



CGA P-28—2022

OSHA PROCESS SAFETY MANAGEMENT AND EPA RISK MANAGEMENT PLAN GUIDANCE DOCUMENT FOR BULK LIQUID HYDROGEN SUPPLY SYSTEMS

FIFTH EDITION

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NOTE—Technical changes from the previous edition are underlined.

NOTE—Appendices A and B (Normative) are a requirement.

NOTE—Appendices C, D, E, F, G, H, I, and J (Informative) are for information only.

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1 Introduction

The U.S. Occupational Safety and Health Administration (OSHA) Process Safety Management (PSM) standard and the U.S. Environmental Protection Agency (EPA) Risk Management Program (RMP) rule require that some U.S. industrial gas facilities comply with these regulations. For the purpose of this publication, OSHA PSM refers to Title 29 of the U.S. *Code of Federal Regulations* (29 CFR) Part 1910.119, “Process Safety Management of Highly Hazardous Chemicals”, and EPA RMP refers to Title 40 of the U.S. *Code of Federal Regulations* (40 CFR) Part 68, “Chemical Accident Prevention Provisions” [1, 2].¹

PSM and RMP regulations require that companies develop a program to prevent accidental releases of regulated toxic and flammable substances and to reduce the severity of releases, which could occur [1]. Hydrogen is one regulated flammable substance under this regulation. Both OSHA PSM and EPA RMP regulations are intended to prevent or lessen consequences of a catastrophic release of a regulated substance from a covered process. Processes are defined broadly to encompass any activity involving a chemical including any use, storage, manufacturing, handling, on-site movement of chemicals, or any combination of these activities. This definition of process also includes any group of vessels that are interconnected and separate vessels that are located so a regulated substance could be involved in a potential release. Transportation activities regulated by the U.S. Department of Transportation (DOT), including pipelines, are excluded from coverage [3].

While PSM requirements focus on facility and worker safety, RMP requirements are concerned with the possible effects on the community outside the facility in the event of a catastrophic fire or loss of containment at the facility. The RMP rule requires the implementation of a risk management program for all covered processes at facilities containing regulated substances above threshold quantities. In addition, the RMP rule requires covered sites to register with EPA and submit a risk management plan. There are no such requirements under PSM. Also, PSM does not allow a tiered approach and requires a 14-element prevention program for all covered processes.

The RMP rule requires the implementation of a risk management program for all covered processes at stationary sources containing regulated substances above threshold quantities. A full RMP is comprised of a hazard assessment, a management system, a prevention program, and an emergency response program. However, the RMP rule allows for a tiered approach to regulating stationary sources subject to the rule. There are three tiers or program levels. The placement of a facility into one of the three regulatory tiers is based on the facility’s accidental release history, its offsite impact potential, and types of processes operated at the site. In short, a facility that presents a greater risk to offsite receptors shall comply with more stringent requirements than those that present a lower risk to offsite receptors. Appendix A compares regulatory requirements for each tier, known as programs 1, 2, and 3. The RMP rule requires the submission of a risk management plan document. The plan document summarizes the key elements of the RMP at the stationary source.

More details about the application of OSHA PSM and EPA RMP to hydrogen supply systems and other compressed gas and cryogenic fluid systems can be found in CGA P-29, *Guideline for Application of OSHA PSM and EPA RMP to the Compressed Gas Industry* [4]. CGA P-29 gives examples of covered systems and details about calculating threshold quantities of covered compressed gases.

2 Purpose

This publication is designed to help owners and operators of liquid hydrogen bulk tanks comply with PSM and RMP rules in addition to the requirements of CGA H-5, *Standard for Bulk Hydrogen Supply Systems (an American National Standard)* [5]. CGA H-5 refers to NFPA 55, *Compressed Gases and Cryogenic Fluids Code*, for the minimum setback distances between bulk hydrogen systems and exposures [5, 6]. The distances for worst-case release scenarios in 7.3 and alternative release scenarios in 7.4 of this publication are not intended to replace the NFPA 55 setback distances [6].

3 Scope

Hydrogen is a PSM and RMP regulated flammable substance at a threshold quantity of 10 000 lb (4536 kg). PSM and RMP rules apply when the total weight of hydrogen in the bulk tank plus the weight of hydrogen in the process

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

meets or exceeds 10 000 lb (4536 kg). More details about calculating the 10 000 lb (4536 kg) system threshold quantity can be found in Appendix B.

PSM regulations apply to processes with chemicals at or above a threshold quantity listed in Appendix A of 29 CFR Part 1910.119 or to processes with flammable or combustible liquids in quantities of 10 000 lb (4536 kg) or more. Hydrogen is not listed in Appendix A of 29 CFR Part 1910.119, but it is considered a flammable gas. Hydrogen is covered by OSHA PSM when it is present in quantities greater than 10 000 lb (4536 kg).

RMP regulations are different and apply only to processes that use chemicals in amounts larger than the quantities listed in its Tables 1 and 2 (toxic substances) and Tables 3 and 4 (flammable substances). Hydrogen is listed in its Tables 3 and 4 at a 10 000 lb (4536 kg) threshold quantity. Therefore, hydrogen is covered by RMP regulations when it is present in quantities greater than 10 000 lb (4536 kg) [2].

Typically, large hydrogen systems are covered by both PSM and RMP regulations. However, in certain cases only one or neither of these regulations can apply:

- PSM regulations exempt retail facilities that have been typically defined as locations that receive more than one half of their income from direct sales to outside customers (for example, a commercial gasoline service station); and
- RMP regulations do not apply to the storage of flammable gases that are used for fuel.

The responsibility for compliance with these regulations is typically that of the end-use customer (i.e., the process owner). This is because the customer normally operates the liquid hydrogen supply system daily and, more so than the gas supplier personnel, is the most likely to be involved in an incident involving a release. However, since industrial gas employees visit these installations periodically to perform maintenance and to deliver hydrogen into the system, the hydrogen supplier shall cooperate with customers in fulfilling the regulation requirements.

Both regulations apply only to equipment used for permanent storage of gas at customer locations, where permanent equipment is different from transportation equipment. However, some transportation equipment is covered if it is left on-site. For example:

- Weight of hydrogen in a liquid hydrogen trailer is not added to that in the storage tank if the trailer is only used for delivering hydrogen and is not left on-site for supplying hydrogen to a customer. If the tank alone has less than 10 000 lb (4536 kg) but the tank and delivery trailer have a combined weight of greater than 10 000 lb (4536 kg), the system is not covered by these regulations; or
- If a liquid hydrogen trailer is left on-site to deliver hydrogen to the customer (such as using a liquid trailer with a portable vaporizer), and the weight of hydrogen is greater than 10 000 lb (4536 kg), then the system is covered by these regulations. Liquid trailers generally hold less than 10 000 lb (4536 kg) of hydrogen.

Temporary or portable liquid hydrogen tank is covered if it has greater than 10 000 lb (4536 kg) of hydrogen.

Nonconnected hydrogen storage systems are not covered if each one individually is less than 10 000 lb (4536 kg) of hydrogen and are far enough apart that an incident occurring at one storage system would not affect another.

Typically, a tank with a nominal gross volume of 18 000 gal (68 140 L) or less holds less than 10 000 lb (4536 kg) of hydrogen and is excluded from PSM and RMP regulations. Appendix C of this publication lists regulatory sections and a breakdown of responsibility between the hydrogen supplier and the hydrogen customer.

This publication provides generic information necessary to support the hazard assessment and the process hazard analysis (PHA) portion of the prevention program. Specifically, it includes a typical system flow diagram (TSFD), a typical system HAZOP, and offsite consequence analysis (OCA) information for a bulk liquid hydrogen system. Tables and charts for assessments of appropriate worst-case and alternative-case release scenarios are also included. In addition, information is provided to assist in the development and submission of a typical risk management plan.

Under RMP, the consequences of a worst-case scenario and an alternate-release scenario for each covered process shall be modeled. Off-site impact on public or environmental receptors or both shall be determined. No such modeling is required under PSM.

Under RMP, a risk management plan that includes information about a facility's hazard assessment, prevention program, and emergency response program shall be submitted to EPA. This plan is available for public review. Under PSM, no submittals to OSHA are required, and PSM information does not enter the public record. Facilities covered by the RMP rule shall also:

- Compile and report a history of accidental releases for the 5 years before the submission of the RMP plan as provided in 40 CFR 68.42 [2];
- Develop a management system to oversee the implementation of all elements of the RMP for program 2 or program 3 regulated processes as provided in 40 CFR 68.15 [2];
- Determine one of three program levels to assign the covered process as provided in 40 CFR 68.10 and comply with the applicable program level general requirements as provided in 40 CFR 68.12. Details for program 2 are provided in 40 CFR 68.48 through 68.60, and program 3 details are provided in 40 CFR 68.65 through 68.87 [2];
- Develop and implement an emergency response program for the purpose of protecting public health and the environment as provided in 40 CFR 68.95, except as provided in paragraph (b) of 40 CFR 68.90 [2]; and
- Prepare and submit a single RMP as provided in 40 CFR 68.150 that includes the information required by 40 CFR 68.155 through 68.185 for all covered processes [2].

As illustrated previously, this publication does not represent a total RMP nor does it provide all the information required in a complete risk management plan submission. It also does not provide a complete program for compliance with PSM regulations in the workplace. The nature of this publication is to provide guidance only and not to present a complete or model program for complying with PSM and RMP regulations. Each individual company shall exercise its own judgment regarding how they use this publication and how they achieve PSM and RMP compliance.

4 Definitions

4.1 Publication terminology

4.1.1 Shall

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

4.1.2 Should

Indicates that a procedure is recommended.

4.1.3 May

Indicates that the procedure is optional.

4.1.4 Will

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

4.1.5 Can

Indicates a possibility or ability.

4.2 Technical definitions

4.2.1 Level of risk

Magnitude of a risk or combination of risks, expressed in terms of the combination of consequences and their likelihood.

4.2.2 Risk evaluation

Process of comparing the results of risk analysis with risk criteria to determine whether the risk and/or its magnitude is acceptable or tolerable.

5 Typical hydrogen system

A typical hydrogen system consists of a storage tank, flow controls, vaporizers, low temperature protection, and other safety systems. More details about hydrogen systems can be found in CGA H-5 [5].

5.1 Flow diagram

Typical hydrogen system flow diagrams (consistent with the options found in CGA H-3, *Standard for Cryogenic Hydrogen Storage*) can be found in Appendix D [7]. The numbers in parentheses in this section refer to parts of the diagrams.

5.2 System description

5.2.1 Storage tank

Hydrogen tanks are constructed with a liquid container suspended inside a vacuum casing. Gas- and liquid-phase piping passes through the ends of the casing. All lines are designed with sufficient flexibility to prevent excessive stress due to expansion and contraction of the piping, liquid container, and suspension system because of thermal changes. All liquid lines are gas trapped inside the casing to prevent liquid from standing in these lines when these lines are not in use.

The liquid container is insulated by a powder or wrapped insulation material. The annular space between the liquid container and the casing is evacuated and sealed. An adsorbent is factory installed in the vacuum space to help maintain the vacuum. There is an evacuation valve (4) on the tank. The annular space vacuum is measured by a vacuum probe (26A) through the vacuum probe valve (3A).

More details about liquid hydrogen tanks can be found in CGA H-3 [7].

5.2.2 Tank piping and controls

The tank is filled through the fill connection (25), the liquid-fill valve (10), and the gas-fill valve (11). The fill piping is vacuum insulated by a system that is separate from the casing vacuum system. The fill-piping vacuum is measured by a vacuum probe (26B) through the vacuum-probe valve (3B). Fill valves (10 and 11) are purged through the purge valve (13).

The tank-fill termination indicator (23) connects to the liquid container through the full trycock valve (1). The tank pressure can be reduced by manually blowing down through the blow-down valve (7).

Container pressure is indicated by the pressure gauge (5). Container content is displayed on the level gauge (6). These gauges (5 and 6) are connected to the liquid container through isolation valves (24A and 24B).

5.2.3 Safety devices

A rupture disk (casing relief) (2) provides overpressure protection for the casing. The rupture disk also protects the liquid container from overpressure in the event of a leak into the annular space from the liquid container.

Overpressure protection for the liquid container is provided by dual pressure relief valves (20A and 20B) and rupture disks (9A and 9B). The three-way diverter valve (22) permits the operation of one set of protective devices while the other set is isolated for maintenance. This arrangement prevents both sets of relief devices from being valved out of the circuit at the same time.

Discharge sides of all rupture disks, safety valves, the blow-down valve, full trycocks valve, and purge valves are piped into a primary vent stack. The primary vent stack is weather protected to prevent moisture from flowing into the stack. Condensation is drained from the stack through the drain valve/condensate trap (32).

The emergency shutoff valve (21) is a spring-loaded, fail-closed valve. The valve is normally held open by use of a mechanical or pneumatic system. In the event of an emergency, the shutoff valve can be closed by releasing the mechanical system or depressurizing the pneumatic system. Fire near the valve will activate it automatically by melting the fusible link (34).

5.2.4 Tank pressure and flow controls

Controls on most hydrogen tanks are nonelectrical. Most pressure control devices are pressure regulators and backpressure valves.

During operation, tank pressure forces liquid product through the liquid withdrawal line. One or more regulators (19, 39) in the liquid withdrawal line control pressure to the customer. Valve 21 is an emergency shutoff device (refer to 5.2.3).

The tank pressure tends to decrease as liquid is withdrawn. When the tank pressure drops below the operating setpoint, the pressure regulator (18) opens and allows liquid to flow to the pressure-building coil (31). Vaporized product returns to the tank through the gas product isolation valve (17) and builds tank pressure providing the driving force for continued liquid withdrawal. When the tank pressure rises to the setpoint, the regulator closes and pressure building stops.

The economizer circuit operates when the tank pressure rises above the setpoint of the economizer regulator (35). If pipeline withdrawal occurs at this time, gas flows from the tank through the gas product isolation valve (17), economizer regulator (35), and check valve (30) to the pipeline. Gas flow through this circuit continues until the tank pressure falls to below the backpressure valve setpoint. At this point, the system reverts to liquid phase withdrawal. The primary purpose of the economizer system is to save liquid by preferentially supplying gas to the customer.

5.2.5 Vaporizers

Typically, ambient air vaporizers are used to convert the liquid hydrogen product to gas for customer use. These vaporizers are protected by safety devices (46B and 8H) piped to a properly sized vent stack.

5.2.6 Low temperature protection system

A low temperature shutoff switch is provided in the vaporizer discharge piping to prevent the flow of cold gas (-20°F [-29°C] or below) in the event of a loss of heat source and/or consumption over vaporizer capacity. When activated, the shutoff switch closes an isolation valve to prevent embrittlement of carbon steel piping.

5.2.7 Tow-away interlock safety system

Many systems in use today use a tow-away interlock safety system to prevent hydrogen releases during vessel fill operations due to the inadvertent movement of the trailer. Some of these systems incorporate a link between a manual flag control placed in front of the fill connection and pneumatics for the trailer brakes. The delivery hose cannot be connected to the fitting on the trailer until the flag is moved. Once the flag is moved, the air pressure is removed from brakes preventing the trailer from rolling. Once the fill is complete, the trailer cannot be moved until the delivery hose is disconnected and the flag moved back in front of the fill connection.

5.3 System options

5.3.1 Alternate vent stack

The purpose of the alternate vent stack is to act as a backup to the primary vent stack. The alternate vent stack protects the vessel if the primary relief system, the primary vent stack, or both become blocked or inoperable. The operation of the alternate vent stack is the same as the primary except there is normally only one rupture disk and no pressure relief valve.

5.3.2 Liquid hydrogen pump skid

The skid is an electrically powered pumping and control system for transforming low pressure liquid hydrogen into high pressure liquid hydrogen. By virtue of an electric motor and controls, the skid normally offers high- and low-flow capability. Pump inlet valves supply liquid not only for pumping but also for cooling down the pump during operation. The pump vapor return allows for the recovery of product boiled off during the cooldown process.

5.3.3 High pressure receiver

The high pressure receiver performs two functions for the hydrogen system. First, it is used as an accumulator to allow for peak shaving of customer usage. Second, it allows for high pressure gas storage so the liquid pumps are not in constant use.

6 Typical system process hazard analysis

An example of a PHA summary report is included in this publication (see Appendix E). This typical PHA was developed for bulk liquid hydrogen systems using the HAZOP method. This HAZOP is meant to be used as an example and is not meant to replace the site specific HAZOP or other PHA methodology. Design should incorporate recognized and generally accepted good engineering practice in accordance with industry standards. See Sections 9 and 10 for references regarding design. Users should customize their PHA to include design and operational documentation, site-specific hazards, safeguards, and recommendations, and to ensure their PHA is consistent with the process used at the facility. Users of this publication may wish to use the HAZOP in Appendix E as the starting point for PHAs of the hydrogen system located at their facility.

6.1 HAZOP methodology

The process was divided into manageable and logical segments called nodes, and each node was analyzed using a typical HAZOP deviation matrix. Hazards of the process, previous incidents, engineering and administrative controls, consequences of failure of controls, general human factors, and facility-siting items were considered. As part of the HAZOP, a risk evaluation is performed to determine the level of risk achieved with the engineering and administrative controls in place. HAZOP nodes (Appendix E) are as follows:

- Node 1: delivery trailer, hose, and fill line to the storage vessel;
- Node 2: storage tank;
- Node 3: pressure buildup circuit and economizer;
- Node 4: hydrogen line—liquid through the vaporizer to the customer;
- Node 5: hydrogen pump;
- Node 6: vent stacks; and
- Node 7: general items.

6.2 Process hazards

Deviations from normal operating parameters that can have potentially hazardous consequences were identified using the HAZOP deviation matrix, see Table 1.

6.3 Previous incidents

Previous incidents occurring within the industry that had some applicability to this process were considered in the analysis. Such incidents were useful in developing causes, determining consequences, and identifying effective safeguards.

6.4 Engineering and administrative controls

Hazardous deviations that could result in the potential release of hydrogen were evaluated, and consideration was given to whether a system was in place to reduce the likelihood of a release. If a system was in place, the existing level of protection was evaluated, and its effectiveness determined. These controls are categorized as either engineering, which are automatic and use mechanical devices, or process-control instrumentation for safe operation and shutdown of the process, or administrative, involving procedures, schedules, and staffing. Within HAZOP worksheets, these controls are listed under causes if their failure or malfunction results in a potentially hazardous consequence. Safeguards list the proper prevention or mitigation of the hazardous consequence.

Table 1—HAZOP deviation matrix

Design parameters	Guide words						
	No	Less	More	As well as	Part of	Reverse	Other than
Flow	No flow	Low flow	High flow		Misdirected flow	Reverse flow	
Containment	Loss of containment						
Pressure	Vacuum	Low pressure	High pressure				
Temperature		Low temperature	High temperature				
Metallurgy/material selection							Incompatible material
Level	No level	Low level	High level				
Composition				Contaminants			Wrong material
Phase (change of state)		Liquid to vapor	Vapor to liquid				
Utilities	Loss of power or utilities						Improperly classified electrical equipment
Static electricity			Buildup/discharge				

6.5 Consequences of failure of controls

The criteria used when developing causes was to limit the scope of consideration to the node being analyzed. Consequences of the deviation were then viewed on a wider basis. For example, “What might consequences be throughout the complete facility and neighboring public should the deviation occur?” It was assumed that all existing protections, indications, procedures, and programs failed, and an effort was made under those conditions to determine the worst-case consequence. Consequences of failure of controls are listed within HAZOP worksheets in Appendix E. Consequences affecting employees and the public have been identified using a range-of-effects scale. The definitions of ranges are listed in Table 2.

Table 2—Range of effects on employees, the public, and the environment

Release size	Description of effects on persons and the environment
Small (S)	A release that could potentially cause injury, adverse health effects, or death to personnel in the immediate vicinity of the release with little or no likelihood of environmental damage.
Medium (M)	A release that could potentially cause injury, adverse health effects, or death to personnel throughout the unit/process that is under review; or localized acute environmental impact within the facility that could require special response operations.
Large (L)	A release that could potentially cause injury, adverse health effects, or death to people (both employees and the public) either throughout the facility or outside the facility; or widespread acute environmental impact either within or outside the facility that could require special response operations.

6.6 Facility-siting factors

A facility-siting factors checklist should be completed as part of the HAZOP. A checklist can be found in Appendix F, Table F-1 [8].

6.7 Human factors

A human-factors checklist should be completed as part of the HAZOP. A checklist can be found in Appendix F, Table F-2 [8].

6.8 Range of effects on employees, the public, and the environment

Descriptions of consequences were considered and documented during the HAZOP in terms of:

- potential hydrogen releases;
- personal injury;
- violent reactions (fire/explosion);
- equipment damage; and
- possible ignition sources.

Employees and the public could suffer a range of effects, and the environment could be harmed. Descriptions of consequences include reasonable large-release effects, assuming safeguards failed. Less severe effects were also documented. For example, if the ultimate consequence of high pressure in the system (assuming safeguards failed) could be a large release of hydrogen, the analysis would also include the less severe consequence of relieving hazardous materials through a relief device. The analysis would then concentrate on whether the system is adequately protected against high pressure and whether the relief device discharges to a safe location. This examination provides a more complete analysis than one that focuses solely on large-release events. Consequences affecting employees, the public, or the environment are indicated within HAZOP worksheets using the terms in Table 2.

As noted in Table 2, each release size can have a broad range of effects on personnel. The severity of injuries depends largely on one's proximity to the release, which in turn is dependent upon various site-specific factors (such as spacing distances and operating procedures). These site-specific factors may be taken into account so that in addition to ranking each consequence based on release size, the severity of each consequence may also be classified based on potential effects. One such classification scheme is presented in Appendix F, Table F-3. These rankings are only meaningful for an actual facility; they are not included on typical system HAZOP worksheets in Appendix E.

6.9 HAZOP findings

The worksheets representing the HAZOP findings are found in Appendix E.

7 Hazard assessment (RMP only)

7.1 Introduction

The hazard assessment portion of the RMP rule is concerned with offsite consequences of accidents involving the release of hazardous substances. A worst-case release scenario is required for all program levels. For program levels 2 and 3, an alternative-release scenario shall also be considered. Offsite consequences are estimated in terms of population affected and environmentally sensitive areas impacted. These and other aspects of the hazard assessment portion of the RMP rule will be covered in detail in the following sections.

7.2 Offsite consequence analysis parameters

The RMP rule defines certain parameters and conditions that shall be used in the analysis of offsite consequences. For purposes of this publication, only those parameters and conditions applicable to analyses of hydrogen are described.

7.2.1 Endpoints for impact circle determination

In analyzing offsite consequences for flammable material releases, an impact circle is defined which is centered on the point of release and has a radius equal to the distance to the endpoint of the event. The following three different endpoints are defined, each depending on the hazardous event that ensues:

- 1 psi overpressure for vapor cloud explosions (VCE);
- 5 kW/m² for 40 s or greater exposure to radiant heat from burning flammables; and
- lower flammable limit (LFL) (4% for hydrogen) for the formation of unburned flammable clouds.

7.2.2 Ambient conditions and release parameters

The OCA will require the definition of ambient conditions and parameters of the release. The RMP rule specifies how the ambient conditions and release parameters are chosen.

7.2.2.1 Wind speed and atmospheric stability class

As described in following sections, the worst-case release data models the instantaneous release of the entire vessel contents with the entire previously contained vessel inventory entering the explosive cloud. Such a scenario is independent of wind speed and atmospheric stability class, so no wind speed or atmospheric stability class need be chosen for the worst-case analysis.

Alternative-release scenarios cover a wide range of possible release events that often are based upon dispersion of the flammable material and therefore dependent on the proper choice of wind speed and atmospheric stability class. In general, the RMP rule permits the use of typical meteorological conditions for the location under consideration. However, the methodology provided in this publication is derived from EPA's *Risk Management Program Guidance for Offsite Consequence Analysis* (RMP OCA guidance) [9]. These same meteorological conditions as used to generate tables in that document shall be used for results to be valid. These conditions are D stability class and a 3 m/s wind speed.

7.2.2.2 Ambient temperature and humidity

Ambient temperature and humidity are not used in the worst-case analysis. For the alternative-release analysis, 77 °F [25 °C] and 50% relative humidity should be selected for consistency with the methodology used in EPA's RMP OCA guidance [9].

7.2.2.3 Height of release

The worst-case scenario is defined as a ground-level release. Alternative-release scenarios are determined by the release event; however, for purposes of this publication, the alternative scenario is also taken to be a ground-level release (see 7.4).

7.2.2.4 Surface roughness

Two terrain categories are specified in the RMP rule: urban and rural. The owner/operator shall choose the type of terrain that most closely matches that of the site topography. Urban is chosen for sites where large obstacles such as buildings and trees are located in the immediate vicinity of the liquid hydrogen tank. Rural is chosen where the terrain is essentially flat and unobstructed.

The worst-case endpoint distance is independent of topography. For the alternative-release scenario, tables and charts for both urban and rural terrain are provided.

7.2.2.5 Gas density

The RMP rule requires that models or tables used for dispersion analysis appropriately account for gas density. In keeping with this requirement, this publication properly accounts for the nearly neutral density of cold hydrogen gas boiloff from liquid hydrogen releases.

7.2.2.6 Release temperature

While not applicable to the worst-case release for flammables, a release temperature that is appropriate for the event shall be used for the assessment of alternative-release cases. For liquid hydrogen releases, the release temperature is the boiling point at the local atmospheric pressure conditions (–423 °F at 14.7 psi [–253 °C at 101 kPa]).²

7.3 Worst-case release scenario

The worst-case release scenario for a liquid hydrogen tank is modeled as a catastrophic release whereby the entire tank content is instantaneously released to the atmosphere, forming an explosive cloud that detonates. The reported distance to the 1 psi overpressure endpoint is based on a trinitrotoluene (TNT) equivalency method with 10% of the material in the cloud contributing to the explosion. This distance is not meant to replace any setback distances between the hydrogen system and exposures required in NFPA 55 [6].

Accounting for active mitigation systems is not permitted, but administrative controls that limit the tank inventory to less than its full capacity may be taken into account. The RMP rule permits credit to be taken for passive mitigation systems; however, none are likely to exist or be applicable to a liquid hydrogen storage tank. For example, liquid hydrogen tanks of the size considered in this publication are not permitted inside buildings (a passive mitigation system), and the outer casing of a typical double-wall liquid hydrogen tank is not considered passive mitigation. No other types of passive mitigation systems have been identified for an event of this nature.

For flammable substances such as liquid hydrogen, one worst-case release scenario shall be reported that is estimated to have the greatest distance to the 1 psi overpressure endpoint with additional worst cases reported if different public receptors are affected. For a site with a single liquid hydrogen tank, catastrophic failure of the tank as described previously would be modeled as the single reported worst-case scenario. For adjacent liquid hydrogen tanks in a multiple tank system, failure of the tank with the largest inventory will generally represent the single reported worst-case scenario. However, widely spaced tanks can result in the need to report more than one worst case if the location of the tanks is such that different public receptors could be affected by catastrophic failure of each tank.

The first step in computing the distance to the 1 psi overpressure endpoint is determining the tank inventory. If applicable, take into account administrative controls that limit the tank level to less than its full capacity. The liquid in the tank is likely to be thermally stratified to some degree that complicates the calculation of the exact mass in the tank even if the volume is known precisely. To be conservative, it is suggested that the density of the coldest liquid in the tank be used to convert the volume in gallons to mass in pounds (W). In most cases it is conservative to assume that the average liquid density corresponds to the saturation pressure of 30 psi (207 kPa), a boiling point of –415 °F (–248 °C), which equates to a density of 0.5423 lb/gal. The mass calculation will need to be adjusted if design conditions or the observed tank pressure differ significantly (see Appendix G, Table G-1).

The distance (measured in ft) to the 1 psi overpressure endpoint is calculated from the tank inventory, measured in pounds. The distance can be read from Figure H-1 in Appendix H or from Table G-2 in Appendix G. Alternatively, the distance to 1 psi overpressure endpoint can be determined most accurately by using the following equation:

$$D \text{ (ft)} = 58.65 \times W_f \text{ (lb)}^{1/3}$$

For reporting purposes, the distance in feet can be converted to miles.

Repeat the process for other liquid hydrogen tanks on the site if different public receptors could be affected.

² kPa shall indicate gauge pressure unless otherwise noted as (kPa, abs) for absolute pressure or (kPa, differential) for differential pressure. All kPa values are rounded off per CGA P-11, *Guideline for Metric Practice in the Compressed Gas Industry* [10].

7.4 Alternative-release scenarios

In addition to the worst-case release scenario, the RMP rule requires an owner/operator to consider other less catastrophic release scenarios. Alternative-release cases are any release events more likely to occur than the worst case that reach an endpoint offsite, unless no such scenario exists. A case may be judged to be more likely to occur than the worst case without performing a probabilistic assessment. This is not meant to replace any setback distances between the hydrogen system and exposures required in NFPA 55 [6].

Only one alternative-release case representing all the flammable regulated substances on-site needs to be reported in the risk management plan. To determine that one case, it is necessary to examine several possible release scenarios as follows.

7.4.1 Selecting alternative-release scenarios to consider

In addition to qualified judgment and expertise, three resources shall be considered in selecting alternative-release scenarios for further study. These are:

7.4.1.1

The five scenarios as listed in 40 CFR 68.28(b) of the RMP rule [2]:

- transfer hose releases due to splits or sudden hose uncoupling;
- process piping releases from failures at flanges, joints, welds, valves and valve seals, and drains or bleeds;
- process vessel or pump releases due to cracks, seal failure, or drain, bleed, or plug failure;
- vessel overfilling and spill, or overpressurization and venting through relief valves or rupture disks; and
- shipping container mishandling and breakage or puncturing leading to a spill.

7.4.1.2

The five-year accident history listing “all accidental releases from covered processes that resulted in deaths, injuries, or significant property damage on-site, or known offsite deaths, injuries, evacuations, sheltering in place, property damage, or environmental damage” [2].

7.4.1.3

The hazard review or PHA completed as part of the prevention program.

For purposes of this publication, all release scenarios postulated in the typical system HAZOP as well as known actual accidental hydrogen releases are categorized into one of the five required cases listed in 7.4.1.1. After considering each of these cases, conclusions in Table 3 are drawn.

Based on the previous analysis, it was determined that the most likely alternative-release scenario having an offsite impact would be a process piping failure resulting in a liquid release at grade. An accidental release of this type can occur due to mechanical failure, corrosion, failure of a piping component (such as joint or a valve), impact by a vehicle, or other cause.

Table 3—Alternative-release scenarios

Alternative-release scenario		Conclusions
1	Transfer hose release due to splits or sudden hose uncoupling.	The likelihood of sudden hose uncoupling due to inadvertent movement of the liquid hydrogen trailer during the off-loading process is minimized by the trailer tow-away protection. Hose splits would result in a liquid release at grade. The flow rate for such a release generally would be less than that for a process piping failure since the flow is limited by the trailer pressure and trailer pump (if used).
2	Process piping releases from failures at flanges, joints, welds, valves and valve seals, and drains or bleeds.	A release from a gaseous piping failure would be less severe than a release from a liquid line of the same size. Failure of a liquid line would result in a liquid hydrogen spill at grade.
3	Process vessel or pump releases due to cracks, seal failure, or drain/bleed/plug failure.	Likely to be small flow releases with no offsite impact.
4	Vessel overfilling and spill, or over-pressurization and venting through relief valves or rupture disks.	Releases through a well-designed vent stack. Not expected to have any offsite impact.
5	Shipping container mishandling and breakage or puncturing leading to a spill.	A trailer (shipping container) failure would be no worse than the worst case for a single stationary container of the same size. Other failures associated with the trailer would fall into one of the previous four types.

7.4.2 Modeling the alternative-release scenario

Of several liquid lines on a typical liquid hydrogen tank, the largest diameter line should be chosen for the alternative-release case. The flow rate through the pipe (in lb/min) during a release is computed based upon tank pressure, liquid head, fluid density, the line's resistance to flow (based primarily upon its diameter, length, and number of bends), and the open area available to flow at the exit. However, several of these parameters have already been chosen based on the typical liquid hydrogen tank and its piping configuration. To compute the alternative-release flow rate, users need only select the tank pressure and pipe diameter. Each parameter, whether selected by the user or preselected as typical, is described as follows:

- Tank pressure—the highest normal operating pressure should be used. The inner vessel pressure safety valve set pressure can be used as a safe and conservative upper limit;
- Liquid head—since liquid hydrogen is a very low density material, the amount of pressure exerted by the weight of the liquid column (the liquid head) will be small and can usually be ignored;
- Fluid density—to be conservative, the fluid density at the bottom of the tank (the coldest and most dense liquid) is used to compute the flow rate (see Appendix B);
- Line length and configuration—if the liquid line fails close to the tank, the pressure drop will be low, resulting in a high flow rate. Conversely, if the liquid line fails farther from the tank, the pressure drop will be higher, resulting in a lower flow rate. However, even if the failure is assumed to occur at or near the outer casing, the length of piping shall account for the piping within the annular space. Piping on liquid hydrogen tanks extends through the annular space and always makes several bends before exiting through the outer casing. A line length of 8 ft (2.4 m) with 4 elbows is typical of the length and configuration of a liquid line that fails at or near the outer casing. This length and configuration was used to develop the flow rate versus tank pressure charts in this document; and
- Pipe-break flow area—flow rate versus pressure chart has been computed for 20% open area (see Appendix B). This flow area is characteristic of a crack, split, or partially crushed break but is much greater than that of a typical leak.

7.4.3 Progression of events following a liquid release

The alternative-release scenario is a continuous liquid spill. The spill generates a flammable vapor cloud that can ignite if it comes in contact with a source of ignition. Ignition of the gas cloud can result in a flash fire, jet fire, detonation, or deflagration. A progression or sequence of these events is also possible. For example, the ignition

of the flammable cloud could result first in a flash fire that can then transition to a deflagration or VCE due to flame speed runup or the burning zone entering a congested area. After the deflagration or VCE, the release can continue to burn as a jet fire.

Only one endpoint distance is reported, however, so it is not necessary to compute a distance to endpoint for all four events described previously. A deflagration can never generate a larger endpoint distance than a VCE, and it is also extremely unlikely that the jet fire could result in a distance to endpoint greater than the flash fire for the chosen alternative-release scenario. Consequently, this publication provides means to compute endpoint distances for the VCE and flash fire events only.

7.4.4 Computing the distance to endpoints

Two endpoints shall be computed for the alternative-release scenario—the flash fire and VCE endpoints. The greatest endpoint distance shall be reported. The following step-by-step approach is used:

- Determine the tank pressure and the diameter of the largest liquid line on the storage tank. If flow rate is known, skip to step c);
- Refer to Figure H-2 or Table G-3 to find the flow rate for the tank pressure and line size;
- Determine the flash fire endpoint LFL distances using the charts in Appendix H or tables in Appendix G;
- Determine the VCE endpoint distance using the same charts or tables, then skip to step e). Alternatively, greater accuracy can be achieved by using the procedure in the following equation;

Compute the total released mass of hydrogen (W_f) during the time it takes to reach the distance to the LFL by means of the following formula (where 9.843 ft/s is the wind speed and is equivalent to 3 m/s):

$$\text{Mass released } (W_f, \text{ lb}) = \left(\frac{\text{Flash fire endpoint distance (ft)}}{9.843 \text{ ft/s}} \right) \times \left(\frac{1 \text{ min}}{60 \text{ s}} \right) \times \text{Flow rate (lb/min)}$$

NOTE—Since the flash fire endpoint distance in this formula is based on a wind speed of 3 m/s, use of any other wind speed will yield inaccurate results.

Use the following equation to calculate the distance to the 1 psi overpressure endpoint for the VCE:

$$D \text{ (ft)} = 39.26 \times W_f \text{ (lb)}^{1/3} + 0.5 \times \text{LFL distance (ft)}$$

NOTE—This is equivalent to equation C-1 in EPA's RMP OCA guidance with a yield of 0.03 rather than 0.1 and the center of the explosion located halfway out to the flash fire endpoint distance [9].

- Compare distances determined in steps c) and d) and choose the larger of the two as the radius of the impact circle; and
- For reporting purposes, convert the endpoint distance from feet to miles.

7.5 Identifying offsite receptors

Using the impact circle previously determined, the RMP rule gauges offsite consequences of the worst-case and alternative-case releases in terms of the population affected and environmentally sensitive areas impacted.

The population affected is reported in two ways, by estimating the residential population within the impact circle and by listing the presence within the impact circle of other places where people can gather or a significant population can exist. These include institutions such as schools, hospitals, and prisons, commercial and industrial buildings, parks, and recreation areas.

The potential exposure of environmentally sensitive areas to radiant heat or overpressure is reported by identifying and listing any of the following environmental receptors that fall within the impact circle: national and state parks, forests, monuments, wildlife sanctuaries, preserves, and refuges, and federal wilderness areas. U.S. Geological Survey (USGS) maps and EPA's Landview program can be used to identify offsite public and environmental receptors [11, 12].

8 Risk management plan submission

Endpoint distances, types of public and environmental receptors located within impact circles, the residential population located within impact circles, and the program level shall be reported in a risk management plan along with other parameters such as:

- total inventory of the covered materials contained within the facility;
- amount of hydrogen released;
- release scenario (such as VCE, flash fire, etc.); and
- passive and active mitigation measures considered.

The risk management plan shall be submitted to the EPA using the EPA RMP* eSubmit online system. Details can be found at www.epa.gov/rmp. This submittal also includes the following information:

- stationary source (the facility);
- 5-year accident history;
- prevention program; and
- emergency response plan.

A detailed list of the current RMP rule, guidance for facilities, submission requirements, and available training is provided on the EPA RMP website [13].

9 References

Unless otherwise specified, the latest edition shall apply.

[1] *Code of Federal Regulations*, Title 29 (Labor) Part 1910.119, U.S. Government Printing Office.
www.gpo.gov

[2] *Code of Federal Regulations*, Title 40 (Protection of Environment) Part 68, U.S. Government Printing Office.
www.gpo.gov

[3] *Code of Federal Regulations*, Title 49 (Transportation) Parts 100-180, U.S. Government Printing Office.
www.gpo.gov

[4] CGA P-29, *Guideline for Application of OSHA PSM and EPA RMP to the Compressed Gas Industry*, Compressed Gas Association, Inc. www.cganet.com

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

[6] NFPA 55, *Compressed Gases and Cryogenic Fluid Code*, National Fire Protection Association.
www.nfpa.org

[7] CGA H-3, *Standard for Cryogenic Hydrogen Storage*, Compressed Gas Association, Inc. www.cganet.com

[8] Battelle, Process Safety and Risk Management, *Human Factors in Process Operations and Process Hazard Analysis – Facility Siting Review*. This reference was provided through the Process Safety Institute's "Process Hazard Analysis - Using the Hazard and Operability (HAZOP) and What-If Checklist Techniques," course, Battelle Memorial Institute. www.battelle.org

[9] *Risk Management Program Guidance for Offsite Consequence Analysis*, U.S. Environmental Protection Agency. www.epa.gov

- [10] CGA P-11, *Guideline for Metric Practice in the Compressed Gas Industry*, Compressed Gas Association, Inc. www.cganet.com
- [11] *Maps, Imagery, and Publications* United States Geological Survey, USGS National Center. www.usgs.gov
- [12] *Computer –Aided Management of Emergency Operations (CAMEO)/LandView 6*, U.S. Environmental Protection Agency. www.epa.gov
- [13] EPA's Risk Management Planning website: www.epa.gov/rmp
- [14] *Federal Register*, Vol. 61, No. 120, pgs. 31670-31671, Table 2, U.S. Government Printing Office. www.gpo.gov
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- [17] *Lees' Loss Prevention in the Process Industries: Hazard Identification, Assessment, and Control*, vol. 1, 2nd ed., Table 12.25, Butterworth-Heinemann. www.sciencedirect.com
- [18] ALOHA 5.4.7, Office of Emergency Management, EPA and Emergency Response, NOAA, September 2016. www.epa.gov/emergencies/content/cameo/aloha
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- [20] CGA G-5.5, *Standard for Hydrogen Vent Systems*, Compressed Gas Association, Inc. www.cganet.com
- [21] NFPA 70, *National Electrical Code®*, National Fire Protection Association. www.nfpa.org
- [22] CGA P-40, *Calculation Method for the Analysis and Prevention of Overpressure During Refilling of Cryogenic Tanks with Rupture Disk(s)*, Compressed Gas Association, Inc. www.cganet.com
- [23] ASME B31.12, *Hydrogen Piping and Pipelines*, American Society of Mechanical Engineers. www.asme.org

10 Additional references

- ASME Boiler & Pressure Vessel Code, American Society of Mechanical Engineers. www.asme.org
- ASME B31.3, *Process Piping*, American Society of Mechanical Engineers. www.asme.org
- CGA G-5, *Hydrogen*, Compressed Gas Association, Inc. www.cganet.com
- CGA G-5.4, *Standard for Hydrogen Piping Systems at User Locations*, Compressed Gas Association, Inc. www.cganet.com
- CGA P-59, *Prevention of Excessive Pressure During Filling of Cryogenic Vessels*, Compressed Gas Association, Inc. www.cganet.com
- General Guidance on Risk Management Programs*, Environmental Protection Agency. Environmental Protection Agency. www.epa.gov
- Guidelines for Chemical Process Quantitative Risk Analysis*, Center for Chemical Process Safety, American Institute of Chemical Engineers. www.aiche.org/ccps
- Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVES*, Center for Chemical Process Safety of the American Institute of Chemical Engineers. www.aiche.org/ccps

Handbook of Compressed Gases, Compressed Gas Association, Inc. www.cganet.com

Process Hazard Analysis - Using the Hazard and Operability (HAZOP) and What-If Checklist Techniques, course by the Process Safety Institute, Battelle Memorial Institute. www.battelle.org

Appendix A—Risk management program requirements (Normative)

Program 1	Program 2	Program 3
Hazard assessment		
Worst-case analysis	Worst-case analysis Alternative releases	Worst-case analysis Alternative releases
5-year accident history	5-year accident history	5-year accident history
Management program		
	Document management system	Document management system
Prevention program		
Certify no additional steps needed	Safety information Hazard review Operating procedures Training Maintenance Incident investigation Compliance audit	Process safety information PHA Operating procedures Training Mechanical integrity Incident investigation Compliance audit Management of change Prestartup review Contractors Employee participation Hot work permits
Emergency response program		
Coordinate with local responders	Develop plan and program <u>and coordinate with local responders</u>	Develop plan and program <u>and coordinate with local responders</u>
Risk management plan contents		
Executive summary	Executive summary	Executive summary
Registration	Registration	Registration
Worst-case data	Worst-case data Alternative-release data	Worst-case data Alternative-release data
5-year accident history	5-year accident history Prevention program data Emergency response data	5-year accident history Prevention program data Emergency response data
Certification	Certification	Certification

Source: *Federal Register* Vol. 61, No. 120, pgs. 31670-31671, Table 2 [14].

Appendix B—Technical background (Normative)

B1 Inventory calculation

The mass of hydrogen stored in a vessel is calculated from the vessel's internal volume and the density of liquid being stored. The total internal volume of the vessel is not used in the calculation since the vessel is never filled completely for hydraulic reasons. Vessel manufacturers normally specify the vessel size in gross water volume (gal).

To calculate the mass, first calculate the actual product volume:

Product volume (gal) = Gross water volume (gal) × Maximum fill level (% of vessel volume)

The product volume is then multiplied by the density of the liquid hydrogen to calculate the mass of hydrogen.

However, determination of the liquid hydrogen density inside a storage vessel is difficult because the density is constantly changing. It is dependent on factors such as the saturation pressure of the delivered liquid, the liquid level of the tank at the time of fill, the vessel wall temperature in the vapor region at the time of fill, the operating pressure of the tank, the rate of heat leak that varies by size of tank as well as tank manufacturer, the insulation used, the frequency of fillings, and the usage rate.

The density of liquid hydrogen decreases significantly as the saturation pressure increases. This makes it impractical to assume a specific liquid density that can be applied generically to all tanks.

Table G-1 lists densities of liquid hydrogen at various saturation pressures, starting at 0 psi. These numbers are taken from National Aeronautics and Space Administration (NASA) SP-3089, *Hydrogen Technological Survey—Thermophysical Properties* [15]. The table also shows the total weight of liquid hydrogen as a function of saturation pressure and tank net volume. Using 0 psi hydrogen as the calculation basis is unnecessarily conservative in most applications. Tanks may have administrative or engineering controls in place to limit the extent of filling. For example, an 18 000 gal (68 137 L) (nominal) tank size may be filled only to the full trycock volume of 17 000 gal (64 352 L) to allow room for liquid expansion. Using the full trycock volume and the 30 psi (205 kPa) density provides a total weight of 9219 lb (4182 kg) of hydrogen. Using the nominal tank capacity and the 0 psi density provides a total weight of 10 624 lb (4819 kg) that would incorrectly trigger these PSM and RMP requirements.

In Table G-1, as the saturation pressure increases, the liquid hydrogen warms and becomes less dense.

Hydrogen bulk stations are required to operate at a pressure in excess of the customer's requirement to provide sufficient pressure and flow. For standard bulk stations this is 80 psi to 120 psi (550 kPa to 825 kPa). Should the bulk vessel operate at a pressure less than 40 psi (275 kPa), either a specific study shall be done or a saturation pressure of 0 psi shall be used corresponding to a density of 4.42 lbm/ft³. The liquid in the vessel is at a thermodynamic state that can be determined by experimental or measurement technique. For standard calculations a value of 30 psi (205 kPa) saturated liquid is considered to be extremely conservative, yielding a density of 4.0561 lbm/ft³. If site-specific values are chosen to be used in the mass calculation, then the test shall be at the actual working conditions for the bulk vessel, after the maximum delivery possible. This accounts for the densest possible product being received to mix with any residual liquid in the vessel and the mass of the vessel itself.

If the actual density is to be used in the calculation, an engineering methodology shall be used. Two examples of methodologies are listed as follows:

- Temperature probe shall be located in the liquid line of the vessel within close proximity to the liquid isolation valve, on the outlet side. The temperature shall be taken while liquid is being withdrawn from the vessel at a sufficient rate not to have any vapor in the line. The pressure shall be read off an indicator. Using appropriate thermodynamic tables, find the density from the corresponding pressure and temperature that will be used for mass calculations; or
- Alternative method is to have the maximum delivery possible made to the bulk vessel, allow for stabilization of the pressure (1 hour). Then open the vent valve on the vessel and allow the pressure to drop to the point

where the rate of pressure decay changes noticeably and the pressure gauge needle stops dropping or momentarily increases or moves erratically. Close the vent valve on the vessel. The pressure at which this occurs is the saturation pressure of the liquid. Using appropriate thermodynamic tables, find the density from the corresponding pressure on the saturated liquid line that will be used for mass calculations.

B2 Thermal stratification of liquid in hydrogen tanks

Natural convection in fluids contained in vessels that become heated via conduction through the vessel walls results in fluid temperature stratification. This common phenomenon frequently occurs in hydrogen storage tanks.

As heat leak warms the hydrogen liquid, the tank becomes thermally stratified. Colder liquid (lower saturation pressure) exists at the bottom, with progressively warmer liquid (higher saturation pressure) toward the top. All of the liquid in the tank is not saturated at the tank pressure. Only a relatively thin top layer of liquid could actually be setting the tank pressure. The lower levels are comprised of strata or horizontal layers of increasingly sub-cooled liquid (relative to the tank pressure) down to the saturation pressure of the liquid at delivery conditions.

With time, the total tank contents become stratified. In general, the layer of liquid responsible for maintaining the saturation pressure increases as the total contents of the tank approach saturation conditions. The degree and rate of stratification are dependent on the same factors that affect the determination of liquid hydrogen density as discussed previously under inventory calculation.

B3 Determining a mass flow from a piping breach

The liquid flow from a piping breach will exit the hole in two-phase flow. The liquid saturation condition will influence the level of flashing and choke on the mass flow rate. A typical liquid storage tank will see liquid saturations that are roughly 1/2 the incremental pressure over 15 psi (103 kPa). Fauske reports on methods for determining two-phase flow [16]. The presented equations for flow are modified to consider liquid with sub-cool and can be summarized as below.

$$W = \frac{\pi}{4} \times (d)^2 \times \frac{1}{\sqrt{K}} \times \sqrt{1609 \times (P - P_{sat}) \times Rho(P_{sat}) + 4347 \times \frac{P_{sat}}{P} \times \left[\frac{h_{fg}(P)}{(V_{vap}(P) - V_{liq}(P))} \right]^2 \times \frac{1}{(T_{vap}(P) \times C_{p_{liq}}(P))}}$$

Where:

W = mass flowrate of hydrogen in lb/min

d = inside diameter of the pipe in inches

K = characteristic restriction of the piping and breach

$$K(\beta) = 2.9 + \left[\frac{\sqrt{1 - \beta^4 \times (1 - 0.605^2)}}{0.605 \times \beta^2} \right]^2$$

Here the assumptions are for a length to diameter ratio (L/D) of the piping of 120, a sharp-edged inlet and outlet, a friction factor of 0.02 and beta is the ratio of hole size to d . A 20% area hole has a beta=0.447.

P = tank pressure in psi

P_{sat} = liquid saturation pressure in psi

$Rho(P_{sat})$ = liquid density in lb/ft³ at liquid saturation pressure

$H_{fg}(P)$ = heat of vaporization of the liquid at tank pressure in BTU/lb

$V_{vap}(P)$ = specific volume of saturated vapor at tank pressure in ft³/lb