

CGA P-40—2017

**CALCULATION METHOD FOR THE
ANALYSIS AND PREVENTION OF
OVERPRESSURE DURING
REFILLING OF CRYOGENIC
TANKS WITH RUPTURE DISK(S)**

FOURTH EDITION

PREFACE

As part of a program of harmonization of industry standards, the Compressed Gas Association (CGA) has published [CGA P-40](#), *Calculation Method for the Analysis and Prevention of Overpressure During Refilling of Cryogenic Tanks with Rupture Disk(s)*, jointly produced by members of the International Harmonization Council.

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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Work Item 16-049
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NOTE—Technical changes from the previous edition are underlined.

NOTE—Appendix A (Normative) is a requirement.

NOTE—Appendices B, C, D, and E (Informative) are for information only.

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1 Introduction

Cryogenic transports often use pumping systems that discharge product at pressures exceeding the working pressure of the liquid storage tank being filled. In North America, pumping systems for transferring oxygen, nitrogen, or argon are typically capable of delivering pressures greater than 400 psi (2760 kPa).^{1,2} The cryogenic storage tank being refilled usually has a maximum allowable working pressure (MAWP) that is considerably less than the pump discharge pressure. Depending on the inherent tank design safety factors and the size and flow capacity of the tank pressure relief system, the potential to overpressure the tank during operator-attended manual refill operations exists. [CGA P-59, Prevention of Overpressure During Filling of Cryogenic Vessels](#) was written in response to overpressure events that occurred in the compressed gas industry [2]. [CGA P-59](#) discusses the requirements necessary to ensure that cryogenic storage tanks are not overpressurized in manual refill operations [2].

It is the responsibility of each tank owner to complete a technical evaluation of the storage tank fill and relief device piping. This technical evaluation shall be repeated any time a change is made in either the pump flow and pressure capability or the tank fill and relief system flow capacities. The storage tank owner shall ensure that pump operators are trained and certified.

2 Scope

This publication provides technical guidance and the complete equation set needed to determine if a particular vessel can or cannot be overpressurized during the refill operation. Acceptable engineering controls for the protection of cryogenic storage tanks and transport tanks with rupture disk(s) as part of the relief system are provided. The application of these engineering controls constitutes a minimum standard.

The calculations in this publication may be used to evaluate each pumping system and cryogenic tank combination in use with oxygen, nitrogen, or argon. It applies to tanks filled either by pump from a cryogenic transport or by a ground-mounted pump. This applies to cryogenic tanks greater than 265 gal (1000 L) water capacity. This does not apply to cryogenic tanks with flat bottoms. For flat bottomed cryogenic tanks, refer to [CGA P-8.9, Bulk Liquid Oxygen, Nitrogen, and Argon Storage Systems at Production Sites](#) [3].

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 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, Metric Practice Guide for the Compressed Gas Industry](#) [1].

² References are shown by bracketed numbers and are listed in order of appearance in the reference section.

4 Nomenclature

Table 1 contains the definitions of the variables used in this standard.

Table 1—Definition of variables

Symbol	Definition	U.S. customary units (abbreviation)	Metric units (abbreviation)
A	Intermediate variable used in calculation of friction factor		
C	Flow coefficient for an orifice		
C_v	Flow coefficient for valves	gallons per minute per psi (gal/min/psi)	
d	Internal line diameter	inches (in)	millimeters (mm)
d_{disc}	Nominal pipe diameter of the rupture disk <u>corresponding to the certified flow resistance</u> as specified by the manufacturer	inches (in)	millimeters (mm)
d_{fill}	Reference internal diameter for the fill line	inches (in)	millimeters (mm)
d_{ori}	Diameter of the fill orifice	inches (in)	millimeters (mm)
d_{rel}	Reference internal diameter for the pressure relief line	inches (in)	millimeters (mm)
f_t	Friction factor (Fanning friction factor used)		
K	Flow resistance coefficient		
K_b	Flow resistance through a single bend of 90-degrees		
K_{fill}	Flow resistance of the fill line with fill valve in the full open condition. See Figure 1.		
K_{ori}	Flow resistance of the restricting fill line orifice sized so the pressure at the top of the tank during the fill operation cannot exceed the <u>upper pressure limit (UPL)</u> . See Figure 1.		
K_R	Certified flow resistance for a rupture disk		
K_{rel}	Flow resistance of the relief system piping from the liquid container up to the rupture disk. See Figure 1. If a diverter valve is present, calculations shall assume it to be in the fully diverted position		
K_{truck}	Flow resistance of the pump to the tee that branches to the fill valves except for the fill orifice. See Figure 1.		
L	Length	feet (ft)	meters (m)
P_{atm}	Atmospheric pressure: 14.696 psia or 1.013 bar, abs	pounds per square inch, absolute (psia)	bar, absolute (bar, abs)
<u>UPL</u>	Tank <u>UPL</u> . This is the maximum pressure that is permissible at the top of the tank under the conditions discussed in CGA P-59 [2] .	pounds per square inch, gauge (psi)	bar, gauge (bar)
P_{mawp}	Tank MAWP per <i>ASME Boiler & Pressure Vessel Code</i> (ASME Code) or local code equivalent [4].	pounds per square inch, gauge (psi)	bar, gauge (bar)
P_{sup}	Pressure at the inlet of the pump. (Approximately equal to the supply tank pressure).	pounds per square inch, gauge (psi)	bar, gauge (bar)
P_{test}	Test pressure as prescribed by the ASME Code and as recorded on form U1, U1-A, or R-2 or local code equivalent [4].	pounds per square inch, gauge (psi)	bar, gauge (bar)
Q	Flow rate	gallons per minute (gal/min)	liters per minute (L/min)
Q_{rel_max}	The flow through the relief system so the pressure loss is ΔP_{rel_max}	gallons per minute (gal/min)	liters per minute (L/min)
r	Radius of a pipe bend	inches (in)	millimeters (mm)

Symbol	Definition	U.S. customary units (abbreviation)	Metric units (abbreviation)
Re	Reynolds number		
V_{liq}	Vertical distance from the bottom of the liquid container to the normal fill level for the tank. See Figure 1.	feet (ft)	meters (m)
V_{pmp}	Vertical distance from the pump to the top of the storage tank liquid container. See Figure 1.	feet (ft)	meters (m)
V_{rel}	Vertical distance from the relief device to the top of the storage tank liquid container. See Figure 1.	feet (ft)	meters (m)
V_{tank}	Vertical distance from grade to the top of the storage tank outer container	feet (ft)	meters (m)
ΔP	Pressure loss through pipe and piping components	pounds per square inch, differential (psid)	bar, differential (bar, dif)
ΔP_{disc}	Pressure loss through a rupture disk	pounds per square inch, differential (psid)	bar, differential (bar, dif)
ΔP_{fill_line}	Frictional pressure loss through the fill line	pounds per square inch, differential (psid)	bar, differential (bar, dif)
ΔP_{ori}	Pressure loss through the fill line orifice	pounds per square inch, differential (psid)	bar, differential (bar, dif)
ΔP_{pmp}	Pump discharge curve for the highest capacity pump expected to fill the tank	pounds per square inch, differential (psid)	bar, differential (bar, dif)
ΔP_{rel_max}	The maximum frictional pressure loss through the relief system so <u>UPL</u> is not exceeded at the top of the tank	pounds per square inch, differential (psid)	bar, differential (bar, dif)
α	Proportionality constant for pipe and tube fitting flow resistance used in Appendix A equation (2b)		
β	Diameter ratio (smaller/larger)		
ε	Absolute roughness	inches (in)	millimeters (mm)
μ	Absolute viscosity	centipoise (cp)	Pascal seconds (Pa s)
ρ	Fluid density	pounds (mass) per cubic foot (lbm/ft ³)	kilograms per cubic meter (kg/m ³)
ρ_{des}	Density of the highest density lading for which the tank is designed	pounds (mass) per cubic foot (lbm/ft ³)	kilograms per cubic meter (kg/m ³)
θ	Angle of a bend	degrees	degrees

5 Preventing overpressurization

5.1 Methods

[CGA P-59](#) outlines a number of methods that protect storage tanks from overpressure during refill [2]. One method describes increasing the size of the relief system rupture disk or other component external to the tank if these are found to be restrictive. In some cases due to the internal piping, modifying external components has limited value. When this is the case, installing an external protection device that closes at a prescribed pressure or installing a permanent resistance in the fill piping are possible ways to prevent overpressurization. The solution used shall be inherently reliable, not exclusively dependent upon the driver or operator to take action and shall not introduce other hazards. The use of a liquid relief valve on the tank fill line sized to relieve the full flow capacity

of the pump is not recommended because it introduces other hazards associated with large releases of cryogenic fluids to the atmosphere.

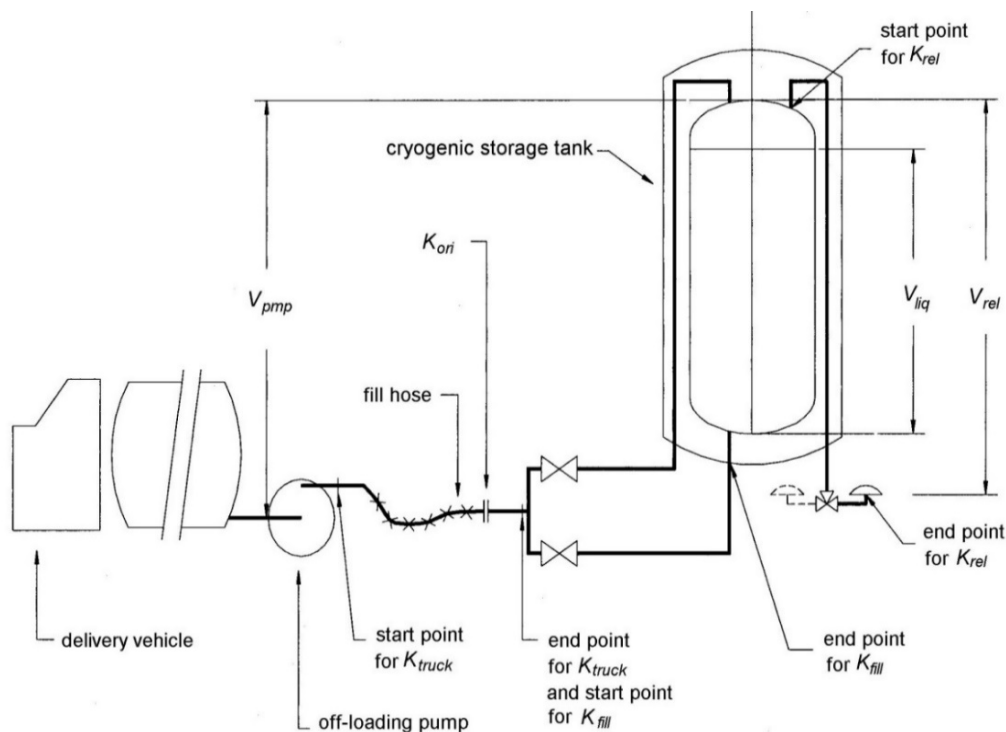
5.2 External protection device

A number of external protection devices have been developed specifically to address the issues of overpressure protection during operator-attended refilling. These include control valves installed in the fill line that are actuated by a pressure signal from the vapor space of the storage tank. Closure of the external protection device is accomplished by a pilot system that includes a pressure relief valve or a rupture disk that functions at a setpoint below the upper pressure limit (UPL). The large flow capacity of these valves avoids the operating penalty of the restrictive orifice solution.

5.3 Tank fill and relief system

As illustrated in Figure 1, the tank filling system consists of the cryogenic transport pump and piping; the product transfer hose and connections; and the storage tank, fill piping, and fill line components. The tank relief system consists of the piping from the vapor space of the storage tank, the diverter valve if used, and the tank rupture disk.

Many cryogenic storage tanks use relief device lines and components equal to or smaller than the fill lines. Normally a diverter valve, pressure relief valve, and rupture disk are used in a dual relief device assembly to facilitate maintenance. Pressure relief valves and rupture disks are sized for normal operation as well as for exposure of the tank to a fire. Normal operation is often limited to loss of vacuum or uncontrolled pressure building operation. The relief devices might not be sized for the maximum capacity of the refill system. Many older style, lower MAWP storage tanks have a relief capacity between 80 gal/min to 90 gal/min (300 L/min to 340 L/min). Following the calculation methods outlined in Section 6, orifice sizes will typically range from 0.35 in to 0.50 in (10 mm to 13 mm) diameter, effectively reducing the fill rate from a nominal 200 gal/min to as low as 80 gal/min (760 L/min to as low as 300 L/min). Since this clearly is not workable from an operating standpoint, especially with large storage tanks, alternative solutions such as an external protection device should be considered. It is left to the analyst to determine the optimum solution for a particular situation.



NOTES

- 1 K_{truck} and K_{fill} exclude K_{ori} .
- 2 If a diverter valve exists in the relief line, assume it is in the fully diverted position.

Figure 1—System configuration

6 Calculations

The steps described in 6.1 to 6.9 are used to determine if the relief system incorporated into the cryogenic tank will relieve product at a rate that is greater than the rate at which it can be pumped from the cryogenic source. In this analysis, the tank pressure is allowed to rise above MAWP as prescribed in 6.2. For the purpose of these calculations, the flow capacity of any pressure relief valve is ignored. The cryogenic tank test pressure can be found in the tank pressure vessel documentation (for ASME Code, test pressure can be found on the pressure vessel U-1, U-1A, or R-2 forms) [4].

The information, equations, and assumptions in 6.1 to 6.9 are used in the equation sets, example worksheets, and blank worksheets in the appendices. Figure 1 depicts the equipment and piping for a typical tank filling operation. References for flow resistances and distances are indicated. Appendix A contains the calculation equation sets. Appendix B presents an example when an orifice is necessary to prevent overpressure during refilling and includes a sketch of the sample relief line and liquid fill line for this example. Appendix C presents an example when additional flow restriction in the fill line is not required and includes a sketch of the sample relief line and liquid fill line for this example. Appendix D contains blank worksheets that may be used to complete the analysis described in 6.1 to 6.9. Appendix E contains useful reference data for cryogenic fluids, tanks, pipes, tubes, pumps, and flow orifices that can be helpful when completing an analysis using the blank worksheets in Appendix D.

NOTE—These calculations are based on liquid flow with sufficient subcooling available to prevent two phase flow from occurring in the piping. Two phase flow is not addressed in these calculations.

6.1 Step 1: Input tank and piping data

Collect input data specific for the tank being analyzed including the following:

- tank owner's name;
- tank capacity and configuration;
- manufacturer's serial number;
- National Board Inspection Code (NBIC) number;
- product service;
- whether or not the tank is suitable for argon, nitrogen, and oxygen;
- tank MAWP and test pressure; and
- overall height of the tank.

NOTE—Much of the previously mentioned input data information is found on the tank dataplate or the manufacturer's documentation such as ASME U-1, U-1A, or R-2 forms.

Inspect the tank relief line from where it exits the tank casing to the discharge of the rupture disk. Enter the different pipe and tube sizes found on the relief line into worksheet D1.

Inspect the tank liquid phase fill line from the fill connection to the point where it enters the casing. Enter the different pipe and tube sizes into worksheet D1.

6.2 Step 2: Determine tank upper pressure limit, UPL

Step 2 and worksheet D2 are based on the assumption that the tank design includes a vacuum jacket.

If the tank test pressure is known, then, the UPL is the lesser of:

$$\underline{UPL} = P_{mawp} \cdot 1.5; \text{ or}$$

$$\underline{UPL} = P_{test} - P_{atm}$$

If the test pressure is unknown, the tank UPL can be estimated from the following:

U.S. customary units:

$$UPL = 1.1 \left(P_{mawp} + (\rho_{des} - \rho) \cdot \frac{V_{liq}}{144} + P_{atm} \right) - P_{atm}$$

Metric units:

$$UPL = 1.1 \left(P_{mawp} + \frac{(\rho_{des} - \rho) \cdot V_{liq} \cdot 9.81}{100000} + 1 \right) - 1$$

For calculation purposes assume that $V_{liq} = V_{tank} - 3 \text{ ft}$ ($V_{liq} = V_{tank} - 0.91 \text{ m}$). See Figure 1.

6.3 Step 3: Determine maximum frictional pressure loss through the relief system, ΔP_{rel_max}

The maximum pressure loss allowed through the relief system is equal to the UPL at the top of the tank plus the liquid head pressure as measured from the top of the tank to the rupture disk inlet.

U.S. customary units:

$$\Delta P_{rel_max} = UPL + \frac{V_{rel} \cdot \rho}{144}$$

Metric units:

$$\Delta P_{rel_max} = UPL + \frac{V_{rel} \cdot \rho \cdot 9.81}{100000}$$

For calculation purposes assume that $V_{rel} = V_{tank} - 2 \text{ ft}$ ($V_{rel} = V_{tank} - 0.61 \text{ m}$). See Figure 1.

Use worksheet D3.

6.4 Step 4: Determine flow resistance of the pressure relief system, K_{rel}

Analyze the relief line from where it exits the tank casing to the discharge of the rupture disk. Note the different pipe and tube sizes and fittings along the entire length of line. Use actual component sizes and C_v s. Calculate the resistance of each segment using equations (2a) to (2i) in Appendix A or worksheet D4. If a diverter valve exists, assume it is in the fully diverted position. Convert the resistance of each segment to a common diameter using equation (3) in Appendix A. Total all resistances to determine K_{rel} . See Figure 1.

Step 4 and worksheet D4 are based on the following engineering assumptions:

- The calculation reference diameter is 1.481 in (37.6 mm). All tabulated resistances are converted to this diameter;
- The line friction factor, f_t , is equal to 0.0125;
- The inlet nozzle resistance is based upon a sharp-edged entrance, a 6 in (150 mm) nozzle length, and pipe schedule 40S;
- The internal line bend resistance corresponds to a 90-degree, 8 in (200 mm) radius bend; two 45-degree, 12 in (300 mm) radius bends; and a 1.185 in (30.1 mm) ID line;
- The internal relief line is pipe schedule 5S and is equal in length to the overall height of the tank;
- If the rupture disk certified flow resistance is unknown or cannot be obtained from the manufacturer, use $K_R = 2.4$; and
- The flow capacity of any safety relief valve is neglected.

6.5 Step 5: Calculate maximum flow rate through the relief system, Q_{rel_max}

Since the flow resistance and the maximum permissible pressure drop across the relief system is known, use the equation below or worksheet D5 to calculate the maximum flow through the relief system. A factor of 0.9 is used to modify the basic equation (1b) in Appendix A for the calculation of relieving capacity to allow for uncertainties inherent in this method. This is in accordance with the ASME Code, Section VIII, Division 1, paragraph UG-127(b) [4].

U.S. customary units:

$$Q_{rel_max} = 0.9 \cdot \sqrt{\frac{\Delta P_{rel_max} \cdot d_{rel}^4}{0.00001799 \cdot K_{rel} \cdot \rho}}$$

Metric units:

$$Q_{rel_max} = 0.9 \cdot 21.07 \cdot \sqrt{\frac{\Delta P_{rel_max} \cdot d_{rel}^4}{K_{rel} \cdot \rho}}$$

6.6 Step 6: Determine flow resistance of the truck and tank fill system, K_{truck} and K_{fill}

Analyze the fill line from the cryogenic transport pump discharge, through the fill connection, to the point where the line enters the casing. Note the different pipe and tube sizes and fittings along the entire length of line. Use actual component sizes and C_v s and worksheet D6. Convert the resistance of each component to a common diameter using equation (3) in Appendix A and worksheet D6. Determine a flow resistance for the standard truck components, K_{truck} , and a separate resistance for the tank liquid phase components, K_{fill} . See Figure 1.

Step 6 and worksheet D6 are based on the following engineering assumptions:

- The calculation reference diameter is 1.481 in (37.6 mm). All tabulated resistances are converted to this diameter;
- The liquid fill line friction factor, f_t , is equal to 0.0138 for an assumed 50% of flow total through the liquid phase fill line. It is assumed that the liquid phase fill valve is fully opened;
- The resistance of standard fill system truck components is equal to 11.519 at a 1.481 in (37.6 mm) reference diameter. These include truck-mounted components, transfer hose, and fill connection indicated in Figure 1;
- The internal liquid line is assumed to be 3 ft (0.91 m) in length and schedule 5S. Internal line bend resistance corresponds to two 90-degree, 10 in (254 mm) radius bends and a 1.770 in (45 mm) ID line; and
- The internal nozzle resistance is based on a sharp-edged exit, a 6 in (152 mm) nozzle length, and pipe schedule 40S.

6.7 Step 7: Determine pressure loss through the fill system, ΔP_{fill_line}

Calculate the pressure drop across the fill line without an orifice at the flow capacity of the relief system. Use the basic equation (1a) in Appendix A to calculate a separate value for the fill system truck components and the tank liquid phase components. Assume that 50% of the total flow is through the tank liquid phase fill line.

U.S. customary units:

$$\Delta P_{fill_line} = \frac{0.00001799 \cdot K_{truck} \cdot \rho \cdot Q_{rel_max}^2}{d_{fill}^4} + \frac{0.00001799 \cdot K_{fill} \cdot \rho \cdot (Q_{rel_max}/2)^2}{d_{fill}^4}$$

Metric units:

$$\Delta P_{fill_line} = \frac{K_{truck} \cdot \rho \cdot Q_{rel_max}^2}{21.07^2 d_{fill}^4} + \frac{K_{fill} \cdot \rho \cdot (Q_{rel_max}/2)^2}{21.07^2 d_{fill}^4}$$

Use worksheet D7.

6.8 Step 8: Determine fill line orifice pressure drop, ΔP_{ori}

Subtract the fill line pressure drop, the liquid head from the top of the tank to the pump inlet, and the UPL at the top of the tank from the sum of the supply pressure and pump pressure rise as shown in the equation below. The pressure rise across the pump, ΔP_{pmp} , is determined by interpolation of the pump curve for the actual lading at the relief system flow capacity. A positive value for ΔP_{ori} indicates that a restricting orifice is needed to match the fill rate to the capacity of the relief system.

U.S. customary units:

$$\Delta P_{ori} = \Delta P_{pmp}(Q_{rel_max}, \rho) + P_{sup} - \Delta P_{fill_line} - V_{pmp} \frac{\rho}{144} - UPL$$

Metric units:

$$\Delta P_{ori} = \Delta P_{pmp}(Q_{rel_max}, \rho) + P_{sup} - \Delta P_{fill_line} - \frac{(V_{pmp} \cdot \rho \cdot 9.81)}{100000} - UPL$$

Step 8 and worksheet D8 are based upon the following engineering assumptions:

- For calculation purposes assume that $V_{pmp} = V_{tank} - 6 \text{ ft}$ ($V_{pmp} = V_{tank} - 1.83 \text{ m}$). See Figure 1;
- The pump performance curve used in the worksheets is an example of a pump's capacity attainable with some cryogenic transport off-loading systems; and
- $P_{sup} = 30 \text{ psi}$ (2.1 bar).

It is essential that the analyst use the pump curve for the actual pump and components used in a delivery system. Anytime the delivery pump or system characteristics change, this analysis shall be redone to check fill line orifice sizing. This is a major disadvantage of the fill line orifice solution.

6.9 Step 9: Determine required fill orifice flow resistance, K_{ori} and size, d_{ori}

Using the value for ΔP_{ori} computed previously and equation (1c) in Appendix A, compute the flow resistance coefficient required.

Use worksheet D9.

U.S. customary units:

$$K_{ori} = \frac{\Delta P_{ori} \cdot d_{fill}^4}{0.00001799 \cdot \rho \cdot Q_{rel_max}^2}$$

Metric units:

$$K_{ori} = \frac{21.07^2 \Delta P_{ori} \cdot d_{fill}^4}{\rho \cdot Q_{rel_max}^2}$$

Where:

$$K_{ori} = \frac{1 - \beta^2}{C \cdot \beta^4} \quad \text{and} \quad \beta = \frac{d_{ori}}{d_{fill}}$$

Compute the orifice size by varying d_{ori} until the required resistance is obtained. Alternatively, use worksheet D9 to select an orifice from a list of typical sizes. Select the standard orifice size that has a resistance just greater than K_{ori} .

7 References

Unless otherwise specified, the latest edition shall apply.

[1] [CGA P-11](#), *Metric Practice Guide for the Compressed Gas Industry*, Compressed Gas Association, Inc. www.cganet.com

[2] [CGA P-59](#), *Prevention of Overpressure During Filling of Cryogenic Vessels*, Compressed Gas Association, Inc. www.cganet.com

NOTE—This publication is part of an international harmonization program for industry standards. The technical content of each regional document is identical, except for regional regulatory requirements. See the referenced document preface for a list of harmonized regional references.

[3] [CGA P-8.9](#), *Bulk Liquid Oxygen, Nitrogen, and Argon Storage Systems at Production Sites*, Compressed Gas Association, Inc. www.cganet.com

NOTE—This publication is part of an international harmonization program for industry standards. The technical content of each regional document is identical, except for regional regulatory requirements. See the referenced document preface for a list of harmonized regional references.

[4] *ASME Boiler & Pressure Vessel Code*, ASME International. www.asme.org

[5] Coker, A.K., "Understanding Two-Phase Flow in Process Piping", *Chemical Engineering Progress*, November 1990, page 60, American Institute of Chemical Engineers. www.aiche.org

[6] Crane Technical Paper No. 410, 1976, *Flow of Fluids through Valves, Fittings, and Pipes*, Crane Valve Group. www.craneco.com

Appendix A—Equation sets for the analysis and prevention of overpressure during refilling of cryogenic storage tanks (Normative)

Equations 1e and 1f in Equation set 1 come from Coker, A. K., "Understanding Two-Phase Flow in Process Piping" [5]. The remaining equations in Equation set 1 and the equations in Equation sets 2 and 3 come from Crane Technical Paper No. 410, *Flow of Fluids through Valves, Fittings, and Pipes* [6].

Equation set 1: Frictional pressure loss through pipe and pipe components

U.S. customary units	Metric units	Equation
$\Delta P = \Delta P(Q, K, d, \rho) = \frac{0.00001799 \cdot K \cdot \rho \cdot Q^2}{d^4}$	$\Delta P = \Delta P(Q, K, d, \rho) = \frac{K \cdot \rho \cdot Q^2}{21.07^2 d^4}$	(1a)
$Q = Q(\Delta P, K, d, \rho) = \sqrt{\frac{\Delta P \cdot d^4}{0.00001799 \cdot K \cdot \rho}}$	$Q = Q(\Delta P, K, d, \rho) = 21.07 \sqrt{\frac{\Delta P \cdot d^4}{K \cdot \rho}}$	(1b)
$K = K(\Delta P, Q, d, \rho) = \frac{\Delta P \cdot d^4}{0.00001799 \cdot \rho \cdot Q^2}$	$K = K(\Delta P, Q, d, \rho) = \frac{21.07^2 \Delta P \cdot d^4}{\rho \cdot Q^2}$	(1c)
$K = f_t \cdot \frac{12 \cdot L}{d}$	$K = f_t \cdot \frac{10^3 \cdot L}{d}$	(1d)
$f_t = \frac{1}{4 \cdot \log^2 \left(\frac{\varepsilon}{3.7065 \cdot d} - \frac{5.0452 \cdot \log(A)}{Re} \right)}$		(1e) [5]
$A = \frac{\left(\frac{\varepsilon}{d} \right)^{1.1098}}{2.8257} + \left(\frac{7.149}{Re} \right)^{.8981}$		(1f) [5]
$Re = 50.6 \cdot \frac{Q \cdot \rho}{d \cdot \mu}$	$Re = 0.02122 \cdot \frac{Q \cdot \rho}{d \cdot \mu}$	(1g)

Equation set 2: Flow resistance of various components [6]

Bends: $K = \frac{\theta}{90} \bullet K_b$ Where: $\theta \leq 90^\circ$

$$K = \left(\frac{\theta}{90} - 1 \right) \bullet \left(.25 \bullet \pi \bullet f_t \bullet \frac{r}{d} + 0.5 \bullet K_b \right) + K_b \quad \text{Where: } \theta > 90^\circ \quad (2a)$$

Is interpolated from:

$\frac{r}{d}$	1	1.5	2	3	4	6	8	10	12	14	16	20
$\frac{K_b}{f_t}$	20	14	12	12	14	17	24	30	34	38	42	50

Fittings: $K = \alpha \bullet f_t$ (2b)

Fitting type	α
90-degree elbow	30
45-degree elbow	16
Short radius elbow	40
Tee through run	20
Tee through branch	60
Swing check valve	100

Orifice: $K_{ori} = \frac{1 - \beta^2}{C^2 \bullet \beta^4}$ (2c)

C may be interpolated from the following table:

β	C
0.2	.5975
0.3	.6004
0.4	.6057
0.45	.6111
0.5	.6214
0.55	.6335
0.6	.6510
0.65	.6715
0.7	.7007
0.725	.7182
0.75	.7386

Pipe:

U.S. customary units

Metric units

Equation

$$K = f_t \cdot \frac{12 \cdot L}{d}$$

$$K = f_t \cdot \frac{10^6 \cdot L}{d} \quad (2d)$$

Sharp contraction: $K = \frac{(1-\beta^2)}{2 \cdot \beta^4}$ (for larger diameter) (2e)

Sharp-edged entrance: $K = 0.5$ (2f)

Pipe exit: $K = 1.0$ (2g)

Sharp expansion: $K = (1-\beta^2)^2$ (for smaller diameter) (2h)

Valve:

U.S. customary units

Metric units

$$K = \frac{891 \cdot d^4}{C_v^2}$$

$$K = \frac{0.002141 \cdot d^4}{C_v^2} \quad (2i)$$

Equation set 3: Converting to an alternative line size [6]

$$K_1 = K_2 \cdot \left(\frac{d_1}{d_2} \right)^4 \quad (3)$$

Equation set 4: Pump discharge characteristics

$$\Delta P_{pmp} = \Delta P_{pmp}(\rho, Q) \quad (4)$$

Appendix B—Sample calculation 1—orifice is required (Informative)

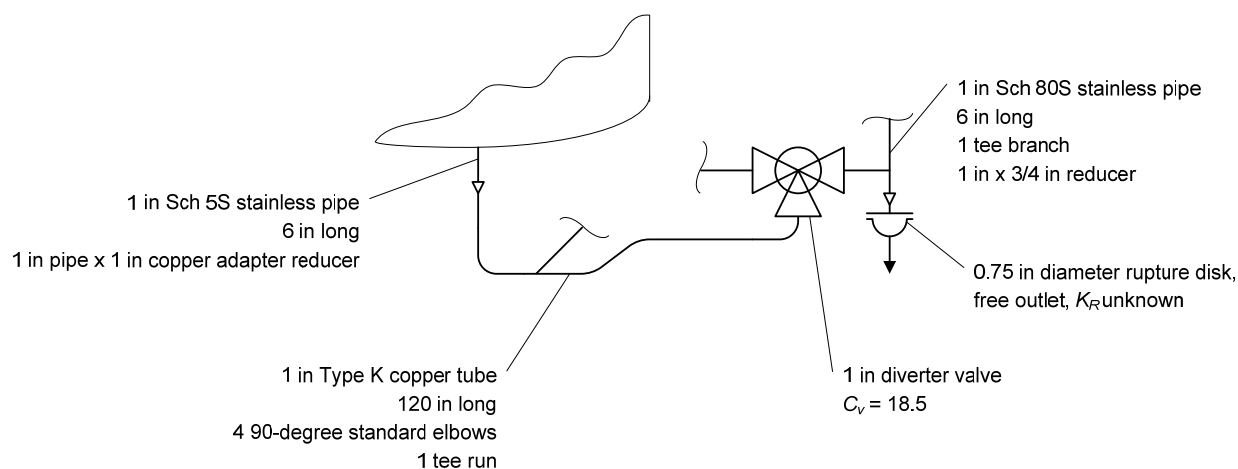


Figure B-1—Sample calculation 1—relief line sketch

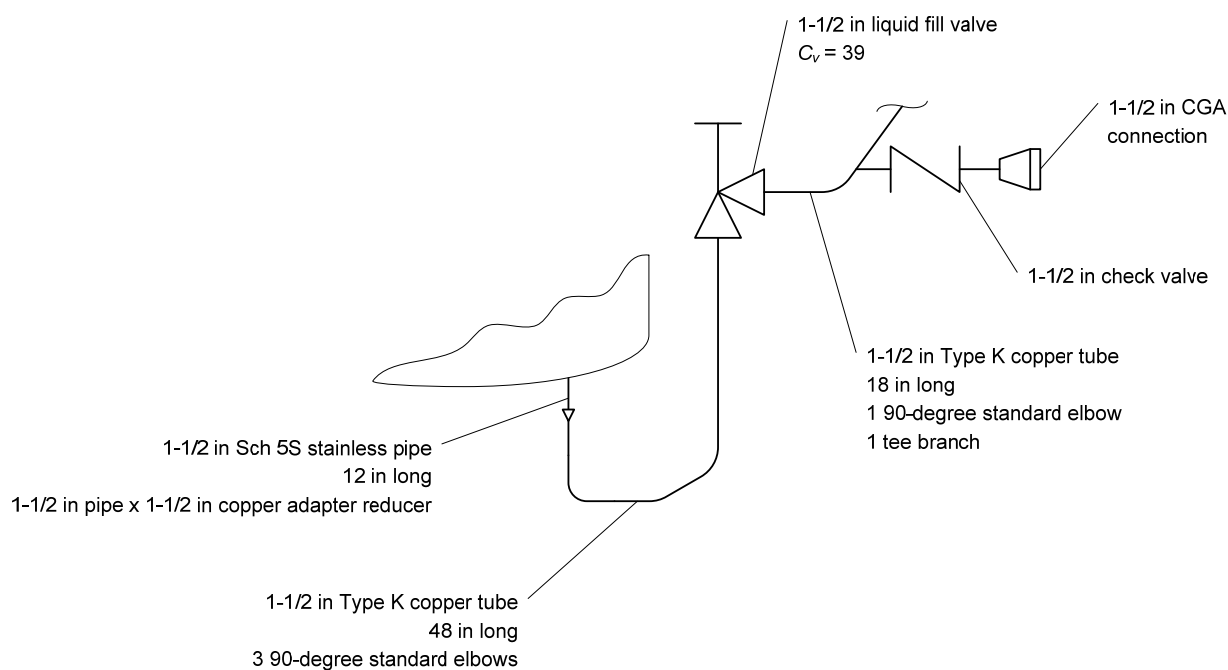


Figure B-2—Sample calculation 1—fill line sketch