of the flammable cloud (to determine energy) and the flame speed (energy release rate) of the resulting explosion. Blast loads and their resulting pressure and impulse/duration increase as the size of the flammable cloud that participates in the VCE increases. As the flame speed increases as the initial turbulence due to the jet increases for hydrogen free-jet VCEs. Blast curve methods can be used for hydrogen free-jet VCE blast load predictions. The choice of the curve is dependent on the release mass flow rate of hydrogen. Either the ME (multi-energy) strength index or the Baker-Strehlow-Tang (BST) vapor cloud explosion model can be used. It is expected that blast loads will be the dominant hazard to people inside of buildings from hydrogen vents.

The jet explosion blast overpressure is a function of the release mass flowrate and expanded velocity (or Mach number) at the vent exit.

Where the Mach number of the hydrogen vent release is more than 0.5 use the methods found in *Hydrogen jet vapor cloud explosion: A model for predicting blast size and application to risk assessment*, Jallais et al. [15]. See Table 3.

For Mach number of the hydrogen release equal to or less than 0.2, predictions using Table 3 will be conservative, it is therefore acceptable to use the model reported by Stock et al. in *Scaling of vapor cloud explosions after turbulent jet release* (1989), for this flow velocity regime [16].

Whereas for lower releases velocity with the Mach number less than 0.5 Miller approaches presented by Equation 1 and Equation 2 are recommended as shown in *Hydrogen Jet Explosion: New Tests, Blast and Fireball Models*, Amy Shen et al. [17]. The models noted in this reference are assessed with hydrogen inventories between 10% and 75% concentration in air.

A more detailed analysis can be performed using Computational Fluid Dynamics models when more accurate results are needed.

Table 3—Mass flow versus TNO ME strength index and BST MF flame speed

Mass flow kg/s	TNO ME strength index	BST MF flame speed
< = 0.1	4	0.31
0.1 - 1.0	5	0.41
1.0 - 10	6	0.7
NOTES TNO = The Netherlands Organisation for Applied Scientific Research ME = Multi-energy BST = Baker-Strehlow-Tang MF = Mach flame		

5.1.7 Noise from venting

The noise from a hydrogen vent stack release should be assessed with respect to neighbours and regulator limits. The sound can be estimated from various sources. Figure 4 offers an estimated dB level given the release rate and the distance from the release point. Other factors, including potential background noise and noise reflection can influence sound distribution. Local regulations should be referenced to evaluate the exposure time relative to dB level. In the event an unacceptable noise level is identified, mitigations such as increased vent diameter, location of the vent stack, and other methods may be used to reach a suitable noise level.

For example, OSHA regulations in Title 29 of the U.S. *Code of Federal Regulations* (29 CFR) Part 1910.95, *Occupational noise exposure*, allow up to 15 minutes at 115 dB [18].

Figures 4 and 5 show the relationship of sound level dB and range for a fully choked flow. Sound levels for a release that are less than a choke flow should be multiplied by a nominal Mach number.

$$\text{Nominal Mach Number} = \frac{\text{Determined Mass Flow Rate from Section 5.1.1}}{\text{Mass Flow at Choke from Appendix A}}$$

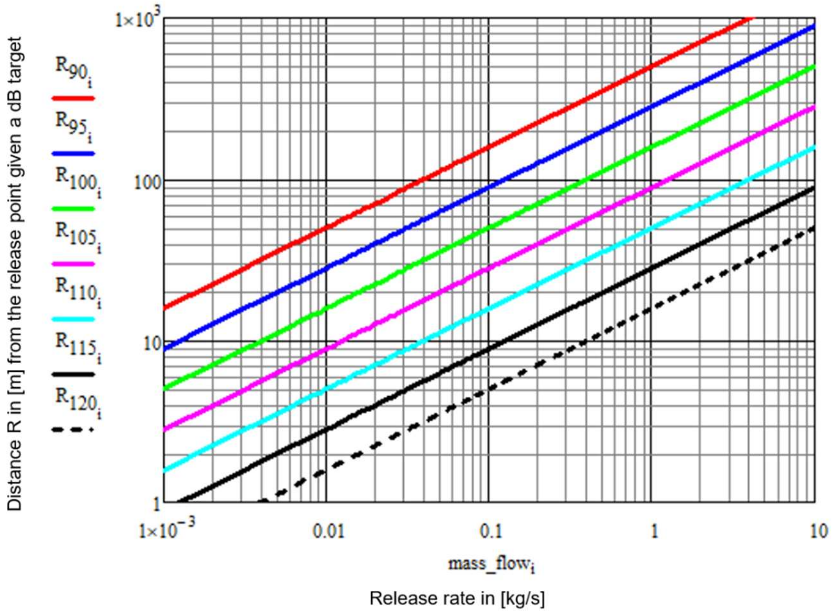

Figure 4—Sound level estimates based on ambient release for a choke flow

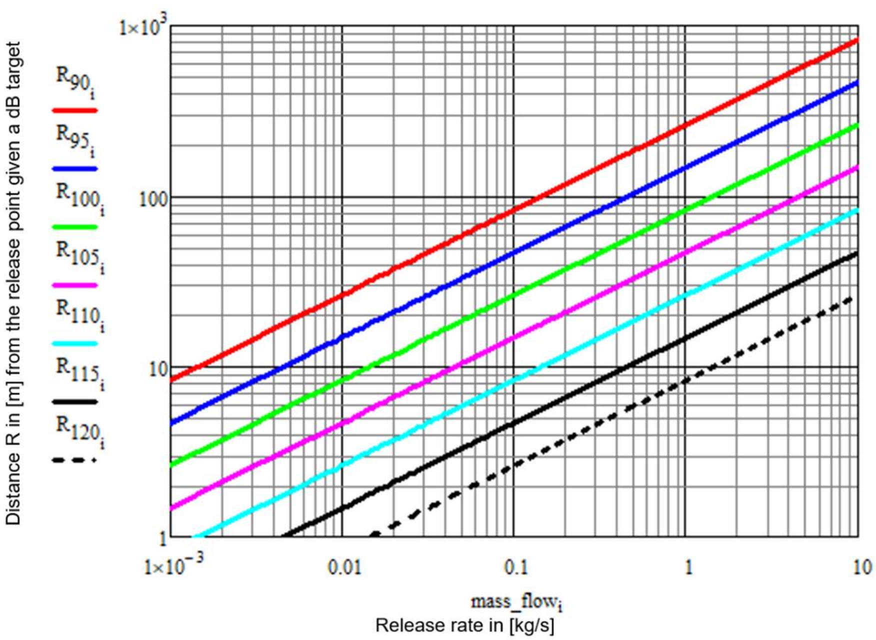

Figure 5—Sound level estimates based on cryogenic release for a choke flow

5.2 Designing a vent stack

Discharges of gaseous hydrogen shall be disposed of through an engineered vent system in accordance with this publication. The gaseous hydrogen is discharged into the air at the exit of the vent system. The discharge may be either manually controlled or by automatic control devices on the storage system. Typical system components that control discharge include:

- purging of piping or components;
- manual or automatic vent valves;
- pressure control devices such as back pressure regulators or control valves; and
- PRD activation.

Some applications (e.g., venting through a manual valve) permit the sizing criteria to be based on high exit velocities for plume dispersion. See 5.1 for details.

Interconnecting hydrogen vent sources to a common stack is permitted if the vent system is designed to handle the flow from all discharges without overpressurization of any portion of the vent system under expected scenarios. Excess pressure in the vent system can cause failure of connected apparatus and can reduce flow capacity of the PRDs that discharge into the vent system. Sizing of discharging devices (e.g., manual vent valves and control valves) into the vent system on interconnecting sources shall be considered in the vent stack design. It is possible that large valves can have higher flow rates than pressure relief valves and then become the maximum determining flow factor in calculating back pressures (if under expected scenarios). This is more critical on high pressure systems that may have small orifice relief devices.

The pressure drop in the vent system shall not exceed 10% pressure drop of the lowest relief valve setpoint when all expected relief valves are discharging. The 10% maximum allowable backpressure is to prevent premature closing of the relief valve (chatter), which will reduce the expected flow from the device. The flow calculations shall take into consideration the back pressure on the vent stack to ensure sufficient relieving flow is available. While proper sizing for reclosing relief valves shall take into account the inlet pressure drop to the PRD inlet, this publication evaluates vent piping sizing and the effects of outlet piping on the PRD only.

Design considerations for chatter shall not apply to nonreclosing relief devices. These devices are generally disks that when activated will allow the full pressure upstream of the device to flow through the vent piping downstream of the device until the upstream storage pressure equalizes with atmospheric pressure at the vent stack outlet. Examples include burst disks and temperature-pressure relief devices (TPRD). The designer of the vent system shall ensure the vent system has enough capacity to relieve the full discharge flow of the relief device and the vent system maximum allowable working pressure (MAWP) shall be designed to withstand the transient pressure peak generated upon activation.

When multiple systems share a relief vent, the potential for systems of higher pressures to affect the functionality of the lower pressure system shall be considered. Back pressure from the higher pressure system can reduce the stability and capacity of a lower pressure system. This means that typically a bulk liquid tank will have one set of vent stacks that would be independent from high pressure tubes, pumps, and compressors. See CGA S-1.2, CGA S-1.3, or ISO 21013-3 for details on addressing these concerns [2, 3, 6].

Hydrogen vent stacks do not require inerting of the vent stack or a flare to ignite gases exiting the vent system during operation. If inerting is required for maintenance or other non-routine procedures, vent stacks connected to a liquid hydrogen source shall not be inerted with any gas other than helium as other gases can solidify at hydrogen temperatures. All valves and flow-control devices connected to the vent stack system shall have permanent identification tags. An alternative is to purge the vent stack first by gaseous hydrogen at ambient temperature, then by an inert gas.

See Figure 6 for an example of typical vent stack mounting and grounding.

5.2.1 Size

The size of a vent stack is determined by the available pressure drop that permits adequate flow of PRDs and by the minimum exit velocity required for dispersion of the vent gases. The vent system piping shall be sized so the vent line pressure drop will not reduce the relieving capacity of the PRD(s) connected to the venting system to a value that is less than code requirements. The discharge line shall be sized in accordance with CGA S-1.2, CGA S-1.3, or ISO 21013-3 [2, 3, 6].

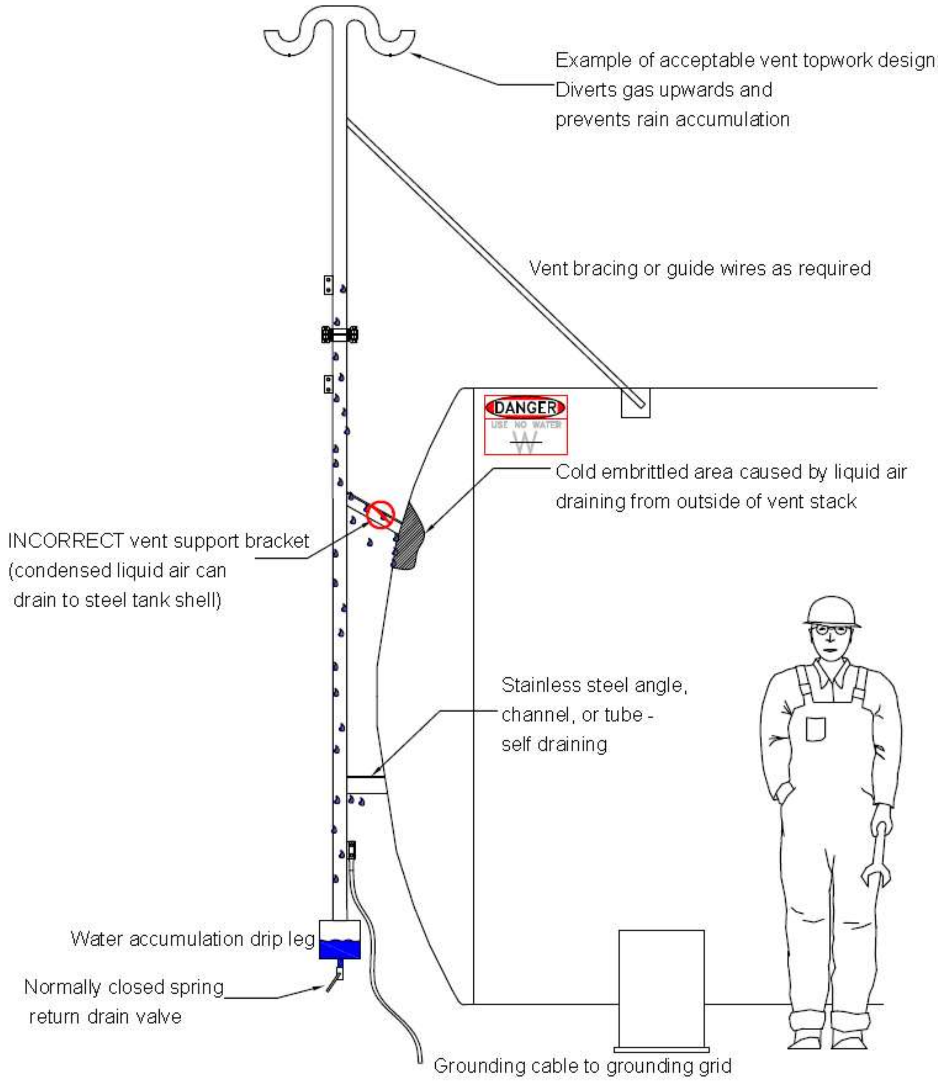

Figure 6—Example of a typical vent stack mounting and grounding

5.2.2 Pressure, pressure drop, and deflagration

Vent systems are subject to a range of pressures that can exceed the operating pressure of the system. Transient pressures resulting from release of a non-reclosing PRD or deflagration in the vent stack exert forces upon the vent system that could result in damage to equipment and unintended releases of hydrogen near ignition sources or personnel.

The flow capacity of the vent system shall be adequate to handle the flow rate of the relief devices in the system as calculated in CGA S-1.2, S-1.3, or ISO 21013-3 [2, 3, 6]. Piping and connections immediately downstream of a non-reclosing PRD shall be designed to withstand the transient pressure peak generated upon activation.

Hydrogen has a higher velocity flow than other flammable gases like natural gas. Vent system designs for other flammable gases should not be assumed to be adequate for hydrogen.

Burst pressure of vent piping shall meet requirements of 5.2.5.1 to prevent damage from deflagration or detonation.

A relief device's discharge vent piping shall not be reduced in size below the outlet port size of the device and may need to be increased to prevent excessive pressure drop. Under special circumstances (noncoded relief valves), the orifice of the relief valve as compared to the body size can allow a reduction in the outlet piping but shall be verified by detailed calculations only.

The vent system shall be designed for a pressure equal to or greater than the storage system MAWP unless a more detailed analysis indicates that another pressure is more appropriate. The vent system is typically designed to withstand a minimum of 580 psi (40 bar). Ductile materials shall be used for the construction of such systems. See 5.2.6 for additional information.

5.2.3 Gas discharge minimum height requirements

High exit velocities in a vertically released vent and the density of hydrogen in relation to air will aid in its dispersion and dilution in the atmosphere. The vent exit minimum elevation should be as determined in 5.1. For stationary equipment, the vent exit shall be at least 10 ft (3 m) above grade; or 2 ft (0.61 m) above adjacent equipment; or 5 ft (1.5 m) above rooftops. Vent stacks for mobile equipment, such as tube trailers and ISO containers, may be shorter than the stated minimums to meet highway height restrictions.

5.2.4 Discharge of liquid

Hydrogen in liquid phase should be converted to gaseous phase or supercritical phase prior to exiting a vent stack outlet. If liquid will be released to the atmosphere, a separate risk analysis shall be completed.

5.2.5 Design pressure

Vent systems shall be designed for the full flow of any relief device and/or vent valves attached to the venting system that could plausibly be activated simultaneously taking into account the backpressure in the stack and any additional relief devices in a common vent. Significant back pressure can develop under certain conditions (e.g., rupture disk or high pressure releases) and can impede the function of devices in a common vent. The design pressure shall be determined by the engineer using PRD guidance or alternatively, the vent piping design pressure can match the design inlet pressure to the relief device. Piping shall be designed, constructed, and maintained in accordance with a locally recognized piping code or standard such as ASME B31.12, *Hydrogen Piping and Pipelines* [19].

5.2.5.1 Design pressure for deflagration and detonation

With the presence of air in a vent stack, a potentially explosive mixture can form with hydrogen being vented from valve leakage, maintenance venting, or relief device activation. Piping that can remain cold because it is insulated and is exposed to air can form solid air or solid oxygen. When such solids are exposed to hydrogen later, combustion and explosion can occur.

It is possible for the ignition of an explosive mixture in a vent system to result in a deflagration or detonation. Deflagrations are possible at any length to diameter (L/D) ratios. However, system geometry, length, and complexity can increase the likelihood of one occurring as does gas temperature and flow rate.

Simpler hydrogen vent systems in the scope of this publication (mainly straight runs, smaller diameter [less than 3 inch nominal pipe size (NPS) or nominal diameter 80 mm (DN80)] liquid or gas systems at user sites) shall be designed for deflagrations to prevent a pipe rupture or catastrophic failure in the vent system. A deflagration can result in a pressure increase in the stack of up to 150 psi (10 bar) and when designed for this pressure has been shown to be adequate (i.e., typical SCH10).

Detonations and deflagration to detonation transitions are possible but unlikely in simple vent systems. The design of vent pipes shall include provisions to prevent pipe burst. If a system complexity or risk review demonstrates the need to design for a detonation, a minimum design pressure of 580 psi (40 bar) shall be used.

Each user may use the method of their choice to calculate the pipe wall thickness. Users may use any validated method for vent piping design to account for overpressure from detonation. One such method can be found in NFPA 67*, Recommended Practice on Explosion Protection for Gaseous Mixtures in Piping Systems* [20]. For example, at ambient conditions a theoretical required piping wall thickness can be determined as shown in Table 4. The table can be used for carbon or stainless steel vent pipes. This does not apply to flange and fitting design.

Table 4—Example minimum wall thickness for vent pipe detonation at ambient conditions

	1 inch NPS or DN25	2 inch NPS or DN50	3 inch NPS or DN80	4 inch NPS or DN100
Minimum pipe thickness in mm	0.69	1.25	1.84	2.37
NOTE—The examples in this table have been developed based on the method described in NFPA 67 with the addition of a safety factor for the recognized peak overpressure that can exceed the steady state detonation effect described [20].				

For larger or complex systems, the designer should assess the need for an inert gas purge to remove atmospheric air/oxygen and prevent the formation of an explosive mixture. Caution should be used in cryogenic systems to prevent any impacts from freezing the inert gas in the vent system.

Design of the vent stack should include the noise impact of a deflagration or detonation and limit exposure to personnel in the area.

5.2.6 Materials

Single-wall, uninsulated piping is used for warm and cold gaseous hydrogen venting.

Piping, tubing, fittings, valves, accessory equipment, gaskets, and thread sealants shall be suitable for hydrogen service at the pressure and temperatures involved and shall maintain their integrity under the high temperatures of fire conditions.

Material specifications and thickness requirements for vent piping and tubing shall conform to a locally recognized pressure piping code or standard, for example ASME B31.12 [19]. Vent piping used for cold gas shall be fabricated from material meeting the impact test requirements of the piping code when tested at the minimum operating temperature to which the piping can be subjected in service.

Austenitic (300 series) stainless steel meeting the piping code requirements is the preferred choice for hydrogen vent systems. Type 304 stainless steel has well documented mechanical characteristics when exposed to fluctuations between ambient, liquid hydrogen temperatures, and high temperatures to the top of the vent stack from vent fires. It is also resistant to corrosion, which minimizes particles that could provide the energy to ignite hydrogen vent fires.

Use of carbon steel is limited to warm gas or gaseous hydrogen at ambient temperature or within temperature limits of the piping code. Contamination, rust, or carbon particles flowing through a carbon steel vent stack can provide an ignition source in the enriched hydrogen atmosphere, often resulting in a vent stack fire. Low melting point materials such as aluminum, copper, brass, and bronze have reduced strength at elevated temperatures and shall not be used on hydrogen vent stacks. These materials can weaken and fail when exposed to external fires. This can cause the vent piping to fail unexpectedly.

Gray, ductile, or malleable iron shall not be used in a hydrogen vent system.

Plastic piping, tubes, fittings, or components of any kind shall not be used for pressure containment in hydrogen vent systems.

5.2.7 Components

Welded, screwed, or bolted components of a vent stack should comply with applicable ASME or equivalent locally recognized codes and standards. System components should be used in accordance with manufacturers' recommendations.

Select a flange gasket material that performs well at both the service temperature and in a fire. Flanged joints on hydrogen vent piping shall have a metal-to-metal seal or a gasket of material that is difficult to ignite, like graphite. Soft elastomers and plastics with melting temperatures less than 1000 °F (538 °C) are prohibited.

5.2.8 Mechanical design

The vent structure shall be designed to withstand the ice, wind, and seismic loads as well as possible flooding loads in accordance with the local building code. The force of the venting gas shall also be taken into consideration on the design and anchoring of the vent system. If venting cold gas, cold embrittlement of the vent stack material shall be accounted for in the design.

The following formula may be used to calculate the reaction force generated by a compressible fluid at a steady state flow. See CGA H-5, *Standard for Bulk Hydrogen Supply Systems* (an American National Standard) [21]:

$$F = \left(\frac{W}{366}\sqrt{\frac{kT}{(k+1)M}}\right) + (A \bullet P)$$

Where:

F = Reaction force (lb)

W = Mass flow of the gas (lb/hr)

k = Ratio of the specific heats (C_p/C_v) at the outlet conditions = 1.41 for hydrogen

C_p = Specific heat at constant pressure

C_v = Specific heat at constant volume

T = Temperature at the vent stack outlet (Rankine or °F +459.67)

M = Molecular weight of the gas (2.01 for Hydrogen)

A = Area of the vent stack at the point of discharge (in^2)

P = Static pressure within the vent stack outlet piping (psi)

Note that the reaction force can be considerably larger than the $A \bullet P$, which many users could have assumed as a good estimate. The vent stack designer shall determine the mass flow (W) and the discharge pressure (P) at the outlet of the vent tube. On rupture disk assemblies, the flow through the small diameter tube is typically choked flow and shall be calculated accordingly.

Clamps and clamping systems shall be designed to sustain the thrust generated by the reaction force. Many commercially available clamping systems have low clamping forces along the axis of the tube.

Supersonic flows may require special considerations to predict the loading effects of shock waves on tees, elbows, and other fluid impingement points. An appropriate dynamic load factor should be considered for piping design. For more information, see ASME B31.3, *Process Piping* [22].

The vent system shall be designed to restrain the thrust of the reaction forces resulting from full-flow discharge of fluid under any operating or failure condition. To prevent deflection or damage to the vent system support and bracing of the piping shall be designed to compensate for the reaction forces and given allowance for generation of shock waves. See Figure 7 for an illustration of reaction forces created by the discharge of compressed gases.

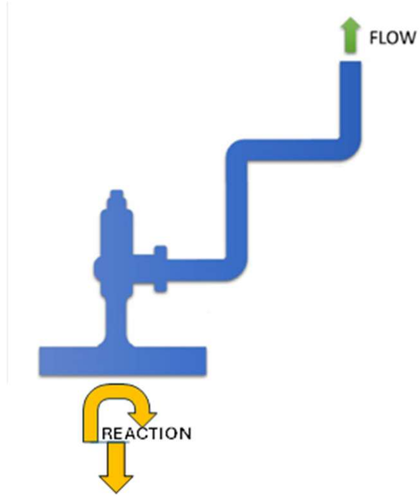

Figure 7—Reaction forces from discharge of gas

5.2.9 Temperature isolation

Thermal contraction of the vent piping shall be accounted for in the design of vent systems that can discharge cold vapor.

Bulk liquid tank's liquid piping systems can be subject to temperatures as cold as –423 °F (–253 °C). The vent stack support system shall be designed to allow for the contraction caused by potential 500 °F (260 °C) temperature changes. Stainless steel will shrink approximately 0.050 in/ft (1.27 mm) from ambient to liquid hydrogen temperatures.

Bulk liquid hydrogen tanks typically have the vent stack(s) attached to the outer vacuum jacket to provide structural support and stability. The vacuum jacket is typically fabricated from low alloy carbon steels with a minimum design metal temperature (MDMT) of –20 °F (–28.8 °C). The designer shall ensure that there is thermal isolation between the vent stack, which can cool to temperatures as cold as –423 °F (–253 °C), and the steel shell. The vent stack can cool to temperatures low enough to condense air on the outer surface of the stack. The condensed air droplets will migrate down the surface of the stack and can be blown from the surface by winds or other air movements.

The brackets used to support the vent stack shall be stainless steel or other noncorrosive and minimally conductive materials.

Angle or channel support brackets shall be installed to be self-draining and not allow the accumulation of condensed liquid air droplets or create a path directing the condensation toward non-resilient structures. Unless the support brackets are a minimum of 2 ft (0.61 m) in length, these brackets shall not be inclined downwards from the stack towards the vacuum jacket, see Figure 6.

The designer shall consider the material of choice to maintain integrity when exposed to heat.

Hydrogen is flammable in air over an extremely wide range of concentrations and the ignition energy is very low. Therefore, a vent stack fire on a hydrogen system should be considered a design event and not something that should be considered an emergency. See 5.1 for details on determining height and location for vent stacks.

5.2.10 Drains

Condensate drains are required on all hydrogen vent stacks subject to cold vapors. The vent stack will condense and freeze moisture from the ambient air caused by cryopumping of moist air inside the cold interior of the vent piping. This water ice/moisture will eventually accumulate throughout the interior of the stack.

The stack shall be designed with either a water accumulation drip leg below all active gas flow ports or a water accumulation chamber, see Figures 8 and 9.

The bottom of the stack shall be equipped with either a manual or automatic drain that can be used to remove accumulated condensation.

Normally closed spring actuated ball valves are used to ensure that the vent is closed automatically after the stack has been manually drained.

Maintenance and filling procedures shall include routine draining of the vent stacks and verification of the drain operation.

The bottom of the vent stack(s) shall be located at a height above grade to facilitate drainage and maintenance. This is critical in climates subject to snow, ice, and flooding to allow access to the drain valve(s) or systems, prevent blockage, and allow drainage caused by natural events, see Figure 8.

The design of the vent stack shall consider water draining down the inside of the vent stack. Devices that are connected to the vent stack shall have an upward slope from the vent stack to the device to prevent water from accumulating in the device, see Figures 8 and 9.

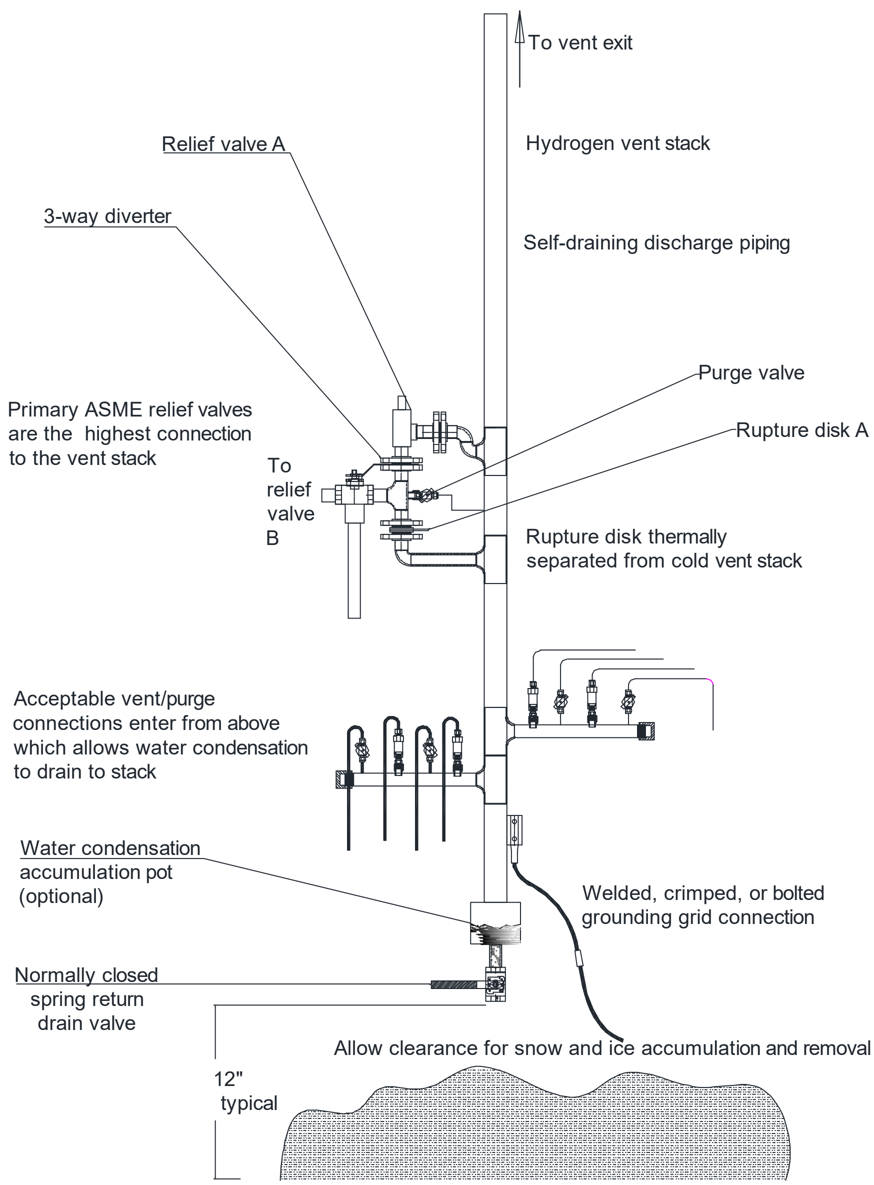

Figure 8—Example of an acceptable hydrogen vent stack design

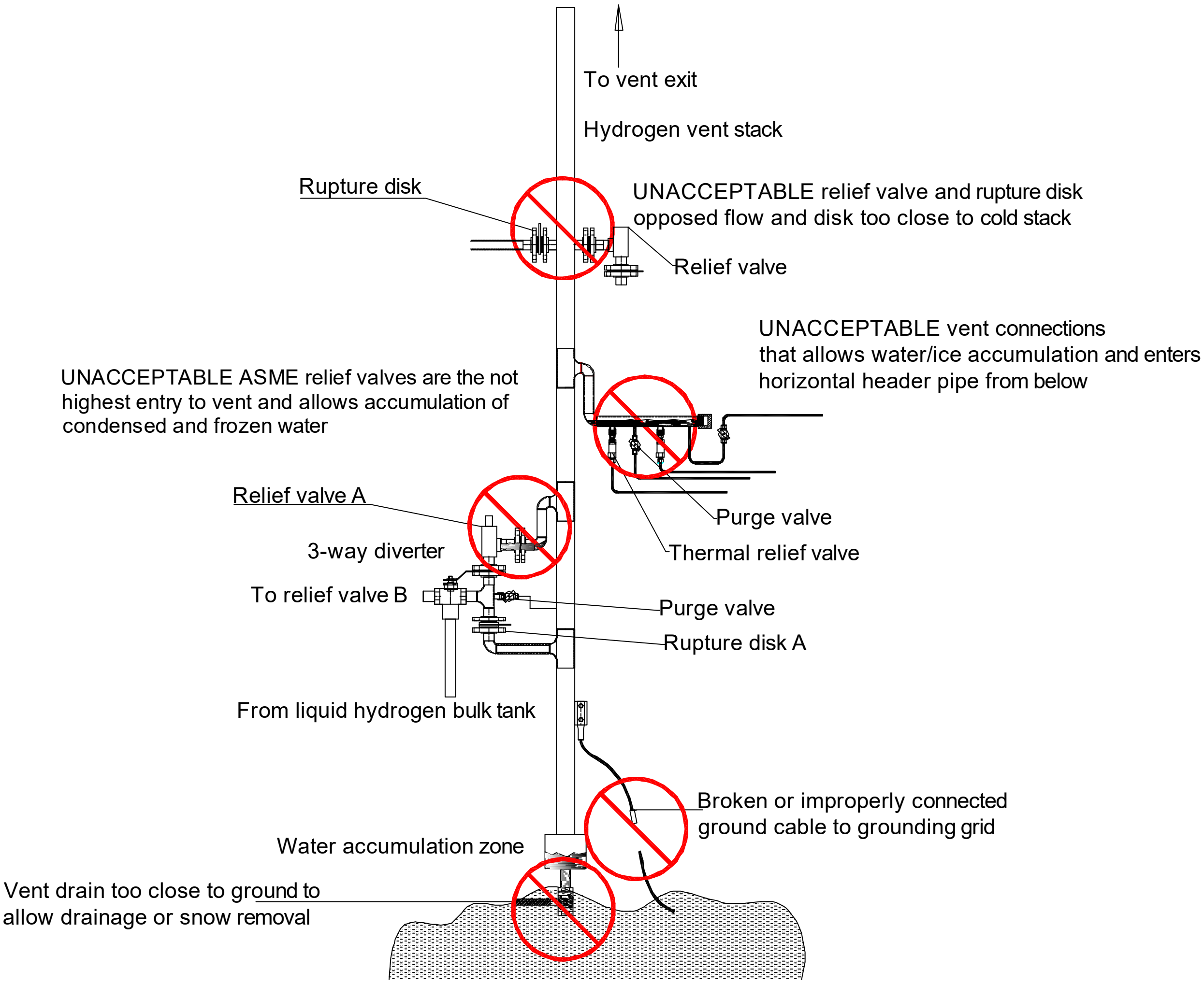

Figure 9—Example of an improperly configured hydrogen vent stack design

5.2.11 Topworks

The vent exit shall not vent downward since it can direct flow to an area of potential personnel exposure. When nominally horizontal exits (45° to 90° from vertical) are unavoidable, alternate methods as approved by the AHJ are encouraged. Parameter modifications as outlined in 5.2.11.1 may be used. If a fixed vent cap is used, it shall be designed to be removed within the expected discharge pressure when the relief device activates and not cause back pressure, which compromises the relief device performance (see Figure 10).

Topworks that split the flow should account for the reduced exit velocity as provided in 5.2.11.2.

Hydrogen vent systems shall be protected against the hazards caused by entering of debris and/or insects inside the vent pipes resulting in potential obstruction. Use of vent protectors equipped with wire screens is possible provided the proper mesh size is selected to avoid flow obstruction.

Figures 10, 11, 12, and 13 indicate vent system designs that are acceptable. These figures are provided as examples only. Other designs are acceptable if they meet the requirements of this publication. The design of the vent exit shall substantially restrict the entrance of rain, snow, and debris into the vent opening and shall not direct vented gas downward.

Figures 14, 15, 16, 17, 18, and 19 indicate vent systems, which can be common to nonflammable gases that are not acceptable because they either direct the hydrogen downward or create an unbalanced thrust that could cause deflection or damage to the vent stack during high velocity discharges.

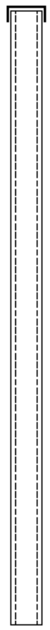

Figure 10—Example of an acceptable vent stack configuration with vent cap for relief device

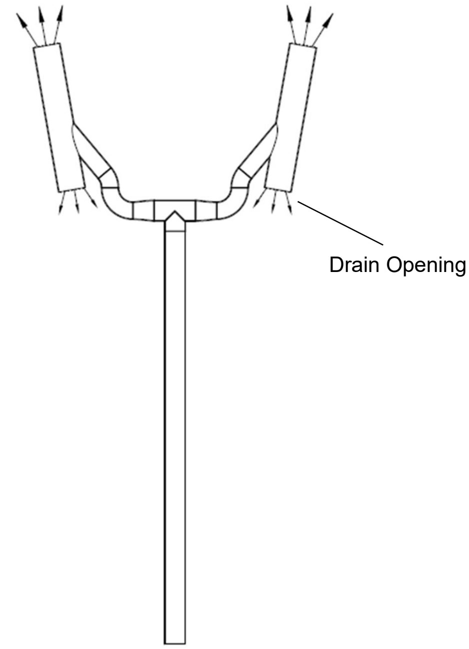

Figure 11—Example of an acceptable vent stack configuration with split vertical discharge

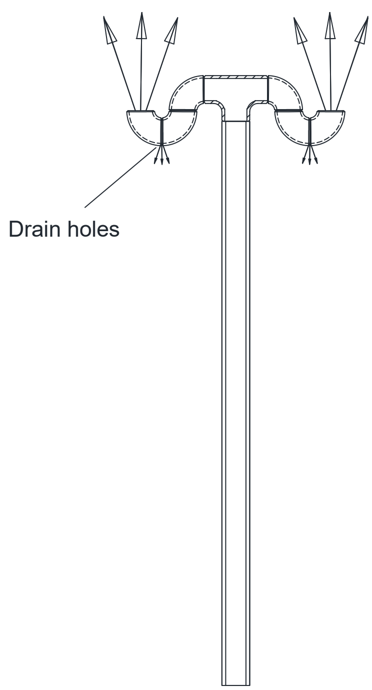

Figure 12—Example of an acceptable vent stack configuration with water drainage holes

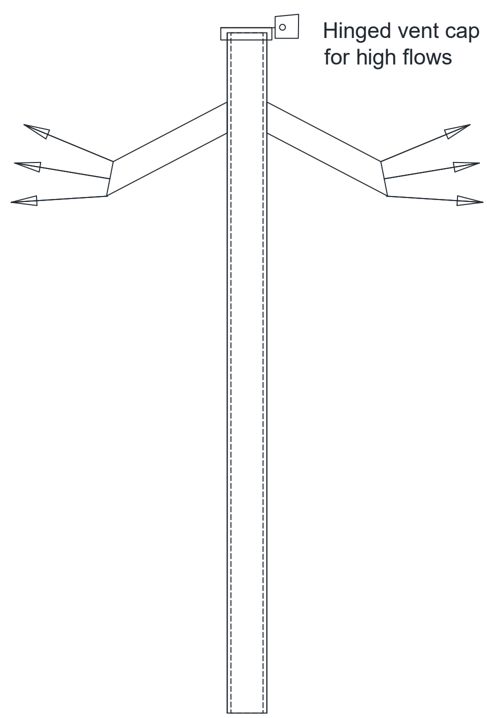

Figure 13—Example of an acceptable vent stack configuration with top hinged vent cap

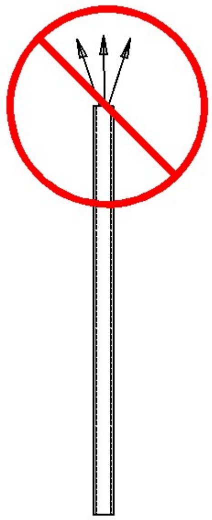

Figure 14—Example of an unacceptable vent stack that allows water accumulation

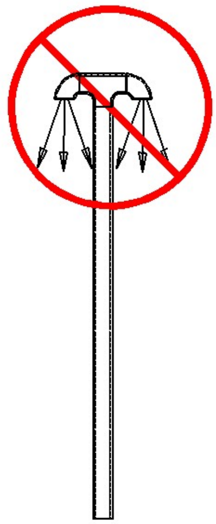

Figure 15—Example of an unacceptable vent stack that diverts gas downward

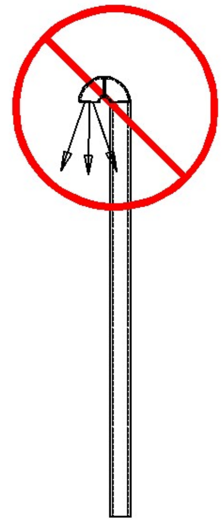

Figure 16—Example of an unacceptable vent stack that diverts gas downward; unbalanced thrust

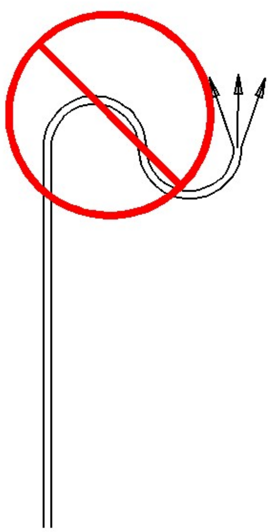

Figure 17—Example of an unacceptable vent stack with no drain (water can freeze in trap); unbalanced thrust

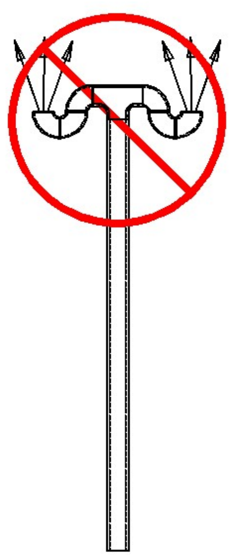

Figure 18—Example of an unacceptable vent stack with no drain holes

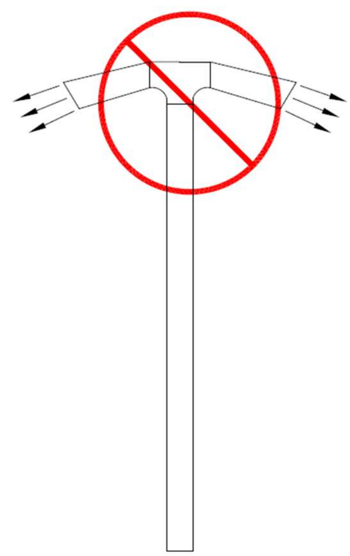

Figure 19—Example of an unacceptable vent stack configuration with a miter cut

5.2.11.1 Horizontal exits

Horizontal exits may use Figure 20 as an alternative to Figure 2.

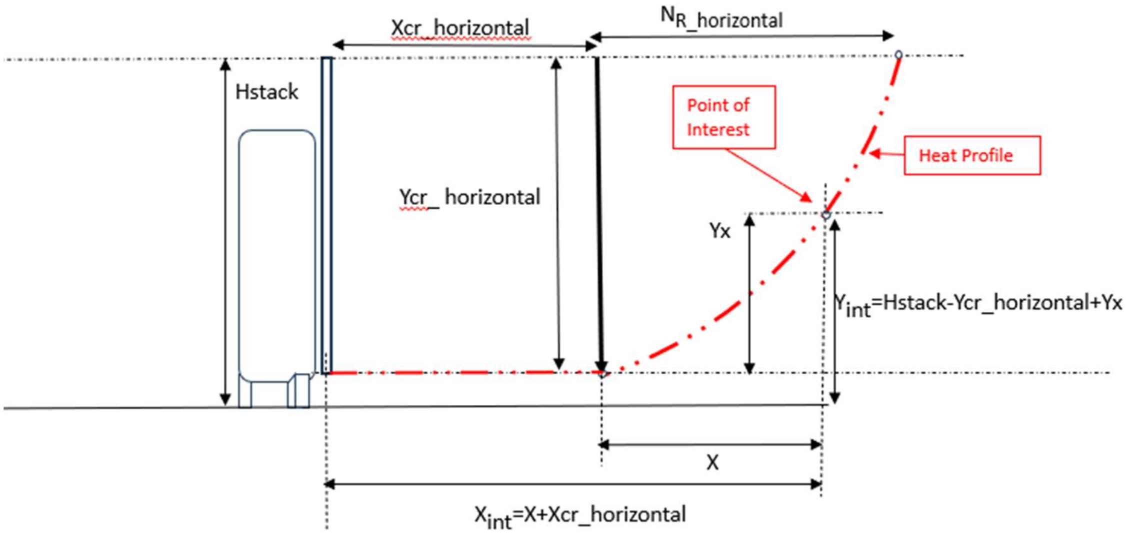

Figure 20—Heat flux parameters

$$N_{R\_horizontal} = \left(\frac{SF}{1 + \left\{ \frac{5\ m/s}{U_{h2}} \right\}^{0.5}} \cdot N_{R\_4.732} \right) \cdot \sqrt{\frac{4.732}{\text{Heat of Interest}}}$$

SF = 1.1 for Cryogenic

SF = 1.25 for Warm

$X_{cr\_horizontal} = N_{R\_horizontal}$

$Y_{cr\_horizontal} = -N_{R\_horizontal}$

Where:

- Diameter is the diameter of the release point in [mm]
- mdot is the design mass flowrate in [kg/s]
- $N_{R\ 4.732}$ is the N_R for heat flux 4.732 kW/m^2 given an *mdot* and diameter
- Heat of Interest is the heat flux of interest in [kW/m^2]
- U_{h2} is the velocity of hydrogen in [m/s]
- $U_{h2} = (mdot/\rho_{h2}) / (\frac{\pi}{4}\ dia^2)$
  - ρ_{h2} = 0.084 kg/m^3 if ambient, ρ_{h2} = 0.308 kg/m^3 if cryogenic
  - dia = the inside diameter of the referenced release in meters

5.2.11.2 Split flow exits

When the vent topworks splits the flow, the velocity of the exiting gas is reduced. Accordingly, an equivalent diameter for the release shall be determined. The split diameter is $(4 \cdot \text{net area}/\pi)^{0.5}$. When the flow is split into two equal areas the equivalent diameter is 1.414 • the vent diameter. The equivalent diameter is used in Appendix A to determine the heat flux parameters given the full design mass flow rate.

5.2.12 Additional vent stack components

Vent lines shall not be fitted with any components that can result in unacceptable backpressures, blockage potentials, or any restriction that prevents the free release of hydrogen to the atmosphere.

Flame arrestors shall not be fitted on the vent stack as this can cause a restriction that prevents the free release of hydrogen to the atmosphere.

5.3 Installation

Installation of hydrogen venting systems shall be supervised by personnel familiar with proper practices and applicable standards of the construction and use of hydrogen systems. All vent piping shall be installed, inspected, and tested in accordance with the provisions of the locally recognized piping code. When installing pipe anchors and supports consideration shall be given to thermal expansion and contraction of the piping.

Shields, catch pans, or thermal barriers are acceptable ways to lessen exposure of personnel to uninsulated cold vent piping and to prevent any condensed liquefied air from contacting piping, structural members, and surfaces not suitable for cryogenic temperatures. Where insulation is used as a protective measure it shall be made of a noncombustible material with a vapor-tight outer covering to prevent the condensation of air and subsequent oxygen enrichment within the insulation. The outside shield shall prevent break down of the insulation during normal operating conditions. Uninsulated piping and equipment that can reach liquid hydrogen temperature shall not be installed above asphalt surfaces or other combustible materials, which are not compatible with the oxygen-enriched liquid resulting from cooling and condensing air. Drip pans may be installed under uninsulated piping and equipment to collect and vaporize this condensed liquid.

5.3.1 Connections

Piping joints shall be suitable for hydrogen service at their operating pressures and temperatures. For guidance on the design, material selection, and cleaning requirements for piping systems in hydrogen applications, see AIGA 087 [9].

Joints in vent piping and tubing shall preferably be welded but may also be threaded, flanged, brazed, or made with a suitable mechanical fitting. Soft solder joints are not permitted. Welded and brazed joints shall be completed by qualified welders, and brazed connections shall use a brazing alloy with a melting point above 1000 °F (538 °C).

Threaded joints can be seal welded or backbrazed to reduce potential leakage. Threaded joints on components requiring removal shall be made leak-tight with a thread sealant suitable for high temperatures to provide fire-safe conditions.

Mechanical fittings can be used within the guidelines and limitations of locally recognized piping codes and standards. When selecting and applying a fitting, the designer shall consider the possible adverse effects on the joint due to operating conditions. The fitting manufacturer’s recommendation should be obtained for the particular application.

The mechanical joints in vent lines should not be located near the mechanical joints in other fluid lines in a multi-line pipe rack. Vent piping should not be unnecessarily exposed to external forces that result in deformation.

5.3.2 Inspections

Quality assurance measures to ensure leak integrity at maximum back pressure shall be implemented. Such measures may include pressure testing, visual inspection, nondestructive examinations or combinations thereof.

5.3.3 Grounding

All vent stacks shall be grounded and meet the requirements of regional codes (e.g., for North America, NFPA 70, *National Electrical Code®*, for Europe IEC 60204-1 – *Safety of machinery – Electrical equipment of machines – Part 1: General requirements*) for integrity and system design [23, 24]. See also NFPA 77, *Recommended Practice on Static Electricity* and NFPA 780, *Standard for the Installation of Lightning Protection Systems*, for information on bonding for static electricity and lightning protection [25, 26]. The stacks are taller than the surrounding equipment and exposures and as a result are subject to lightning strikes and other overhead exposures and therefore shall be connected to an engineered grounding grid. Hence no additional lightning protection is required.

The vent stack shall have continuity across the entire system and jumper straps may be required if dielectric components are used.

The vent stack shall be grounded with a resistance to earth of no more than 25 ohms.

All vent system ground cables shall be connected directly to a common grounding grid.

The vent stack shall be grounded directly to the grounding grid.

Locate ground cables to minimize tripping hazards as personnel could be working in close proximity to vent stacks.

5.3.4 Protection from impact

The vent stack shall be protected from impact using physical barriers. Protection typically consists of either of the following:

- Bollards/guard posts/bumper posts.
- All other means approved by the AHJ, such as:
  - Jersey barriers
  - Ribbon railings.

For further examples, see CGA H-5, and NFPA 2 [21, 7].

6 Manual operation of vent system

Hydrogen vent systems shall be operated only by individuals who are knowledgeable about the hazards of hydrogen product (both liquid and gaseous) and the use of hydrogen storage and transfer equipment.

Before manually operating a hydrogen vent system, the operator should perform a visual inspection of the system including any moving parts to ensure that it is not mechanically damaged or prevented from operating by an accumulation of ice or other debris. The operator should confirm that the vent header/pipe and vent pipe support system are intact and in good working order. The operator should open the drain system to drain any potential accumulated water.

When preparing to manually vent the hydrogen system, the operator should make note of local environmental conditions, wind direction, and the proximity of other equipment in the area. The operator should watch the vent plume at all times and adjust the vent rate so the plume does not pose a hazard to adjacent equipment or to third parties.

When venting cold gas product in large volumes or for extended periods of time, operators should take precautions to protect themselves and passersby from exposure to droplets of liquid air, which frequently form on the vent system and rain down on the ground below. Significant contact with liquid air can cause cryogenic burns and can lead to localized oxygen enrichment of clothing. Incidental contact with liquid air droplets is generally not hazardous.

Under normal circumstances, manual venting shall be continued at a low rate until the operator confirms that there are no vent system leaks, that the vent plume is directed safely, and that neither the operator nor passersby are exposed to significant contact with liquid air. Once this has been confirmed, the operator can increase the vent rate as required, but shall continuously monitor the vent system for leaks and the vent plume for safe dispersion. Venting should be discontinued if leaks develop in the vent system or the plume drifts in an unsafe direction.

It is not uncommon for the exhausting hydrogen to ignite. If designed in accordance with this standard, the vent stack provides an adequate level of safety in the event of a hydrogen fire at the vent stack exit.

7 Maintenance

PPE shall be worn by all personnel performing maintenance activities near hydrogen storage systems and facilities. This PPE may include but is not limited to equipment such as safety shoes, gloves, safety glasses, hard hat, fire retardant coveralls, personal atmospheric monitor (PAM), etc.

Prior to any work on a vent stack, ensure that the vent stack has been purged of hydrogen. For additional information on servicing hydrogen equipment, see AIGA 126, *Standard Procedures for Hydrogen Supply Systems* [27].

All personnel should be alert and aware of the occurrence of occasional stack fires. Only qualified, trained personnel should isolate and shut off the source of hydrogen in the event of a stack fire.

7.1 Visual inspection

The operator should visually determine that the vent system discharge is free from potential operational obstructions or hazards such as bird nests, insect hives, vegetation, etc. The inspector should also visually inspect the support system, guide wires, brackets, weldments, etc.

7.2 Physical inspection

The vent stack shall be included in site safety inspections. These inspections of the site and equipment should occur at least once per year and shall be performed by the hydrogen supplier's representative. For more information, see CGA H-5 and NFPA 2 [21, 7].

If the vent system is equipped with a water drain device (sump) at the bottom of vent stack, operators should check the sump for accumulated moisture before venting. This test is not applicable when ambient temperatures are below freezing since ice can accumulate in the sump. If the presence of ice is suspected, an alternate method should be devised to verify its presence. It should then be determined whether the ice will affect the performance of the vent system.

The grounding system to the vent stack shall be inspected and checked to confirm the continuity to earth is less than 25 ohms. All cables and connections shall be inspected to ensure the integrity of the grounding system.

Trained service technicians shall check all vent system valves on a periodic basis as required by local codes, such as NFPA 2, to ensure proper operational functions [7]. All third parties performing the inspection be trained and have a corresponding work permit before any intervention.

7.3 Field work

Only trained service technicians shall conduct any repairs or modifications to the vent stack system. Repairs or modifications shall comply with manufacturer instructions and follow a management of change (MOC) procedure.

WARNING: *Always assume a hydrogen-rich atmosphere exists within the vent stack. Before and during any type of repair work, an inert gas purge should be used within the system. A hydrogen-rich atmosphere can result in a fire, leading to equipment damage, death, or serious injury.*

An open flame shall not compromise the criteria used to locate a vent. Work requiring an open flame shall be conducted only after the entire system is purged and inerted.

During any type of work on a hydrogen system, personnel shall be aware of the extremely low temperature associated with liquid hydrogen and the hazard this poses.

All sources of hydrogen that are piped to a vent stack shall be reviewed before the repair of any specific vent system. Depending on the repairs involved, these sources may have to be disconnected or piped to a temporary vent system. Personnel shall be aware of any releases that occur while repairing a vent system.

When removing or replacing a relief device(s) tied to a common vent stack, care shall be taken to prevent one or more of the devices from lifting while the work is performed.

To prevent hydrogen in unwanted areas:

a) Review the system design to understand which valves need to be locked out;

b) Depressurize the piping system to the vent stack, where possible; and

c) Reduce the inlet pressure to relief devices to no greater than 80% of the MAWP of the vessel.

When multiple valves or PRDs are connected to a vent stack, there is the potential of one valve discharging into a stack while authorized personnel are performing maintenance on another valve or PRD. One solution is to install full-area stop valves on the inlet and/or outlet of PRDs for maintenance. Closing a full-area stop valve on the outlet of a PRD that is being replaced will prevent the backflow of hydrogen from another device that is connected to the same stack. Such full-area stop valves shall be locked open and shall be provided with manual vent valves for maintaining pressure during maintenance operations in accordance with locally recognized piping codes and standards. If the full-area stop valve is closed, authorized personnel shall be present at all times in order to maintain the vessel pressure below 80% of the MAWP of the pressure vessel and shall again lock or seal the full-area stop valve in the open position before leaving the station.

8 Emergency response

The following considerations shall be included as an element of the overall site emergency response plan.

Emergency responders shall not attempt to extinguish a vent stack fire with water or other fire extinguishing agents. The only approved method for extinguishing a vent stack fire is to shut off the hydrogen flow. Extinguishing a vent fire could, in fact, create more of a hazard than allowing the fire to burn itself out.

Water shall not be used by emergency responders to attempt to put out a vent stack fire. Water used to cool adjacent equipment should be directed away from the vent stack(s) because it can freeze the outlet of the stack closed obstructing the only discharge point to maintain a safe operating pressure.

Vent stacks on cryogenic hydrogen storage tanks shall have at least one sign near the vent stack indicating not to use water on the vent stack discharge in the event of a fire. The sign shall be readily visible to emergency response personnel. See Figure 6 of this publication and section 10.2 of CGA H-5 [21].

WARNING: *Never spray water on a hydrogen vent stack discharge. A vent stack discharging cold gaseous hydrogen (–423 °F [–253 °C]) will instantly freeze water on the outlet and potentially obstruct the discharge area to the point where there is no flow and no means to safely relieve the system pressure, leading to overpressure which can result in death or serious injury. A vent stack discharging gaseous hydrogen at ambient temperatures could freeze prior to the operation of a PRD effectively preventing safe relieving of pressure.*

Emergency responders may direct water for cooling on the bulk tank and other equipment but shall direct water spray away from the vent stack outlets.

9 References

Unless otherwise specified, the latest edition shall apply.

[1] CGA S-1.1, *Pressure Relief Device Standards–Part 1–Cylinders for Compressed Gases*, Compressed Gas Association, Inc. www.cganet.com

[2] CGA S-1.2, *Pressure Relief Device Standards–Part 2–Portable Containers for Compressed Gases*, Compressed Gas Association, Inc. www.cganet.com

[3] CGA S-1.3, *Pressure Relief Device Standards–Part 3–Stationary Storage Containers for Compressed Gases*, Compressed Gas Association, Inc. www.cganet.com

[4] ISO 21013-1, *Cryogenic vessels — Pressure-relief accessories for cryogenic service*, *Part 1: Reclosable pressure-relief valves*, International Organization for Standardization. www.iso.org

[5] ISO 21013-2, *Cryogenic vessels — Pressure-relief accessories for cryogenic service, Part 2: Non-reclosable pressure-relief devices*, International Organization for Standardization. www.iso.org

[6] ISO 21013-3, *Cryogenic vessels — Pressure-relief accessories for cryogenic service, Part 3: Sizing and capacity determination*, International Organization for Standardization. www.iso.org

[7] NFPA 2, *Hydrogen Technologies Code*, National Fire Protection Association. www.nfpa.org

[8] CGA P-11, *Guideline for Metric Practice in the Compressed Gas Industry*, Compressed Gas Association, Inc. www.cganet.com

[9] AIGA 087, *Standard for Hydrogen Piping Systems at User Locations*, Asia Industrial Gases Association. https://asiaiga.org/

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[11] SAND2023-12548, *Technical Justifications for Liquid, Hydrogen Exposure Distances; Development of Uniform Harm Criteria for Use in Quantitative Risk Analysis of the Hydrogen Infrastructure*, Ehrhart, et al. Sandia National Laboratories, www.sandia.gov

[12] NFPA 2112, *Standard on Flame-Resistant Clothing for Protection of Industrial Personnel Against Short-Duration Thermal Exposures from Fire,* National Fire Protection Association. www.nfpa.org

[13] NFPA 1970, *Standard on Protective Ensembles for Structural and Proximity Firefighting, Work Apparel, Open-Circuit Self-Contained Breathing Apparatus (SCBA) for Emergency Services, and Personal Alert Safety Systems (PASS),* National Fire Protection Association. www.nfpa.org

[14] NFPA 497, *Recommended Practice for the Classification of Flammable Liquids, Gases, or Vapors and of Hazardous (Classified) Locations for Electrical Installations in Chemical Process Areas,* National Fire Protection Association. www.nfpa.org

[15] Jallais, S., Vyazmina, E., Miller, D., and Thomas, J.K., "*Hydrogen Jet Vapor Cloud Explosion: A Model for Predicting Blast Size and Application to Risk Assessment*", 13th Global Congress on Process Safety, San Antonio, March 26-29, 2017

[16] M. Stock, W. Geiger, and H. Giesbrecht. 1989. "*Scaling of vapor cloud explosions after turbulent jet release*." 12th Int. Symp. On the Dynamics of Explosions and Reactive Systems. Ann Arbor, MI

[17] A. Shen, D.Miller, E. Lutostansky, S. Overa, D. Malik, K. Macon, T. Paschal K. Thomas, *Hydrogen Jet Explosion: New Tests, Blast and Fireball Models*, 2025 Spring Meeting and 21st Global Congress on Process Safety, Dallas, TX, April 6-10, 2025

[18] *Code of Federal Regulations*, Title 29(Labor), 1910.95, *Occupational noise exposure*, U.S. Government Printing Office. www.gpo.gov

[19] ASME B31.12, *Hydrogen Piping and Pipelines*, American Society of Mechanical Engineers. www.asme.org

[20] NFPA 67, *Recommended Practice on Explosion Protection for Gaseous Mixtures in Piping Systems*, National Fire Protection Association. www.nfpa.org

[21] CGA H-5, *Standard for Bulk Hydrogen Supply Systems* (an American National Standard), Compressed Gas Association, Inc. www.cganet.com

[22] ASME B31.3, *Process Piping*, American Society of Mechanical Engineers. www.asme.org

[23] NFPA 70, *National Electrical Code*®, National Fire Protection Association. www.nfpa.org

[24] IEC 60204-1 – *Safety of machinery – Electrical equipment of machines – Part 1: General requirements,* International Electrotechnical Commission. www.iec.ch

[25] NFPA 77, *Recommended Practice on Static Electricity*, National Fire Protection Association. www.nfpa.org

[26] NFPA 780, *Standard for the Installation of Lightning Protection Systems*, National Fire Protection Association. www.nfpa.org

[27] Miller, D. 2016*, New model for predicting thermal radiation from flares and high pressure jet fires for hydrogen and syngas*, American Institute of Chemical Engineers. www.aiche.org

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Appendix A—Heat flux profile parameters (Normative)

A1 Design basis of heat profiles

Generalized curve fits for the heat flux profiles are derived by implementing the model in Appendix B1 for a range of mass flow rates and the following input parameters. An independent analysis may be required if local conditions vary significantly from these inputs.

1. The ambient temperature is set to 293 K
    a. Variations in ambient temperature of up to 30 K from this value show a less than 10% potential variation in heat flux prediction.
2. The ambient relative humidity is set to 50%
    a. Variations in ambient humidity of up to 40% from this value show a less than 10% potential variation in heat flux prediction.
3. The ambient wind is set to 5 m/s
    a. 5 m/s is a commonly referenced wind speed in other industry publications.
    b. 5 m/s represents a high statistical probability average wind speed for most locations.
    c. For normal industrial areas the wind shear interpretation makes 5 m/s reasonable at lower elevations (as compared to higher wind speeds such as 9 m/s at a standard height of 10m).
    d. 5 m/s in the prescribed methodology produces results that are consistent with industry experience over the last several decades.
    e. Wind speeds greater than 5 m/s will eventually break up the hydrogen cloud and flame such that radiation dosage with such a flame is reduced.
4. The release temperature is set to 80 K for cryogenic releases and 293 K for ambient releases
    a. 293 K is a widely recognized standard ambient temperature.
    b. 80 K is an appropriate value for cryogenic hydrogen venting due to liquefaction of air on the pipe.
5. The inside diameter of the vent is set to a series of anticipated pipe sizes
    a. 0.18 inch for a 1/4 inch x 0.035 inch ODT
    b. 1.097 inch for a 1 inch SCH10S pipe
    c. 2.157 inch for a 2 inch SCH10S pipe
    d. 3.26 inch for a 3 inch SCH10S pipe
    e. 4.26 inch for a 4 inch SCH10S pipe
    f. 10.42 inch for a 10 inch SCH10S pipe

The following curve fits can be used to determine the generalized heat flux parameters. The mass flux row should be for a row referenced mass flow no less than the design mass flow being studied. Alternatively, the generalized heat flux parameters can be taken from the subsequent tabled values. The asterisked(*) mass flow rate value is the theoretical choked flow in the pipe. Values beyond choked flow may be selected if such values are verified as possible by other analysis.

When the diameter of the vent topworks is not listed in Tables A-1 through A-24, the flux parameters for the diameter can be derived by linear interpolation from parameters determined by closest tabulated diameters greater than and less than the diameter of interest that is not listed in the table.

A2 Cryogenic release modeling and curve fits

Flux Parameters *Xcr*, *Ycr* and N_R are in meters, *mdot* is in kg/s and transition is the mass flow rate for transition from one curve to the next in kg/s

$$Parameter(mdot) = A \bullet (mdot - B)^2 + C \bullet (mdot - B) + D$$

When *mdot*<transition

$$Parameter(mdot) = a \bullet mdot^b + c$$

When *mdot*>transition

Table A-1—Heat flux parameter curve-fit coefficients for cryogenic releases through 1/4 inch ODT

Xcr_cryogenic

Coefficient	0.25ODT” pipe (MFlow: 0.0001 - 0.2 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	-8.896837E+04	-1.956152E+05	-1.047443E+05	-1.129615E+05
B	1.248672E-03	1.315069E-03	1.571888E-03	3.318014E-03
C	4.529882E+01	2.529846E+01	-4.403365E+01	-4.710810E+02
D	6.798920E-01	7.772578E-01	7.090916E-01	2.276686E-01
Transition	3.712984E-03	3.091346E-03	3.690989E-03	3.659533E-03
a	1.976113E+00	1.154236E+00	5.585091E-01	1.412066E+04
b	1.641814E-01	2.358962E-01	2.324717E-01	8.022156E-07
c	-5.372751E-01	-9.027977E-02	-6.449586E-03	-1.412055E+04

Ycr_cryogenic

Coefficient	0.25ODT” pipe (MFlow: 0.0001 - 0.2 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
a	-1.151154E+01	-4.600195E+00	-2.152026E+00	-6.897470E-01
b	4.098539E-01	4.043692E-01	4.361138E-01	5.807748E-01
c	1.617370E-02	-1.929073E-03	-2.457409E-02	-1.976537E-02

Nr_cryogenic

Coefficient	0.25ODT” pipe (MFlow: 0.0001 - 0.2 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	-9.824273E+04	-1.002590E+05	-1.018942E+05	-1.795126E+05
B	3.841570E-03	3.095086E-03	3.265172E-03	2.779958E-03
C	-7.551191E+01	-9.546859E+01	-2.176154E+02	-3.440006E+02
D	1.622212E+00	1.137994E+00	9.818799E-01	1.225871E+00
Transition	3.717978E-03	3.596101E-03	3.780239E-03	3.896007E-03
a	1.834904E+01	1.115270E+01	7.227971E+00	2.082143E+05
b	4.362144E-01	4.495666E-01	2.720235E-01	1.324045E-06
c	3.142112E-02	1.766882E-01	-7.422945E-01	-2.082122E+05

Table A-2—Heat flux parameter curve-fit coefficients for cryogenic releases through 1 inch pipe

	Coefficient	1” pipe (MFlow: 0.001 - 0.6 Kg/s)			
		1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
Xcr_cryogenic	A	-2.260082E+02	-2.140942E+02	-2.076171E+02	-1.676924E+02
	B	9.294862E-02	1.035258E-01	1.128329E-01	1.465876E-01
	C	-2.300436E+01	-2.964862E+01	-3.556919E+01	-4.710637E+01
	D	1.886188E+00	1.394526E+00	9.015584E-01	-9.026059E-01
	Transition	1.268317E-01	1.249900E-01	1.243342E-01	1.207803E-01
	a	-3.963532E+04	-1.364307E+00	2.810957E+00	3.675329E+03
	b	-1.367821E-05	-2.181782E-01	1.175610E-01	2.517198E-05
	c	3.963729E+04	2.807110E+00	-1.734950E+00	-3.674932E+03

	Coefficient	1” pipe (MFlow: 0.001 - 0.6 Kg/s)			
		1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
Ycr_cryogenic	a	-1.527034E+01	-6.644520E+00	-3.444728E+00	-1.431727E+00
	b	4.453823E-01	4.707450E-01	5.480851E-01	8.844588E-01
	c	-4.052225E-01	-3.741284E-01	-3.494352E-01	-2.385336E-01

	Coefficient	1” pipe (MFlow: 0.001 - 0.6 Kg/s)			
		1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
Nr_cryogenic	A	-4.329320E+02	-3.902677E+02	-4.118938E+02	-4.047855E+02
	B	1.396741E-01	1.108015E-01	9.049126E-02	7.509390E-02
	C	-9.938938E+00	-5.192843E+00	-3.472570E+00	-6.072397E+00
	D	8.845476E+00	5.648349E+00	4.751051E+00	4.449758E+00
	Transition	1.244342E-01	1.274586E-01	1.268578E-01	1.338518E-01
	a	2.247962E+01	1.303509E+01	9.450430E+00	6.754033E+00
	b	4.202002E-01	5.069601E-01	5.161055E-01	3.705185E-01
	c	-4.680608E-01	8.661107E-01	8.241451E-01	-5.105443E-01

Table A-3—Heat flux parameter curve-fit coefficients for cryogenic releases through 2 inch pipe

Xcr_cryogenic

Coefficient	2” pipe (MFlow: 0.001 - 1.2 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	-3.197598E+02	-3.469327E+02	-3.664672E+02	-4.161383E+02
B	1.189383E-01	1.092349E-01	1.055688E-01	1.009577E-01
C	-4.672136E+00	-1.231654E+00	-6.727327E-01	-9.003706E-01
D	5.899540E+00	5.997940E+00	6.062865E+00	6.210654E+00
Transition	2.160375E-01	2.132735E-01	2.127227E-01	2.095190E-01
a	-3.893813E+05	-4.393668E+05	-4.491504E+05	-3.921800E+05
b	1.228154E-06	1.191131E-06	1.309559E-06	1.483941E-06
c	3.893830E+05	4.393681E+05	4.491513E+05	3.921803E+05

Ycr_cryogenic

Coefficient	2” pipe (MFlow: 0.001 - 1.2 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
a	-1.698900E+01	-7.714363E+00	-4.006587E+00	-1.359929E+00
b	3.894555E-01	3.600595E-01	3.483100E-01	3.927659E-01
c	1.257795E-01	7.706670E-02	-4.372552E-02	-2.229077E-01

Nr_cryogenic

Coefficient	2” pipe (MFlow: 0.001 - 1.2 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	-2.772999E+02	-2.118799E+02	-2.442526E+02	-2.168220E+02
B	2.115933E-01	2.009332E-01	1.758235E-01	1.992012E-01
C	-1.128006E+01	-8.051895E+00	-6.782338E+00	-7.036232E+00
D	1.201200E+01	8.559677E+00	8.071425E+00	9.830217E+00
Transition	1.941450E-01	2.078969E-01	2.183027E-01	3.160445E-01
a	1.862601E+01	6.961211E+00	2.953662E+00	6.373225E-06
b	5.664149E-01	1.016822E+00	2.056506E+00	-8.280879E+00
c	4.763955E+00	7.083855E+00	7.213406E+00	5.959461E+00

Table A-4—Heat flux parameter curve-fit coefficients for cryogenic releases through 3 inch pipe

	Coefficient	3” pipe (MFlow: 0.001 - 2.5 Kg/s)			
		1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
Xcr_cryogenic	A	-2.909079E+01	-2.958622E+01	-3.014887E+01	-3.063853E+01
	B	4.659599E-01	4.564394E-01	4.697635E-01	4.850293E-01
	C	-6.921444E+00	-7.493434E+00	-9.287011E+00	-1.200672E+01
	D	6.296780E+00	6.087172E+00	5.730802E+00	5.002817E+00
	Transition	7.401152E-01	7.334800E-01	7.292924E-01	7.147112E-01
	a	6.242192E-03	4.169814E-03	1.369568E-03	3.026981E-04
	b	4.843218E+00	4.952502E+00	5.930704E+00	6.894641E+00
	c	2.211278E+00	1.739500E+00	1.289657E+00	6.287618E-01

	Coefficient	3” pipe (MFlow: 0.001 - 2.5 Kg/s)			
		1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
Ycr_cryogenic	a	-1.826274E+01	-8.576731E+00	-4.660550E+00	-1.798335E+00
	b	3.896443E-01	3.572098E-01	3.317135E-01	3.032049E-01
	c	1.335148E-01	1.289654E-01	2.858850E-02	-1.128666E-01

	Coefficient	3” pipe (MFlow: 0.001 - 2.5 Kg/s)			
		1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
Nr_cryogenic	A	-9.003860E+01	-9.110111E+01	-9.182483E+01	-9.702403E+01
	B	4.491714E-01	3.629674E-01	3.223101E-01	3.185170E-01
	C	-6.139244E+00	-5.204308E+00	-1.476975E+00	-1.427513E-01
	D	1.801443E+01	1.200559E+01	1.114745E+01	1.258377E+01
	Transition	4.622343E-01	4.039391E-01	4.265130E-01	5.334553E-01
	a	1.879736E+01	5.862766E+00	1.376046E+00	3.227769E-02
	b	5.370495E-01	8.700247E-01	1.671807E+00	4.694597E+00
	c	5.499168E+00	8.975102E+00	9.665396E+00	8.069044E+00

Table A-5—Heat flux parameter curve-fit coefficients for cryogenic releases through 4 inch pipe

Xcr_cryogenic

Coefficient	4” pipe (MFlow: 0.001 - 14.0 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	-3.415086E+01	-3.550562E+01	-3.698025E+01	-4.016480E+01
B	5.015043E-01	5.110708E-01	4.839386E-01	4.722432E-01
C	-4.965928E+00	-6.784970E+00	-5.903274E+00	-6.989463E+00
D	9.252472E+00	9.056476E+00	9.148354E+00	9.101102E+00
Transition	8.633009E-01	8.583472E-01	8.556549E-01	8.446219E-01
a	2.273795E-02	8.931191E-03	4.195731E-03	1.813507E-03
b	1.710400E+00	1.953839E+00	2.106604E+00	2.146143E+00
c	2.967895E+00	2.411579E+00	1.841316E+00	9.276231E-01

Ycr_cryogenic

Coefficient	4” pipe (MFlow: 0.001 - 14.0 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
a	-1.806650E+01	-8.252294E+00	-4.279321E+00	-1.460635E+00
b	4.311065E-01	4.338673E-01	4.497942E-01	5.241624E-01
c	-6.176433E-01	-5.680488E-01	-5.844357E-01	-5.547250E-01

Nr_cryogenic

Coefficient	4” pipe (MFlow: 0.001 - 14.0 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	-3.444988E+01	-2.839851E+01	-3.057935E+01	-3.894559E+01
B	9.170177E-01	7.493659E-01	8.303797E-01	5.813124E-01
C	-1.060864E+01	-3.885914E+00	-1.365102E+01	-2.652123E+00
D	2.249794E+01	1.556547E+01	1.232940E+01	1.501799E+01
Transition	8.209107E-01	8.511280E-01	8.702195E-01	9.252991E-01
a	2.391431E+01	1.129581E+01	5.607680E+00	8.778962E-01
b	4.405480E-01	5.004787E-01	5.952497E-01	1.031986E+00
c	1.276252E+00	4.455622E+00	6.574661E+00	8.687081E+00

Table A-6—Heat flux parameter curve-fit coefficients for cryogenic releases through 10 inch pipe

	Coefficient	10" pipe (MFlow: 0.001 - 25.0 Kg/s)			
		1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
Xcr_cryogenic	A	-5.737590E-01	-5.490593E-01	-5.194311E-01	-4.657324E-01
	B	2.561653E+00	3.215929E+00	-2.271590E+00	-2.249964E+00
	C	7.622917E-01	-1.997724E-01	5.282969E+00	4.324528E+00
	D	1.208808E+01	1.161690E+01	-2.523465E+00	-3.029589E-01
	Transition	6.896151E+00	6.828105E+00	6.752658E+00	6.575991E+00
	a	3.720606E-09	2.727453E-09	1.528810E-09	2.592746E-10
	b	6.096876E+00	6.129820E+00	6.229435E+00	6.588711E+00
	c	4.612036E+00	3.730910E+00	2.850196E+00	1.585686E+00

	Coefficient	10" pipe (MFlow: 0.001 - 25.0 Kg/s)			
		1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
Ycr_cryogenic	a	-2.146663E+01	-1.051341E+01	-6.158307E+00	-2.831838E+00
	b	4.087784E-01	3.953494E-01	3.785211E-01	3.576562E-01
	c	-2.540733E-01	-3.582751E-01	-3.539456E-01	-4.241020E-01

	Coefficient	10" pipe (MFlow: 0.001 - 25.0 Kg/s)			
		1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
Nr_cryogenic	A	-6.015273E+00	-4.311264E+00	-4.012739E+00	-4.837390E+00
	B	5.386177E+00	5.850287E+00	6.034815E+00	5.955290E+00
	C	-3.373609E+01	-2.929718E+01	-2.981211E+01	-3.731762E+01
	D	-1.814725E+00	-1.968454E+01	-2.949854E+01	-4.540993E+01
	Transition	2.966090E+00	2.943531E+00	2.947908E+00	3.169141E+00
	a	2.136018E+01	7.058274E+00	1.183360E+00	8.548050E-04
	b	4.768600E-01	6.000445E-01	9.510828E-01	2.905025E+00
	c	8.725933E+00	1.555746E+01	2.098257E+01	2.098727E+01

Table A-7—Heat flux parameters for cryogenic releases through 1/4 inch ODT

mdot	1.577 kW/m²			4.732 kW/m²			9.46 kW/m²			20 kW/m²		
kg/s	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)
0.0001	0.51	–0.25	0.53	0.46	–0.11	0.52	0.55	–0.06	0.65	0.57	–0.02	0.86
0.0002	0.53	–0.33	0.59	0.51	–0.15	0.57	0.57	–0.08	0.69	0.60	–0.02	0.92
0.0003	0.56	–0.40	0.66	0.55	–0.18	0.62	0.60	–0.09	0.73	0.62	–0.03	0.97
0.0004	0.58	–0.45	0.72	0.59	–0.20	0.67	0.62	–0.10	0.77	0.64	–0.03	1.03
0.0005	0.60	–0.49	0.78	0.63	–0.21	0.71	0.64	–0.10	0.80	0.66	–0.03	1.08
0.0006	0.61	–0.53	0.83	0.66	–0.23	0.75	0.65	–0.11	0.84	0.67	–0.03	1.12
0.0007	0.63	–0.57	0.89	0.69	–0.25	0.79	0.67	–0.12	0.87	0.69	–0.03	1.16
0.0008	0.64	–0.60	0.94	0.71	–0.26	0.83	0.68	–0.12	0.90	0.70	–0.03	1.20
0.0009	0.65	–0.63	0.99	0.73	–0.27	0.86	0.69	–0.13	0.93	0.71	–0.03	1.24
0.0010	0.66	–0.66	1.04	0.75	–0.28	0.90	0.70	–0.13	0.95	0.71	–0.03	1.27
0.0020	0.66	–0.89	1.43	0.70	–0.37	1.12	0.67	–0.17	1.09	0.65	–0.04	1.38
0.0030	0.49	–1.05	1.62	0.26	–0.44	1.15	0.43	–0.20	1.03	0.37	–0.04	1.14
0.00357*	0.30*	–1.13*	1.64*	0.22*	–0.47*	1.07*	0.20*	–0.21*	0.90*	0.10*	–0.05*	0.84*
0.0040	0.26	–1.18	1.68	0.22	–0.50	1.11	0.15	–0.22	0.87	0.05	–0.05	0.63
0.0050	0.29	–1.30	1.85	0.24	–0.54	1.21	0.16	–0.24	0.97	0.06	–0.05	0.69
0.0100	0.39	–1.73	2.49	0.30	–0.72	1.58	0.19	–0.31	1.32	0.06	–0.07	0.88
0.0500	0.67	–3.36	5.00	0.48	–1.37	3.08	0.27	–0.61	2.46	0.08	–0.14	1.32
0.1000	0.82	–4.46	6.75	0.58	–1.81	4.14	0.32	–0.81	3.12	0.09	–0.20	1.51
0.2000	0.98	–5.94	9.12	0.70	–2.40	5.59	0.38	–1.09	3.92	0.10	–0.29	1.70

* Theoretical choked flow, refer to Appendix A1.

Table A-8—Heat flux parameters for cryogenic releases through 1 inch pipe

mdot	1.577 kW/m²			4.732 kW/m²			9.46 kW/m²			20 kW/m²		
kg/s	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)
0.001	2.09	–1.11	1.90	2.18	–0.63	1.51	2.28	–0.43	1.76	2.40	–0.24	2.68
0.002	2.11	–1.36	2.01	2.20	–0.73	1.59	2.29	–0.46	1.83	2.40	–0.24	2.73
0.003	2.13	–1.55	2.12	2.21	–0.81	1.67	2.30	–0.49	1.90	2.40	–0.25	2.78
0.004	2.14	–1.71	2.22	2.22	–0.87	1.75	2.31	–0.52	1.97	2.40	–0.25	2.84
0.005	2.16	–1.85	2.33	2.24	–0.92	1.83	2.32	–0.54	2.04	2.41	–0.25	2.89
0.006	2.18	–1.97	2.44	2.25	–0.97	1.91	2.33	–0.56	2.10	2.41	–0.25	2.94
0.007	2.19	–2.08	2.54	2.26	–1.02	1.98	2.34	–0.58	2.17	2.41	–0.26	2.99
0.008	2.21	–2.18	2.65	2.27	–1.06	2.06	2.35	–0.59	2.23	2.40	–0.26	3.03
0.009	2.22	–2.28	2.75	2.28	–1.10	2.13	2.36	–0.61	2.30	2.40	–0.26	3.08
0.010	2.24	–2.37	2.85	2.29	–1.13	2.21	2.36	–0.63	2.36	2.40	–0.26	3.13
0.020	2.36	–3.08	3.83	2.38	–1.43	2.90	2.41	–0.75	2.95	2.37	–0.28	3.56
0.030	2.44	–3.61	4.73	2.42	–1.65	3.52	2.42	–0.85	3.45	2.31	–0.30	3.90
0.040	2.47	–4.05	5.53	2.41	–1.83	4.06	2.39	–0.94	3.88	2.21	–0.32	4.16
0.050	2.46	–4.43	6.26	2.37	–2.00	4.52	2.32	–1.02	4.22	2.08	–0.34	4.35
0.060	2.40	–4.77	6.89	2.28	–2.14	4.90	2.20	–1.09	4.47	1.92	–0.36	4.45
0.070	2.30	–5.08	7.44	2.15	–2.27	5.21	2.04	–1.15	4.65	1.72	–0.37	4.47
0.080	2.15	–5.36	7.90	1.97	–2.40	5.44	1.85	–1.21	4.74	1.49	–0.39	4.41
0.090	1.95	–5.63	8.27	1.76	–2.51	5.59	1.61	–1.27	4.75	1.23	–0.41	4.27
0.100	1.71	–5.88	8.56	1.50	–2.62	5.66	1.32	–1.32	4.68	0.93	–0.43	4.05
0.135*	0.88*	–6.66*	9.22*	0.70*	–2.96*	5.59*	0.49*	–1.50*	4.19*	0.21*	–0.48*	2.71*
0.200	1.09	–7.86	10.96	0.87	–3.49	6.63	0.59	–1.78	4.94	0.25	–0.58	3.21
0.300	1.31	–9.34	13.09	1.03	–4.14	7.95	0.71	–2.13	5.90	0.29	–0.73	3.81
0.400	1.47	–10.56	14.83	1.14	–4.69	9.06	0.79	–2.43	6.71	0.31	–0.88	4.30
0.500	1.59	–11.62	16.33	1.22	–5.17	10.04	0.86	–2.71	7.43	0.33	–1.01	4.71
0.600	1.69	–12.57	17.67	1.28	–5.60	10.93	0.91	–2.95	8.08	0.35	–1.15	5.08
*	Theoretical choked flow, refer to Appendix A1.											

Table A-9—Heat flux parameters for cryogenic releases through 2 inch pipe

mdot	1.577 kW/m²			4.732 kW/m²			9.46 kW/m²			20 kW/m²		
kg/s	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)
0.001	2.00	–1.03	2.09	2.07	–0.56	1.70	2.13	–0.41	1.79	2.14	–0.31	2.71
0.002	2.07	–1.38	2.19	2.14	–0.75	1.78	2.20	–0.50	1.87	2.22	–0.34	2.79
0.003	2.14	–1.64	2.30	2.21	–0.88	1.85	2.28	–0.57	1.95	2.31	–0.36	2.86
0.004	2.21	–1.85	2.40	2.29	–0.98	1.93	2.35	–0.63	2.03	2.39	–0.38	2.94
0.005	2.28	–2.03	2.51	2.36	–1.07	2.00	2.42	–0.68	2.10	2.47	–0.39	3.02
0.006	2.35	–2.19	2.61	2.43	–1.15	2.08	2.50	–0.72	2.18	2.54	–0.41	3.10
0.007	2.42	–2.33	2.71	2.50	–1.22	2.15	2.57	–0.76	2.25	2.62	–0.42	3.17
0.008	2.48	–2.47	2.81	2.57	–1.28	2.23	2.64	–0.79	2.33	2.70	–0.43	3.25
0.009	2.55	–2.59	2.92	2.64	–1.34	2.30	2.71	–0.82	2.41	2.77	–0.44	3.32
0.010	2.61	–2.70	3.02	2.70	–1.39	2.37	2.78	–0.85	2.48	2.85	–0.45	3.40
0.020	3.23	–3.58	3.99	3.35	–1.81	3.08	3.44	–1.07	3.20	3.56	–0.52	4.13
0.030	3.79	–4.21	4.92	3.92	–2.11	3.75	4.02	–1.22	3.87	4.18	–0.57	4.81
0.040	4.28	–4.72	5.78	4.42	–2.34	4.37	4.53	–1.35	4.49	4.72	–0.61	5.46
0.050	4.70	–5.16	6.59	4.85	–2.55	4.95	4.97	–1.46	5.06	5.18	–0.64	6.05
0.060	5.06	–5.55	7.35	5.22	–2.72	5.49	5.33	–1.55	5.58	5.55	–0.67	6.61
0.070	5.36	–5.91	8.05	5.51	–2.88	5.98	5.62	–1.63	6.05	5.84	–0.70	7.12
0.080	5.60	–6.23	8.69	5.74	–3.03	6.43	5.84	–1.71	6.48	6.05	–0.73	7.59
0.090	5.77	–6.53	9.28	5.89	–3.16	6.85	5.98	–1.78	6.85	6.17	–0.75	8.01
0.10	5.87	–6.80	9.82	5.98	–3.29	7.21	6.06	–1.84	7.18	6.21	–0.77	8.39
0.20	3.42	–8.95	12.25	3.03	–4.24	8.57	2.73	–2.33	7.76	2.04	–0.95	9.82
0.30	2.27	–10.50	14.18	1.94	–4.92	9.13	1.58	–2.68	7.46	1.00	–1.07	6.92
0.40	2.14	–11.76	15.85	1.79	–5.47	9.83	1.41	–2.96	7.66	0.83	–1.17	5.97
0.50	2.03	–12.84	17.34	1.67	–5.93	10.52	1.28	–3.19	7.92	0.70	–1.26	5.96
0.513*	2.02*	–12.97*	17.53*	1.66*	–5.99*	10.62*	1.27*	–3.22*	7.96*	0.69*	–1.27*	5.96*
0.60	1.94	–13.80	18.71	1.57	–6.34	11.22	1.17	–3.40	8.25	0.60	–1.34	5.96
0.70	1.87	–14.66	19.98	1.49	–6.71	11.93	1.08	–3.58	8.63	0.51	–1.41	5.96
0.80	1.81	–15.45	21.18	1.42	–7.04	12.63	1.00	–3.75	9.08	0.43	–1.47	5.96
0.90	1.75	–16.18	22.31	1.36	–7.35	13.34	0.93	–3.91	9.59	0.36	–1.53	5.96
1.00	1.70	–16.86	23.39	1.31	–7.64	14.05	0.87	–4.05	10.17	0.30	–1.58	5.96
1.10	1.65	–17.51	24.42	1.26	–7.91	14.75	0.82	–4.19	10.81	0.24	–1.63	5.96
1.20	1.61	–18.11	25.42	1.21	–8.16	15.46	0.77	–4.31	11.51	0.19	–1.68	5.96
*	Theoretical choked flow, refer to Appendix A1.											

Table A-10—Heat flux parameters for cryogenic releases through 3 inch pipe

mdot	1.577 kW/m²			4.732 kW/m²			9.46 kW/m²			20 kW/m²		
kg/s	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)
0.001	3.23	–1.10	2.68	3.36	–0.60	1.95	3.46	–0.44	2.14	3.64	–0.33	2.85
0.002	3.25	–1.49	2.76	3.38	–0.80	2.01	3.48	–0.56	2.20	3.65	–0.39	2.91
0.003	3.27	–1.77	2.83	3.40	–0.95	2.07	3.50	–0.65	2.26	3.67	–0.42	2.97
0.004	3.29	–1.99	2.90	3.42	–1.06	2.13	3.52	–0.72	2.31	3.69	–0.45	3.03
0.005	3.31	–2.18	2.98	3.44	–1.16	2.19	3.53	–0.78	2.37	3.71	–0.47	3.09
0.006	3.33	–2.35	3.05	3.46	–1.25	2.25	3.55	–0.83	2.43	3.72	–0.49	3.15
0.007	3.35	–2.51	3.13	3.48	–1.33	2.31	3.57	–0.87	2.48	3.74	–0.51	3.21
0.008	3.37	–2.65	3.20	3.50	–1.40	2.37	3.59	–0.91	2.54	3.76	–0.53	3.27
0.009	3.39	–2.78	3.27	3.52	–1.47	2.43	3.61	–0.95	2.60	3.78	–0.54	3.33
0.010	3.40	–2.90	3.34	3.54	–1.53	2.49	3.63	–0.98	2.65	3.79	–0.56	3.39
0.020	3.60	–3.84	4.07	3.72	–1.99	3.07	3.81	–1.24	3.20	3.96	–0.66	3.98
0.030	3.79	–4.52	4.77	3.90	–2.32	3.64	3.98	–1.43	3.73	4.12	–0.73	4.55
0.040	3.97	–5.08	5.45	4.08	–2.59	4.18	4.15	–1.57	4.25	4.28	–0.79	5.10
0.050	4.14	–5.55	6.12	4.25	–2.81	4.71	4.32	–1.70	4.74	4.43	–0.84	5.63
0.060	4.31	–5.97	6.77	4.41	–3.01	5.22	4.47	–1.80	5.22	4.57	–0.88	6.14
0.070	4.48	–6.35	7.40	4.56	–3.19	5.71	4.63	–1.90	5.67	4.71	–0.92	6.63
0.080	4.63	–6.69	8.01	4.72	–3.35	6.18	4.77	–1.99	6.11	4.84	–0.95	7.10
0.090	4.79	–7.01	8.60	4.86	–3.50	6.64	4.91	–2.07	6.53	4.96	–0.98	7.55
0.10	4.93	–7.31	9.18	5.00	–3.64	7.07	5.04	–2.14	6.94	5.08	–1.01	7.98
0.20	6.08	–9.62	13.95	6.06	–4.70	10.43	6.04	–2.70	9.95	5.94	–1.22	11.24
0.30	6.64	–11.29	16.93	6.54	–5.45	11.97	6.44	–3.10	11.13	6.18	–1.36	12.55
0.40	6.63	–12.65	18.10	6.42	–6.05	11.69	6.23	–3.41	10.48	5.80	–1.47	11.93
0.50	6.03	–13.81	18.45	5.70	–6.57	12.18	5.42	–3.67	10.10	4.82	–1.57	9.36
0.60	4.85	–14.83	19.79	4.40	–7.02	12.73	4.01	–3.91	10.25	3.22	–1.65	8.07
0.70	3.08	–15.76	21.02	2.51	–7.42	13.27	1.99	–4.11	10.42	1.01	–1.73	8.08
0.80	2.21	–16.61	22.17	1.74	–7.79	13.80	1.29	–4.30	10.61	0.63	–1.79	8.08
0.90	2.22	–17.39	23.26	1.74	–8.13	14.32	1.29	–4.47	10.82	0.63	–1.85	8.09
1.00	2.22	–18.13	24.30	1.74	–8.45	14.84	1.29	–4.63	11.04	0.63	–1.91	8.10
1.10	2.22	–18.82	25.28	1.75	–8.74	15.34	1.29	–4.78	11.28	0.63	–1.96	8.12
1.173*	2.22*	–19.30*	25.98*	1.75*	–8.95*	15.71*	1.29*	–4.89*	11.46*	0.63*	–2.00*	8.14*
1.20	2.23	–19.47	26.23	1.75	–9.02	15.85	1.29	–4.92	11.53	0.63	–2.01	8.15
1.30	2.23	–20.09	27.14	1.75	–9.29	16.34	1.30	–5.06	11.80	0.63	–2.06	8.18
1.40	2.24	–20.69	28.02	1.76	–9.54	16.83	1.30	–5.18	12.08	0.63	–2.10	8.23
1.50	2.26	–21.25	28.87	1.77	–9.78	17.32	1.30	–5.30	12.38	0.63	–2.15	8.29
1.60	2.27	–21.80	29.69	1.78	–10.02	17.80	1.31	–5.42	12.68	0.64	–2.19	8.36
1.70	2.29	–22.32	30.49	1.80	–10.24	18.28	1.32	–5.53	13.01	0.64	–2.23	8.46
1.80	2.32	–22.83	31.27	1.82	–10.45	18.75	1.33	–5.64	13.34	0.65	–2.26	8.58
1.90	2.35	–23.32	32.03	1.84	–10.66	19.22	1.35	–5.74	13.69	0.65	–2.30	8.73
2.00	2.39	–23.79	32.77	1.87	–10.86	19.69	1.37	–5.84	14.05	0.66	–2.33	8.90
2.50	2.74	–25.97	36.25	2.13	–11.77	21.99	1.60	–6.29	16.03	0.80	–2.49	10.45

* Theoretical choked flow, refer to Appendix A1.

Table A-11—Heat flux parameters for cryogenic releases through 4 inch pipe

mdot	1.577 kW/m²			4.732 kW/m²			9.46 kW/m²			20 kW/m²		
kg/s	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)
0.001	3.18	–1.54	3.31	3.28	–0.98	2.57	3.37	–0.78	2.62	3.48	–0.59	3.44
0.002	3.21	–1.86	3.36	3.31	–1.12	2.61	3.40	–0.85	2.65	3.51	–0.61	3.48
0.003	3.24	–2.09	3.41	3.34	–1.23	2.65	3.43	–0.90	2.69	3.54	–0.62	3.53
0.004	3.27	–2.29	3.47	3.37	–1.32	2.68	3.46	–0.94	2.73	3.57	–0.64	3.57
0.005	3.30	–2.46	3.52	3.40	–1.40	2.72	3.49	–0.98	2.76	3.60	–0.65	3.61
0.006	3.33	–2.61	3.57	3.43	–1.46	2.76	3.52	–1.01	2.80	3.63	–0.65	3.65
0.007	3.36	–2.75	3.62	3.46	–1.53	2.80	3.55	–1.04	2.84	3.66	–0.66	3.70
0.008	3.39	–2.87	3.67	3.48	–1.58	2.84	3.58	–1.07	2.87	3.69	–0.67	3.74
0.009	3.41	–2.99	3.73	3.51	–1.64	2.88	3.61	–1.10	2.91	3.72	–0.68	3.78
0.010	3.44	–3.10	3.78	3.54	–1.69	2.91	3.64	–1.12	2.95	3.75	–0.69	3.82
0.020	3.73	–3.96	4.29	3.83	–2.08	3.29	3.93	–1.32	3.31	4.05	–0.74	4.24
0.030	4.00	–4.60	4.80	4.10	–2.37	3.66	4.21	–1.47	3.67	4.34	–0.79	4.64
0.040	4.27	–5.13	5.30	4.37	–2.61	4.03	4.48	–1.59	4.02	4.62	–0.82	5.04
0.050	4.53	–5.58	5.80	4.64	–2.82	4.39	4.75	–1.70	4.36	4.89	–0.86	5.43
0.060	4.79	–5.99	6.29	4.89	–3.00	4.75	5.00	–1.79	4.70	5.16	–0.89	5.82
0.070	5.04	–6.36	6.77	5.14	–3.17	5.10	5.26	–1.88	5.03	5.41	–0.92	6.19
0.080	5.28	–6.70	7.24	5.38	–3.33	5.44	5.50	–1.96	5.35	5.66	–0.94	6.56
0.090	5.51	–7.02	7.71	5.62	–3.47	5.78	5.74	–2.03	5.67	5.90	–0.97	6.92
0.100	5.74	–7.31	8.17	5.85	–3.61	6.11	5.96	–2.10	5.99	6.14	–0.99	7.27
0.200	7.65	–9.64	12.39	7.73	–4.67	9.13	7.84	–2.66	8.78	8.03	–1.18	10.37
0.300	8.87	–11.37	15.93	8.91	–5.46	11.58	8.98	–3.07	10.97	9.11	–1.33	12.68
0.400	9.40	–12.79	18.77	9.37	–6.11	13.46	9.38	–3.42	12.54	9.40	–1.46	14.22
0.500	9.26	–14.02	20.93	9.13	–6.68	14.77	9.04	–3.72	13.50	8.88	–1.57	14.98
0.600	8.43	–15.11	22.40	8.17	–7.18	15.51	7.97	–3.99	13.85	7.55	–1.67	14.95
0.700	6.92	–16.11	23.18	6.51	–7.64	15.69	6.15	–4.23	13.59	5.43	–1.77	14.15
0.800	4.73	–17.03	23.27	4.13	–8.06	15.30	3.59	–4.46	12.72	2.50	–1.85	12.58
0.900	2.99	–17.88	24.11	2.42	–8.45	15.17	1.84	–4.67	11.84	0.93	–1.94	10.22
1.00	2.99	–18.68	25.19	2.42	–8.82	15.75	1.85	–4.86	12.18	0.93	–2.02	9.56
1.10	2.99	–19.44	26.22	2.42	–9.17	16.30	1.85	–5.05	12.51	0.93	–2.09	9.66
1.20	3.00	–20.16	27.19	2.42	–9.50	16.83	1.85	–5.23	12.83	0.93	–2.16	9.75
1.30	3.00	–20.85	28.12	2.43	–9.82	17.34	1.85	–5.40	13.13	0.93	–2.23	9.84
1.40	3.01	–21.50	29.01	2.43	–10.12	17.82	1.85	–5.56	13.43	0.93	–2.30	9.93
1.50	3.01	–22.13	29.87	2.43	–10.41	18.29	1.85	–5.72	13.71	0.93	–2.36	10.02
1.60	3.02	–22.74	30.69	2.43	–10.69	18.75	1.85	–5.87	13.99	0.93	–2.42	10.11
1.70	3.02	–23.33	31.49	2.44	–10.96	19.19	1.85	–6.02	14.27	0.93	–2.48	10.21
1.80	3.03	–23.89	32.26	2.44	–11.22	19.61	1.86	–6.16	14.53	0.93	–2.54	10.30
1.90	3.04	–24.44	33.01	2.44	–11.47	20.03	1.86	–6.30	14.79	0.93	–2.60	10.39
2.00	3.04	–24.98	33.73	2.45	–11.72	20.44	1.86	–6.43	15.05	0.94	–2.66	10.48
2.002*	3.04*	–24.99*	33.75*	2.45*	–11.72*	20.44*	1.86*	–6.43*	15.05*	0.94*	–2.66*	10.48*
2.50	3.08	–27.44	37.08	2.47	–12.85	22.32	1.87	–7.05	16.25	0.94	–2.92	10.95
3.00	3.12	–29.63	40.08	2.49	–13.86	24.03	1.88	–7.60	17.36	0.95	–3.15	11.41
3.50	3.16	–31.62	42.80	2.51	–14.78	25.60	1.90	–8.10	18.40	0.95	–3.37	11.89
4.00	3.21	–33.46	45.32	2.55	–15.63	27.06	1.92	–8.57	19.37	0.96	–3.58	12.36

mdot	1.577 kW/m²			4.732 kW/m²			9.46 kW/m²			20 kW/m²		
kg/s	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)
4.50	3.27	–35.17	47.67	2.58	–16.42	28.43	1.94	–9.00	20.30	0.97	–3.77	12.83
5.00	3.32	–36.78	49.87	2.62	–17.16	29.73	1.97	–9.41	21.19	0.98	–3.95	13.31
6.00	3.46	–39.73	53.94	2.71	–18.52	32.15	2.02	–10.16	22.87	1.01	–4.29	14.27
8.00	3.76	–44.90	61.05	2.93	–20.91	36.44	2.18	–11.49	25.91	1.08	–4.90	16.19
10.00	4.14	–49.37	67.22	3.21	–22.98	40.22	2.38	–12.64	28.66	1.18	–5.44	18.14
12.00	4.56	–53.35	72.74	3.56	–24.82	43.63	2.63	–13.67	31.19	1.30	–5.93	20.09
14.00	5.04	–56.98	77.76	3.96	–26.50	46.77	2.93	–14.61	33.55	1.45	–6.38	22.06

* Theoretical choked flow, refer to Appendix A1.

Table A-12—Heat flux parameters for cryogenic releases through 10 inch pipe

mdot	1.577 kW/m^2			4.732 kW/m^2			9.46 kW/m^2			20 kW/m^2		
kg/s	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)
0.001	6.37	–1.53	5.42	6.58	–1.04	4.18	6.80	–0.80	4.29	7.07	–0.66	5.29
0.005	6.39	–2.72	5.54	6.60	–1.65	4.26	6.81	–1.18	4.37	7.08	–0.85	5.37
0.010	6.41	–3.52	5.70	6.61	–2.06	4.37	6.83	–1.43	4.46	7.09	–0.97	5.47
0.050	6.55	–6.56	6.92	6.75	–3.57	5.20	6.94	–2.34	5.19	7.18	–1.39	6.27
0.060	6.59	–7.05	7.23	6.78	–3.82	5.41	6.97	–2.48	5.37	7.20	–1.46	6.47
0.070	6.63	–7.49	7.53	6.81	–4.03	5.61	7.00	–2.60	5.56	7.22	–1.52	6.66
0.080	6.66	–7.90	7.83	6.84	–4.23	5.82	7.03	–2.72	5.74	7.24	–1.57	6.86
0.090	6.70	–8.28	8.13	6.88	–4.42	6.02	7.06	–2.83	5.92	7.27	–1.62	7.05
0.10	6.73	–8.63	8.43	6.91	–4.59	6.23	7.08	–2.93	6.09	7.29	–1.67	7.25
0.50	8.08	–16.42	19.41	8.11	–8.35	13.65	8.13	–5.09	12.58	8.07	–2.63	14.21
1.00	9.50	–21.72	30.43	9.36	–10.87	20.99	9.20	–6.51	18.88	8.83	–3.26	20.73
3.00	12.31	–33.89	44.79	11.63	–16.59	29.20	10.89	–9.69	24.35	9.56	–4.62	22.63
5.00	10.54	–41.70	54.74	9.51	–20.22	34.10	8.43	–11.68	26.45	6.57	–5.46	21.08
7.00	4.61	–47.81	62.75	3.73	–23.05	38.25	2.85	–13.22	28.51	1.59	–6.10	21.23
9.00	4.61	–52.96	69.63	3.73	–25.42	41.94	2.85	–14.50	30.55	1.59	–6.64	21.49
10.0	4.62	–55.28	72.77	3.73	–26.49	43.66	2.85	–15.08	31.56	1.59	–6.88	21.67
10.5	4.62	–56.39	74.28	3.74	–26.99	44.49	2.85	–15.35	32.06	1.59	–6.99	21.78
11.0	4.62	–57.46	75.75	3.74	–27.49	45.31	2.85	–15.62	32.56	1.59	–7.10	21.89
11.5	4.62	–58.51	77.18	3.74	–27.97	46.12	2.86	–15.88	33.06	1.59	–7.21	22.02
11.6	4.62	–58.72	77.46	3.74	–28.06	46.28	2.86	–15.93	33.16	1.59	–7.23	22.04
11.7	4.62	–58.92	77.75	3.74	–28.16	46.44	2.86	–15.98	33.26	1.59	–7.25	22.07
11.8	4.62	–59.13	78.03	3.74	–28.25	46.59	2.86	–16.03	33.36	1.59	–7.27	22.10
11.9	4.63	–59.33	78.31	3.74	–28.35	46.75	2.86	–16.08	33.46	1.59	–7.29	22.13
12.00*	4.63*	–59.53*	78.59*	3.74*	–28.44*	46.91*	2.86*	–16.13*	33.56*	1.59*	–7.31*	22.15*
12.1	4.63	–59.74	78.86	3.74	–28.53	47.07	2.86	–16.18	33.66	1.59	–7.33	22.18
12.5	4.63	–60.53	79.96	3.75	–28.90	47.69	2.86	–16.37	34.06	1.59	–7.41	22.30
13.0	4.64	–61.51	81.30	3.75	–29.34	48.45	2.86	–16.61	34.55	1.59	–7.51	22.46
14.0	4.65	–63.39	83.91	3.76	–30.20	49.95	2.87	–17.08	35.54	1.59	–7.70	22.81
15.0	4.67	–65.20	86.43	3.78	–31.03	51.40	2.88	–17.52	36.53	1.60	–7.88	23.22
20.0	4.93	–73.30	97.85	3.99	–34.72	58.15	3.04	–19.49	41.42	1.68	–8.69	26.13
25.0	5.85	–80.28	107.86	4.74	–37.89	64.26	3.63	–21.18	46.26	2.01	–9.38	30.83

* Theoretical choked flow, refer to Appendix A1.

A3 Ambient release modeling and curve fits

Flux parameters *Xcr*, *Ycr* and N_R are in meters, *mdot* is in kg/s and transition is the mass flow rate for transition from one curve to the next in kg/s

$$Parameter(mdot) = A \cdot (mdot - B)^2 + C \cdot (mdot - B) + D$$

When mdot<transition

$$Parameter(mdot) = a \cdot mdot^b + c$$

When mdot>transition

Table A-13—Heat flux parameter curve fit coefficients for ambient releases through 1/4 inch ODT

Xcr_ambient

Coefficient	0.25" ODT (MFLow: 0.0001 - 0.1 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	-4.150398E+02	-5.178361E+02	-6.177627E+02	-7.903892E+02
B	-6.083242E-01	-6.056434E-01	-6.045817E-01	-6.054117E-01
C	-2.334149E+01	-1.526541E+01	-1.546946E+01	-5.296825E+00
D	1.682348E+02	1.996696E+02	2.356652E+02	2.934481E+02
Transition	6.825190E-04	6.613011E-04	6.243780E-04	5.612875E-04
a	2.671665E+00	8.037004E-01	4.715883E-01	2.345865E-01
b	8.194488E-01	4.318837E-01	3.492828E-01	2.917486E-01
c	7.906695E-02	2.080579E-02	-3.510542E-03	-2.153861E-02

Ycr_ambient

Coefficient	0.25" ODT (MFLow: 0.0001 - 0.1 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	7.425145E+04	1.408130E+04	-2.740603E+03	-1.447596E+04
B	5.838297E-03	3.757350E-02	6.075227E-02	2.039930E-02
C	3.979693E+02	8.843527E+02	-4.104309E+02	-5.949805E+02
D	-4.223663E-01	1.325667E+01	-1.485388E+01	-6.122930E+00
Transition	2.096723E-03	2.049701E-03	2.242972E-03	2.103739E-03
a	-1.163637E+01	-4.999720E+00	-2.681617E+00	-6.695179E-01
b	3.795793E-01	3.817411E-01	4.636310E-01	4.150224E-01
c	2.478485E-01	8.152980E-02	-6.331681E-02	-3.108318E-02

Nr_ambient

Coefficient	0.25" ODT (MFLow: 0.0001 - 0.1 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	N/A	3.998992E+01	-1.791982E+01	-2.238915E+02
B	N/A	-1.043098E+00	-1.006710E+00	-9.846462E-01
C	N/A	-3.467869E+00	-3.928793E+00	-8.988483E+00
D	N/A	-3.945849E+01	2.262227E+01	2.265586E+02
Transition	N/A	8.738736E-04	1.486151E-03	9.284567E-04
a	1.736787E+01	9.950418E+00	6.453850E+00	2.727644E+00
b	4.214172E-01	4.384439E-01	3.968456E-01	3.251924E-01
c	-5.612631E-02	6.144765E-02	-4.053028E-02	-6.056661E-02

Table A-14—Heat flux parameter curve fit coefficients for ambient releases through 1 inch pipe

Xcr_ambient

Coefficient	1" pipe (MFlow: 0.001 - 1.00 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	-5.633114E+03	-5.372398E+03	-5.640968E+03	-4.752394E+03
B	5.248057E-03	3.397707E-03	3.535672E-03	-7.050184E-04
C	1.062380E+01	1.801979E+01	6.033172E+00	2.241846E+01
D	1.482791E+00	1.482136E+00	1.519483E+00	1.539450E+00
Transition	2.070078E-02	2.054487E-02	1.981195E-02	1.937860E-02
a	8.573056E-01	6.380422E-01	5.532898E-01	2.459244E-01
b	8.160998E-01	7.945705E-01	6.109856E-01	5.310860E-01
c	2.656358E-01	1.823842E-01	7.289485E-02	4.252183E-02

Ycr_ambient

Coefficient	1" pipe (MFlow: 0.001 - 1.00 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	1.899351E+04	1.201299E+04	8.928571E+03	2.992424E+03
B	9.910855E-03	7.555646E-03	5.886461E-03	8.913314E-03
C	5.838203E+01	2.106854E+01	1.166300E+01	3.000393E+01
D	-1.901308E+00	-8.480369E-01	-4.462012E-01	-1.091386E-01
Transition	9.639595E-03	9.609865E-03	9.497118E-03	1.130486E-02
a	-1.654333E+01	-7.898978E+00	-4.612039E+00	-2.390409E+00
b	4.211462E-01	3.979023E-01	3.509763E-01	2.675180E-01
c	4.264146E-01	4.901332E-01	6.119647E-01	7.003182E-01

Nr_ambient

Coefficient	1" pipe (MFlow: 0.001 - 1.00 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	-1.863636E+04	-2.011364E+04	-2.484848E+04	-3.125000E+04
B	1.374850E-02	1.059350E-02	9.242634E-03	6.490771E-03
C	-9.477735E+01	-6.029168E+01	-5.927032E+01	-2.119589E+01
D	3.040955E+00	2.274665E+00	2.310233E+00	2.445488E+00
Transition	1.233048E-02	1.283724E-02	1.310044E-02	1.271452E-02
a	2.147294E+01	1.221637E+01	7.844820E+00	4.603890E+00
b	4.510063E-01	4.991815E-01	6.282454E-01	7.276628E-01
c	1.804674E-01	6.490504E-01	1.196804E+00	9.109246E-01

Table A-15—Heat flux parameter curve fit coefficients for ambient releases through 2 inch pipe

	Coefficient	2" pipe (MFlow: 0.001 - 1.5 Kg/s)			
		1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
Xcr_ambient	A	-1.534872E+02	-9.853525E+01	-4.098032E+01	1.263179E+02
	B	-9.482502E-03	-1.689343E-02	-5.257279E-02	-2.800883E-02
	C	-1.426974E+00	-9.572162E+00	-1.712569E+01	-4.783385E+01
	D	2.113186E+00	2.384411E+00	3.310263E+00	3.690622E+00
	Transition	8.980422E-02	8.723387E-02	8.241157E-02	7.511031E-02
	a	-2.145523E+05	-1.519466E+05	-1.039989E+05	2.235419E-01
	b	-7.850614E-07	-1.053849E-06	-1.068534E-06	8.747221E-01
	c	2.145532E+05	1.519473E+05	1.039995E+05	7.802314E-02

	Coefficient	2" pipe (MFlow: 0.001 - 1.5 Kg/s)			
		1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
Ycr_ambient	A	6.081955E+03	3.843531E+03	2.783286E+03	1.748039E+03
	B	8.309584E-03	1.906259E-02	9.957521E-03	5.021911E-02
	C	-1.468612E+02	1.298168E+01	-3.025747E+01	1.304179E+02
	D	-2.485670E+00	-1.593811E+00	-8.607470E-01	1.959551E+00
	Transition	2.508157E-02	2.520863E-02	2.581711E-02	2.613881E-02
	a	-1.763524E+01	-8.547188E+00	-5.011167E+00	-2.421907E+00
	b	4.451903E-01	4.404604E-01	4.337523E-01	4.023862E-01
	c	1.801644E-01	3.207017E-01	3.853410E-01	3.915178E-01

	Coefficient	2" pipe (MFlow: 0.001 - 1.5 Kg/s)			
		1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
Nr_ambient	A	-7.341432E+02	-5.636763E+02	-4.929112E+02	-6.622992E+02
	B	3.505535E-02	5.311232E-02	1.825929E-02	5.018311E-02
	C	7.916031E+01	2.223783E+01	4.079846E+01	-1.499023E+01
	D	5.502146E+00	4.335572E+00	2.700011E+00	3.325118E+00
	Transition	7.969877E-02	8.190487E-02	8.526719E-02	8.599774E-02
	a	2.277599E+01	1.277891E+01	8.198840E+00	5.080936E+00
	b	4.475930E-01	4.778701E-01	5.542584E-01	5.827888E-01
	c	2.316314E-01	6.431409E-01	1.125893E+00	7.226101E-01

Table A-16—Heat flux parameter curve fit coefficients for ambient releases through 3 inch pipe

Xcr_ambient

Coefficient	3" pipe (MFlow: 0.001 - 5.00 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	-1.136290E+03	-1.194282E+03	-1.248868E+03	-1.382352E+03
B	4.442344E-02	4.396054E-02	4.521000E-02	4.877631E-02
C	-7.193396E+00	-1.070295E+01	-1.800167E+01	-3.654562E+01
D	3.677609E+00	3.660761E+00	3.625582E+00	3.456195E+00
Transition	9.101706E-02	8.944223E-02	8.825149E-02	8.546273E-02
a	6.157812E-02	4.987050E-02	3.554113E-02	3.776637E-02
b	1.804677E+00	1.793240E+00	1.778566E+00	1.459764E+00
c	8.747801E-01	7.028417E-01	5.366734E-01	2.539256E-01

Ycr_ambient

Coefficient	3" pipe (MFlow: 0.001 - 5.00 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	1.640876E+03	1.069706E+03	7.943057E+02	6.088402E+02
B	8.257059E-02	4.649865E-03	-1.235149E-02	1.375713E-02
C	1.107276E+02	-7.875109E+01	-7.648505E+01	-1.723910E+01
D	-3.258906E+00	-1.019372E+00	4.232316E-01	-5.848081E-01
Transition	5.946438E-02	5.966499E-02	5.885883E-02	5.792287E-02
a	-1.894116E+01	-9.421367E+00	-5.824772E+00	-3.396102E+00
b	4.239599E-01	4.116374E-01	3.827282E-01	3.204581E-01
c	7.831979E-01	8.380254E-01	9.744912E-01	1.204520E+00

Nr_ambient

Coefficient	3" pipe (MFlow: 0.001 - 5.00 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	-7.313259E+02	-6.750253E+02	-8.111841E+02	-1.299136E+03
B	2.897795E-02	3.777794E-02	4.545701E-02	4.806813E-02
C	9.796905E+01	5.523269E+01	3.218305E+01	2.761022E+01
D	5.301159E+00	4.554226E+00	4.756116E+00	6.316090E+00
Transition	9.448727E-02	9.848623E-02	9.737232E-02	1.087376E-01
a	2.287131E+01	1.203891E+01	7.240221E+00	3.315493E+00
b	4.615999E-01	5.190162E-01	5.979284E-01	7.072890E-01
c	8.835471E-01	1.804302E+00	2.442113E+00	2.519125E+00

Table A-17—Heat flux parameter curve fit coefficients for ambient releases through 4 inch pipe

Xcr_ambient

Coefficient	4" pipe (MFlow: 0.001 - 6.0 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	-5.600115E+01	-5.098448E+01	-4.636524E+01	-3.737631E+01
B	3.275131E-01	3.610890E-01	2.934949E-01	3.517588E-01
C	-2.108194E+01	-2.406895E+01	-1.736869E+01	-2.117635E+01
D	1.814612E+00	7.829694E-01	1.837272E+00	2.583344E-01
Transition	3.727842E-01	3.688306E-01	3.628822E-01	3.568781E-01
a	2.032724E-01	1.662687E-01	1.559305E-01	2.598640E-01
b	1.076494E+00	1.076605E+00	9.690962E-01	5.444421E-01
c	6.751689E-01	5.367666E-01	3.504917E-01	6.546654E-04

Ycr_ambient

Coefficient	4" pipe (MFlow: 0.001 - 6.0 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	1.549561E+03	9.156997E+02	7.694112E+02	5.461377E+02
B	1.174705E-02	6.432578E-03	3.200281E-03	1.853371E-02
C	-1.349746E+02	-8.239415E+01	-6.385013E+01	-2.340344E+01
D	-2.935429E+00	-1.146515E+00	-5.377753E-01	-7.610450E-01
Transition	6.605176E-02	7.013976E-02	6.976862E-02	8.068541E-02
a	-1.795660E+01	-8.443412E+00	-4.883497E+00	1.256122E+06
b	4.563654E-01	4.682619E-01	4.695128E-01	-7.664082E-07
c	-4.996317E-01	-2.462349E-01	2.034306E-02	-1.256125E+06

Nr_ambient

Coefficient	4" pipe (MFlow: 0.001 - 6.0 Kg/s)			
	1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
A	-6.904514E+02	-5.449306E+02	-6.277394E+02	-2.870655E+02
B	3.831539E-02	4.145019E-02	5.075149E-03	5.231492E-02
C	9.189145E+01	6.146063E+01	1.021998E+02	5.561280E+01
D	6.301455E+00	4.895755E+00	1.960468E+00	6.167826E+00
Transition	1.001761E-01	1.196736E-01	1.257566E-01	2.669580E-01
a	2.295730E+01	1.173481E+01	6.525906E+00	1.689769E+00
b	4.552489E-01	5.128574E-01	6.134853E-01	1.000249E+00
c	1.289590E+00	2.418825E+00	3.322677E+00	4.428195E+00

Table A-18—Heat flux parameter curve fit coefficients for ambient releases through 10 inch pipe

	Coefficient	10" pipe (MFlow: 0.001-12 Kg/s)			
		1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
Xcr_ambient	A	-1.262517E+02	-1.317694E+02	-1.358099E+02	-1.469099E+02
	B	2.862672E-01	2.923319E-01	3.095412E-01	2.878869E-01
	C	-3.532817E+00	-6.439591E+00	-1.256858E+01	-9.421336E+00
	D	1.140304E+01	1.150086E+01	1.130094E+01	1.168880E+01
	Transition	5.201160E-01	5.207477E-01	5.205050E-01	5.185331E-01
	a	-8.349425E+05	-7.333131E+05	-8.130580E+05	-4.689903E+05
	b	1.043648E-06	1.083422E-06	8.359519E-07	1.037738E-06
	c	8.349456E+05	7.333157E+05	8.130601E+05	4.689916E+05

	Coefficient	10" pipe (MFlow: 0.001-12 Kg/s)			
		1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
Ycr_ambient	A	6.045496E+02	3.401432E+02	2.191644E+02	1.458855E+02
	B	6.116021E-02	1.747714E-02	3.775982E-02	3.153943E-02
	C	-6.076310E+01	-6.307762E+01	-3.296791E+01	-2.192982E+01
	D	-7.315820E+00	-1.892335E+00	-1.984747E+00	-1.075576E+00
	Transition	5.219494E-02	4.857542E-02	4.253189E-02	2.731630E-02
	a	-1.702857E+01	-7.162869E+00	-3.566741E+00	-1.422964E+00
	b	4.990931E-01	5.526730E-01	6.135105E-01	6.985247E-01
	c	-2.821656E+00	-2.178802E+00	-1.623069E+00	-8.652822E-01

	Coefficient	10" pipe (MFlow: 0.001-12 Kg/s)			
		1.577 kW/m^2	4.732 kW/m^2	9.46 kW/m^2	20 kW/m^2
Nr_ambient	A	-2.568322E+01	-1.731243E+01	-1.658953E+01	-2.161771E+01
	B	5.414598E-01	3.918745E-01	-9.657332E-02	1.253917E-01
	C	2.089686E+01	1.730836E+01	2.931993E+01	2.134417E+01
	D	2.227714E+01	1.220246E+01	2.342835E-01	6.739665E+00
	Transition	9.857676E-01	1.002277E+00	1.021142E+00	1.039576E+00
	a	2.442735E+01	1.134347E+01	5.527300E+00	2.389626E+00
	b	4.547646E-01	5.159093E-01	6.172789E-01	7.442742E-01
	c	2.223042E+00	4.960274E+00	6.681375E+00	5.725868E+00

Table A-19—Heat flux parameters for ambient releases through 1/4 inch ODT

mdot	1.577 kW/m^2			4.732 kW/m^2			9.46 kW/m^2			20 kW/m^2		
kg/s	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)
0.0001	0.39	–0.11	0.32	0.42	–0.07	0.22	0.43	–0.10	0.50	0.45	–0.05	0.59
0.0002	0.34	–0.21	0.44	0.35	–0.11	0.28	0.36	–0.12	0.50	0.35	–0.05	0.55
0.0003	0.29	–0.29	0.52	0.29	–0.14	0.33	0.28	–0.13	0.49	0.26	–0.05	0.50
0.0004	0.24	–0.35	0.60	0.22	–0.17	0.37	0.20	–0.14	0.49	0.16	–0.06	0.46
0.0005	0.18	–0.40	0.66	0.16	–0.19	0.40	0.13	–0.14	0.49	0.06	–0.06	0.41
0.0006	0.13	–0.45	0.71	0.09	–0.21	0.43	0.05	–0.15	0.48	0.01	–0.06	0.37
0.0007	0.09	–0.49	0.76	0.06	–0.23	0.46	0.03	–0.16	0.48	0.01	–0.06	0.32
0.0008	0.09	–0.53	0.81	0.06	–0.25	0.49	0.04	–0.16	0.47	0.01	–0.07	0.28
0.0009	0.09	–0.56	0.85	0.06	–0.26	0.51	0.04	–0.17	0.47	0.01	–0.07	0.23
0.0010	0.09	–0.60	0.89	0.06	–0.28	0.53	0.04	–0.17	0.47	0.01	–0.07	0.23
0.00176*	0.09*	–0.80*	1.15*	0.07*	–0.36*	0.67*	0.05*	–0.21*	0.48*	0.02*	–0.08*	0.29*
0.0020	0.10	–0.85	1.21	0.08	–0.39	0.71	0.05	–0.21	0.51	0.02	–0.08	0.30
0.0030	0.10	–1.04	1.45	0.09	–0.46	0.84	0.06	–0.25	0.60	0.02	–0.09	0.35
0.0040	0.11	–1.18	1.64	0.10	–0.53	0.95	0.07	–0.27	0.68	0.03	–0.10	0.39
0.0050	0.11	–1.31	1.80	0.10	–0.58	1.04	0.07	–0.29	0.75	0.03	–0.11	0.43
0.0100	0.14	–1.78	2.43	0.13	–0.78	1.39	0.09	–0.38	1.00	0.04	–0.13	0.55
0.0500	0.31	–3.48	4.86	0.24	–1.51	2.74	0.16	–0.73	1.93	0.08	–0.22	0.97
0.1000	0.48	–4.61	6.53	0.32	–1.99	3.68	0.21	–0.99	2.55	0.10	–0.29	1.23

* Theoretical choked flow, refer to Appendix A1.

Table A-20—Heat flux parameters for ambient releases through 1 inch pipe

mdot	1.577 kW/m²			4.732 kW/m²			9.46 kW/m²			20 kW/m²		
kg/s	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)
0.001	1.34	–0.91	1.22	1.41	–0.47	1.00	1.47	–0.29	1.11	1.56	–0.16	1.62
0.002	1.39	–1.17	1.58	1.45	–0.59	1.31	1.50	–0.36	1.44	1.57	–0.17	1.91
0.003	1.43	–1.40	1.91	1.47	–0.69	1.57	1.51	–0.41	1.71	1.56	–0.18	2.14
0.004	1.46	–1.58	2.19	1.49	–0.77	1.80	1.52	–0.44	1.94	1.54	–0.18	2.30
0.005	1.48	–1.73	2.44	1.50	–0.82	1.98	1.52	–0.45	2.11	1.51	–0.18	2.41
0.006	1.49	–1.84	2.66	1.49	–0.85	2.13	1.50	–0.44	2.24	1.48	–0.17	2.45
0.007	1.48	–1.91	2.83	1.48	–0.86	2.23	1.47	–0.42	2.32	1.43	–0.16	2.43
0.008	1.47	–1.94	2.97	1.45	–0.84	2.30	1.43	–0.38	2.35	1.37	–0.13	2.34
0.009	1.44	–1.94	3.07	1.41	–0.79	2.32	1.38	–0.32	2.32	1.31	–0.11	2.20
0.010	1.41	–1.95	3.13	1.37	–0.77	2.30	1.32	–0.30	2.25	1.23	–0.07	1.99
0.020	0.41	–2.76	3.86	0.30	–1.18	2.38	0.12	–0.56	1.87	0.07	–0.14	1.18
0.030	0.31	–3.35	4.60	0.22	–1.47	2.77	0.14	–0.74	2.06	0.08	–0.24	1.27
0.040	0.33	–3.84	5.21	0.23	–1.70	3.10	0.15	–0.88	2.24	0.09	–0.31	1.35
0.050	0.34	–4.26	5.74	0.24	–1.91	3.39	0.16	–1.00	2.39	0.09	–0.37	1.43
0.060	0.35	–4.63	6.22	0.25	–2.09	3.65	0.17	–1.11	2.54	0.10	–0.43	1.51
0.066*	0.36*	–4.84*	6.48*	0.26*	–2.19*	3.79*	0.18*	–1.16*	2.62*	0.10*	–0.45*	1.55*
0.070	0.36	–4.97	6.65	0.26	–2.25	3.89	0.18	–1.20	2.67	0.10	–0.47	1.58
0.100	0.40	–5.85	7.78	0.28	–2.67	4.52	0.21	–1.44	3.04	0.11	–0.59	1.77
0.200	0.50	–7.97	10.57	0.36	–3.67	6.12	0.28	–2.01	4.05	0.15	–0.85	2.34
0.300	0.59	–9.54	12.66	0.43	–4.40	7.35	0.34	–2.41	4.88	0.17	–1.03	2.83
0.500	0.75	–11.93	15.89	0.55	–5.50	9.29	0.44	–3.00	6.27	0.21	–1.29	3.69
1.000	1.12	–16.12	21.65	0.82	–7.41	12.87	0.63	–4.00	9.04	0.29	–1.69	5.51

* Theoretical choked flow, refer to Appendix A1.

Table A-21—Heat flux parameters for ambient releases through 2 inch pipe

mdot	1.577 kW/m²			4.732 kW/m²			9.46 kW/m²			20 kW/m²		
kg/s	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)
0.001	2.08	–1.09	1.95	2.18	–0.57	1.65	2.28	–0.37	1.85	2.41	–0.22	2.46
0.002	2.08	–1.32	2.08	2.17	–0.70	1.73	2.25	–0.44	1.91	2.37	–0.26	2.51
0.003	2.07	–1.53	2.21	2.15	–0.81	1.81	2.23	–0.52	1.96	2.33	–0.30	2.56
0.004	2.07	–1.74	2.34	2.14	–0.92	1.88	2.21	–0.58	2.02	2.29	–0.33	2.60
0.005	2.06	–1.93	2.46	2.13	–1.02	1.96	2.19	–0.64	2.07	2.25	–0.36	2.65
0.006	2.05	–2.11	2.58	2.11	–1.11	2.04	2.17	–0.70	2.13	2.21	–0.39	2.69
0.007	2.05	–2.28	2.70	2.10	–1.19	2.11	2.14	–0.75	2.18	2.17	–0.41	2.74
0.008	2.04	–2.44	2.82	2.09	–1.27	2.19	2.12	–0.79	2.23	2.13	–0.43	2.78
0.009	2.03	–2.58	2.94	2.07	–1.34	2.26	2.10	–0.83	2.28	2.09	–0.45	2.82
0.01	2.03	–2.72	3.06	2.06	–1.40	2.33	2.08	–0.86	2.33	2.06	–0.46	2.86
0.02	1.94	–3.37	4.14	1.90	–1.58	2.98	1.85	–0.88	2.77	1.69	–0.39	3.17
0.03	1.82	–3.52	5.08	1.72	–1.50	3.52	1.62	–0.71	3.11	1.34	–0.20	3.36
0.04	1.67	–4.03	5.88	1.52	–1.75	3.95	1.37	–0.86	3.35	1.02	–0.27	3.41
0.05	1.49	–4.47	6.52	1.30	–1.96	4.26	1.12	–0.98	3.50	0.73	–0.33	3.33
0.06	1.27	–4.86	7.02	1.07	–2.15	4.46	0.86	–1.09	3.54	0.46	–0.39	3.11
0.07	1.03	–5.22	7.37	0.81	–2.33	4.55	0.60	–1.20	3.49	0.22	–0.44	2.77
0.08	0.76	–5.55	7.59	0.53	–2.49	4.53	0.32	–1.29	3.34	0.10	–0.49	2.29
0.09	0.46	–5.86	7.98	0.32	–2.64	4.69	0.26	–1.38	3.28	0.11	–0.53	1.97
0.10	0.48	–6.15	8.36	0.34	–2.78	4.90	0.27	–1.46	3.41	0.11	–0.57	2.05
0.20	0.59	–8.43	11.31	0.45	–3.89	6.57	0.35	–2.11	4.49	0.13	–0.88	2.71
0.254*	0.63*	–9.40*	12.57*	0.49*	–4.35*	7.28*	0.38*	–2.38*	4.96*	0.15*	–1.00*	3.01*
0.30	0.66	–10.14	13.52	0.52	–4.71	7.83	0.40	–2.59	5.33	0.16	–1.10	3.24
0.40	0.71	–11.55	15.35	0.56	–5.39	8.89	0.43	–2.98	6.06	0.18	–1.28	3.70
0.50	0.75	–12.77	16.93	0.60	–5.98	9.82	0.45	–3.32	6.71	0.20	–1.44	4.12
0.60	0.78	–13.87	18.35	0.63	–6.50	10.65	0.47	–3.63	7.30	0.22	–1.58	4.50
1.00	0.86	–17.46	23.01	0.71	–8.23	13.42	0.53	–4.63	9.32	0.30	–2.03	5.80
1.50	0.93	–20.94	27.54	0.77	–9.90	16.15	0.57	–5.59	11.39	0.40	–2.46	7.16

* Theoretical choked flow, refer to Appendix A1.

Table A-22—Heat flux parameters for ambient releases through 3 inch pipe

mdot	1.577 kW/m²			4.732 kW/m²			9.46 kW/m²			20 kW/m²		
kg/s	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)
0.001	1.85	–1.37	1.99	1.92	–0.72	1.61	1.98	–0.46	1.72	2.05	–0.27	2.14
0.002	1.94	–1.53	2.13	2.01	–0.80	1.71	2.07	–0.51	1.83	2.14	–0.30	2.29
0.003	2.03	–1.68	2.26	2.10	–0.89	1.82	2.16	–0.56	1.93	2.23	–0.33	2.43
0.004	2.11	–1.83	2.40	2.18	–0.97	1.92	2.25	–0.62	2.03	2.32	–0.36	2.58
0.005	2.20	–1.97	2.53	2.26	–1.05	2.02	2.33	–0.66	2.13	2.41	–0.39	2.72
0.006	2.28	–2.12	2.66	2.35	–1.12	2.12	2.41	–0.71	2.22	2.49	–0.41	2.86
0.007	2.36	–2.26	2.79	2.42	–1.20	2.21	2.49	–0.76	2.32	2.57	–0.44	2.99
0.008	2.43	–2.39	2.92	2.50	–1.27	2.31	2.57	–0.80	2.41	2.65	–0.47	3.12
0.009	2.51	–2.52	3.05	2.58	–1.34	2.41	2.64	–0.85	2.50	2.72	–0.49	3.25
0.01	2.58	–2.65	3.18	2.65	–1.41	2.50	2.71	–0.89	2.60	2.79	–0.51	3.38
0.02	3.18	–3.76	4.36	3.23	–1.98	3.36	3.29	–1.22	3.41	3.36	–0.67	4.52
0.03	3.54	–4.55	5.40	3.58	–2.33	4.08	3.61	–1.39	4.06	3.66	–0.70	5.39
0.04	3.69	–5.00	6.29	3.68	–2.47	4.67	3.69	–1.40	4.56	3.67	–0.62	6.01
0.05	3.60	–5.12	7.04	3.55	–2.39	5.13	3.51	–1.26	4.89	3.41	–0.41	6.36
0.06	3.29	–4.96	7.64	3.18	–2.12	5.45	3.09	–1.01	5.05	2.87	–0.17	6.46
0.07	2.75	–5.35	8.09	2.57	–2.31	5.63	2.41	–1.13	5.06	2.06	–0.24	6.30
0.08	1.98	–5.71	8.40	1.72	–2.49	5.68	1.49	–1.24	4.90	0.97	–0.31	5.87
0.09	0.99	–6.04	8.56	0.70	–2.66	5.60	0.54	–1.34	4.58	0.26	–0.37	5.19
0.10	0.88	–6.35	8.78	0.70	–2.81	5.45	0.54	–1.44	4.27	0.26	–0.42	4.25
0.20	0.88	–8.79	11.76	0.71	–4.02	7.03	0.54	–2.17	5.21	0.26	–0.82	3.58
0.30	0.88	–10.59	14.00	0.71	–4.90	8.25	0.54	–2.70	5.97	0.26	–1.10	3.93
0.40	0.89	–12.06	15.87	0.71	–5.62	9.29	0.54	–3.13	6.63	0.26	–1.33	4.25
0.50	0.89	–13.34	17.49	0.72	–6.24	10.21	0.55	–3.49	7.23	0.27	–1.52	4.55
0.58*	0.90*	–14.24*	18.66*	0.72*	–6.69*	10.87*	0.55*	–3.75*	7.66*	0.27*	–1.65*	4.77*
0.60	0.90	–14.47	18.95	0.72	–6.80	11.04	0.55	–3.82	7.78	0.27	–1.68	4.83
0.70	0.91	–15.50	20.28	0.73	–7.30	11.81	0.56	–4.11	8.29	0.28	–1.82	5.10
0.80	0.92	–16.45	21.52	0.74	–7.76	12.53	0.56	–4.37	8.78	0.28	–1.96	5.35
0.90	0.93	–17.33	22.67	0.74	–8.18	13.20	0.57	–4.62	9.24	0.29	–2.08	5.60
1.00	0.94	–18.16	23.75	0.75	–8.58	13.84	0.57	–4.85	9.68	0.29	–2.19	5.83
1.50	1.00	–21.71	28.46	0.81	–10.29	16.66	0.61	–5.83	11.67	0.32	–2.66	6.94
2.00	1.09	–24.63	32.38	0.88	–11.69	19.06	0.66	–6.62	13.40	0.36	–3.04	7.93
3.00	1.32	–29.39	38.86	1.06	–13.97	23.10	0.79	–7.89	16.41	0.44	–3.62	9.73
4.00	1.63	–33.31	44.25	1.30	–15.83	26.53	0.96	–8.93	19.03	0.54	–4.09	11.36
5.00	2.00	–36.69	48.96	1.60	–17.44	29.56	1.16	–9.81	21.40	0.65	–4.48	12.87

* Theoretical choked flow, refer to Appendix A1.

Table A-23—Heat flux parameters for ambient releases through 4 inch pipe

mdot	1.577 kW/m²			4.732 kW/m²			9.46 kW/m²			20 kW/m²		
kg/s	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)
0.001	2.73	–1.31	1.91	2.84	–0.67	1.52	2.95	–0.39	1.53	3.09	–0.18	2.56
0.002	2.74	–1.47	2.05	2.85	–0.76	1.62	2.96	–0.46	1.64	3.09	–0.22	2.64
0.003	2.76	–1.64	2.20	2.86	–0.85	1.73	2.97	–0.52	1.75	3.10	–0.27	2.73
0.004	2.77	–1.80	2.34	2.88	–0.94	1.83	2.98	–0.59	1.85	3.10	–0.31	2.81
0.005	2.79	–1.95	2.47	2.89	–1.03	1.93	2.99	–0.65	1.95	3.11	–0.34	2.89
0.006	2.80	–2.11	2.61	2.90	–1.11	2.03	3.00	–0.71	2.05	3.11	–0.38	2.98
0.007	2.82	–2.26	2.75	2.91	–1.19	2.13	3.01	–0.77	2.15	3.12	–0.42	3.06
0.008	2.83	–2.41	2.88	2.93	–1.27	2.23	3.02	–0.83	2.25	3.12	–0.45	3.14
0.009	2.85	–2.55	3.01	2.94	–1.35	2.33	3.03	–0.88	2.35	3.13	–0.49	3.22
0.010	2.86	–2.69	3.15	2.95	–1.43	2.42	3.03	–0.94	2.45	3.13	–0.52	3.30
0.020	3.00	–3.94	4.39	3.06	–2.10	3.33	3.12	–1.39	3.35	3.17	–0.79	4.07
0.030	3.13	–4.88	5.49	3.16	–2.58	4.12	3.19	–1.70	4.12	3.20	–0.96	4.78
0.040	3.25	–5.51	6.45	3.25	–2.88	4.81	3.26	–1.85	4.76	3.23	–1.01	5.44
0.050	3.35	–5.83	7.28	3.34	–3.00	5.38	3.32	–1.84	5.28	3.25	–0.96	6.04
0.060	3.45	–5.84	7.97	3.41	–2.93	5.85	3.36	–1.68	5.68	3.26	–0.79	6.58
0.070	3.53	–5.84	8.52	3.47	–2.68	6.21	3.40	–1.38	5.95	3.26	–0.52	7.06
0.080	3.60	–6.17	8.93	3.52	–2.83	6.46	3.43	–1.47	6.09	3.25	–0.14	7.49
0.090	3.66	–6.48	9.21	3.56	–2.98	6.60	3.45	–1.56	6.11	3.24	–0.21	7.86
0.100	3.71	–6.78	9.34	3.59	–3.12	6.63	3.46	–1.64	6.01	3.22	–0.31	8.17
0.200	3.59	–9.11	12.32	3.34	–4.22	7.56	3.06	–2.27	5.75	2.61	–0.98	8.12
0.300	2.35	–10.87	14.56	2.06	–5.05	8.75	1.72	–2.75	6.44	1.25	–1.37	4.93
0.400	0.75	–12.32	16.42	0.60	–5.74	9.75	0.41	–3.16	7.04	0.16	–1.65	5.10
0.500	0.77	–13.59	18.03	0.62	–6.35	10.64	0.43	–3.51	7.59	0.18	–1.86	5.27
0.600	0.79	–14.72	19.48	0.63	–6.89	11.45	0.45	–3.82	8.09	0.20	–2.04	5.44
0.700	0.81	–15.76	20.81	0.65	–7.39	12.19	0.46	–4.11	8.57	0.21	–2.19	5.61
0.800	0.84	–16.72	22.03	0.67	–7.85	12.88	0.48	–4.38	9.01	0.23	–2.31	5.78
0.900	0.86	–17.61	23.17	0.69	–8.28	13.54	0.49	–4.63	9.44	0.25	–2.43	5.95
0.988*	0.88*	–18.36*	24.12*	0.70*	–8.64*	14.08*	0.50*	–4.84*	9.80*	0.26*	–2.52*	6.10*
1.000	0.88	–18.46	24.25	0.70	–8.69	14.15	0.51	–4.86	9.85	0.26	–2.53	6.12
1.500	0.99	–22.11	28.90	0.79	–10.46	16.87	0.58	–5.89	11.69	0.32	–2.92	6.96
2.000	1.10	–25.14	32.76	0.89	–11.93	19.16	0.66	–6.74	13.31	0.38	–3.20	7.81
3.000	1.34	–30.15	39.15	1.08	–14.37	23.03	0.80	–8.16	16.13	0.47	–3.59	9.50
4.000	1.58	–34.30	44.44	1.28	–16.41	26.31	0.95	–9.34	18.60	0.55	–3.86	11.19
5.000	1.82	–37.93	49.06	1.48	–18.19	29.21	1.09	–10.38	20.84	0.62	–4.08	12.88
6.000	2.07	–41.18	53.19	1.68	–19.78	31.83	1.24	–11.31	22.91	0.69	–4.25	14.57

* Theoretical choked flow, refer to Appendix A1.

Table A-24—Heat flux Parameters for ambient releases through 10 inch pipe

mdot	1.577 kW/m²			4.732 kW/m²			9.46 kW/m²			20 kW/m²		
kg/s	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)	X_{cr} (m)	Y_{cr} (m)	N_R (m)
0.001	2.14	–1.47	3.48	2.19	–0.76	2.79	2.25	–0.48	2.94	2.30	–0.27	3.75
0.005	2.41	–2.00	3.68	2.47	–1.05	2.92	2.53	–0.67	3.04	2.60	–0.39	3.86
0.010	2.74	–2.62	3.92	2.82	–1.40	3.07	2.88	–0.90	3.17	2.96	–0.54	3.99
0.050	5.19	–6.56	5.80	5.32	–3.55	4.26	5.41	–2.19	4.18	5.62	–1.04	5.01
0.1	7.68	–8.22	8.05	7.87	–4.19	5.68	7.97	–2.49	5.36	8.27	–1.15	6.18
0.5	4.88	–14.87	21.37	4.48	–7.06	13.87	3.98	–3.95	11.82	3.08	–1.74	11.70
1.0	3.10	–19.85	26.65	2.64	–9.34	16.33	2.16	–5.19	12.44	1.38	–2.29	8.87
1.5	2.75	–23.67	31.60	2.31	–11.14	18.94	1.89	–6.20	13.78	1.18	–2.75	8.96
2.0	2.50	–26.89	35.70	2.09	–12.69	21.18	1.69	–7.08	15.16	1.04	–3.17	9.73
2.5	2.30	–29.72	39.28	1.91	–14.06	23.16	1.54	–7.88	16.41	0.93	–3.56	10.45
3.0	2.15	–32.29	42.48	1.76	–15.32	24.95	1.41	–8.62	17.57	0.85	–3.93	11.14
3.5	2.01	–34.64	45.40	1.64	–16.49	26.61	1.31	–9.32	18.66	0.77	–4.28	11.80
4.0	1.90	–36.84	48.11	1.54	–17.59	28.15	1.22	–9.97	19.69	0.71	–4.61	12.43
4.5	1.79	–38.90	50.63	1.44	–18.63	29.61	1.14	–10.60	20.67	0.65	–4.93	13.05
5.0	1.70	–40.84	53.01	1.36	–19.61	30.98	1.07	–11.20	21.61	0.60	–5.24	13.64
5.5	1.62	–42.70	55.26	1.28	–20.56	32.29	1.00	–11.77	22.51	0.55	–5.55	14.22
5.6	1.60	–43.06	55.69	1.27	–20.74	32.55	0.99	–11.89	22.69	0.54	–5.61	14.34
5.7	1.59	–43.41	56.13	1.25	–20.92	32.80	0.98	–12.00	22.87	0.53	–5.66	14.45
5.8	1.57	–43.77	56.56	1.24	–21.10	33.05	0.97	–12.11	23.04	0.53	–5.72	14.57
5.9*	1.56*	–44.15*	57.02*	1.23*	–21.30*	33.32*	0.95*	–12.23*	23.23*	0.52*	–5.79*	14.69*
6.0	1.54	–44.47	57.40	1.21	–21.46	33.55	0.94	–12.33	23.39	0.51	–5.84	14.79
8.0	1.29	–50.89	65.11	0.98	–24.78	38.12	0.75	–14.40	26.63	0.37	–6.95	16.96
10.0	1.10	–56.56	71.83	0.81	–27.75	42.17	0.60	–16.27	29.58	0.26	–7.97	18.99
12.0	0.94	–61.68	77.85	0.66	–30.46	45.84	0.47	–18.00	32.31	0.17	–8.94	20.92

* Theoretical choked flow, refer to Appendix A1.

Appendix B—Development of heat flux parameter curve-fits (Informative)

B1 Design basis heat model

Generalized curve fits for the heat flux profiles are derived by implementing the Miller model, (*New model for predicting thermal radiation from flares and high pressure jet fires for hydrogen and syngas*, Miller, D) [28].

Details of the model reduction to computer code (MathCad) are shown in Appendix C [29].

The model was run with the inputs parameters as outlined in Appendix A1.

The model outputs are tabulated where *Xcr* and *Ycr* as is referenced in Section 5.1.3. The parameter Xlim is listed and is the *x* dimension at the vent stack height to the heat profile of question. This value Xlim is then used to calculate the N_R value as per the formula in Section 5.1.4. The tabulated values for model outputs are listed in Tables B-1 to B-6 for cryogenic releases and Tables B-7 to B-12 for ambient releases.

These tabulated values were then generalized to curve fits. The summary verification of the curve fits is noted in Appendix B2 for cryogenic releases and Appendix B3 for ambient releases. The summary tables for the curve-fit coefficients are shown in Appendix A2 for cryogenic releases and Appendix A3 for ambient releases.

B2 Heat flux parameters curve fit cryogenic release

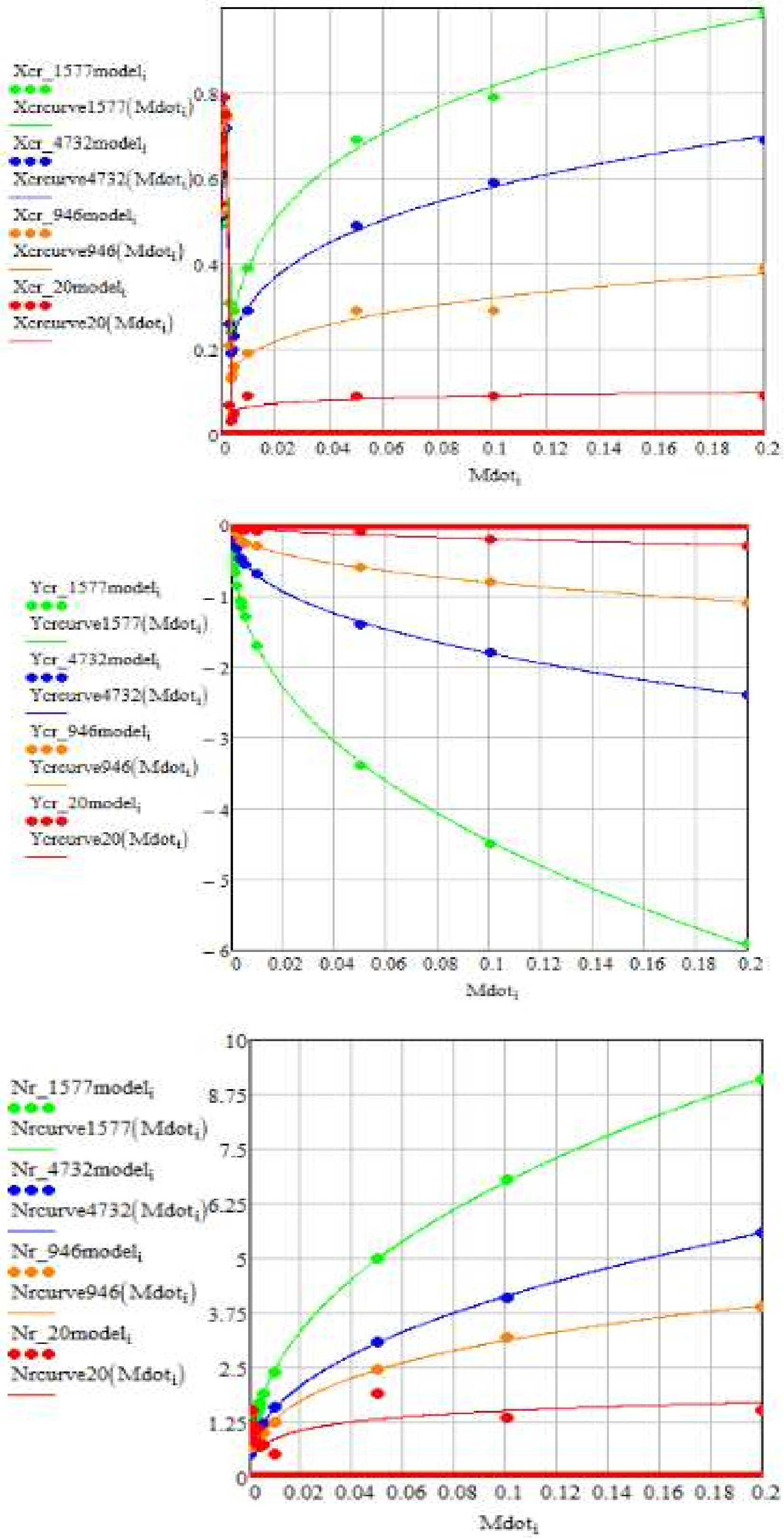

Figure B-1—Curve-fit verification for cryogenic releases—1/4 inch ODT

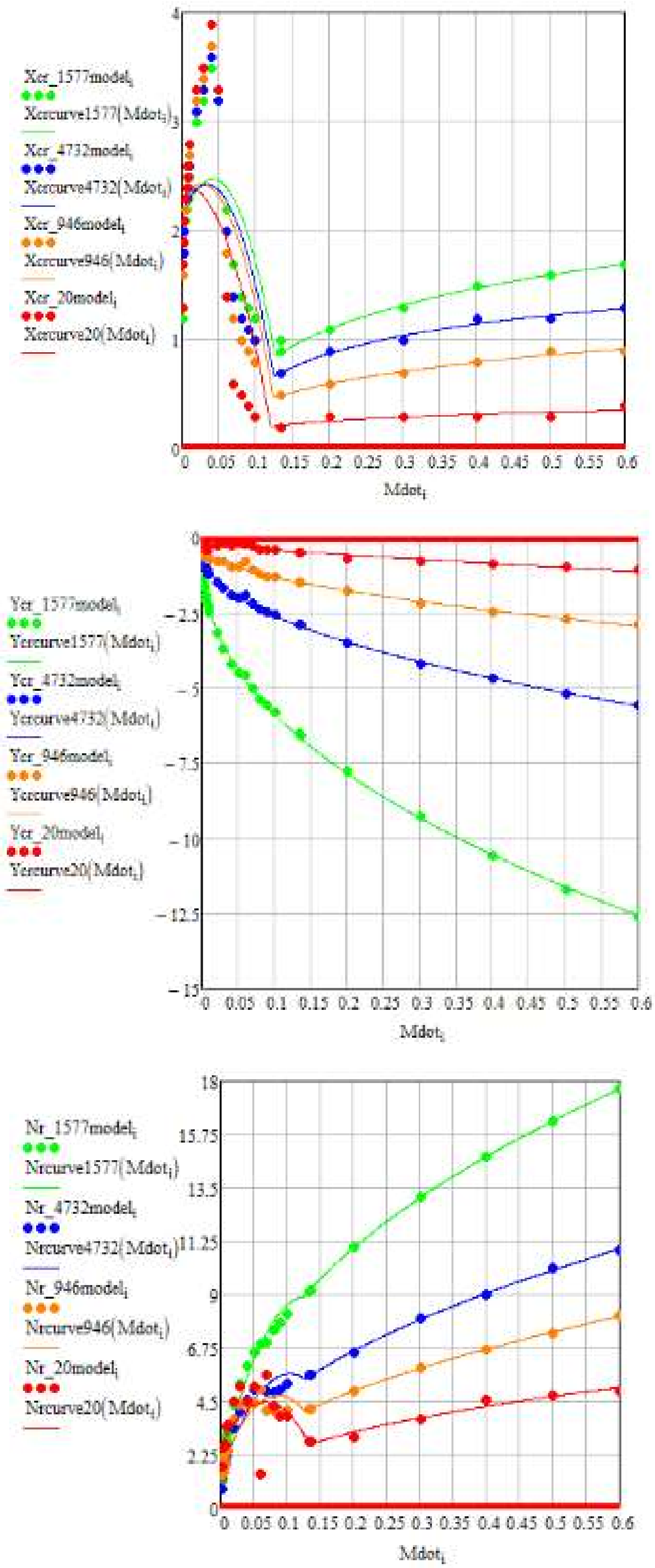

Figure B-2—Curve-fit verification for cryogenic releases—1 inch pipe

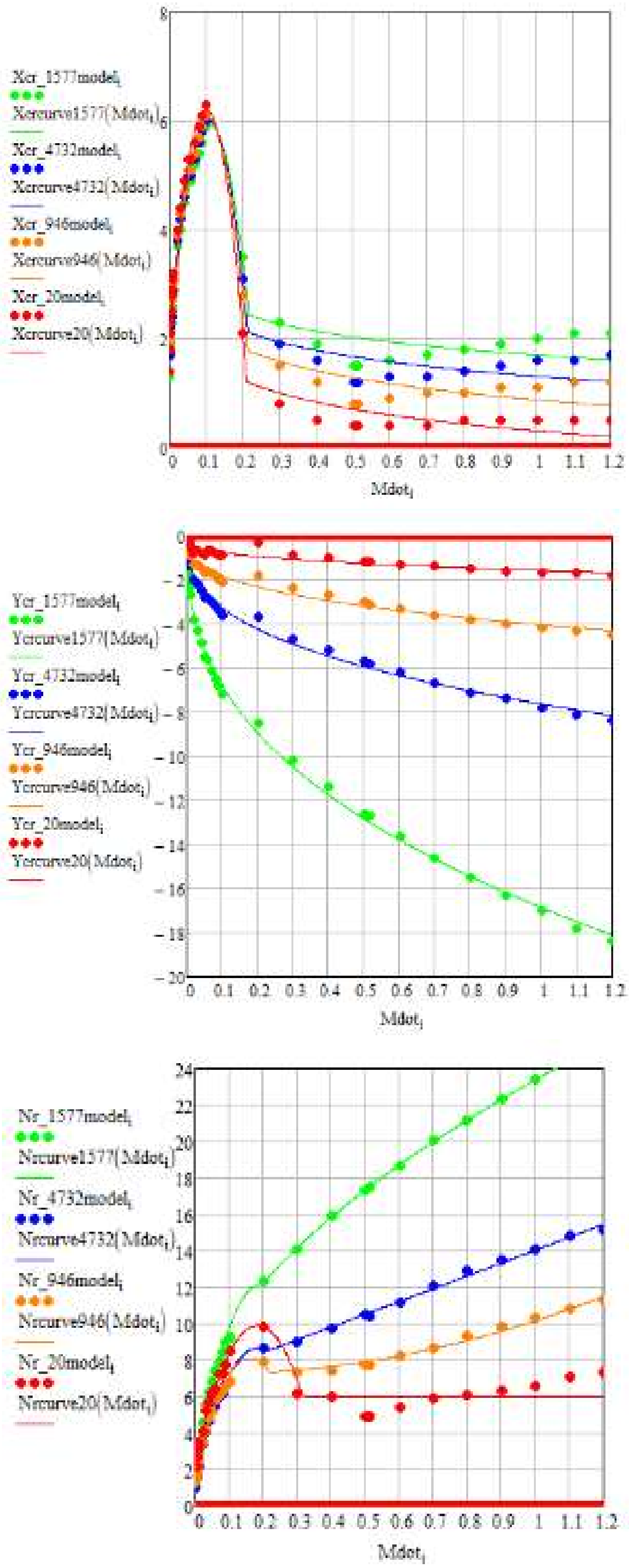

Figure B-3—Curve-fit verification for cryogenic releases—2 inch pipe

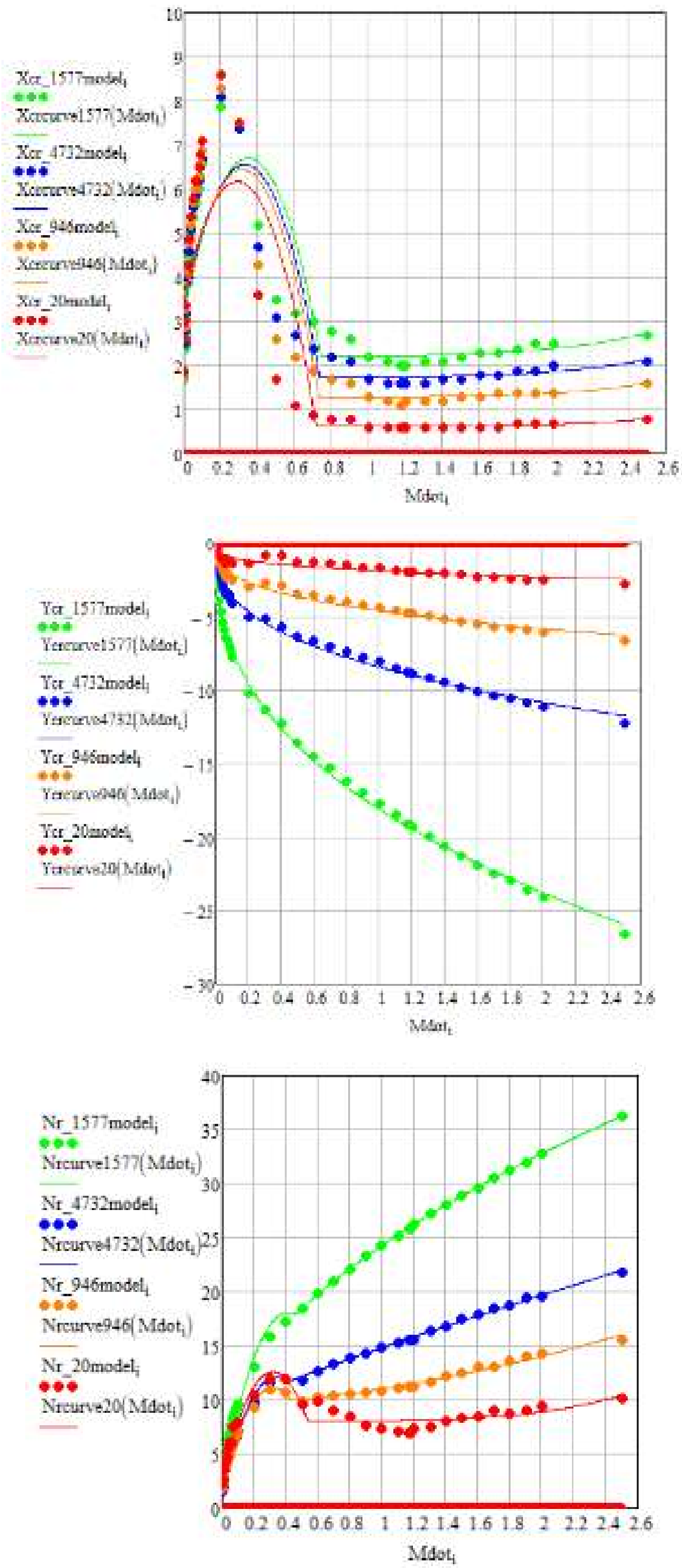

Figure B-4—Curve-fit verification for cryogenic releases—3 inch pipe

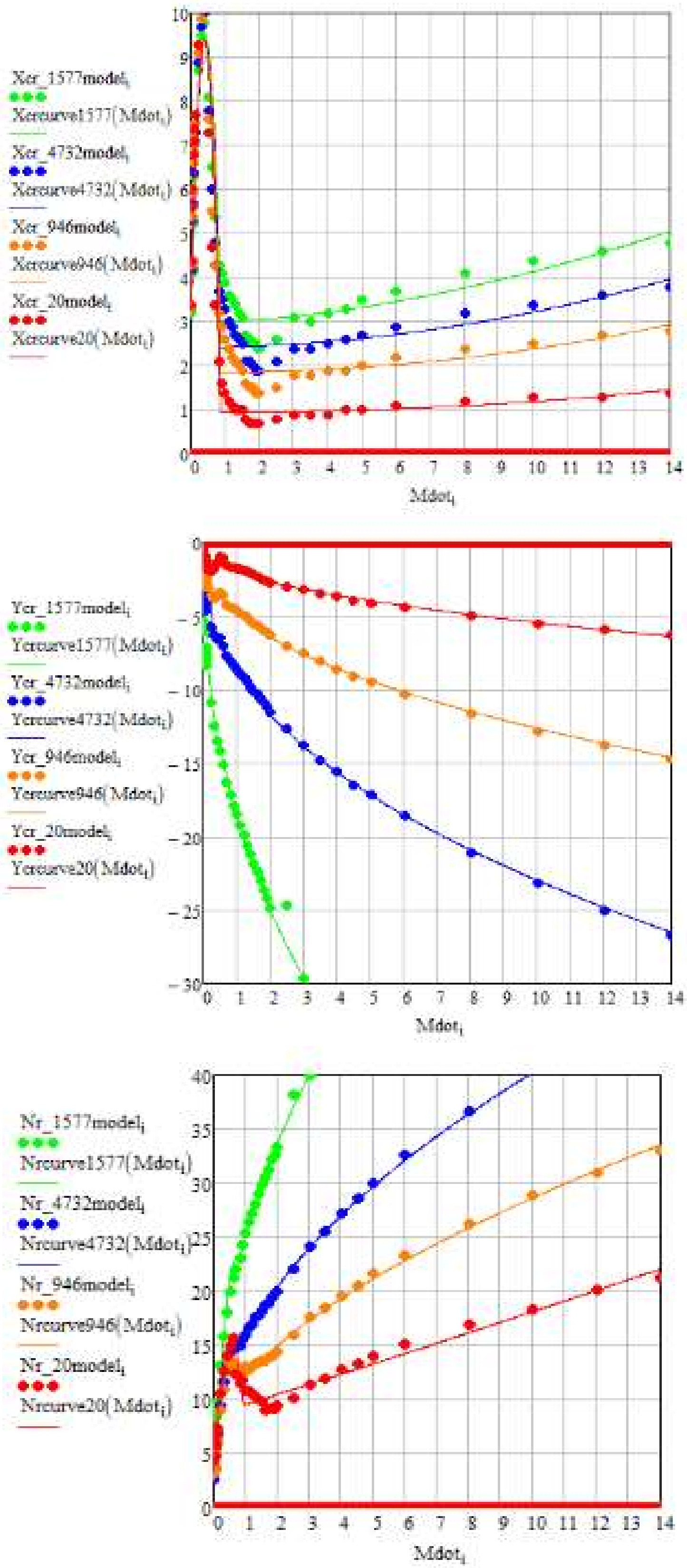

Figure B-5—Curve-fit verification for cryogenic releases—4 inch pipe

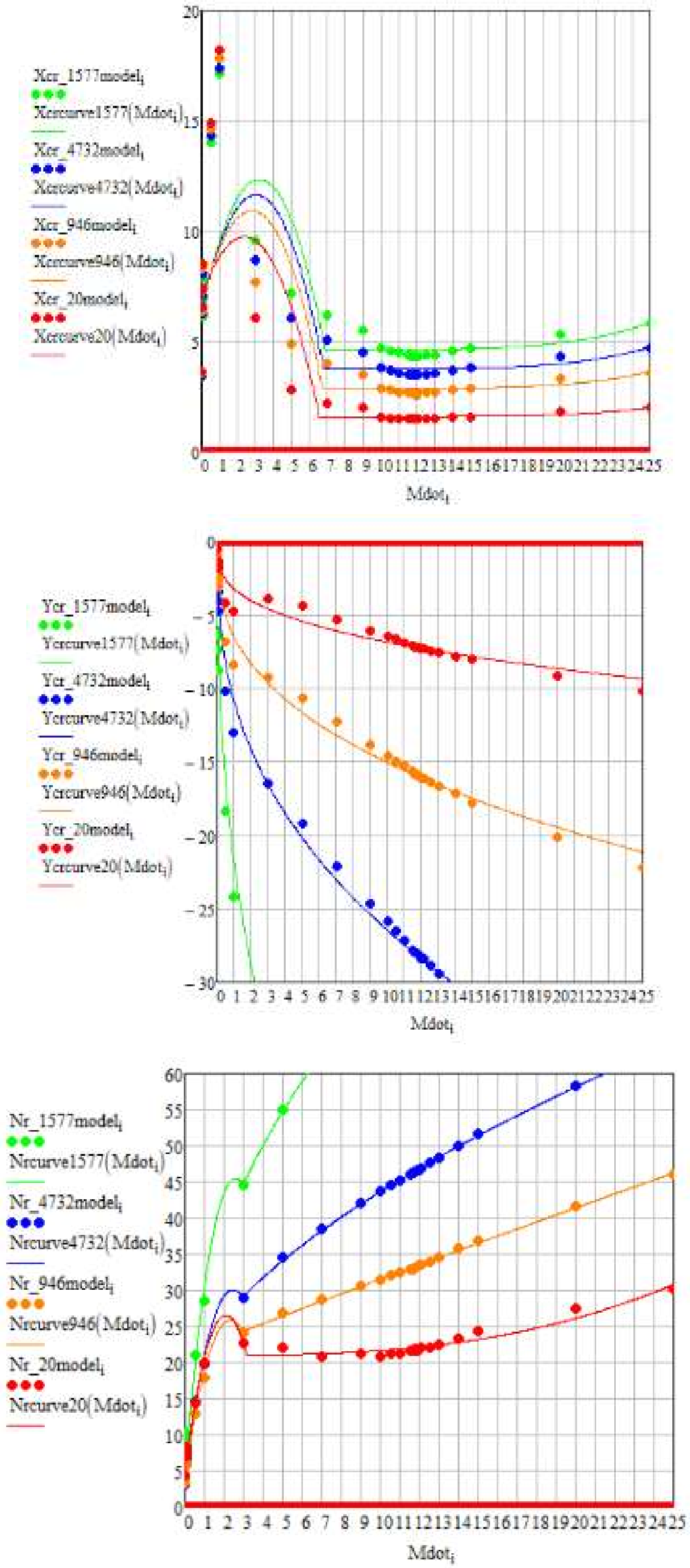

Figure B-6—Curve-fit verification for cryogenic releases—10 inch pipe

Table B-1—Model output for 1/4 inch ODT at cryogenic temperatures

Mdot	1.577 kW/m^2				4.732 kW/m^2				9.46 kW/m^2				20 kW/m^2			
[kg/s]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]
0.0001	0.408	–0.273	0.790	0.40	0.422	–0.137	0.719	0.39	0.433	–0.083	0.706	0.49	0.44	–0.046	0.70	0.74
0.0002	0.489	–0.351	1.002	0.55	0.507	–0.163	0.890	0.53	0.521	–0.089	0.849	0.65	0.54	–0.037	0.78	0.83
0.0003	0.568	–0.427	1.178	0.65	0.588	–0.201	1.040	0.61	0.604	–0.112	0.993	0.73	0.62	–0.048	0.92	0.95
0.0004	0.590	–0.451	1.275	0.75	0.612	–0.194	1.096	0.70	0.629	–0.091	1.001	0.81	0.65	–0.018	0.82	0.87
0.0005	0.630	–0.505	1.382	0.81	0.653	–0.222	1.182	0.74	0.672	–0.107	1.083	0.84	0.69	–0.025	0.91	0.94
0.0006	0.622	–0.508	1.425	0.89	0.646	–0.201	1.180	0.81	0.666	–0.076	1.025	0.89	0.69	–0.014	0.87	1.14
0.0007	0.642	–0.554	1.495	0.93	0.665	–0.225	1.234	0.83	0.686	–0.091	1.081	0.90	0.71	–0.006	0.83	1.34
0.0008	0.676	–0.590	1.582	0.99	0.701	–0.241	1.305	0.88	0.722	–0.099	1.144	0.95	0.75	–0.005	0.87	1.54
0.0009	0.694	–0.629	1.644	1.03	0.719	–0.262	1.353	0.90	0.741	–0.111	1.192	0.97	0.77	–0.001	0.83	1.74
0.0010	0.712	–0.665	1.704	1.07	0.737	–0.280	1.399	0.92	0.759	–0.122	1.236	0.99	0.79	–0.007	0.91	1.05
0.0020	0.719	–0.860	2.010	1.40	0.719	–0.340	1.530	1.14	0.739	–0.130	1.260	1.11	0.75	–0.032	1.01	1.08
0.0030	0.309	–1.060	1.750	1.51	0.259	–0.470	1.100	0.99	0.209	–0.230	0.790	0.85	0.07	–0.060	0.43	1.12
0.003574*	0.239*	–1.110*	1.770*	1.61*	0.189*	–0.480*	1.060*	1.03*	0.129*	–0.230*	0.710*	0.85*	0.03*	–0.06*	0.32*	0.74*
0.0040	0.259	–1.170	1.870	1.69	0.199	–0.500	1.120	1.10	0.139	–0.240	0.750	0.90	0.04	–0.07	0.34	0.68
0.0050	0.289	–1.290	2.070	1.87	0.229	–0.560	1.250	1.21	0.159	–0.270	0.840	0.99	0.05	–0.08	0.38	0.72
0.0100	0.390	–1.700	2.700	2.42	0.290	–0.700	1.600	1.58	0.190	–0.300	1.000	1.24	0.09	–0.10	0.40	0.53
0.0500	0.690	–3.400	5.400	4.96	0.490	–1.400	3.100	3.13	0.290	–0.600	1.900	2.46	0.09	–0.10	0.70	1.91
0.1000	0.790	–4.500	7.200	6.82	0.590	–1.800	4.000	4.13	0.290	–0.800	2.400	3.18	0.09	–0.2	0.8	1.36
0.2000	0.990	–5.900	9.500	9.09	0.690	–2.400	5.300	5.63	0.390	–1.100	3.100	3.89	0.09	–0.3	1	1.53

* Theoretical choked flow, refer to Appendix A1.

Table B-2—Model output for 1 inch pipe at cryogenic temperatures

Mdot	1.577 kW/m²				4.732 kW/m²				9.46 kW/m²				20 kW/m²			
[kg/s]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]
0.001	1.19	–0.90	2.30	1.13	1.29	–0.40	2.00	0.83	1.29	–0.20	2.00	1.36	1.29	–0.10	2.00	2.57
0.002	1.59	–1.20	3.00	1.43	1.59	–0.60	2.70	1.33	1.59	–0.40	2.60	1.48	1.69	–0.20	2.50	1.74
0.003	1.79	–1.50	3.60	1.84	1.79	–0.70	3.10	1.58	1.89	–0.50	3.00	1.48	1.89	–0.20	2.90	2.65
0.004	1.99	–1.70	4.00	2.04	1.99	–0.90	3.40	1.55	2.09	–0.50	3.30	1.71	2.09	–0.30	3.30	2.59
0.005	2.09	–1.90	4.30	2.24	2.19	–1.00	3.70	1.65	2.19	–0.60	3.60	1.97	2.29	–0.30	3.50	2.61
0.006	2.19	–2.10	4.70	2.55	2.29	–1.10	4.00	1.88	2.39	–0.70	3.80	1.77	2.39	–0.40	3.80	2.69
0.007	2.39	–2.20	5.00	2.65	2.39	–1.20	4.20	1.97	2.49	–0.70	4.10	2.20	2.59	–0.40	4.00	2.69
0.008	2.29	–2.20	5.10	2.89	2.39	–1.10	4.30	2.21	2.49	–0.60	4.10	2.46	2.49	–0.30	3.90	3.46
0.009	2.39	–2.30	5.40	3.12	2.49	–1.20	4.50	2.28	2.59	–0.70	4.30	2.44	2.59	–0.30	4.00	3.46
0.01	2.49	–2.50	5.60	3.19	2.59	–1.20	4.70	2.46	2.69	–0.70	4.40	2.45	2.79	–0.30	4.20	3.49
0.02	2.99	–3.20	7.20	4.38	3.09	–1.50	5.90	3.39	3.19	–0.80	5.50	3.75	3.29	–0.30	4.90	4.50
0.03	3.19	–3.70	8.20	5.25	3.29	–1.70	6.60	4.08	3.39	–0.80	5.90	4.35	3.49	–0.20	4.90	5.11
0.04	3.49	–4.20	9.20	5.99	3.59	–1.90	7.30	4.58	3.69	–1.00	6.50	4.46	3.89	–0.30	5.50	4.50
0.05	3.29	–4.50	9.50	6.54	3.19	–2.00	7.20	5.03	3.29	–1.00	6.10	4.46	3.29	–0.20	4.70	5.11
0.06	2.19	–4.60	8.70	6.91	1.99	–1.90	5.90	4.98	1.79	–0.80	4.50	5.01	1.39	–0.25	2.20	1.45
0.07	1.69	–5.00	8.40	7.01	1.39	–2.20	5.50	4.95	1.19	–1.10	4.00	4.15	0.59	–0.30	2.40	5.64
0.08	1.39	–5.40	8.60	7.52	1.19	–2.40	5.40	4.90	0.99	–1.20	3.90	4.14	0.49	–0.40	2.30	4.32
0.09	1.29	–5.60	8.80	7.84	1.09	–2.50	5.40	4.97	0.89	–1.30	3.80	3.92	0.39	–0.40	2.10	3.88
0.10	1.19	–5.80	9.00	8.17	0.99	–2.60	5.50	5.22	0.79	–1.30	3.80	4.15	0.29	–0.40	2.00	3.88
0.135*	0.89*	–6.60*	9.70*	9.18*	0.69*	–2.90*	5.60*	5.61*	0.49*	–1.50*	3.70*	4.18*	0.19*	–0.50*	1.80*	2.84*
0.20	1.09	–7.80	11.60	10.99	0.89	–3.50	6.70	6.58	0.59	–1.80	4.40	4.94	0.29	–0.70	2.20	2.97
0.30	1.29	–9.30	13.80	13.07	0.99	–4.20	8.00	7.96	0.69	–2.20	5.30	5.94	0.29	–0.80	2.60	3.75
0.400	1.49	–10.60	15.70	14.83	1.19	–4.70	9.10	9.01	0.79	–2.50	6.00	6.69	0.29	–0.90	3.00	4.55
0.500	1.59	–11.70	17.20	16.27	1.19	–5.20	10.00	10.07	0.89	–2.70	6.60	7.40	0.29	–1.00	3.20	4.75
0.600	1.69	–12.60	18.60	17.65	1.29	–5.60	10.80	10.88	0.89	–2.90	7.10	8.11	0.39	–1.10	3.50	4.96

* Theoretical choked flow, refer to Appendix A1.

Table B-3—Model output for 2 inch pipe at cryogenic temperatures

Mdot	1.577 kW/m^2				4.732 kW/m^2				9.46 kW/m^2				20 kW/m^2			
[kg/s]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]
0.001	1.29	–0.90	2.40	1.13	1.39	–0.40	2.20	1.02	1.39	–0.20	2.10	1.36	1.39	–0.10	2.10	2.57
0.002	1.69	–1.20	3.20	1.55	1.69	–0.60	2.90	1.52	1.79	–0.40	2.80	1.48	1.79	–0.20	2.80	2.65
0.003	1.89	–1.50	3.80	1.97	1.99	–0.80	3.40	1.64	1.99	–0.50	3.30	1.97	2.09	–0.30	3.20	2.20
0.004	2.09	–1.80	4.30	2.26	2.19	–0.90	3.80	1.89	2.29	–0.60	3.60	1.73	2.29	–0.30	3.60	3.01
0.005	2.29	–2.00	4.70	2.46	2.39	–1.00	4.10	1.97	2.49	–0.60	3.90	1.97	2.49	–0.30	3.90	3.49
0.006	2.49	–2.10	5.10	2.67	2.49	–1.10	4.40	2.21	2.59	–0.70	4.20	2.20	2.69	–0.40	4.20	3.05
0.007	2.59	–2.30	5.40	2.87	2.69	–1.20	4.60	2.12	2.69	–0.70	4.40	2.44	2.79	–0.40	4.40	3.44
0.008	2.69	–2.40	5.70	3.09	2.79	–1.30	4.90	2.36	2.89	–0.80	4.70	2.45	2.89	–0.50	4.60	3.17
0.009	2.79	–2.60	5.90	3.16	2.89	–1.40	5.10	2.44	2.99	–0.90	4.90	2.48	3.09	–0.50	4.80	3.17
0.01	2.89	–2.70	6.20	3.39	2.99	–1.40	5.30	2.61	3.09	–0.90	5.10	2.71	3.19	–0.50	5.00	3.54
0.02	3.69	–3.80	8.20	4.58	3.79	–2.00	6.90	3.43	3.89	–1.30	6.60	3.49	3.99	–0.80	6.40	4.05
0.03	3.99	–4.30	9.40	5.56	4.19	–2.20	7.80	4.07	4.29	–1.30	7.30	4.15	4.39	–0.70	7.00	5.23
0.04	4.49	–4.90	10.60	6.27	4.59	–2.50	8.70	4.64	4.69	–1.50	8.20	4.87	4.89	–0.80	7.80	5.71
0.05	4.89	–5.50	11.60	6.85	4.99	–2.80	9.60	5.20	5.09	–1.70	8.90	5.13	5.29	–0.90	8.50	6.19
0.06	4.89	–5.60	12.10	7.45	4.99	–2.80	9.80	5.54	5.09	–1.60	9.10	5.84	5.29	–0.70	8.20	6.42
0.07	5.19	–6.10	12.90	7.93	5.29	–3.00	10.50	6.03	5.39	–1.70	9.60	6.08	5.59	–0.70	8.70	7.28
0.08	5.39	–6.50	13.60	8.44	5.59	–3.20	11.00	6.18	5.69	–1.80	10.10	6.31	5.89	–0.80	9.20	7.27
0.09	5.59	–6.80	14.30	8.98	5.79	–3.40	11.60	6.67	5.89	–2.00	10.60	6.56	6.09	–0.90	9.70	7.71
0.10	5.89	–7.20	14.90	9.24	5.99	–3.60	12.00	6.83	6.09	–2.10	11.00	6.80	6.29	–0.90	10.10	8.54
0.20	3.49	–8.50	15.20	12.32	3.09	–3.70	10.20	8.69	2.79	–1.80	7.80	7.89	2.09	–0.30	4.50	9.87
0.30	2.29	–10.20	15.80	14.05	1.89	–4.70	9.80	9.01	1.49	–2.40	6.90	7.31	0.79	–0.90	4.00	6.19
0.40	1.89	–11.40	17.10	15.85	1.59	–5.20	10.20	9.74	1.19	–2.70	6.90	7.40	0.49	–1.00	3.80	5.99
0.50	1.49	–12.60	18.10	17.25	1.19	–5.70	10.50	10.46	0.79	–3.00	6.90	7.72	0.39	–1.20	3.60	4.91
0.513*	1.49*	–12.70*	18.30*	17.48*	1.19*	–5.80*	10.50*	10.37*	0.79*	–3.10*	7.00*	7.77*	0.39*	–1.20*	3.60*	4.89*
0.514	1.49	–12.70	18.30	17.48	1.19	–5.80	10.50	10.37	0.79	–3.10	7.00	7.77	0.39	–1.20	3.60	4.89
0.600	1.59	–13.60	19.60	18.73	1.29	–6.20	11.30	11.19	0.89	–3.30	7.50	8.28	0.39	–1.30	3.90	5.40
0.700	1.69	–14.60	21.00	20.08	1.29	–6.70	12.10	12.07	0.99	–3.60	8.00	8.63	0.39	–1.40	4.20	5.90
0.800	1.79	–15.50	22.20	21.19	1.39	–7.10	12.90	12.89	0.99	–3.80	8.50	9.33	0.49	–1.50	4.50	6.12
0.900	1.89	–16.30	23.40	22.35	1.49	–7.40	13.50	13.45	1.09	–4.00	9.00	9.83	0.49	–1.60	4.70	6.35
1.00	1.99	–17.00	24.50	23.41	1.59	–7.80	14.20	14.10	1.09	–4.20	9.40	10.33	0.49	–1.70	4.90	6.58
1.10	2.09	–17.80	25.60	24.43	1.59	–8.10	14.80	14.83	1.19	–4.30	9.80	10.78	0.49	–1.70	5.10	7.11
1.20	2.09	–18.40	26.50	25.40	1.69	–8.40	15.30	15.23	1.19	–4.50	10.20	11.28	0.49	–1.80	5.30	7.34

* Theoretical choked flow, refer to Appendix A1.

Table B-4—Model output for 3 inch pipe at cryogenic temperatures

Mdot	1.577 kW/m²				4.732 kW/m²				9.46 kW/m²				20 kW/m²			
[kg/s]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]
0.001	1.29	–0.90	2.50	1.26	1.39	–0.40	2.20	1.02	1.39	–0.30	2.20	1.24	1.49	–0.10	2.10	1.91
0.002	1.69	–1.30	3.30	1.65	1.79	–0.60	3.00	1.52	1.79	–0.40	2.90	1.74	1.89	–0.20	2.80	2.17
0.003	1.99	–1.60	4.00	2.06	2.09	–0.80	3.50	1.64	2.09	–0.50	3.40	1.97	2.19	–0.30	3.30	2.20
0.004	2.19	–1.80	4.40	2.26	2.29	–0.90	3.90	1.89	2.29	–0.60	3.80	2.20	2.39	–0.30	3.70	3.01
0.005	2.39	–2.00	4.90	2.58	2.49	–1.00	4.20	1.97	2.59	–0.60	4.10	2.21	2.59	–0.40	4.00	2.70
0.006	2.59	–2.20	5.30	2.77	2.69	–1.10	4.60	2.21	2.69	–0.70	4.40	2.44	2.79	–0.40	4.30	3.05
0.007	2.69	–2.40	5.60	2.96	2.79	–1.20	4.80	2.28	2.89	–0.80	4.70	2.45	2.99	–0.40	4.60	3.44
0.008	2.89	–2.50	5.90	3.06	2.89	–1.30	5.10	2.53	2.99	–0.80	4.90	2.68	3.09	–0.50	4.80	3.17
0.009	2.99	–2.70	6.20	3.26	3.09	–1.40	5.30	2.44	3.09	–0.90	5.10	2.69	3.19	–0.50	5.00	3.53
0.01	3.09	–2.80	6.50	3.48	3.19	–1.50	5.60	2.69	3.29	–0.90	5.40	2.94	3.39	–0.50	5.30	3.92
0.02	3.89	–3.90	8.50	4.68	3.99	–2.10	7.30	3.67	4.09	–1.30	6.90	3.70	4.29	–0.80	6.80	4.35
0.03	4.49	–4.70	10.00	5.59	4.59	–2.50	8.50	4.32	4.79	–1.60	8.00	4.03	4.89	–1.00	7.80	4.75
0.04	4.99	–5.40	11.30	6.39	5.09	–2.90	9.40	4.66	5.19	–1.90	8.90	4.58	5.39	–1.10	8.70	5.55
0.05	5.39	–5.90	12.30	7.00	5.59	–3.20	10.30	5.07	5.69	–2.10	9.70	4.89	5.79	–1.20	9.40	6.05
0.06	5.79	–6.50	13.30	7.59	5.89	–3.50	11.00	5.49	5.99	–2.30	10.40	5.39	6.19	–1.40	10.10	6.17
0.07	5.69	–6.60	13.80	8.29	5.89	–3.40	11.30	6.01	5.99	–2.10	10.60	6.12	6.19	–1.10	10.10	7.52
0.08	5.99	–7.00	14.60	8.80	6.19	–3.60	11.90	6.34	6.29	–2.30	11.10	6.19	6.49	–1.20	10.60	7.66
0.09	6.29	–7.40	15.30	9.19	6.49	–3.90	12.50	6.59	6.59	–2.40	11.70	6.65	6.79	–1.30	11.10	7.81
0.10	6.59	–7.80	16.00	9.58	6.69	–4.10	13.10	7.07	6.89	–2.50	12.20	6.90	7.09	–1.40	11.60	7.98
0.20	7.89	–10.20	20.60	13.03	8.09	–5.10	16.60	9.66	8.29	–3.00	15.10	9.24	8.59	–1.40	13.80	10.41
0.30	7.39	–11.30	22.50	15.76	7.39	–5.20	17.10	11.68	7.49	–2.70	14.70	10.99	7.49	–0.80	11.80	12.04
0.40	5.19	–12.30	21.70	17.24	4.69	–5.70	14.90	12.00	4.29	–2.90	11.60	10.68	3.59	–0.80	7.90	12.04
0.50	3.49	–13.60	21.30	18.47	3.09	–6.40	13.60	11.84	2.59	–3.50	10.10	9.82	1.69	–1.30	6.50	9.57
0.60	3.19	–14.50	22.30	19.85	2.69	–6.70	13.90	12.74	2.19	–3.60	10.00	10.28	1.09	–1.30	6.00	9.94
0.70	2.99	–15.30	23.20	21.00	2.39	–7.00	14.10	13.30	1.89	–3.80	9.90	10.35	0.89	–1.40	5.70	8.98
0.80	2.79	–16.20	24.10	22.12	2.19	–7.40	14.50	13.95	1.69	–4.00	10.00	10.64	0.79	–1.50	5.60	8.48
0.90	2.59	–17.00	25.00	23.28	2.09	–7.80	14.80	14.26	1.59	–4.20	10.10	10.73	0.79	–1.70	5.60	7.67
1.00	2.19	–17.70	25.60	24.34	1.69	–8.10	14.90	14.83	1.29	–4.40	10.00	10.83	0.59	–1.70	5.30	7.39
1.10	2.09	–18.50	26.40	25.23	1.59	–8.50	15.30	15.31	1.19	–4.60	10.20	11.13	0.59	–1.90	5.40	7.05

Mdot	1.577 kW/m²				4.732 kW/m²				9.46 kW/m²				20 kW/m²			
[kg/s]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]
1.173*	1.99*	–19.10*	27.00*	25.92*	1.59*	–8.80*	15.60*	15.55*	1.09*	–4.80*	10.30*	11.24*	0.59*	–2.00*	5.50*	7.03*
1.20	1.99	–19.30	27.30	26.25	1.59	–8.90	15.70	15.64	1.19	–4.80	10.40	11.25	0.59	–2.00	5.60	7.29
1.30	2.09	–20.00	28.30	27.18	1.59	–9.20	16.30	16.37	1.19	–5.00	10.80	11.74	0.59	–2.10	5.80	7.53
1.40	2.09	–20.60	29.20	28.15	1.69	–9.50	16.80	16.77	1.19	–5.20	11.20	12.24	0.59	–2.10	6.00	8.03
1.50	2.19	–21.30	30.10	28.94	1.69	–9.80	17.40	17.49	1.29	–5.30	11.50	12.48	0.59	–2.20	6.20	8.25
1.60	2.29	–21.90	30.90	29.64	1.79	–10.10	17.90	17.91	1.29	–5.50	11.90	12.99	0.59	–2.30	6.40	8.50
1.70	2.29	–22.50	31.80	30.61	1.79	–10.40	18.40	18.47	1.39	–5.70	12.20	13.11	0.59	–2.30	6.60	9.02
1.80	2.39	–23.00	32.60	31.35	1.89	–10.60	18.80	18.80	1.39	–5.80	12.50	13.55	0.69	–2.40	6.70	8.74
1.90	2.49	–23.60	33.40	32.05	1.89	–10.90	19.30	19.36	1.39	–5.90	12.80	13.99	0.69	–2.50	6.90	8.98
2.00	2.49	–24.10	34.10	32.79	1.99	–11.20	19.70	19.61	1.39	–6.10	13.10	14.29	0.69	–2.50	7.10	9.47
2.50	2.69	–26.60	37.60	36.21	2.09	–12.30	21.70	21.78	1.59	–6.70	14.40	15.60	0.79	–2.80	7.80	10.18

*   Theoretical choked flow, refer to Appendix A1.

Table B-5—Model output for 4 inch pipe at cryogenic temperatures

Mdot	1.577 kW/m^2				4.732 kW/m^2				9.46 kW/m^2				20 kW/m^2			
[kg/s]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]
0.001	1.39	–0.90	2.50	1.13	1.39	–0.40	2.30	1.24	1.39	–0.30	2.20	1.24	1.49	–0.10	2.20	2.57
0.002	1.79	–1.30	3.40	1.65	1.79	–0.60	3.00	1.52	1.89	–0.40	2.90	1.48	1.89	–0.20	2.90	2.65
0.003	1.99	–1.60	4.00	2.06	2.09	–0.80	3.50	1.64	2.19	–0.50	3.40	1.71	2.19	–0.30	3.40	2.59
0.004	2.29	–1.80	4.50	2.26	2.39	–0.90	4.00	1.89	2.39	–0.60	3.80	1.96	2.49	–0.30	3.80	3.01
0.005	2.49	–2.00	5.00	2.58	2.49	–1.00	4.30	2.14	2.59	–0.60	4.20	2.46	2.69	–0.40	4.10	2.69
0.006	2.59	–2.20	5.40	2.89	2.69	–1.10	4.70	2.39	2.79	–0.70	4.50	2.44	2.89	–0.40	4.40	3.05
0.007	2.79	–2.40	5.70	2.96	2.89	–1.20	5.00	2.46	2.89	–0.80	4.80	2.68	2.99	–0.40	4.70	3.86
0.008	2.89	–2.50	6.00	3.18	2.99	–1.30	5.20	2.53	3.09	–0.80	5.00	2.68	3.19	–0.50	5.00	3.53
0.009	2.99	–2.70	6.30	3.38	3.09	–1.40	5.50	2.77	3.19	–0.90	5.30	2.92	3.29	–0.50	5.20	3.90
0.01	3.19	–2.80	6.60	3.48	3.29	–1.50	5.70	2.69	3.29	–0.90	5.50	3.16	3.39	–0.50	5.40	4.29
0.02	4.09	–3.90	8.80	4.79	4.19	–2.10	7.50	3.66	4.29	–1.30	7.10	3.69	4.39	–0.80	7.00	4.66
0.03	4.69	–4.80	10.30	5.68	4.79	–2.50	8.70	4.31	4.89	–1.60	8.30	4.43	4.99	–1.00	8.10	5.34
0.04	5.19	–5.40	11.60	6.50	5.29	–2.90	9.70	4.80	5.39	–1.90	9.20	4.77	5.59	–1.10	9.00	5.84
0.05	5.59	–6.00	12.70	7.21	5.69	–3.30	10.60	5.30	5.89	–2.10	10.00	5.07	5.99	–1.30	9.70	5.94
0.06	5.99	–6.60	13.60	7.69	6.09	–3.60	11.30	5.57	6.19	–2.30	10.70	5.57	6.39	–1.40	10.40	6.44
0.07	6.29	–7.10	14.50	8.30	6.39	–3.80	12.00	6.04	6.59	–2.50	11.30	5.69	6.79	–1.50	11.00	6.66
0.08	6.59	–7.50	15.30	8.81	6.79	–4.10	12.70	6.31	6.89	–2.70	11.90	6.00	7.09	–1.60	11.60	7.16
0.09	6.89	–7.90	16.00	9.20	6.99	–4.30	13.30	6.78	7.19	–2.80	12.40	6.25	7.39	–1.70	12.10	7.37
0.10	7.09	–8.30	16.70	9.71	7.29	–4.60	13.80	6.91	7.49	–3.00	12.90	6.38	7.69	–1.80	12.50	7.33
0.20	8.69	–10.90	21.70	13.21	8.89	–5.70	17.60	9.50	9.09	–3.60	16.30	9.02	9.29	–2.00	15.50	10.64
0.30	9.49	–12.50	25.00	15.87	9.69	–6.30	20.00	11.59	9.89	–3.80	18.20	10.99	10.19	–1.80	16.70	12.67
0.40	9.79	–13.50	27.30	18.11	9.99	–6.60	21.40	13.16	10.19	–3.70	19.10	12.58	10.59	–1.40	16.70	14.03
0.50	8.09	–14.20	27.20	19.96	7.79	–6.50	19.90	14.53	7.59	–3.40	16.50	13.37	7.29	–0.90	12.40	14.96
0.60	6.49	–15.10	26.80	21.21	5.99	–7.00	18.50	14.68	5.49	–3.60	14.60	13.33	4.69	–1.00	10.20	15.68
0.70	5.39	–16.30	26.70	22.08	4.79	–7.70	17.70	14.67	4.29	–4.20	13.60	12.42	3.39	–1.50	9.30	12.39
0.80	4.29	–17.20	26.60	23.07	3.69	–8.10	17.00	14.99	3.19	–4.40	12.60	12.26	2.09	–1.70	8.10	11.47
0.90	4.09	–17.90	27.50	24.26	3.49	–8.30	17.30	15.64	2.89	–4.50	12.50	12.51	1.59	–1.70	7.70	11.83
1.00	3.89	–18.50	28.30	25.35	3.29	–8.60	17.50	16.04	2.59	–4.60	12.50	12.97	1.39	–1.80	7.40	10.93

Mdot	1.577 kW/m²				4.732 kW/m²				9.46 kW/m²				20 kW/m²			
[kg/s]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]
1.10	3.59	–19.20	29.00	26.41	2.99	–8.90	17.70	16.61	2.39	–4.80	12.40	12.84	1.19	–1.80	7.20	10.93
1.20	3.49	–19.90	29.70	27.21	2.89	–9.20	18.00	17.01	2.19	–5.00	12.50	13.13	1.09	–1.90	7.10	10.46
1.30	3.39	–20.60	30.50	28.14	2.69	–9.50	18.30	17.57	2.09	–5.10	12.60	13.38	0.99	–2.00	7.10	10.33
1.40	3.19	–21.20	31.10	28.97	2.59	–9.80	18.50	17.81	1.99	–5.30	12.70	13.47	0.99	–2.10	7.10	9.94
1.50	3.09	–21.80	31.80	29.81	2.49	–10.10	18.80	18.22	1.89	–5.50	12.80	13.57	0.99	–2.20	7.20	9.86
1.60	2.69	–22.40	32.20	30.64	2.09	–10.30	18.80	18.70	1.59	–5.60	12.60	13.62	0.79	–2.30	6.80	9.00
1.70	2.59	–23.00	32.80	31.34	2.09	–10.60	19.10	18.95	1.49	–5.80	12.80	13.93	0.69	–2.40	6.90	9.23
1.80	2.49	–23.60	33.50	32.17	1.99	–10.90	19.40	19.35	1.49	–6.00	13.00	14.04	0.69	–2.50	7.00	9.21
1.90	2.49	–24.20	34.10	32.74	1.89	–11.20	19.70	19.76	1.39	–6.10	13.10	14.29	0.69	–2.60	7.10	9.20
2.00	2.39	–24.80	34.70	33.45	1.89	–11.50	20.00	20.01	1.39	–6.30	13.30	14.41	0.69	–2.70	7.20	9.20
2.002*	2.39*	–24.80*	34.70*	33.45*	1.89*	–11.50*	20.00*	20.01*	1.39*	–6.30*	13.30*	14.41*	0.69*	–2.70*	7.30*	9.44*
2.50	2.59	–24.7	38.3	38.16	2.09	–12.7	22.1	22.11	1.49	–7	14.7	15.96	0.79	–3	8	10.16
3.00	3.09	–29.6	41.7	39.98	2.39	–13.8	24.2	24.13	1.79	–7.5	16.2	17.59	0.89	–3.2	8.8	11.38
3.50	2.99	–31.7	44.3	42.77	2.39	–14.8	25.6	25.60	1.79	–8.1	17.1	18.52	0.89	–3.5	9.3	11.85
4.00	3.19	–33.6	46.9	45.23	2.49	–15.6	27.1	27.21	1.89	–8.6	18.1	19.58	0.89	–3.7	9.9	12.82
4.50	3.29	–35.3	49.4	47.77	2.59	–16.5	28.5	28.59	1.89	–9.1	19	20.64	0.99	–3.9	10.4	13.30
5.00	3.49	–37	51.7	49.91	2.69	–17.2	29.8	29.96	1.99	–9.5	19.9	21.63	0.99	–4.1	10.9	14.03
6.00	3.69	–40	55.9	54.07	2.89	–18.6	32.3	32.55	2.19	–10.3	21.5	23.25	1.09	–4.4	11.8	15.23
8.00	4.09	–45.2	63.1	61.12	3.19	–21.1	36.4	36.69	2.39	–11.6	24.2	26.30	1.19	–5	13.2	16.92
10.00	4.39	–49.7	69.3	67.24	3.39	–23.2	39.9	40.33	2.49	–12.8	26.5	28.92	1.29	–5.5	14.4	18.37
12.00	4.59	–53.6	74.7	72.65	3.59	–25	43	43.56	2.69	–13.8	28.5	31.04	1.29	–5.9	15.5	20.06

* Theoretical choked flow, refer to Appendix A1.

Table B-6—Model output for 10 inch pipe at cryogenic temperatures

Mdot	1.577 kW/m²				4.732 kW/m²				9.46 kW/m²				20 kW/m²			
[kg/s]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]
0.001	1.33	–0.92	2.70	1.48	1.38	–0.43	2.40	1.43	1.42	–0.23	2.29	1.76	1.46	–0.09	2.10	2.33
0.005	2.58	–2.17	5.36	2.87	2.66	–1.14	4.70	2.40	2.73	–0.72	4.55	2.66	2.80	–0.42	4.48	3.57
0.010	3.36	–3.02	7.13	3.86	3.45	–1.60	6.18	3.13	3.54	–1.02	5.95	3.36	3.63	–0.60	5.86	4.45
0.050	6.10	–6.41	13.76	7.78	6.26	–3.47	11.61	5.86	6.40	–2.26	11.03	5.87	6.58	–1.36	10.77	7.14
0.060	6.53	–6.97	14.83	8.43	6.70	–3.79	12.48	6.30	6.85	–2.47	11.83	6.26	7.03	–1.49	11.54	7.57
0.070	6.89	–7.40	15.70	8.94	7.09	–4.00	13.10	6.52	7.29	–2.60	12.40	6.32	7.39	–1.60	12.10	7.73
0.080	7.29	–7.90	16.50	9.32	7.39	–4.30	13.80	6.93	7.59	–2.80	13.10	6.82	7.79	–1.70	12.70	7.94
0.090	7.59	–8.40	17.40	9.93	7.79	–4.50	14.50	7.25	7.89	–3.00	13.70	7.13	8.19	–1.80	13.30	8.15
0.100	7.89	–8.80	18.10	10.32	8.09	–4.80	15.10	7.52	8.29	–3.10	14.20	7.18	8.49	–1.90	13.80	8.37
0.50	13.99	–18.40	34.80	20.97	14.29	–10.20	28.10	14.45	14.59	–6.80	26.00	12.97	14.89	–4.20	25.00	14.27
1.00	17.09	–24.20	45.30	28.54	17.39	–13.00	36.00	19.82	17.79	–8.40	33.00	17.97	18.19	–4.80	31.20	20.03
3.00	9.59	–33.90	52.90	44.62	8.69	–16.50	34.80	28.91	7.69	–9.30	26.70	24.08	6.09	–3.90	18.80	22.66
5.00	7.19	–40.70	60.30	55.00	6.09	–19.20	37.00	34.48	4.89	–10.70	26.30	26.77	2.79	–4.40	16.00	22.03
7.00	6.19	–46.80	67.00	62.91	5.09	–22.10	39.90	38.46	3.99	–12.30	27.60	28.81	2.19	–5.30	16.10	20.90
9.00	5.49	–52.20	73.00	69.76	4.49	–24.70	42.80	42.06	3.49	–13.90	29.20	30.73	1.99	–6.10	16.90	21.27
10.00	4.69	–54.60	75.20	72.83	3.79	–25.90	43.70	43.70	2.89	–14.60	29.40	31.37	1.59	–6.50	16.70	20.81
10.50	4.59	–55.90	76.50	74.20	3.69	–26.50	44.40	44.52	2.79	–15.00	29.90	32.00	1.49	–6.70	17.00	21.30
11.00	4.49	–57.10	77.90	75.74	3.59	–27.20	45.10	45.27	2.69	–15.30	30.30	32.56	1.49	–6.90	17.20	21.33
11.50	4.39	–58.30	79.10	77.02	3.49	–27.80	45.80	46.10	2.69	–15.70	30.80	33.01	1.49	–7.10	17.50	21.60
11.60	4.39	–58.50	79.40	77.34	3.49	–27.90	45.90	46.18	2.69	–15.80	30.80	32.91	1.49	–7.20	17.60	21.62
11.70	4.29	–58.70	79.70	77.79	3.49	–28.00	46.00	46.27	2.69	–15.90	30.90	32.98	1.49	–7.20	17.60	21.62
11.80	4.29	–59.00	79.90	77.95	3.49	–28.10	46.20	46.51	2.69	–15.90	31.00	33.15	1.49	–7.20	17.70	21.85
11.90	4.29	–59.20	80.20	78.27	3.49	–28.20	46.30	46.59	2.59	–16.00	31.10	33.40	1.49	–7.30	17.70	21.65
12.00*	4.29*	–59.40*	80.40*	78.46*	3.49*	–28.40*	46.40*	46.62*	2.59*	–16.10*	31.20*	33.47*	1.49*	–7.30*	17.80*	21.87*
12.10	4.29	–59.60	80.80	78.91	3.49	–28.40	46.60	46.92	2.69	–16.10	31.30	33.47	1.49	–7.30	17.90	22.09
12.50	4.39	–60.50	81.90	79.90	3.49	–28.90	47.30	47.66	2.69	–16.40	31.80	34.04	1.49	–7.50	18.10	22.14
13.00	4.39	–61.50	83.30	81.37	3.59	–29.40	48.10	48.39	2.69	–16.70	32.30	34.60	1.49	–7.60	18.40	22.61
14.00	4.59	–63.60	86.00	83.90	3.69	–30.40	49.70	50.02	2.79	–17.20	33.40	35.84	1.59	–7.90	19.10	23.36
15.00	4.69	–65.50	88.60	86.50	3.79	–31.30	51.20	51.56	2.89	–17.80	34.40	36.79	1.59	–8.10	19.70	24.30
20.00	5.29	–74.20	100.30	97.93	4.29	–35.50	58.00	58.38	3.29	–20.20	39.00	41.66	1.79	–9.20	22.30	27.46
25.00	5.79	–81.60	110.40	107.85	4.69	–39.10	63.80	64.23	3.59	–22.20	43.00	46.08	1.99	–10.20	24.60	30.16

* Theoretical choked flow, refer to Appendix A1.

B3 Heat flux parameters curve fit ambient release

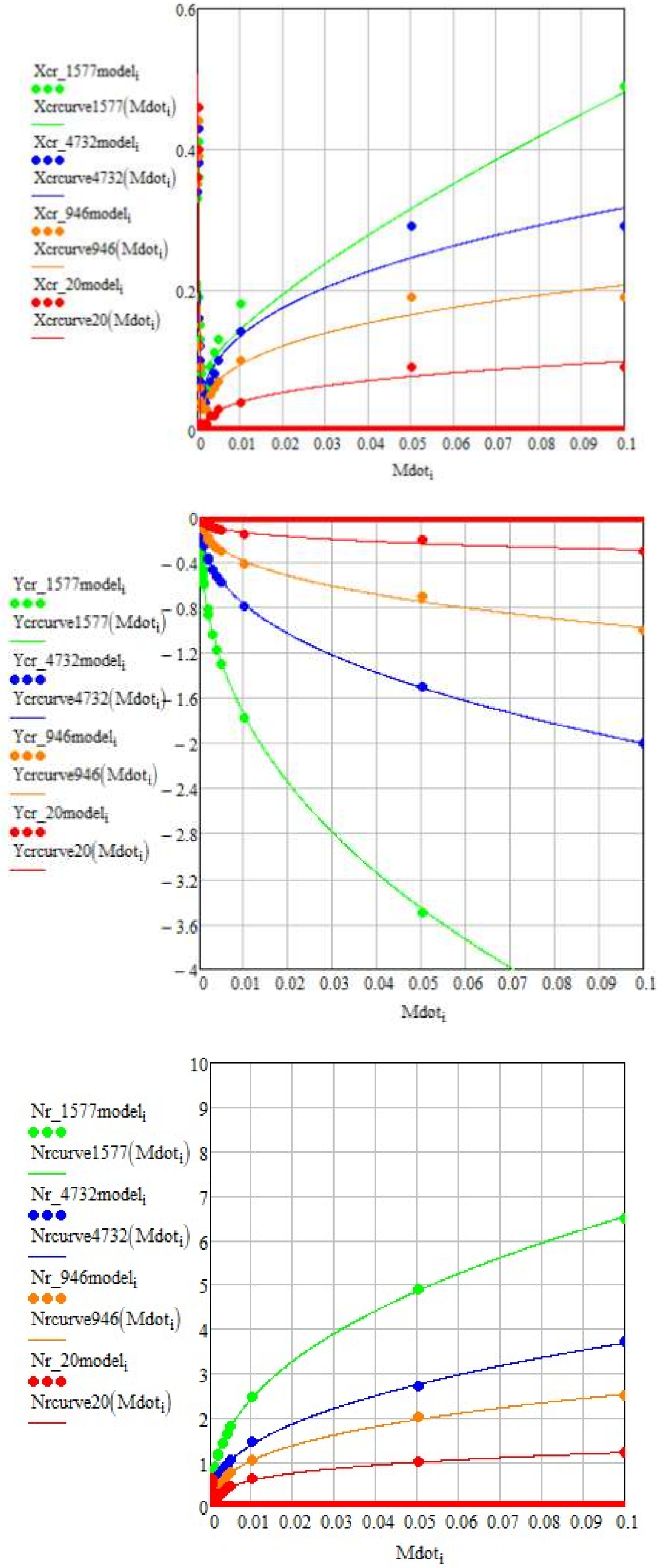

Figure B-7—Heat flux parameters curve fit ambient release—1/4 inch ODT

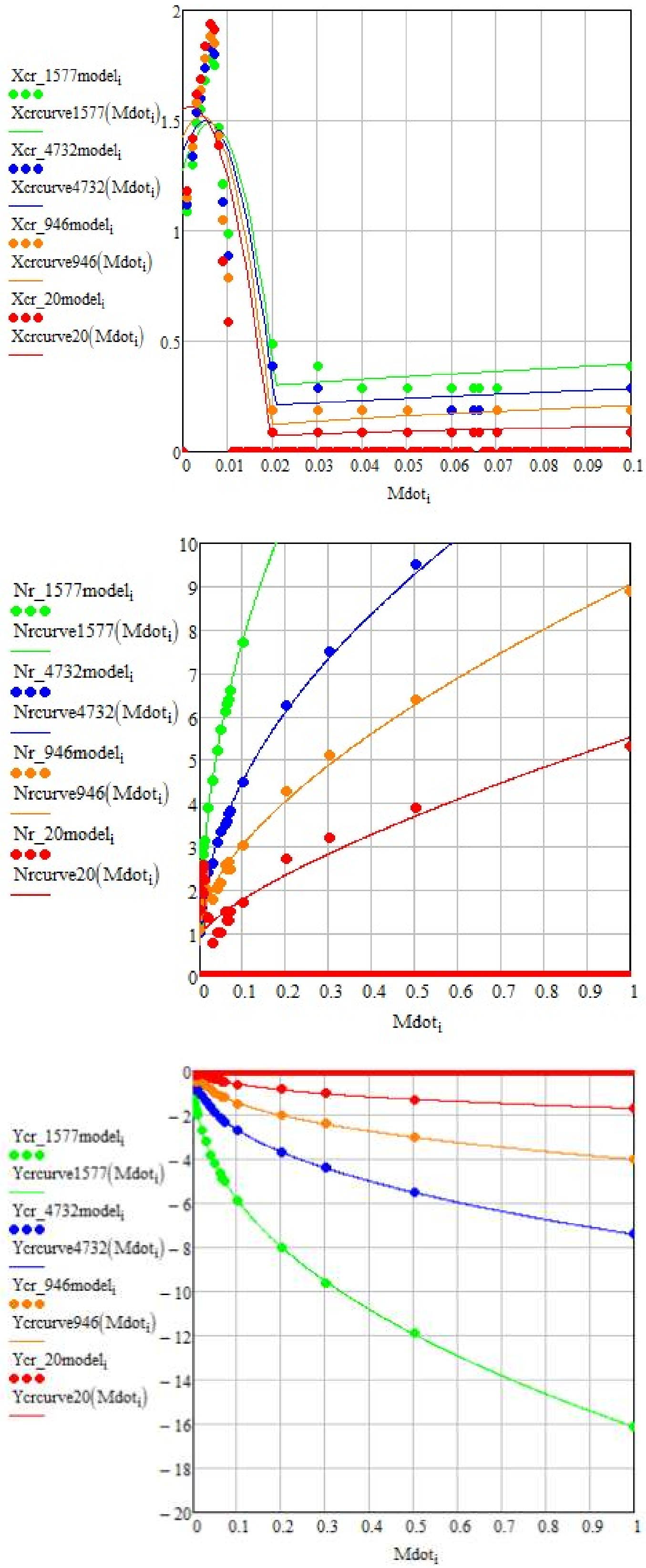

Figure B-8—Heat flux parameters curve fit ambient release—1 inch pipe

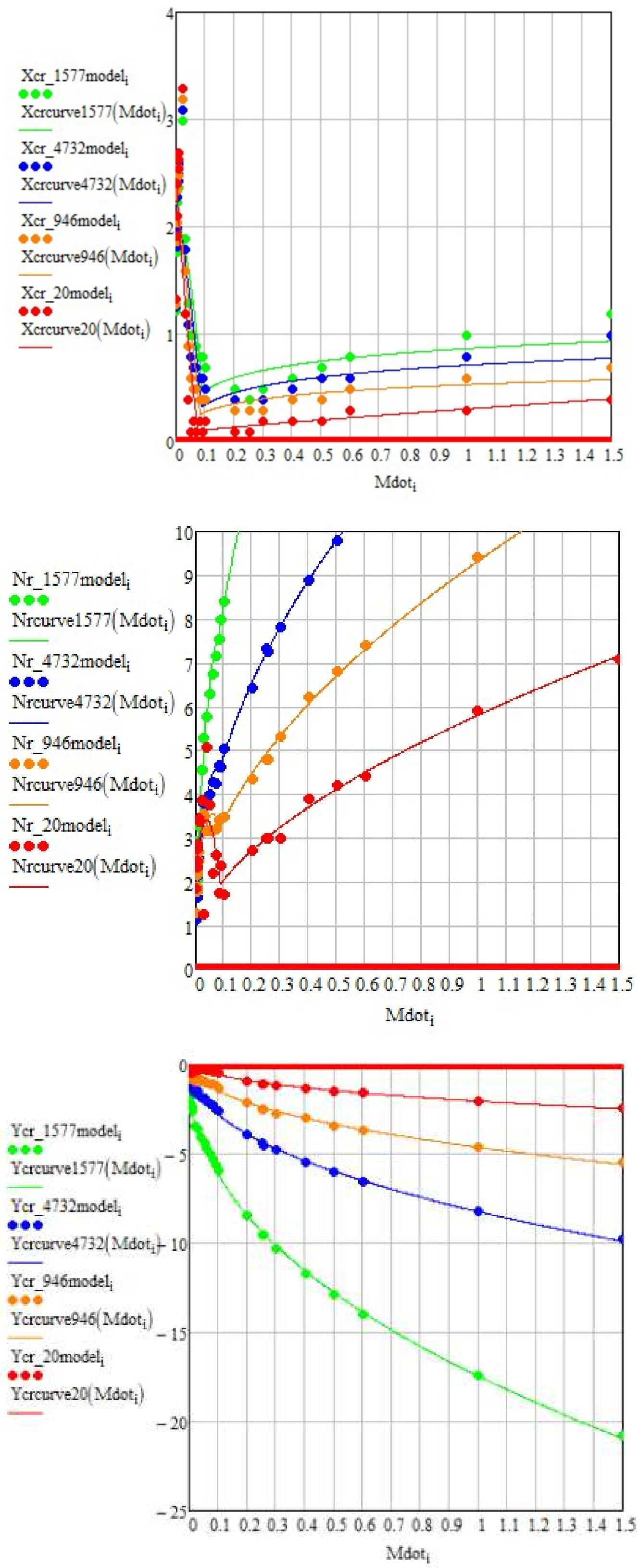

Figure B-9—Heat flux parameters curve fit ambient release—2 inch pipe

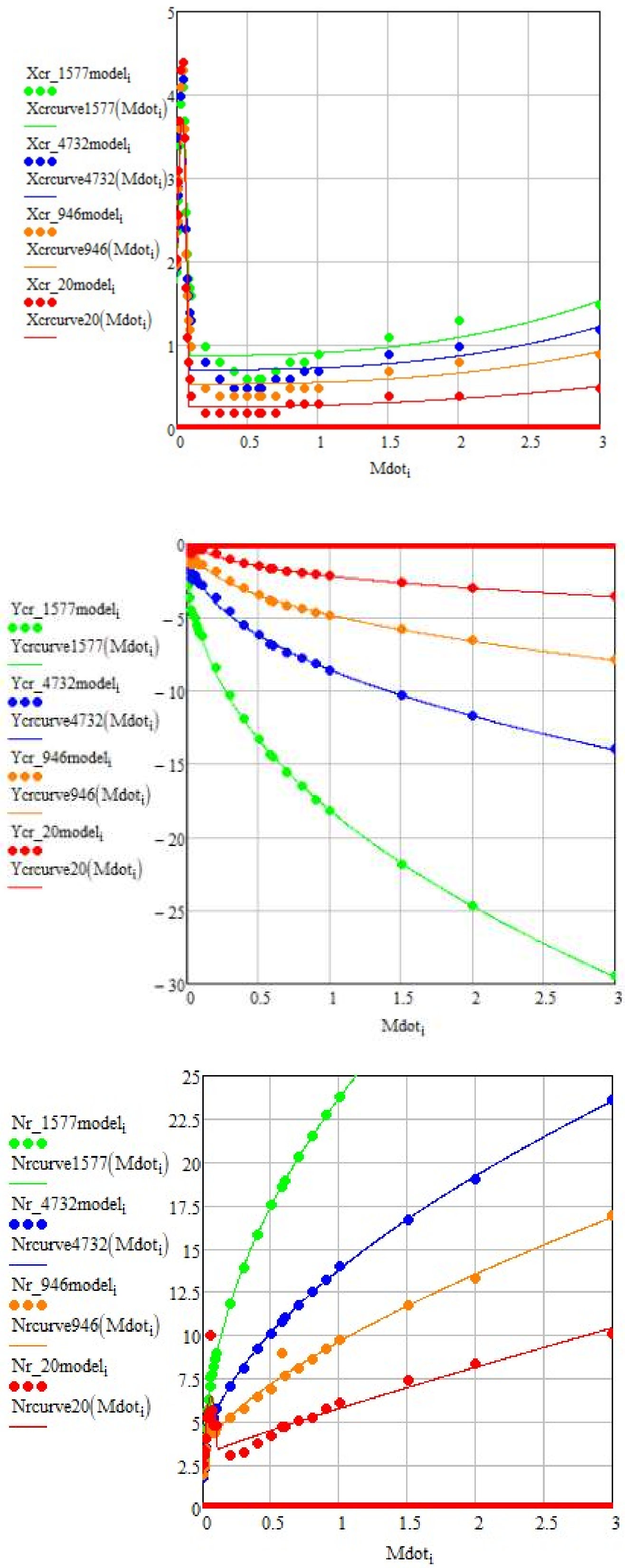

Figure B-10—Heat flux parameters curve fit ambient release—3 inch pipe

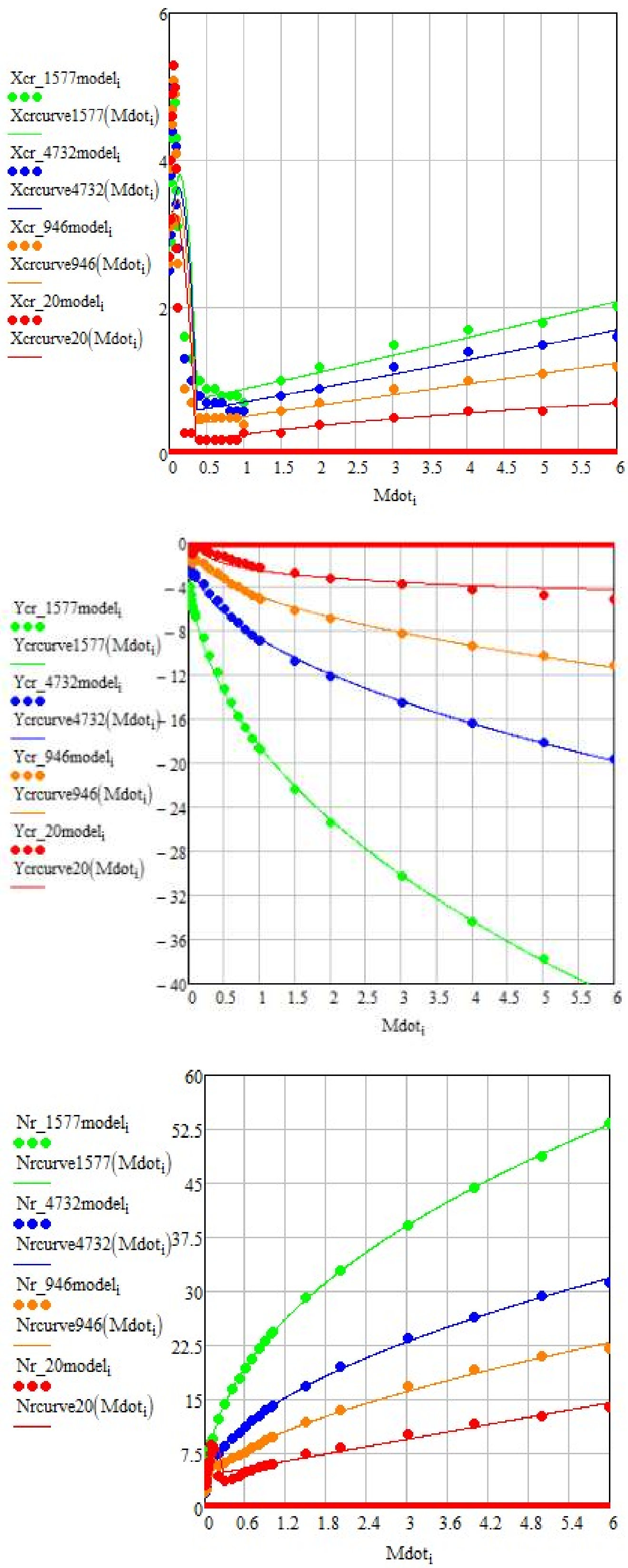

Figure B-11—Heat flux parameters curve fit ambient release—4 inch pipe

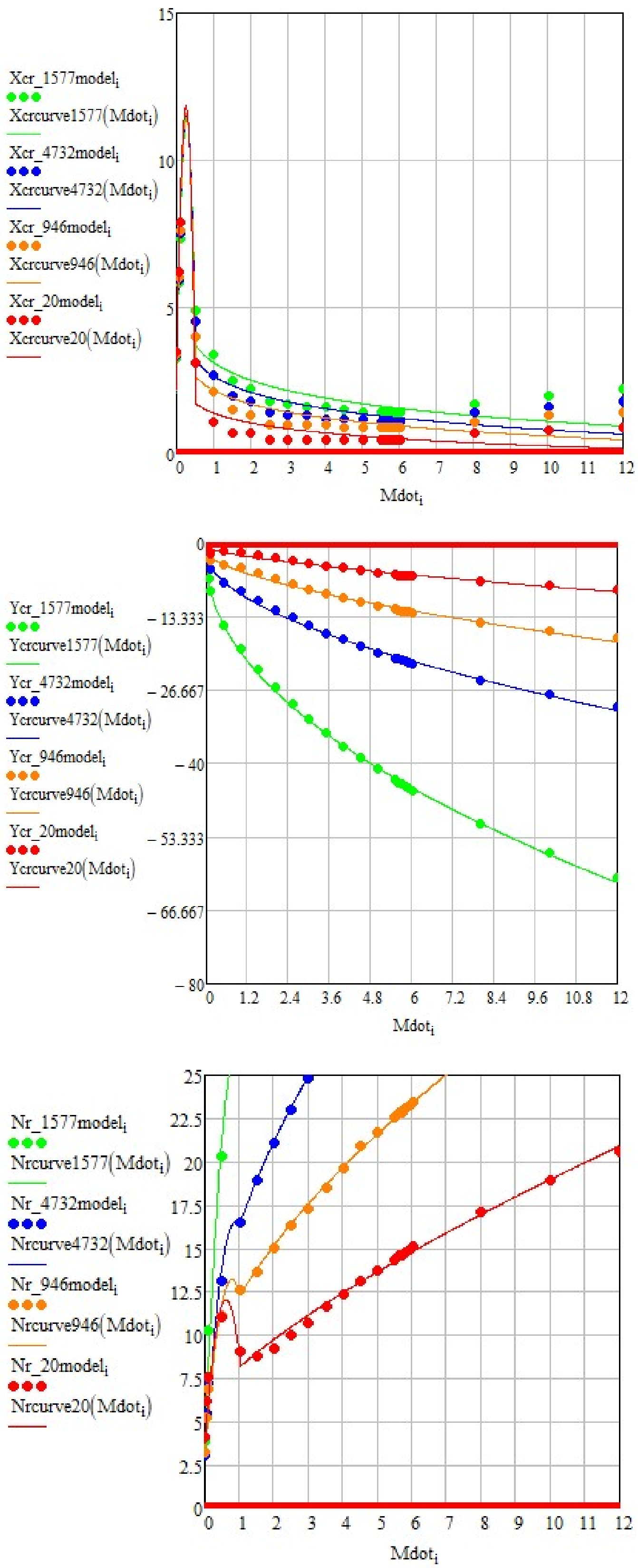

Figure B-12—Heat flux parameters curve fit ambient release—10 inch pipe

Table B-7—Model output for 1/4 inch ODT at ambient temperatures

Mdot	1.577 kW/m^2				4.732 kW/m^2				9.46 kW/m^2				20 kW/m^2			
[kg/s]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]
0.0001	0.33	–0.23	0.69	0.40	0.34	–0.10	0.60	0.39	0.35	–0.04	0.54	0.45	0.361	–0.005	0.43	0.51
0.0002	0.362	–0.312	0.842	0.53	0.38	–0.13	0.69	0.47	0.39	–0.05	0.61	0.51	0.400	–0.035	0.60	0.57
0.0003	0.41	–0.38	0.99	0.62	0.43	–0.16	0.81	0.53	0.44	–0.07	0.71	0.57	0.457	–0.002	0.51	0.63
0.0004	0.19	–0.39	0.77	0.63	0.16	–0.15	0.50	0.46	0.12	–0.05	0.34	0.51	0.0029	–0.007	0.08	0.48
0.0005	0.15	–0.45	0.80	0.69	0.12	–0.18	0.49	0.47	0.09	–0.08	0.34	0.43	0.009	–0.013	0.10	0.33
0.0006	0.13	–0.47	0.80	0.71	0.10	–0.19	0.47	0.46	0.06	–0.08	0.30	0.40	0.0090	–0.010	0.08	0.26
0.0007	0.10	–0.50	0.83	0.78	0.07	–0.20	0.47	0.49	0.40	–0.09	0.29	0.12	0.007	–0.021	0.08	0.15
0.0008	0.09	–0.54	0.84	0.79	0.06	–0.22	0.47	0.49	0.04	–0.10	0.28	0.34	0.009	–0.020	0.09	0.17
0.0009	0.08	–0.57	0.89	0.85	0.06	–0.24	0.49	0.51	0.04	–0.11	0.30	0.37	0.008	–0.032	0.11	0.17
0.0010	0.08	–0.60	0.91	0.88	0.06	–0.25	0.50	0.51	0.03	–0.11	0.30	0.39	0.009	–0.030	0.10	0.15
0.00176*	0.05*	–0.81*	1.13*	1.13*	0.04*	–0.36*	0.61*	0.63*	0.03*	–0.18*	0.38*	0.43*	0.009*	–0.070*	0.17*	0.22*
0.0020	0.06	–0.86	1.20	1.19	0.05	–0.38	0.66	0.68	0.03	–0.20	0.41	0.46	0.009	–0.070	0.19	0.27
0.0030	0.09	–1.04	1.46	1.42	0.07	–0.46	0.81	0.83	0.05	–0.24	0.51	0.56	0.019	–0.090	0.24	0.32
0.0040	0.11	–1.18	1.67	1.62	0.08	–0.53	0.93	0.95	0.06	–0.27	0.60	0.68	0.019	–0.100	0.29	0.42
0.0050	0.13	–1.30	1.86	1.80	0.10	–0.58	1.04	1.05	0.07	–0.30	0.67	0.75	0.029	–0.110	0.32	0.44
0.0100	0.18	–1.77	2.54	2.46	0.14	–0.79	1.43	1.45	0.10	–0.41	0.92	1.03	0.039	–0.150	0.44	0.61
0.0500	0.29	–3.50	5.00	4.92	0.29	–1.50	2.70	2.69	0.19	–0.70	1.70	1.98	0.090	–0.200	0.70	1.03
0.1000	0.49	–4.60	6.70	6.49	0.29	–2.00	3.60	3.74	0.19	–1.00	2.20	2.52	0.090	–0.300	0.90	1.24

* Theoretical choked flow, refer to Appendix A1.

Table B-8—Model output for 1 inch pipe at ambient temperatures

Mdot	1.577 kW/m²				4.732 kW/m²				9.46 kW/m²				20 kW/m²			
[kg/s]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]
0.001	1.09	–0.90	2.24	1.18	1.12	–0.47	1.97	1.01	1.15	–0.30	1.90	1.09	1.18	–0.17	1.88	1.53
0.002	1.30	–1.18	2.86	1.62	1.34	–0.59	2.45	1.34	1.38	–0.34	2.33	1.50	1.42	–0.16	2.20	1.99
0.003	1.49	–1.44	3.36	1.94	1.54	–0.72	2.85	1.55	1.58	–0.43	2.70	1.68	1.62	–0.21	2.56	2.21
0.004	1.55	–1.54	3.65	2.20	1.60	–0.73	3.04	1.79	1.64	–0.39	2.81	1.95	1.69	–0.15	2.49	2.21
0.005	1.68	–1.72	4.00	2.43	1.74	–0.82	3.32	1.93	1.78	–0.45	3.07	2.08	1.84	–0.17	2.73	2.42
0.006	1.78	–1.88	4.29	2.62	1.83	–0.90	3.54	2.08	1.88	–0.50	3.27	2.18	1.94	–0.20	2.93	2.56
0.007	1.75	–1.90	4.41	2.81	1.80	–0.85	3.57	2.27	1.85	–0.42	3.19	2.35	1.91	–0.10	2.61	2.51
0.008	1.47	–1.91	4.26	2.99	1.44	–0.80	3.22	2.38	1.43	–0.34	2.66	2.40	1.39	–0.15	1.47	2.22
0.009	1.21	–1.96	4.09	3.10	1.13	–0.81	2.91	2.36	1.05	–0.34	2.27	2.36	0.86	–0.20	0.01	1.92
0.01	0.99	–2.00	3.90	3.12	0.89	–0.80	2.60	2.23	0.79	–0.30	1.90	2.20	0.59	–0.01	0.80	2.21
0.02	0.49	–2.70	4.20	3.90	0.39	–1.10	2.40	2.39	0.19	–0.50	1.50	1.97	0.09	–0.10	0.60	1.35
0.03	0.39	–3.20	4.70	4.50	0.29	–1.40	2.60	2.61	0.19	–0.70	1.60	1.77	0.09	–0.20	0.60	0.75
0.04	0.29	–3.80	5.30	5.20	0.19	–1.60	2.90	3.10	0.19	–0.80	1.80	2.02	0.09	–0.30	0.80	0.99
0.05	0.29	–4.20	5.80	5.71	0.19	–1.90	3.20	3.33	0.19	–1.00	2.00	2.14	0.09	–0.40	0.90	1.02
0.06	0.29	–4.60	6.20	6.10	0.19	–2.10	3.40	3.50	0.09	–1.10	2.20	2.57	0.09	–0.40	1.10	1.48
0.066*	0.29*	–4.90*	6.50*	6.39*	0.19*	–2.20*	3.60*	3.74*	0.09*	–1.20*	2.30*	2.64*	0.09*	–0.50*	1.10*	1.27*
0.07	0.29	–5.00	6.70	6.61	0.19	–2.30	3.70	3.83	0.19	–1.20	2.30	2.46	0.09	–0.50	1.20	1.48
0.10	0.39	–5.90	7.90	7.73	0.29	–2.70	4.40	4.48	0.19	–1.50	2.80	3.02	0.09	–0.60	1.40	1.73
0.20	0.49	–8.00	10.90	10.77	0.39	–3.70	6.10	6.26	0.29	–2.00	3.90	4.26	0.19	–0.80	2.10	2.68
0.30	0.69	–9.60	13.00	12.69	0.49	–4.40	7.30	7.47	0.39	–2.40	4.70	5.07	0.19	–1.00	2.50	3.17
0.50	0.79	–11.90	16.30	16.06	0.59	–5.50	9.20	9.49	0.49	–3.00	5.90	6.38	0.19	–1.30	3.10	3.91
1.00	1.09	–16.10	21.90	21.50	0.79	–7.40	12.30	12.65	0.59	–4.00	8.00	8.86	0.29	–1.70	4.20	5.35

* Theoretical choked flow, refer to Appendix A1.

Table B-9—Model output for 2 inch pipe at ambient temperatures

Mdot	1.577 kW/m²				4.732 kW/m²				9.46 kW/m²				20 kW/m²			
[kg/s]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]
0.001	1.21	–0.94	2.44	1.28	1.25	–0.48	2.17	1.12	1.28	–0.30	2.11	1.30	1.32	–0.17	2.09	1.83
0.002	1.54	–1.31	3.20	1.71	1.59	–0.68	2.80	1.42	1.63	–0.43	2.71	1.57	1.67	–0.25	2.67	2.13
0.003	1.76	–1.59	3.74	2.03	1.81	–0.84	3.24	1.64	1.86	–0.53	3.12	1.77	1.91	–0.31	3.07	2.33
0.004	1.94	–1.82	4.17	2.28	1.99	–0.97	3.59	1.81	2.04	–0.62	3.44	1.89	2.10	–0.36	3.38	2.46
0.005	2.10	–2.02	4.56	2.51	2.15	–1.08	3.90	1.96	2.21	–0.69	3.74	2.04	2.27	–0.41	3.67	2.60
0.006	2.22	–2.20	4.89	2.72	2.28	–1.18	4.17	2.11	2.34	–0.76	3.98	2.15	2.40	–0.45	3.90	2.73
0.007	2.36	–2.36	5.21	2.90	2.42	–1.27	4.43	2.23	2.48	–0.82	4.22	2.26	2.54	–0.49	4.13	2.83
0.008	2.32	–2.37	5.35	3.12	2.39	–1.21	4.50	2.45	2.45	–0.73	4.25	2.59	2.52	–0.37	4.03	3.27
0.009	2.42	–2.51	5.60	3.27	2.49	–1.28	4.70	2.55	2.55	–0.78	4.43	2.66	2.62	–0.40	4.21	3.36
0.01	2.49	–2.60	5.70	3.28	2.59	–1.30	4.80	2.53	2.69	–0.80	4.50	2.45	2.69	–0.40	4.30	3.44
0.02	2.99	–3.40	7.40	4.56	3.09	–1.60	6.00	3.45	3.19	–0.90	5.50	3.41	3.29	–0.40	5.00	3.86
0.03	1.89	–3.60	6.90	5.29	1.79	–1.50	4.80	3.77	1.59	–0.70	3.70	3.53	1.19	–0.30	2.00	1.24
0.04	1.29	–4.10	6.80	5.75	1.09	–1.80	4.30	3.76	0.89	–0.90	3.10	3.16	0.39	–0.20	1.80	5.07
0.05	0.99	–4.40	7.00	6.30	0.79	–1.90	4.20	4.01	0.59	–0.90	2.80	3.16	0.09	–0.20	1.30	3.76
0.06	0.99	–4.70	7.40	6.72	0.69	–2.00	4.30	4.26	0.49	–1.00	2.80	3.17	0.19	–0.30	1.30	2.20
0.07	0.89	–5.00	7.70	7.14	0.69	–2.20	4.40	4.23	0.49	–1.10	2.90	3.19	0.09	–0.30	1.30	2.59
0.08	0.79	–5.30	8.00	7.55	0.59	–2.30	4.60	4.65	0.39	–1.10	2.90	3.41	0.19	–0.40	1.30	1.74
0.09	0.79	–5.60	8.40	7.97	0.59	–2.50	4.70	4.63	0.39	–1.20	3.00	3.44	0.09	–0.40	1.40	2.35
0.10	0.69	–5.90	8.70	8.39	0.49	–2.60	4.90	5.04	0.39	–1.30	3.10	3.47	0.19	–0.50	1.40	1.71
0.20	0.49	–8.40	11.40	11.29	0.39	–3.90	6.30	6.43	0.29	–2.10	4.00	4.33	0.09	–0.90	2.10	2.69
0.254*	0.39*	–9.50*	12.60*	12.60*	0.29*	–4.50*	7.00*	7.25*	0.29*	–2.50*	4.50*	4.79*	0.09*	–1.10*	2.40*	2.98*
0.30	0.49	–10.30	13.60	13.49	0.39	–4.80	7.60	7.82	0.29	–2.70	4.90	5.29	0.19	–1.20	2.60	3.02
0.40	0.59	–11.70	15.50	15.35	0.49	–5.50	8.70	8.88	0.39	–3.00	5.70	6.20	0.19	–1.30	3.10	3.91
0.50	0.69	–12.90	17.10	16.89	0.59	–6.00	9.60	9.77	0.39	–3.40	6.30	6.84	0.19	–1.50	3.40	4.18
0.60	0.79	–14.00	18.60	18.33	0.59	–6.60	10.50	10.74	0.49	–3.70	6.90	7.40	0.29	–1.60	3.70	4.43
1.00	0.99	–17.40	23.40	23.13	0.79	–8.20	13.20	13.49	0.59	–4.60	8.70	9.45	0.29	–2.00	4.70	5.86
1.50	1.19	–20.80	27.90	27.55	0.99	–9.80	15.80	16.09	0.69	–5.50	10.40	11.32	0.39	–2.40	5.70	7.07

* Theoretical choked flow, refer to Appendix A1.

Table B-10—Model output for 3 inch pipe at ambient temperatures

Mdot	1.577 kW/m^2				4.732 kW/m^2				9.46 kW/m^2				20 kW/m^2			
[kg/s]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]
0.001	1.27	–0.96	2.53	1.31	1.31	–0.49	2.26	1.17	1.34	–0.31	2.20	1.35	1.38	–0.17	2.18	1.97
0.002	1.63	–1.33	3.34	1.77	1.68	–0.69	2.95	1.52	1.72	–0.44	2.86	1.70	1.77	–0.25	2.82	2.33
0.003	1.87	–1.62	3.91	2.10	1.93	–0.85	3.41	1.72	1.97	–0.54	3.30	1.91	2.03	–0.31	3.25	2.56
0.004	2.06	–1.85	4.37	2.37	2.12	–0.98	3.79	1.91	2.17	–0.63	3.64	2.03	2.23	–0.37	3.59	2.69
0.005	2.23	–2.06	4.78	2.61	2.29	–1.09	4.12	2.08	2.35	–0.70	3.96	2.20	2.41	–0.41	3.89	2.88
0.006	2.37	–2.25	5.12	2.81	2.43	–1.20	4.40	2.22	2.49	–0.77	4.22	2.33	2.56	–0.45	4.14	3.00
0.007	2.51	–2.42	5.46	3.01	2.57	–1.29	4.67	2.36	2.64	–0.83	4.47	2.43	2.71	–0.49	4.39	3.13
0.008	2.61	–2.57	5.73	3.18	2.68	–1.38	4.89	2.46	2.74	–0.89	4.67	2.54	2.82	–0.53	4.57	3.16
0.009	2.73	–2.72	6.02	3.35	2.80	–1.46	5.13	2.59	2.87	–0.94	4.89	2.64	2.95	–0.56	4.79	3.31
0.01	2.79	–2.80	6.10	3.36	2.89	–1.50	5.20	2.53	2.99	–0.90	4.90	2.48	3.09	–0.50	4.80	3.17
0.02	3.39	–3.70	7.90	4.60	3.49	–1.90	6.60	3.50	3.59	–1.10	6.10	3.41	3.69	–0.60	5.80	4.01
0.03	3.89	–4.50	9.40	5.62	3.99	–2.30	7.70	4.14	4.09	–1.40	7.20	4.15	4.29	–0.70	6.90	5.22
0.04	4.09	–4.80	10.20	6.29	4.19	–2.40	8.30	4.72	4.29	–1.40	7.60	4.61	4.39	–0.60	6.90	5.55
0.05	3.69	–5.00	10.40	7.00	3.59	–2.30	8.00	5.38	3.59	–1.20	6.90	5.17	3.49	–0.40	5.50	5.25
0.06	2.59	–5.10	9.70	7.51	2.39	–2.20	6.70	5.32	2.09	–1.00	5.20	5.34	1.69	–0.10	3.10	9.99
0.07	2.09	–5.50	9.50	7.74	1.79	–2.40	6.30	5.44	1.59	–1.20	4.70	4.63	1.09	–0.30	2.90	5.61
0.08	1.79	–5.80	9.60	8.16	1.59	–2.60	6.10	5.21	1.29	–1.40	4.50	4.38	0.79	–0.40	2.70	4.76
0.09	1.69	–6.10	9.90	8.57	1.39	–2.70	6.20	5.63	1.19	–1.40	4.40	4.38	0.59	–0.40	2.50	4.76
0.10	1.59	–6.30	10.10	8.90	1.29	–2.80	6.20	5.71	0.99	–1.40	4.30	4.61	0.39	–0.40	2.30	4.76
0.20	0.99	–8.40	12.30	11.81	0.79	–3.70	7.00	7.06	0.49	–1.90	4.50	5.18	0.19	–0.70	2.10	2.96
0.30	0.79	–10.30	14.20	13.88	0.59	–4.60	7.90	8.11	0.39	–2.50	5.10	5.69	0.19	–1.00	2.50	3.17
0.40	0.69	–11.90	16.00	15.80	0.49	–5.50	8.90	9.18	0.39	–3.00	5.80	6.38	0.19	–1.30	3.00	3.69
0.50	0.59	–13.30	17.60	17.53	0.49	–6.20	9.80	10.09	0.39	–3.50	6.40	6.91	0.19	–1.50	3.40	4.18
0.579*	0.59*	–14.30*	18.70*	18.62*	0.49*	–6.80*	10.50*	10.77*	0.39*	–3.80*	–6.90*	8.89*	0.19*	–1.70*	3.80*	4.68*
0.60	0.59	–14.50	19.00	18.94	0.49	–6.90	10.70	11.00	0.39	–3.90	7.00	7.55	0.19	–1.70	3.80	4.68
0.70	0.69	–15.60	20.40	20.25	0.59	–7.40	11.50	11.74	0.39	–4.20	7.50	8.12	0.19	–1.90	4.10	4.97
0.80	0.79	–16.50	21.70	21.50	0.59	–7.80	12.20	12.54	0.49	–4.40	8.00	8.61	0.29	–2.00	4.40	5.22
0.90	0.79	–17.40	22.90	22.75	0.69	–8.20	12.90	13.19	0.49	–4.70	8.50	9.18	0.29	–2.10	4.70	5.68
1.00	0.89	–18.20	24.00	23.77	0.69	–8.60	13.60	13.99	0.49	–4.90	8.90	9.67	0.29	–2.20	5.00	6.14
1.50	1.09	–21.80	28.80	28.51	0.89	–10.30	16.30	16.68	0.69	–5.80	10.80	11.71	0.39	–2.60	6.00	7.35
2.00	1.29	–24.70	32.70	32.32	0.99	–11.70	18.50	18.95	0.79	–6.60	12.30	13.34	0.39	–3.00	6.80	8.35
3.00	1.48	–29.40	39.00	39.09	1.19	–14.00	22.10	23.56	0.89	–7.90	14.70	16.90	0.49	–3.60	8.20	10.06
4.00	1.69	–33.30	44.20	44.31	1.39	–15.80	25.10	26.48	0.99	–8.90	16.60	19.15	0.59	–4.10	9.30	11.30
5.00	1.89	–36.60	48.60	48.77	1.49	–17.40	27.60	29.31	1.09	–9.80	18.20	21.15	0.59	–4.50	10.20	12.51

* Theoretical choked flow, refer to Appendix A1.

Table B-11—Model output for 4 inch pipe at ambient temperatures

Mdot	1.577 kW/m^2				4.732 kW/m^2				9.46 kW/m^2				20 kW/m^2			
[kg/s]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]
0.001	1.29	–0.90	2.40	1.13	1.29	–0.50	2.20	1.08	1.39	–0.30	2.10	0.99	1.39	–0.10	2.10	2.57
0.002	1.69	–1.30	3.30	1.65	1.69	–0.70	2.90	1.40	1.79	–0.40	2.80	1.48	1.79	–0.20	2.80	2.65
0.003	1.89	–1.60	3.90	2.06	1.99	–0.80	3.40	1.64	1.99	–0.50	3.30	1.97	2.09	–0.30	3.20	2.20
0.004	2.09	–1.80	4.40	2.38	2.19	–0.90	3.80	1.89	2.29	–0.60	3.60	1.73	2.29	–0.30	3.60	3.01
0.005	2.29	–2.00	4.80	2.58	2.39	–1.10	4.10	1.88	2.39	–0.70	4.00	2.20	2.49	–0.40	3.90	2.69
0.006	2.49	–2.20	5.10	2.65	2.49	–1.20	4.40	2.12	2.59	–0.70	4.20	2.20	2.69	–0.40	4.20	3.05
0.007	2.59	–2.40	5.50	2.96	2.69	–1.30	4.70	2.20	2.69	–0.80	4.50	2.45	2.79	–0.40	4.40	3.44
0.008	2.69	–2.60	5.80	3.16	2.79	–1.30	4.90	2.36	2.89	–0.90	4.70	2.27	2.89	–0.50	4.60	3.17
0.009	2.79	–2.70	6.10	3.38	2.89	–1.40	5.20	2.61	2.99	–0.90	4.90	2.48	3.09	–0.50	4.80	3.17
0.010	2.89	–2.90	6.30	3.45	2.99	–1.50	5.40	2.69	3.09	–1.00	5.10	2.52	3.19	–0.50	5.00	3.53
0.020	3.69	–4.00	8.30	4.66	3.79	–2.10	7.00	3.50	3.89	–1.40	6.60	3.32	3.99	–0.80	6.40	4.03
0.030	4.29	–4.80	9.90	5.68	4.39	–2.60	8.20	4.09	4.49	–1.70	7.70	3.88	4.59	–1.00	7.50	4.73
0.040	4.49	–5.20	10.80	6.43	4.59	–2.70	8.90	4.79	4.69	–1.70	8.30	4.68	4.89	–0.90	7.90	5.48
0.050	4.89	–5.80	11.80	7.02	4.99	–3.00	9.70	5.20	5.09	–1.90	9.00	4.97	5.29	–1.00	8.60	5.98
0.060	4.89	–6.00	12.40	7.70	4.99	–3.00	10.00	5.68	5.09	–1.70	9.20	5.82	5.29	–0.80	8.40	6.45
0.070	4.79	–6.20	12.90	8.40	4.89	–3.00	10.20	6.20	4.89	–1.70	9.10	6.06	4.99	–0.70	7.90	6.40
0.080	4.29	–6.30	12.80	8.90	4.19	–2.90	9.60	6.50	4.09	–1.50	8.20	6.38	3.89	–0.40	6.50	8.72
0.090	3.59	–6.50	12.40	9.22	3.39	–2.90	8.90	6.68	3.19	–1.50	7.20	6.11	2.79	–0.40	5.20	7.46
0.100	3.09	–6.70	12.20	9.54	2.79	–3.10	8.40	6.63	2.59	–1.60	6.60	5.83	1.99	–0.40	4.50	8.08
0.200	1.59	–8.60	13.30	12.27	1.29	–3.80	7.80	7.48	0.89	–1.90	5.20	5.84	0.29	–0.60	2.50	4.37
0.300	1.29	–10.30	15.10	14.41	0.99	–4.60	8.60	8.59	0.69	–2.40	5.60	6.22	0.29	–0.90	2.70	3.68
0.400	0.99	–11.80	16.70	16.36	0.79	–5.30	9.30	9.48	0.49	–2.80	6.00	6.82	0.19	–1.10	2.90	3.89
0.500	0.89	–13.20	18.20	17.95	0.69	–6.00	10.20	10.54	0.49	–3.20	6.50	7.24	0.19	–1.30	3.30	4.37
0.600	0.89	–14.50	19.60	19.32	0.69	–6.70	11.00	11.28	0.49	–3.70	7.10	7.75	0.19	–1.50	3.70	4.86
0.700	0.79	–15.70	20.90	20.73	0.69	–7.30	11.70	11.95	0.49	–4.00	7.60	8.32	0.19	–1.70	4.10	5.35
0.800	0.79	–16.70	22.20	22.07	0.59	–7.90	12.40	12.78	0.49	–4.40	8.10	8.78	0.19	–1.90	4.40	5.61
0.900	0.79	–17.80	23.30	23.13	0.59	–8.40	13.10	13.52	0.49	–4.70	8.60	9.35	0.19	–2.10	4.70	5.89
0.988*	0.69*	–18.60*	24.20*	24.16*	0.59*	–8.90*	13.60*	13.96*	0.39*	–5.00*	8.90*	9.74*	0.29*	–2.30*	5.00*	5.97*
1.000	0.69	–18.70	24.30	24.25	0.59	–8.90	13.70	14.11	0.39	–5.10	9.00	9.82	0.29	–2.30	5.00	5.97
1.500	0.99	–22.40	29.30	29.09	0.79	–10.70	16.50	16.88	0.59	–6.10	10.90	11.76	0.29	–2.80	6.10	7.43
2.000	1.19	–25.40	33.30	33.00	0.89	–12.10	18.90	19.45	0.69	–6.90	12.50	13.56	0.39	–3.20	7.00	8.43
3.000	1.49	–30.30	39.90	39.50	1.19	–14.50	22.60	23.06	0.89	–8.30	15.00	16.14	0.49	–3.80	8.50	10.34
4.000	1.69	–34.40	45.20	44.72	1.39	–16.40	25.70	26.22	0.99	–9.40	17.10	18.50	0.59	–4.30	9.60	11.59
5.000	1.79	–37.80	49.80	49.39	1.49	–18.10	28.30	28.91	1.09	–10.30	18.80	20.38	0.59	–4.80	10.60	12.84
6.000	1.99	–40.9	53.9	53.39	1.59	–19.6	30.6	31.27	1.19	–11.1	20.3	22.00	0.69	–5.1	11.5	14.01

*	Theoretical choked flow, refer to Appendix A1.

Table B-12—Model output for 10 inch pipe at ambient temperatures

Mdot	1.577 kW/m^2				4.732 kW/m^2				9.46 kW/m^2				20 kW/m^2			
[kg/s]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]	X_{cr} [m]	Y_{cr} [m]	Xlim	N_R [m]
0.001	1.37	–1.01	2.72	1.41	1.41	–0.52	2.43	1.26	1.45	–0.32	2.37	1.49	1.48	–0.18	2.35	2.20
0.005	2.48	–2.18	5.23	2.83	2.56	–1.15	4.55	2.30	2.62	–0.73	4.39	2.51	2.69	–0.43	4.32	3.31
0.01	3.22	–3.03	6.96	3.82	3.31	–1.61	5.99	3.04	3.39	–1.04	5.74	3.18	3.49	–0.61	5.64	4.10
0.05	5.79	–6.40	13.20	7.49	5.89	–3.50	11.00	5.48	5.99	–2.30	10.30	5.19	6.19	–1.40	10.10	6.16
0.1	7.29	–8.80	17.40	10.21	7.49	–4.80	14.30	7.23	7.59	–3.20	13.40	6.87	7.89	–1.90	12.90	7.56
0.5	4.89	–15.10	24.50	20.28	4.49	–7.20	16.20	13.12	3.99	–4.00	12.50	11.05	3.09	–1.60	8.80	10.99
1.0	3.39	–19.20	29.00	26.68	2.69	–8.80	17.30	16.53	2.09	–4.60	11.80	12.55	1.09	–1.80	6.50	9.03
1.5	2.49	–23.00	32.90	31.60	1.99	–10.50	18.90	18.87	1.49	–5.60	12.50	13.62	0.69	–2.30	6.60	8.74
2.0	2.19	–26.30	36.60	35.66	1.79	–12.20	20.90	21.07	1.29	–6.60	13.70	14.97	0.69	–2.80	7.30	9.20
2.5	1.79	–29.30	39.70	39.18	1.39	–13.60	22.40	23.03	0.99	–7.50	14.70	16.28	0.49	–3.30	7.90	9.97
3.0	1.69	–32.00	42.80	42.41	1.29	–15.00	24.10	24.84	0.99	–8.40	15.80	17.26	0.49	–3.70	8.60	10.74
3.5	1.59	–34.50	45.70	45.45	1.29	–16.40	25.80	26.52	0.99	–9.20	17.00	18.53	0.49	–4.20	9.40	11.55
4.0	1.59	–36.90	48.30	48.01	1.19	–17.60	27.30	28.17	0.99	–10.00	18.10	19.64	0.49	–4.60	10.10	12.34
4.5	1.49	–39.10	50.80	50.64	1.19	–18.80	28.80	29.67	0.89	–10.70	19.10	20.85	0.49	–5.00	10.80	13.13
5.0	1.39	–41.10	53.10	53.08	1.19	–19.90	30.10	30.95	0.89	–11.40	20.00	21.72	0.49	–5.40	11.40	13.72
5.5	1.39	–43.10	55.30	55.27	1.09	–20.90	31.40	32.43	0.89	–12.10	20.90	22.60	0.49	–5.80	12.00	14.32
5.6	1.39	–43.50	55.70	55.65	1.09	–21.10	31.60	32.61	0.89	–12.20	21.10	22.84	0.49	–5.90	12.20	14.57
5.7	1.39	–43.80	56.10	56.07	1.09	–21.30	31.80	32.79	0.89	–12.40	21.20	22.83	0.49	–6.00	12.30	14.62
5.8	1.39	–44.20	56.60	56.58	1.09	–21.50	32.10	33.11	0.89	–12.50	21.40	23.08	0.49	–6.00	12.40	14.82
5.9*	1.39*	–44.60*	57.00*	56.97*	1.09*	–21.70*	32.30*	33.29*	0.89*	–12.60*	21.60*	23.32*	0.49*	–6.10*	12.50*	14.87*
6.0	1.39	–44.90	57.40	57.38	1.09	–21.90	32.60	33.62	0.89	–12.70	21.70	23.40	0.49	–6.10	12.60	15.07
8.0	1.69	–51.00	65.30	65.17	1.39	–24.90	37.20	38.20	1.09	–14.50	24.90	26.80	0.69	–7.00	14.50	17.12
10.0	1.99	–56.20	72.10	71.83	1.59	–27.40	41.10	42.19	1.29	–16.00	27.60	29.63	0.79	–7.80	16.10	18.93
12.0	2.19	–60.80	78.10	77.79	1.79	–29.70	44.60	45.70	1.39	–17.30	29.90	32.14	0.89	–8.40	17.50	20.62

* Theoretical choked flow, refer to Appendix A1.

Appendix C—Miller Model Implementation (Informative)

This appendix outlines the algorithm that was used to implement the Miller model [28]. This was accomplished in MathCad 15.0 [29]. Refer to Mathcad manuals to understand the programming symbols and sequencing. Additionally, a dynamic lookup library of thermodynamic properties is embedded into the sequence that determines isentropic expansion and choking flows. Readers interested in implementing their own algorithm will need to establish a thermodynamic variable database.

Various fixed variables

fluid_name = "Para Hydrogen"

$H_c := Hcomb(fluid) = 119.95 \cdot \frac{MJ}{kg}$ Heat of combustion

$M_{air} := 28.96$

$M_{h2} := 2.016$

$Tad := 2377 \cdot K$ based on GCPS 2016: Miller eq 8

$M_{combP} := 24.7$

Inside Diameter of Leaking Pipe

$Tref := 293 \cdot K$ Reference temperature for industry based emperical data sets

$RH := 50\%$ Relative Humidity

Determining the transmissivity of the air per Wayne

$$tau\_wayne(D,T,RH) := \begin{vmatrix} Smm \leftarrow 0.0075 \cdot e^{\left[23.18986-\left(\frac{3816.42}{\frac{T}{K}-46.13}\right)\right]} \\ XairCD \leftarrow 273 \cdot \frac{\frac{D}{m}}{\frac{T}{K}} \\ XairWA \leftarrow 288.651 \cdot \frac{RH \cdot \frac{D}{m} \cdot Smm}{\frac{T}{K}} \\ tau \leftarrow 1.003 - 0.01171 \cdot \log(XairWA) - 0.02368 \cdot \log(XairWA)^2 - 0.03188 \cdot \log(XairCD) + 0.001164 \cdot \log(XairCD)^2 \\ tau \end{vmatrix}$$

$$tau(D,Tamb) := \begin{vmatrix} 1 \text{ if } tau\_wayne(D,Tamb,RH) > 1 \\ tau\_wayne(D,Tamb,RH) \text{ otherwise} \end{vmatrix}$$

$$k(t,p) := \begin{vmatrix} k \leftarrow \frac{CP_{tp}(t,p)}{CV_{tp}(t,p)} \text{ if } Q_{tp}(t,p) \geq 1.0 \\ k \leftarrow \frac{CP_{tq}(t,1)}{CV_{tq}(t,1)} \text{ if } Q_{tp}(t,p) < 1.0 \end{vmatrix}$$

$$C(T,P) := \begin{vmatrix} k \leftarrow k(T,P) \\ c \leftarrow 520 \cdot \sqrt{\left[k \cdot \left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}\right]} \end{vmatrix}$$

$$
\begin{aligned}
&\mathrm{Expdat}(\mathrm{Trelease}, \mathrm{mdot}, d_{pipe}) := \\
&\quad \Delta P \leftarrow 1000 \cdot \mathrm{psi} \\
&\quad \mathrm{errorcheck} \leftarrow 1 \\
&\quad \mathrm{errorlimit} \leftarrow 0.0001 \\
&\quad \text{while errorcheck} > \mathrm{errorlimit} \\
&\qquad \mathrm{Pthroat\_guess} \leftarrow \mathrm{atm} + \Delta P \\
&\qquad S_{throat} \leftarrow S_{tp}(\mathrm{Trelease}, \mathrm{Pthroat\_guess}) \\
&\qquad \rho_{throat} \leftarrow D_{tp}(\mathrm{Trelease}, \mathrm{Pthroat\_guess}) \\
&\qquad u_{throat} \leftarrow \frac{\mathrm{mdot}}{\rho_{throat} \cdot \frac{\pi}{4} \cdot d_{pipe}^{2}} \\
&\qquad H_{throat} \leftarrow H_{ps}(\mathrm{Pthroat\_guess}, S_{throat}) \\
&\qquad H_{exp} \leftarrow H_{ps}(\mathrm{atm}, S_{throat}) \\
&\qquad u_{exp\_E} \leftarrow \left[(H_{throat} - H_{exp}) \cdot 2 + u_{throat}^{2}\right]^{0.5} \\
&\qquad u_{exp\_momentum} \leftarrow u_{throat} + \frac{\mathrm{Pthroat\_guess} - \mathrm{atm}}{u_{throat} \cdot \rho_{throat}} \\
&\qquad \mathrm{errorcheck} \leftarrow \left[\left(\frac{u_{exp\_momentum} - u_{exp\_E}}{u_{exp\_E}}\right)^{2}\right]^{0.5} \\
&\qquad \mathrm{Pthroat\_guess} \leftarrow \mathrm{Pthroat\_guess} - \Delta P \ \text{ if errorcheck} > \mathrm{errorlimit} \\
&\qquad \Delta P \leftarrow \frac{\Delta P}{10} \ \text{ if errorcheck} > \mathrm{errorlimit} \\
&\quad \rho_{exp\_unchoked} \leftarrow D_{ps}(\mathrm{atm}, S_{tp}(\mathrm{Trelease}, \mathrm{Pthroat\_guess})) \\
&\quad T_{exp\_unchoked} \leftarrow T_{ps}(\mathrm{atm}, S_{tp}(\mathrm{Trelease}, \mathrm{Pthroat\_guess})) \\
&\quad \mathrm{Mach}_{throat} \leftarrow \frac{u_{throat}}{W_{dt}(\rho_{throat}, \mathrm{Trelease})} \\
&\quad \mathrm{Mach}_{exp} \leftarrow \frac{u_{exp\_E}}{W_{dt}(\rho_{exp\_unchoked}, T_{exp\_unchoked})} \\
&\quad \mathrm{Choked} \leftarrow \begin{cases} 1 & \text{if } \mathrm{Mach}_{throat} > 1.0 \\ 1 & \text{if } \mathrm{Mach}_{exp} > 1.0 \\ 0 & \text{otherwise} \end{cases} \\
&\quad \mathrm{Pthroat} \leftarrow \begin{cases} \mathrm{ChokeP}(\mathrm{Trelease}, \mathrm{mdot}, d_{pipe}) & \text{if Choked} \\ \mathrm{Pthroat\_guess} & \text{otherwise} \end{cases}
\end{aligned}
$$

This routine uses constant entropy to check for momentum and energy balance at the exit of the vent while checking for sonic velocity and choked flow. Various dynamic lookups are used to import thermodynamic properties of hydrogen.

Routine continued on next page

Routine continued from previous page

$$\begin{aligned}
&Pthroat \leftarrow \begin{cases} ChokeP(Trelease, mdot, d_{pipe}) & \text{if Choked} \\ Pthroat_guess & \text{otherwise} \end{cases} \\
&\rho_{throat} \leftarrow D_{tp}(Trelease, Pthroat) \\
&\rho_{exp} \leftarrow \begin{cases} D_{tp}(T_{exp_unchoked}, atm) & \text{if Choked} \\ D_{ps}(atm, S_{tp}(Trelease, Pthroat)) & \text{otherw} \end{cases} \\
&T_{exp} \leftarrow \begin{cases} T_{pd}(atm, \rho_{exp}) & \text{if Choked} \\ T_{ps}(atm, S_{tp}(Trelease, Pthroat)) & \text{otherw} \end{cases} \\
&u_{throat} \leftarrow \frac{mdot}{\rho_{throat} \cdot \frac{\pi}{4} \cdot d_{pipe}^2} \\
&u_{exp} \leftarrow \begin{cases} W_{dt}(\rho_{exp}, T_{exp}) & \text{if Choked} \\ u_{exp_momentum} & \text{otherwise} \end{cases} \\
&data_0 \leftarrow \frac{Pthroat - atm}{psi} \\
&data_1 \leftarrow \frac{\rho_{throat}}{\frac{kg}{m^3}} \\
&data_2 \leftarrow \frac{u_{throat}}{\frac{m}{s}} \\
&data_3 \leftarrow \frac{\rho_{exp}}{\frac{kg}{m^3}} \\
&data_4 \leftarrow \frac{T_{exp}}{K} \\
&data_5 \leftarrow \frac{u_{exp}}{\frac{m}{s}} \\
&data_6 \leftarrow Mach_{throat} \\
&data_7 \leftarrow Mach_{exp} \\
&data_8 \leftarrow Choked \\
&data_9 \leftarrow \frac{W_{dt}(\rho_{exp}, T_{exp})}{\frac{m}{s}} \\
&data_{10} \leftarrow \frac{W_{dt}(\rho_{throat}, Trelease)}{\frac{m}{s}} \\
&data
\end{aligned}$$

This routine uses constant entropy to check for momentum and energy balance at the exit of the vent while checking for sonic velocity and choked flow. Various dynamic lookups are used to import thermodynamic properties of hydrogen.

The data set is exported from the routine as an array.

$$\text{Fnd\_LBO\_miller}(\text{Trelease}, \text{mdot}, d_{pipe}, \text{Tamb}) :=$$

$$\rho_{air} \leftarrow \rho\_air(\text{Tamb})$$

$$W_{st} \leftarrow \frac{M_{h2}}{15.816 \cdot M_{h2} + 39.5}$$

$$\beta \leftarrow \sqrt{\frac{M_{air} \cdot \text{Tad}}{M_{combP} \cdot \text{Tamb}}}$$

$$\Delta LBO \leftarrow 1 \cdot ft$$

$$LBO \leftarrow 0 \cdot ft$$

$$LBOprecision \leftarrow 0.01 \cdot ft$$

$$u_{exp} \leftarrow \text{Expdat}(\text{Trelease}, \text{mdot}, d_{pipe})_5 \cdot \frac{m}{s}$$

$$\rho_{exp} \leftarrow \text{Expdat}(\text{Trelease}, \text{mdot}, d_{pipe})_3 \cdot \frac{kg}{m^3}$$

$$d_{exp} \leftarrow \sqrt{\frac{\text{mdot}}{\rho_{exp} \cdot u_{exp}} \cdot \frac{4}{\pi}}$$

$$D_s \leftarrow d_{exp} \cdot \left(\frac{\rho_{exp}}{\rho_{air}}\right)^{.5}$$

$$\text{done} \leftarrow 0$$

$$\text{while done} \neq 1$$

$$\quad LBO \leftarrow LBO + \Delta LBO$$

$$\quad \text{error\_chk} \leftarrow \left(\frac{D_s \cdot \beta}{LBO \cdot W_{st}}\right)^{\frac{2}{3}} - \left[0.2 + 0.024 \cdot \left(\frac{g}{D_s^{\,2} \cdot u_{exp}^{\,2}}\right)^{\frac{1}{3}} \cdot LBO\right]$$

$$\quad LBO \leftarrow LBO - \Delta LBO \ \text{ if error\_chk} < 0$$

$$\quad \Delta LBO \leftarrow \frac{\Delta LBO}{10} \ \text{ if error\_chk} < 0$$

$$\quad \text{done} \leftarrow 1 \ \text{ if } \Delta LBO < LBOprecision$$

$$LBO$$

This routine predicts the length of flame with no wind “Lb0”. It is based on the original work by Chamberlain and used in the Miller Method.

$$FLAME\_DATA\_miller(Trelease, mdot, d_{pipe}, u_{wind}, Tamb) :=$$

$$L_{BO} \leftarrow Fnd\_LBO(Trelease, mdot, d_{pipe}, Tam$$

$$\rho_{air} \leftarrow \rho\_air(Tamb)$$

$$u_{exp} \leftarrow Expdat(Trelease, mdot, d_{pipe})_5 \cdot \frac{m}{s}$$

$$\rho_{exp} \leftarrow Expdat(Trelease, mdot, d_{pipe})_3 \cdot \frac{kg}{m^3}$$

$$d_{exp} \leftarrow \sqrt{\frac{mdot}{\rho_{exp} \cdot u_{exp}} \cdot \frac{4}{\pi}}$$

$$D_s \leftarrow d_{exp} \cdot \left(\frac{\rho_{exp}}{\rho_{air}}\right)^{.5}$$

$$Ri \leftarrow \left(\frac{g}{D_s^{\,2} \cdot u_{exp}^{\,2}}\right)^{\frac{1}{3}} \cdot L_{BO}$$

$$Rch \leftarrow \frac{u_{wind}}{u_{exp}}$$

$$\alpha \leftarrow \begin{cases} \left(\frac{8000 \cdot Rch}{Ri}\right) \cdot deg & \text{if } Rch \le 0.05 \\ \left[\frac{1726 \cdot (Rch - 0.026)^{0.5} + 134}{Ri}\right] \cdot deg & \text{otherwise} \end{cases}$$

$$Xng \leftarrow \frac{\frac{L_{BO}}{m}}{174.83 \cdot \left(\frac{d_{pipe}}{m}\right)^{0.8794}}$$

$$Yng \leftarrow \begin{cases} \left(2.0074 \cdot Xng^2 - 1.0103 \cdot Xng + 0.0185\right) & \text{if } Xng > 0.665 \\ \left(0.7873 \cdot Xng^{2.9013}\right) & \text{otherwise} \end{cases}$$

$$mdotng \leftarrow 255.42 \cdot \left(\frac{d_{pipe}}{m}\right)^2 \cdot Yng \cdot \frac{kg}{s}$$

$$\alpha\_miller \leftarrow \begin{cases} (0 \cdot deg) & \text{if } \alpha \cdot \frac{mdotng}{mdot} < 0 \\ (90 \cdot deg) & \text{if } \alpha \cdot \frac{mdotng}{mdot} > 90 \cdot deg \\ \left(\alpha \cdot \frac{mdotng}{mdot}\right) & \text{otherwise} \end{cases}$$

$$R60 \leftarrow \begin{cases} \left[0.026 + \left[\frac{\left(60 \cdot Ri \cdot \frac{mdot}{mdotng} - 134\right)}{1726}\right]^2\right] & \text{if } \frac{60 \cdot Ri \cdot mdot}{mdotng \cdot 8000} > 0.05 \\ \frac{60 \cdot Ri \cdot mdot}{mdotng \cdot 8000} & \text{otherwise} \end{cases}$$

$$uwind60 \leftarrow R60 \cdot u_{exp}$$

This is the main routine used to predict the flame geometry in the Miller Method. This method is based on the original work by Chamberlain for natural gas and is corrected for momentum of hydrogen.

Routine continued next page

Routine continued from previous page

$$uwind60 \leftarrow R60 \cdot u_{exp}$$

$$LBratio60 \leftarrow 0.49 + 0.51 \cdot e^{-0.4 \cdot \frac{uwind60}{\frac{m}{s}}}$$

$$b\_miller \leftarrow \frac{1}{30} \cdot \ln\left(\frac{1}{LBratio60}\right)$$

$$a\_miller \leftarrow e^{-90 \cdot b\_miller}$$

$$L_B \leftarrow \begin{cases} \left(L_{BO} \cdot a\_miller \cdot e^{b\_miller \cdot \frac{\alpha\_miller}{deg}}\right) & \text{if } \alpha\_miller > 60 \cdot deg \\ \left[L_{BO} \cdot \left(0.49 + 0.51 \cdot e^{-0.4 \cdot \frac{u_{wind}}{\frac{m}{s}}}\right)\right] & \text{otherwise} \end{cases}$$

$$b \leftarrow \begin{cases} 0.2 \cdot L_B & \text{if } \alpha = 0 \cdot deg \\ (0.015 \cdot L_B) & \text{if } \alpha = 180 \cdot deg \\ \left[L_B \cdot \frac{\sin\left[\left(0.185 \cdot e^{-20 \cdot Rch} + .015\right) \cdot \alpha\right]}{\sin(\alpha)}\right] & \text{otherwise} \end{cases}$$

$$R_L \leftarrow \left[L_B^{\,2} - (b \cdot \sin(\alpha\_miller))^2\right]^{.5} - b \cdot \cos(\alpha\_miller)$$

$$FData_0 \leftarrow \frac{L_{BO}}{m}$$

$$FData_1 \leftarrow Ri$$

$$FData_2 \leftarrow \frac{u_{wind}}{\frac{m}{s}}$$

$$FData_3 \leftarrow Rch$$

$$FData_4 \leftarrow \frac{\alpha}{deg}$$

$$FData_5 \leftarrow Xng$$

$$FData_6 \leftarrow Yng$$

$$FData_7 \leftarrow \frac{mdotng}{\frac{kg}{s}}$$

$$FData_8 \leftarrow \frac{\alpha\_miller}{deg}$$

$$FData_9 \leftarrow R60$$

$$FData_{10} \leftarrow \frac{uwind60}{\frac{m}{s}}$$

$$FData_{11} \leftarrow LBratio60$$

$$FData_{12} \leftarrow b\_miller$$

$$FData_{13} \leftarrow a\_miller$$

$$FData_{14} \leftarrow \frac{L_B}{m}$$

$$FData_{15} \leftarrow \frac{b}{m}$$

$$FData_{16} \leftarrow \frac{R_L}{m}$$

$$FData$$

This is the main routine used to predict the flame geometry in the Miller Method. This method is based on the original work by Chamberlain for natural gas and is corrected for momentum of hydrogen.

$$Fs\_Miller(mdot) := 0.1691 - 0.01 \cdot \ln\left[\frac{\frac{mdot}{\frac{kg}{s}}}{\frac{\pi}{4} \cdot \left(\frac{d_{pipe}}{m}\right)^2}\right]$$

The radiant heat fraction based on mass flux is used to predict the heat profiles.

Segments = 29 IntesityA = 0 IntesityB = 1

kk := 0, 1.. Segments + 1 LenA = 0 LenB = 0.67

KKA := trunc(Segments · LenA) = 0

KKB := trunc(Segments · LenB) = 19

```
ww := | kk ← 1
      | while kk ≤ Segments + 1
      |   | ww_kk ← | (IntesityA / KKA · kk)  if kk ≤ KKA
      |   |         | [IntesityB − IntesityB / (Segments + 1 − KKB) · (kk − KKB)]  if kk > KKB
      |   |         | [IntesityA + (IntesityB − IntesityA) / (KKB − KKA + 1) · (kk − KKA)]  otherwise
      |   | kk ← kk + 1
      | ww_(Segments+1) ← 0
      | scaling ← Σ_(nn=0)^(Segments+1) ww_nn
      | kk ← 0
      | while kk < Segments + 1
      |   | ww_kk ← ww_kk / scaling
      |   | kk ← kk + 1
      | ww
```

The heat is distributed along the predicted flame length over 30 discrete points that are weighed to a maximum contribution at 2/3 of the flame length.

```
Len(L_F) := | jj ← 1
            | while jj ≤ Segments + 1
            |   | L_jj ← jj / (Segments + 1) · L_F
            |   | jj ← jj + 1
            | L
```

YY is verticak
XX is horizontal (along the jet for a horizontal jet
ZZ is out of the page. (Assume ZZ = 0 for both the jet and the receiver)

Worst case is a horizontal jet wih the receiver in the downstream XX direction

$$
\begin{aligned}
YY(\alpha,\delta,\theta_{vert},b,R_L) :=\ & jj \leftarrow 0 \\
& \alpha \leftarrow if(\theta_{vert} < 45deg, \alpha, 0deg) \\
& \delta \leftarrow if(\theta_{vert} < 45deg, 0deg, \delta) \\
& L_F \leftarrow b + R_L \\
& LL \leftarrow Len(L_F) \\
& YY_{jj} \leftarrow H \\
& \Delta b\_y \leftarrow \cos(\theta_{vert}) \cdot b \\
& \Delta R_{L\_y} \leftarrow \cos(\theta_{vert} + \alpha - \delta) \cdot R_L \\
& \text{while } jj \le Segments + 1 \\
& \quad \Delta Y \leftarrow if\left(LL_{jj} \le b, \frac{LL_{jj} - LL_{jj-1}}{b} \Delta b\_y, \frac{LL_{jj} - LL_{jj-1}}{R_L} \Delta R_{L\_y}\right) \text{ if } jj > 0 \\
& \quad YY_{jj} \leftarrow YY_{jj-1} + \Delta Y \text{ if } jj > 0 \\
& \quad jj \leftarrow jj + 1 \\
& YY
\end{aligned}
$$

A set of point locations, XX and YY are defined along the flame length and tilt.

$$
\begin{aligned}
XX(\alpha,\delta,\theta_{vert},b,R_L) :=\ & jj \leftarrow 0 \\
& \alpha \leftarrow if(\theta_{vert} < 45deg, \alpha, 0deg) \\
& \delta \leftarrow if(\theta_{vert} < 45deg, 0deg, \delta) \\
& L_F \leftarrow b + R_L \\
& LL \leftarrow Len(L_F) \\
& XX_{jj} \leftarrow release\_x\_offset \\
& \Delta b\_x \leftarrow \sin(\theta_{vert}) \cdot b \\
& \Delta R_{L\_x} \leftarrow \sin(\theta_{vert} + \alpha - \delta) \cdot R_L \\
& \text{while } jj \le Segments + 1 \\
& \quad \Delta X \leftarrow if\left(LL_{jj} \le b, \frac{LL_{jj} - LL_{jj-1}}{b} \Delta b\_x, \frac{LL_{jj} - LL_{jj-1}}{R_L} \Delta R_{L\_x}\right) \text{ if } jj > 0 \\
& \quad XX_{jj} \leftarrow XX_{jj-1} + \Delta X \text{ if } jj > 0 \\
& \quad jj \leftarrow jj + 1 \\
& XX
\end{aligned}
$$

$$
\begin{aligned}
Dist(\alpha,\delta,\theta_{vert},b,R_L,Rec\_x,Rec\_y) :=\ & Xjet \leftarrow XX(\alpha,\delta,\theta_{vert},b,R_L) \\
& Yjet \leftarrow YY(\alpha,\delta,\theta_{vert},b,R_L) \\
& jj \leftarrow 0 \\
& \text{while } jj \le Segments + 1 \\
& \quad Dist_{jj} \leftarrow \left[(Rec\_x - Xjet_{jj})^2 + (Yjet_{jj} - Rec\_y)^2\right]^{.5} \\
& \quad jj \leftarrow jj + 1 \\
& Dist
\end{aligned}
$$

A given point of a receptor is used to create an array of distances from that point to each of the heat points (30) along the flame length

$$
q_{rad} := \begin{array}{|l} kk \leftarrow 1 \\ radfrac_0 \leftarrow 0 \\ radfrac_{Segments+1} \leftarrow 0 \\ \text{while } kk < Segments + 1 \\ \quad \begin{array}{|l} radfrac_{kk} \leftarrow Fs(mdot) \cdot \left(H_c \cdot mdot \cdot ww_{kk}\right) \\ kk \leftarrow kk + 1 \end{array} \\ radfrac \end{array}
$$

The heat from any one point along the flame is the product of the radiant heat fraction, the mass flow rate, the weighting factor and the heat of combustion.

$$
FLUX(mdot, \alpha, \delta, b, R_L, Rec\_x, Rec\_y) := \begin{array}{|l} DIST \leftarrow Dist(\alpha, \delta, \theta_{vert}, b, R_L, Rec\_x, Rec\_y) \\ q_{total} \leftarrow \displaystyle\sum_{n=0}^{Segments+1} \left[\frac{q_{rad_n} \cdot tau(DIST_n, Tamb)}{4 \cdot \pi \cdot (DIST_n)^2} \right] \\ q_{total} \end{array}
$$

This formula for FLUX can then be used to calculate a heat flux at a given point or to create a generalized heat flux profile.

Appendix D—Worked examples (Informative)

This appendix offers examples of implementing the options for assessing the limits of the heat flux profiles outlined in Section 5. These examples are intended to be demonstrative of the numeric manipulations and may not be completely comprehensive to an overall vent location study.

In many cases a method of linear interpolation is employed to determine a reasonable set of heat flux parameters. A linear interpolation involves identifying a control variable *X* and then assessing an upper and lower bound set of *X* and *Y*.

Where:

Lower Bound = X_{lower}, Y_{lower}

Upper bound = X_{upper}, Y_{upper}

Control variable = $X_{control}$

Interpolation = $Y_{conrol} = Y_{lower} + \left(\frac{X_{control} - X_{lower}}{X_{upper} - X_{lower}}\right) \bullet (Y_{upper} - Y_{lower})$

D1 Cryogenic trailer restricted radius (using Appendix A curve fit)

D1.1 Example A: Cryogenic trailer restricted radius (using Appendix A curve fit)

A designer has the following trailer design:

1. An engineer has the following:
   - Primary relief valve mass flow requirement per CGA S-1.2 is 0.314 kg/s [2]
   - A 3 inch NPS pipe size vent stack height H_{stack} is 3.5 m above grade
2. Confirm: Restricted radius below the stack to not exceed 20 kW/m^2
3. Confirm: Setback distance from the stack no more than 9.46 kW/m^2 at 1.8 m above grade.

Step 1—Determine the 20 kW/m^2 restricted radius limit below the Vent stack using Y_{cr}

From Table A-4

$Y_{cr} = -1.798335 \bullet 0.314^{0.3032049} - 0.1128666 = -1.38$ m

20 kW/m^2 heat flux extends 3.5 m - 1.38 m = 2.12 m above grade which is higher than 1.8 m, therefore there is no X_{int} to calculate.

Step 2—Determine the flux parameters for controlled radius 9.46 kW/m^2

From Table A-4

$X_{cr} = -30.14887 \bullet (0.314 - 0.4697635)^2 + (-9.287011) \bullet (0.314 - 0.4697635) + 5.730802 = 6.45$ m

$Y_{cr} = -4.66055 \bullet 0.314^{0.3317135} + 0.0285885 = -3.15$ m

$N_R = -91.82483 \bullet (0.314 - 0.3223101)^2 + (-1.476975) * (0.314 - 0.3223101) + 11.14745 = 11.15$ m

Step 3—Determine *X* such that 9.46 kW/m^2 does not extend below 1.8 m

$Y_X = Y_{int} - H_{stack} - Y_{cr} = 1.8 - 3.5 - (-3.15) = 1.45$ m & $X = \sqrt{11.15^2 - (11.15 - 1.45)^2} = 5.5$ m

The distance from the stack for the restricted radius is $X_{int} = X + X_{cr} = 5.5 + 6.45 = 11.95$ m

During offloads a trained operator maintains 12 m distance from vent stack as restricted radius.

D1.2 Example B: Cryogenic trailer restricted radius (using direct Appendix A flux parameters)

A designer has the following trailer design:

1. An engineer has the is listed below:
   - Primary relief valve mass flow requirement per CGA S-1.2 is 0.314 kg/s [2]
   - A 3 inch NPS pipe size vent stack height H_{stack} is 3.5 m above grade
2. Confirm: Restricted radius below the stack to not exceed 20 kW/m2
3. Confirm: Setback distance from the stack no more than 9.46 kW/m2 at 1.8 m above grade.

Step 1—Determine the 20 kW/m^2 restricted radius limit below the Vent stack using Y_{cr}

From Table A-10 next highest mass flow rate (0.4 kg/s)

$Y_{cr} = -1.47$ m

20 kW/m^2 heat flux extends 3.5 m - 1.47 m = 2.03 m above grade which is higher than 1.8 m, therefore there is no X_{int} to calculate.

Step 2—Determine the flux parameters for controlled radius 9.46 kW/m^2

From Table A-10 next highest flow rate (0.4 kg/s)

$X_{cr} = 6.23$ m

$Y_{cr} = -3.41$ m

$N_R = 10.48$ m

Step 3—Determine X such that 9.46 kW/m^2 does not extend below 1.8 m

$Y_x = Y_{int} - H_{stack} - Y_{cr} = 1.8 - 3.5 - (-3.41) = 1.71$ m & $X = \sqrt{10.48^2 - (10.48 - 1.71)^2} = 5.74$ m

The distance from the stack for the restricted radius is $X_{int} = X + X_{cr} = 5.74 + 6.23 = 11.97$ m

During offloads a trained operator maintains 12 m distance from vent stack as restricted radius.

D1.3 Example C: Cryogenic trailer restricted radius (interpolating Appendix B parameters)

A designer has the following trailer design:

1. An engineer has the following system configuration:

– Primary relief valve mass flow requirement per CGA S-1.2 is 0.314 kg/s [2]

– A 3 inch NPS pipe size vent stack height H_{stack} is 3.5 m above grade

2. Confirm: Restricted radius below the stack to not exceed 20 kW/m^2

3. Confirm: Setback distance from the stack no more than 9.46 kW/m^2 at 1.8 m above grade.

1.

Step 1—Determine the 20 kW/m^2 restricted radius limit below the Vent stack using *Ycr*

From Table B-4

Lower Bound: 0.3 kg/s, Y_{cr} = –0.80 m

Upper Bound: 0.4 kg/s, Y_{cr} = –0.80 m

3 inch NPS, MFlow = 0.314 kg/s; Interpolating Y_{cr} = –0.80 m

20 kW/m^2 heat flux extends 3.5 m - 0.80 m = 2.7 m above grade which is higher than 1.8 m therefore there is no X_{int} to calculate.

Step 2—Determine the flux parameters for controlled radius 9.46 kW/m^2

From Table B-4 next highest flow rate (0.4 kg/s)

Lower Bound: 0.30kg/s, X_{cr} = 7.49m, Y_{cr}= -2.7m, NR= 10.99m

Upper Bound: 0.40kg/s, X_{cr} = 4.29m, Y_{cr}= -2.9m, NR= 10.68m

3 inch NPS, MFlow = 0.314 kg/s : Interpolating, X_{cr} = 7.04 m Y_{cr} = –2.73 m N_R = 10.95 m

Step 3—Determine *X* such that 9.46 kW/m^2 does not extend below 1.8 m

$Y_x = Y_{int} - H_{stack} - Y_{cr} = 1.8 - 3.5 - (–2.73) = 1.03$ m & $X = \sqrt{10.95^2 – (10.95 – 1.03)^2} = 4.64$ m

The distance from the stack for the restricted radius is $X_{int} = X + X_{cr} = 4.64 + 7.04 = 11.68$ m

During offloads a trained operator maintains 12 m distance from vent stack as restricted radius.

D2 Bulk hydrogen system with a 25 ft (7.6 m) vent stack and 0.314 kg/s primary relief is acceptable

D2.1 Example A: Bulk hydrogen system (using Appendix A curve fit)

1. An Engineer has the following system configuration:

– Primary relief valve mass flow requirement per CGA S-1.2 is 0.314 kg/s [2]

– A 2 inch pipe size vent stack of 25 ft (7.6 m) height

2. Confirm: Vent stack height is adequate to not require a Restricted (fenced) or PPE, Heat flux < 4.732 kW/m^2

3. Confirm: Buildable property line and setback distance from the stack at 1.8 m above grade is at or below 1.577 kW/m^2

2.

Step 1—Determine the heat flux acceptable for monitored radius (< 4.732 kW/m^2) limit below the stack using Y_{cr}

From Table A-3

$Y_{cr} = –7.714363 \cdot 0.314^{0.3600595} + 0.0770667 = –5.00$ m

4.732 kW/m^2 heat flux extends 7.6 m - 5 m = 2.6 m above grade which is higher than 1.8 m therefore there is no X_{int} to calculate.

Step 2—Determine the flux parameters for 1.577 kW/m^2

From Table A-3

X_{cr}= -389381.3 $\cdot$ 0.314$^{0.000001228154}$ + 389383.0 = 2.25 m

$Y_{cr} = –16.989 \cdot 0.314^{0.3894555} + 0.1257795 = –10.7$ m

$N_R = 18.62601 \cdot 0.314^{0.5664149} + 4.763955 = 14.4$ m

Step 3—Determine X such that 1.577 kW/m^2 does not extend into property line at 1.8 m

$Y_x = Y_{int} - H_{stack} - Y_{cr} = 1.8 - 7.6 - (–10.7)$, $Y_x = 4.9$ m & $X = \sqrt{14.4^2 - (14.4 – 4.9)^2} = 10.83$ m

The distance from the stack for the monitored radius is $X_{int} = X + X_{cr} = 10.83 + 2.25 = 13.08$ m

The vent stack is positioned 13 m from a property line that can be built upon.

D2.2 Example B: Bulk hydrogen system (using direct Appendix A flux parameters)

1. An Engineer has the following system configuration:
   - Primary relief valve mass flow requirement per CGA S-1.2 is 0.314 kg/s [2]
   - A 2 inch pipe size vent stack of 25 ft (7.6 m) height
2. Confirm: Vent stack height is adequate to not require a Restricted (fenced) or PPE, Heat flux < 4.732 kW/m^2
3. Confirm: Buildable property line and setback distance from the stack at 1.8m above grade is at or below 1.577 kW/m^2
3.

Step 1—Determine the 4.732 kW/m^2 limit below the stack using *Ycr*

From Table A-15 next highest mass flow rate (0.4 kg/s)

$Y_{cr} = –5.47$ m

4.732 kW/m^2 heat flux extends 7.6 m - 5.47 m = 2.13 m above grade which is higher than 1.8 m therefore there is no X_{int} to calculate.

Step 2—Determine the flux parameters for 1.577 kW/m^2

From Table A-15 next highest flow rate (0.4 kg/s)

X_{cr} = 2.14 m Y_{cr} = –11.76 m N_R= 15.85 m

Step 3—Determine X such that 1.577 kW/m^2 does not extend below 1.8 m

$Y_x = Y_{int} - H_{stack} - Y_{cr}$ = 1.8 - 7.6 - (–11.76) = 5.96 m & $X = \sqrt{15.85^2 - (15.85 - 5.96)^2} = 12.39$ m

The distance from the stack for the monitored radius is $X_{int} = X + X_{cr}$ = 12.39 + 2.14 = 14.53 m

The vent stack is positioned 14 m from a property line that can be built upon.

D2.3 Example C: Bulk hydrogen system (interpolating Appendix B parameters)

1. An engineer has the following system configuration:
   - Primary relief valve mass flow requirement per CGA S-1.2 is 0.314 kg/s [2]
   - A 2 inch pipe size vent stack of 25 ft (7.6 m) height
2. Confirm: Vent stack height is adequate to not require a restricted (fenced) or PPE, Heat flux < 4.732 kW/m^2
3. Confirm: Buildable property line and setback distance from the stack at 1.8m above grade is at or below 1.577 kW/m^2
4.

Step 1—Determine the 4.732 kW/m^2 limit below the stack using Ycr

From Table B-3

Lower Bound: 0.3 kg/s, Ycr = –4.70 m

Upper Bound: 0.4 kg/s, Ycr = –5.20 m

MFlow = 0.314 kg/s: Interpolating Ycr = –4.77 m

4.732 kW/m^2 heat flux extends 7.6 m - 4.77 m = 2.83 m above grade which is higher than 1.8 m therefore there is no X_{int} to calculate.

Step 2—Determine the flux parameters for 1.577 kW/m^2

From Table B-3 next highest flow rate (0.4 kg/s)

Lower Bound: 0.30 kg/s, X_{cr} = 2.29 m, Y_{cr} = -10.20m, N_R = 14.05 m

Upper Bound: 0.40 kg/s, X_{cr} = 1.89 m, Y_{cr} = -11.40m, N_R = 15.85 m

MFlow = 0.314 kg/s : Interpolating X_{cr} = 2.234 m Y_{cr} = –10.37 m N_R = 14.302 m

Step 3: Determine X such that 1.577 kW/m^2 does not extend below 1.8 m

$Y_x = Y_{int} - H_{stack} - Y_{cr}$ = 1.8 - 7.6 - (–10.37) = 4.57 m & $X = \sqrt{14.302^2 - (14.302 - 4.57)^2} = 10.478$ m

The distance from the stack for the monitored radius is $X_{int} = X + X_{cr}$ = 10.478 + 2.234 = 12.71 m

The vent stack is positioned 13 m from a property line that can be built upon.

D2.4 Example D: Split top vent bulk hydrogen restricted radius (using coefficients in curve fit equation)

1. An engineer has the following system configuration:

   - Primary relief valve mass flow requirement per CGA S-1.3 is 0.27 kg/s [3]
   - A 3 inch SCH10 pipe size vent stack of 25 ft (7.62 m) height splits into 4 inch T top works of 27 inch
     (0.69 m) high. Mass flow of 0.27 kg/s from T top works. Total vent height H_{stack} = 8.31 m
   - With assumption of combining flow after release, Equivalent ID of two 4 inch NPS release is
     - Split release 4 inch NPS total Area, Ac = 2 • (3.14159/4) • 4.26^2
     - Equivalent ID for combined flow of 0.27 kg/s = SQRT ((4/3.14159) • Ac) = 6.025 in.

2. Confirm: Vent stack height is adequate to affirm monitored radius (fenced) or PPE for heat flux < 4.732 kW/m^2 at operator height.

3. Confirm: Buildable property line and setback distance from the stack at 1.8 m above grade is at or below 1.577 kW/m^2

5.

Step 1—Determine monitored radius limit for heat flux (< 4.732 kW/m^2) below the Vent stack using Y_{cr}

From Table A-5 for next higher mass flow of 0.3 kg/s

Lower Bound 4 inch: $Y_{cr} = -8.252294 \cdot 0.3^{0.4338673} + (-0.5680488) = -5.46$ m

Upper Bound 10 inch: $Y_{cr} = -10.51341 \cdot 0.3^{0.3953494} + (-0.3582751) = -6.89$ m

6.025 inch, *MFlow* = 0.3 kg/s : Interpolating, $Y_{cr} = -5.87$ m

4.732 kW/m^2 heat flux extends 8.31 m - 5.87 m = 2.44 m above grade which is higher than 1.8 m, therefore there is no X_{int} to calculate.

Step 2—Determine the flux parameters for 1.577 kW/m^2

From Table A-5

Lower Bound 4 inch NPS parameters:

$X_{cr} = -34.15086 \cdot (0.3 - 0.5015043)^2 + (-4.965928) \cdot (0.3 - 0.5015043) + 9.252472 = 8.87$ m

$Y_{cr} = -18.0665 \cdot 0.3^{0.4311065} + (-0.6176433) = -11.37$ m

$N_R = -34.44988 \cdot (0.3 - 0.9170177)^2 + (-10.60864) \cdot (0.3 - 0.9170177) + 22.49794 = 15.93$ m

Upper Bound 10 inch NPS parameters:

$X_{cr} = -0.573759 \cdot (0.3 - 2.561653)^2 + 0.7622917 \cdot (0.3 - 2.561653) + 12.08808 = 7.43$ m

$Y_{cr} = -21.46663 \cdot 0.3^{0.4087784} + (-0.2540733) = -13.38$ m

$N_R = -6.015273 \cdot (0.3 - 5.386177)^2 + (-33.73609) \cdot (0.3 - 5.386177) + (-1.814725) = 14.16$ m

6.025 inch, *MFlow* = 0.3 kg/s : Interpolating, $X_{cr} = 8.45$ m $Y_{cr} = -11.94$m $N_R = 15.42$ m

Step 3—Determine X such that 1.577 kW/m^2 does not extend into property line at 1.8 m

$Y_x = Y_{int} - H_{stack} - Y_{cr} = 1.8 - 8.31 - (–11.94)$, $Y_x = 5.43$ m & $X = \sqrt{15.42^2 - (15.42 – 5.43)^2} = 11.75$ m

The distance from the stack for the monitored radius is $X_{int} = X + X_{cr} = 11.75 + 8.45 = 20.2$ m

The vent stack is positioned 20 m from a property line that can be built upon.

D2.5 Example E: 4-inch split T top vent bulk hydrogen restricted radius (interpolating Appendix A flux parameters)

1. An engineer has the following system configuration:
   - Primary relief valve mass flow requirement per CGA S-1.3 is 0.27 kg/s [3]
   - A 3 inch SCH10 pipe size vent stack of 25 ft (7.62 m) height splits into 4 inch T top works of 27 inch (0.69 m) high. Mass flow of 0.27kg/s from T top works. Total vent height H_{stack} = 8.31 m
   - With assumption of combining flow after release, Equivalent ID of two 4 inch NPS release is:
     - Split release 4 inch NPS total Area, Ac = 2 • (3.14159/4) • 4.26^2
     - Equivalent ID for combined flow of 0.27 kg/s = SQRT ((4/3.14159) • Ac) = 6.025 in.
2. Confirm: Vent stack height is adequate to affirm monitored radius (fenced) or PPE for Heat flux < 4.732 kW/m^2 at operator height.
3. Confirm: Buildable property line and setback distance from the stack at 1.8 m above grade is at or below 1.577 kW/m^2
6.

Step 1—Determine monitored radius limit for heat flux (< 4.732 kW/m^2) below the vent stack using Ycr

From Table A-10 next highest mass flow rate (0.3 kg/s)

Lower Bound: 4 inch NPS, *MFlow* = 0.3 kg/s, Ycr = –5.46 m

Upper Bound: 10 inch NPS, *MFlow* = 0.3 kg/s, Ycr = –6.47m

6.025 inch, *MFlow* = 0.3 kg/s : Interpolating, Ycr = –5.75 m

4.732 kW/m^2 heat flux extends 8.31 m - 5.75 m = 2.56 m above grade which is higher than 1.8 m, therefore there is no X_{int} to calculate.

Step 2—Determine the flux parameters for 1.577 kW/m^2.

From Table A-10 next highest flow rate (0.3 kg/s)

Lower Bound 4 inch NPS; *MFlow* = 0.3 kg/s, X_{cr} = 8.87 m Y_{cr} = –11.37 m N_R = 15.93 m

Upper Bound 10 inch NPS: *MFlow* = 0.3 kg/s, X_{cr} = 7.41 m Y_{cr} = –12.53 m N_R = 13.92 m

6.025 inch, *MFlow* = 0.3 kg/s: Interpolating, X_{cr} = 8.45 m Y_{cr} = –11.70 m N_R = 15.35 m

Step 3—Determine X such that 1.577 kW/m^2 does not extend below 1.8 m

$Yx = Yint - H_{stack} - Ycr = 1.8 - 8.31 - (–11.70) = 5.19$ m & $X = \sqrt{15.35^2 - (15.35 – 5.19)^2} = 11.51$ m

The distance from the stack for the monitored radius is $X_{int} = X + X_{cr}$ = 11.51 + 8.45 = 19.96 m

The vent stack is positioned 20 m from a property line that can be built upon.

D2.6 Example F: 4-inch Split T Top Vent Bulk Hydrogen Restricted Radius (interpolating Appendix B parameters)

1. An engineer has the following system configuration:
   - Primary relief valve mass flow requirement per CGA S-1.3 is 0.27 kg/s [3]
   - A 3 inch Sch10 pipe size vent stack of 25 ft (7.62 m) height splits into 4 inch T top works of 27 inch (0.69 m) high. Mass flow of 0.27 kg/s from T top works. Total vent height H_{stack} = 8.31 m
   - With assumption of combining flow after release, Equivalent ID of two 4 inch NPS release is:
     - Split release 4 inch NPS total Area, Ac = 2 • (3.14159/4) • 4.26^2
     - Equivalent ID for combined flow of 0.27 kg/s = SQRT (4/3.14159) • Ac) = 6.025 in.
2. Confirm: Vent stack height is adequate to affirm monitored radius (fenced) or PPE for eat flux < 4.732 kW/m^2 at operator height.
3. Confirm: Buildable property line and setback distance from the stack at 1.8 m above grade is at or below 1.577 kW/m^2

Step 1—Determine monitored radius limit for heat flux (< 4.732 kW/m^2) below the vent stack using Y_{cr}

From Table B-5

Lower Bound: 4 inch NPS, *MFlow* = 0.3 kg/s, Y_{cr} = –6.3 m

Upper Bound: 10 inch NPS, *MFlow* = 0.3 kg/s, Y_{cr} = –7.5 m

6.025 inch, *MFlow* = 0.3 kg/s, Interpolating Y_{cr} = –6.64 m

4.732 kW/m^2 heat flux extends 8.31 m - 6.64 m = 1.67 m above grade which is lower than 1.8 m.

Solutions: Determine X_{int} or increase vent stack height.

Step 2—Determine the model parameters for 1.577 kW/m^2

From Table B-5 next highest flow rate (0.3 kg/s)

Lower Bound 4 inch NPS: *MFlow* = 0.3 kg/s, X_{cr} = 9.49 m, Y_{cr} = –12.50 m, N_R = 15.87 m

Upper Bound 10 inch NPS: *MFlow* = 0.3 kg/s, X_{cr} = 10.94 m, Y_{cr} = –13.6m, N_R = 15.65 m

6.025 inch, *MFlow* = 0.3 kg/s: Interpolating X_{cr} = 9.90 m Y_{cr} = –12.81 m N_R = 15.81 m

Step 3—Determine X such that 1.577 kW/m^2 does not extend below 1.8 m

$Y_x = Y_{int} - H_{stack} - Y_{cr}$ = 1.8 - 8.31 - (–12.81) = 6.3 m & $X = \sqrt{15.81^2 - (15.81 - 6.3)^2}$ = 12.63 m

The distance from the stack for the monitored radius is $X_{int} = X + X_{cr}$ =12.63 m + 9.9 m = 22.53 m

The vent stack is positioned 23 m from a property line that can be built upon.

D2.7 Example G: 2 inch split T top horizontal release vent bulk hydrogen restricted radius

1. An Engineer has the following system configuration:
   - Primary relief valve mass flow requirement per CGA S-1.3 is 0.319 kg/s [3]
   - A 2 inch SCH10 pipe size vent stack of 41.38 ft (12.613 m) height splits into 2 inch T top works of 27 inch (0.69 m) high. Mass Flow horizontal of 0.319 kg/s from T top works. Total vent height H_{stack} = 13.303 m
   - With assumption of combining flow after release, Equivalent ID of two 2 inch NPS release is
     - Split release 2 inch NPS total Area, Ac = 2 • (3.14159/4) • 2.157^2
     - Equivalent ID for combined flow 0.319 kg/s = SQRT (4/3.14159) * Area) = 3.05 in.
2. Confirm: Buildable property line and setback distance from the stack at 1.8 m above grade is at or below 1.577 kW/m^2
7.

Step 1—Determine flow and exit velocities for equivalent diameter at 80 K cryogenic release

– VentDia = 2.157

– *mdot* = 0.319 kg/s

– H_{stack} = 13.303 m

– Y_{int} = 1.8 m

– *SFcryo* = 1.1

– *SFamb* = 1.25

– ρh2 = 0.308 $\frac{kg}{m^3}$ at 80K cryogenic release

– N_{R_4732} = 11.245 m from model output

– HeatInt = 4.732 kW/m^2

– DiaEq = 1.414 •

– VentDia = 0.077 m = 3.05 in

$$Qc = \frac{mdot}{\rho h2} = 1.036\ \frac{m^3}{s}$$

$$Uh2 = \frac{Qc}{\left[\frac{\pi}{4}\left(DiaEq \cdot \frac{25.4}{1000}\right)^2\right]} = 219.727\ m/s$$

Step 2—Determine $N_{R\ Horizontal}$, X_{crit} / Y_{crit} horizontal for heat of interest.

$$N_{R\_horizontal} = \left[\frac{SFcryo}{1+\left(\frac{5\frac{m}{s}}{Uh2\frac{m}{s}}\right)} \cdot NR\_4732\right] \cdot \sqrt{\frac{4.732}{HeatInt}} = 10.748\ m$$

$X_{crit\_horizontal} = N_{R\_horizontal}$ = 10.748 m $Y_{crit\_horizontal} = -N_{R\_horizontal}$ = –10.748 m

Step 3—Determine X such that 1.577 kW/m^2 does not extend into property line at 1.8 m

$Y_x = Y_{int} - (H_{stack} + Y_{crit\_horizontal}) = –0.755$ m & $X = \sqrt{10.748^2 - (10.748+(–0.755))^2} = 3.957$ m

The distance from the stack to the property line that can be built upon,

$X_{int} = X + X_{crit\_horizontal} = 3.957 + 10.748 = 14.705$ m

The system is positioned so that the vent stack is 15 m to a property line that can be built upon.

D2.8 Example H: Tube trailer with a 11.5 ft (3.5 m) vent stack and 0.05 kg/s TPRD relief is acceptable (<1.577 kW/m^2) for buildable property line (using Appendix A curve fit)

1. An Engineer has the following system configuration:
   - Primary relief valve mass flow requirement is 0.05 kg/s
   - A 1 inch NPS pipe size vent stack of H_{stack} 11.5 ft (3.5 m) height.
2. Confirm: Vent stack height is adequate to not require a restricted (fenced) or PPE for heat flux < 4.732 kW/m^2
3. Confirm: Buildable property line and setback distance from the stack at 1.8 m above grade is at or below 1.577 kW/m^2

8.

Step 1—Determine the heat flux acceptable for monitored radius (< 4.732 kW/m^2) limit below the stack using Y_{cr}

From Table A-14

$Y_{cr} = –7.898978 \cdot 0.05^{0.3979023} + 0.4901332 = –1.91$ m

4.732 kW/m^2 heat flux extends 3.5 m - 1.91 m = 1.59 m above grade which is lower than 1.8 m.

Solutions: Determine X_{int} or increase vent stack height.

Step 2—Determine the flux parameters for 1.577 kW/m^2

From Table A-14

$X_{cr} = 0.8573056 \cdot 0.050.8160998 + 0.2656358 = 0.34$ m

$Y_{cr} = –16.54333 \cdot 0.050.4211462 + 0.4264146 = –4.26$ m

$N_R = 21.47294 \cdot 0.050.4510063 + 0.1804674 = 5.74$ m

Step 3—Determine X such that 1.577 kW/m^2 does not extend into property line at 1.8 m

$Y_x = Y_{int} - H_{stack} - Y_{cr} = 1.8 - 3.5 - (–4.26)$, $Y_x = 2.56$ m & $X = \sqrt{5.74^2 - (5.74 – 2.56)^2} = 4.78$ m

The distance from the stack for the monitored radius is $X_{int} = X + X_{cr} = 4.78 + 0.34 = 5.12$ m

During offloads a trained operator maintains 6 m distance to a property line that can be built upon.

D2.9 Example I: Bulk hydrogen restricted radius (using direct Appendix A flux parameters)

1. An Engineer has the following system configuration:
   - Primary relief valve mass flow requirement is 0.05 kg/s
   - A 1 inch NPS pipe size vent stack of H_{stack} 11.5 ft (3.5 m) height.
2. Confirm: Vent stack height is adequate to not require a restricted (fenced) or PPE for heat flux < 4.732 kW/m^2
3. Confirm: Buildable property line and setback distance from the stack at 1.8 m above grade is at or below 1.577 kW/m^2
9.

Step 1—Determine the 4.732 kW/m^2 limit below the stack using Y_{cr}

From Table A-20 mass flow rate (0.05 kg/s)

Y_{cr} = –1.91 m

4.732 kW/m^2 heat flux extends 3.5 m - 1.91 m = 1.59 m above grade which is lower than 1.8 m.

Solutions: Determine X_{int} or increase vent stack height.

Step 2—Determine the flux parameters for 1.577 kW/m^2

From Table A-20 flow rate (0.05 kg/s)

X_{cr} = 0.34 m Y_{cr} = –4.26 m N_R = 5.74 m

Step 3—Determine X such that 1.577 kW/m^2 does not extend below 1.8 m

$$Y_x = Y_{int} - H_{stack} - Y_{cr} = 1.8 - 3.5 - (-4.26) = 2.56 \text{ m} \ \ \& \ \ X = \sqrt{5.74^2 - (5.74 - 2.56)^2} = 4.78 \text{ m}$$

The distance from the stack for the monitored radius is $X_{int} = X + X_{cr}$ = 4.78 + 0.34 = 5.12 m

During offloads a trained operator maintains a 6 m distance to a property line that can be built upon.

D2.10 Example J: Bulk Hydrogen Restricted Radius (using direct Appendix B parameters)

1. An Engineer has the following system configuration:
   - Primary relief valve mass flow requirement is 0.05 kg/s
   - A 1 inch NPS pipe size vent stack of H_{stack} 11.5 ft (3.5m) height.
2. Confirm: Vent stack height is adequate to not require a restricted (fenced) or PPE for heat flux < 4.732 kW/m^2
3. Confirm: Buildable property line and setback distance from the stack at 1.8 m above grade is at or below 1.577 kW/m^2
10.

Step 1: Determine the 4.732 kW/m^2 limit below the stack using Y_{cr}

From Table B-8

0.05 kg/s Y_{cr} = –1.90 m

4.732 kW/m^2 heat flux extends 3.5 m - 1.90 m = 1.6 m above grade which is lower than 1.8 m.

Solutions: Determine X_{int} or increase vent stack height.

Step 2—Determine the model parameters for 1.577 kW/m^2

From Table B-8 flow rate (0.05 kg/s)

0.050 kg/s: X_{cr} = 0.29 m, Y_{cr} = –4.20 m, N_R = 5.71 m

Step 3—Determine X such that 1.577 kW/m^2 does not extend below 1.8 m

$Y_x = Y_{int} - H_{stack} - Y_{cr}$ = 1.8 - 3.5 - (–4.20) = 2.5 m & $X = \sqrt{5.71^2 - (5.71 - 2.5)^2} = 4.72$ m

The distance from the stack for the monitored radius is $X_{int} = X + X_{cr}$ = 4.72 + 0.29 = 5.01 m

During offloads a trained operator maintains 5m distance to a property line that can be built upon.

D2.11 Example K: High pressure hydrogen cylinder is vented through a 1/4 in ODT tube (using Appendix A curve fit)

1. An Engineer has the following system configuration:
   - The venting rate is assumed to choke at 0.00176 kg/s
   - A 0.25 inch ODT vent stack of 11.5 ft (3.5 m) height
2. Confirm: Vent stack height is adequate to not require monitoring, Heat flux < 1.577 kW/m^2

Step 1—Determine the heat flux acceptable for monitored radius (< 1.577 kW/m^2) limit below the stack using Y_{cr}

From Table A-13

$Y_{cr} = -11.63637 \cdot 0.00176^{0.3795793} + 0.2478485 = -0.8$ m

1.577 kW/m^2 heat flux extends 3.5 m - 0.8 m = 2.7 m above grade which is higher than 1.8 m.

D2.12 Example L: High pressure hydrogen cylinder is vented through a 1/4 in ODT tube (using direct Appendix A flux parameters)

1. An Engineer has the following system configuration:
   - The venting rate is assumed to choke at 0.00176 kg/s
   - A 0.25 inch ODT vent stack of 11.5 ft (3.5m) height
2. Confirm: Vent stack height is adequate to not require monitoring, Heat flux < 1.577 kW/m^2

11.

Step 1—Determine the heat flux acceptable for monitored radius (< 1.577 kW/m^2) limit below the stack using Y_{cr}

From Table A-19 mass flow rate (0.00176 kg/s)

Y_{cr} = –0.80 m

1.577 kW/m^2 heat flux extends 3.5 m - 0.80 m = 2.7 m above grade which is higher than 1.8 m.

D2.13 Example M: High pressure hydrogen cylinder is vented through a 1/4 in ODT tube (using direct Appendix B parameters)

1. An Engineer has the following system configuration:

   - The venting rate is assumed to choke at 0.00176 kg/s
   - A 0.25 inch ODT vent stack of 11.5 ft (3.5 m) height

2. Confirm: Vent stack height is adequate to not require monitoring, Heat flux < 1.577 kW/m^2
12.

Step 1—Determine the heat flux acceptable for monitored radius (< 1.577 kW/m^2) limit below the stack using Y_{cr}

From Table B-7 mass flow rate (0.00176 kg/s)

0.00176 kg/s Y_{cr} = –0.81m

1.577 kW/m^2 heat flux extends 3.5 m - 0.81 m = 2.7 m above grade which is higher than 1.8 m.