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1 Introduction

Pressure relief devices (PRDs) are viewed as essential safety measures for high-pressure gas storage and distribution systems. These devices are used to prevent the over-pressurization of gas storage vessels and distribution equipment, except in the application of certain toxic gases. PRDs play a critical role in the implementation of most high-pressure gas storage systems and anyone working with these devices should understand their function so they can be designed, installed, and maintained properly to prevent any potentially dangerous or fatal incidents. As such, the intention of this report is to introduce the reader to the function of the common types of PRDs currently used in industry. Since high-pressure hydrogen gas storage systems are being developed to support the growing hydrogen energy infrastructure, several recent failure incidents, specifically involving hydrogen, will be examined to demonstrate the results and possible mechanisms of a device failure. The applicable codes and standards, developed to minimize the risk of failure for PRDs, will also be reviewed. Finally, because PRDs are a critical component for the development of a successful hydrogen energy infrastructure, important considerations for pressure relief devices applied in a hydrogen gas environment will be explored.

2 Pressure Relief Devices (PRDs)

2.1 PRD Background

Although there are several different PRD design platforms developed for gaseous applications, they all have the same basic function. PRDs are installed on high-pressure gas storage containers and related distribution lines in the vicinity of key components for the system as part of the safety system; this is often required by code. In the event of an over-pressure situation induced by, for example, overfilling, exposure to excessive heat, or a liquid to gas phase change, the PRD will activate and allow the gas to escape to a safe location. The PRD should be set such that this venting will relieve excess pressure before the internal pressure exceeds the maximum allowable working pressure (MAWP) for the system, which could result in an explosion or other catastrophic failure [1]. Most PRDs are calibrated to relieve pressure at the MAWP. However, since there is a factor of safety included in the MAWP, PRDs for certain applications can be safely set above MAWP. These exceptions include PRDs used to control a process fluid and supplemental valves to protect the system in the event of fire exposure (see Figure A1 in the Appendix). Another function of PRDs is to prevent damage to any sensitive system elements that might result from exposure to excessively high pressures for which they are not rated.

The PRD requirement is often waived for circumstances where a release may be a higher risk than the impact of an unlikely over-pressurization. For certain toxic gases, pressure relief devices are not permitted because exposure to the gas is considered to be a greater hazard than potential failure of the storage container [2].

It is important to note that pressure relief devices are an engineering control to prevent over-pressure and should not be relied on as a primary system control.

2.2 Common Types of PRDs

There are hundreds of different PRD models commercially available from various companies; however, the vast majority can be categorized by one of the four generic platform types, as listed in Table 1. Each type of PRD performs the same basic function of relieving excess pressure buildup; however, it is important to consult the codes and standards governing pressure relief device selection to ensure that the selected PRD design is appropriate for the intended application.

Table 1. Pressure Relief Device Category Definitions [3]

Type	Description
Frangible burst disk	A non-reclosing metal disk designed to burst when the static pressure at the inlet exceeds the specified set pressure. The bursting of the disk allows the pressurized gas to pass through the outlet vent and relieve the internal pressure of the system. This device empties the entire contents of the system (see Figure A2 in the Appendix).
Fusible metal plug device	A non-reclosing device designed with a metal alloy that has a low melting temperature (either 165°F or 212°F nominal) that yields when exposed to excess temperature and opens the outlet to allow the pressurized gas to escape and relieve the internal pressure of the system. This device empties the entire contents of the system (see Figure A3 in the Appendix).
Frangible burst disk backed by a fusible metal plug	A non-reclosing device designed with a frangible burst disk backed by a fusible metal plug. This device will only operate in the event of both extreme temperature that causes the metal plug to yield and excessive pressure that causes the disk to burst such as in the event of a fire. This device empties the entire contents of the system (see Figure A4 in the Appendix).
Spring-loaded pressure relief valve	A reclosing device in which a spring holds the valve closed until the static pressure increases above the set pressure of the spring. When the valve is exposed to pressure at or above the set pressure the disk unseats, opening the valve and allowing the gas to vent, thus relieving the excess pressure (see Figure A5 in the Appendix). The device will relieve over-pressure up to the maximum relieving pressure, at which point the valve is completely opened. Due to a slight amount of hysteresis, this device will typically relieve pressure back below the set pressure in a stage known as blowdown (see Figure A6 in the Appendix). This device does not empty the entire contents of the system.

Although there are four PRD platform types, there are only two main activation mechanisms—one resulting from over-pressure and the other initiated by elevated temperature. Both activation mechanisms allow the PRD to perform the basic function of relieving excess pressure. It is important to consult the codes and standards governing pressure relief device selection to ensure that the PRD has the appropriate activation mechanism for the intended application. Additionally, it is pertinent that the selected PRD is sized appropriately for the application. If any system changes are made, the PRD sizing and selection should be reevaluated and the PRD should be replaced if necessary.

2.2.1 Advantages and Disadvantages

In order to make sure the appropriate PRD is selected for each application, it is important to understand the advantages and disadvantages of each type of device. A basic breakdown of the benefits and drawbacks of each type of PRD is presented in Table 2.

Table 2. Comparison of Advantages and Disadvantages for Different PRD Types

Type	Advantages	Disadvantages
Frangible burst disk	<ul style="list-style-type: none"> • Reliable operation • Low maintenance • Minimal leakage 	<ul style="list-style-type: none"> • Relieves entire tank contents • Very loud noise when burst • Will not necessarily operate in a fire • Not reusable • Relief set point is not very precise
Fusible metal plug device	<ul style="list-style-type: none"> • Relieves pressure when system is exposed to high temperature (e.g., a fire) to prevent over pressurization • Low maintenance 	<ul style="list-style-type: none"> • Does not protect against over pressure not caused by fire (e.g., filling/compressor error) • Relieves entire tank contents • Not reusable • Must be in position exposed to elevated temperature to operate
Frangible burst disk backed by a fusible metal plug	<ul style="list-style-type: none"> • Protects cylinder from over pressurization caused by fire • Low maintenance 	<ul style="list-style-type: none"> • Only operates if tank becomes over pressurized in a fire • May not relieve pressure if vessel walls are weakened/fail due to fire • Relieves entire tank contents • Not reusable
Spring-loaded pressure relief valve	<ul style="list-style-type: none"> • Easily adjusted set pressure • Does not relieve entire tank contents when operated • Reusable 	<ul style="list-style-type: none"> • Does not reduce tank pressure in the event of a fire • Less reliable than other PRD options if not maintained and inspected regularly • Regular maintenance schedule required

Since each installation has different requirements and constraints, there is no single “best” pressure relief device type. Each type is suited for different applications and has different operation requirements to prevent different over-pressurization scenarios.

2.3 Technical Classifications for PRDs

As outlined in the CGA S-1.1, “Pressure Relief Device Standards Part 1—Cylinders for Compressed Gases,” the four major categories of PRD designs can be further partitioned into 11 pressure relief device designations. These classifications, which are applicable to PRDs for all high-pressure gas storage containers, are listed below.

Type CG-1

Rupture disk device that bursts at a predetermined set pressure.

Type CG-2

A fusible plug device using a fusible alloy with a nominal yield temperature of 165°F (73.9°C). This device is only to be used for service not exceeding 500 psig (3,540 kPa) at 68°F (20°C).

Type CG-3

A fusible plug device using a fusible alloy with a nominal yield temperature of 212°F (100°C). This device is only to be used for service not exceeding 500 psig (3,540 kPa) at 68°F (20°C).

Type CG-4

A combination device using a frangible burst disk backed by a fusible alloy with a nominal yield temperature of 165°F (73.9°C).

Type CG-5

A combination device using a frangible burst disk backed by a fusible alloy with a nominal yield temperature of 212°F (100°C).

Type CG-7

A pressure relief valve that opens to relieve excess system pressure and then closes and reseals to prevent further fluid flow once the pressure is below the set relief pressure of the device. These devices are not be used for service exceeding 500 psig (3,540 kPa).

Type CG-8

A rupture disk followed in series by a pressure relief valve.

Type CG-9

A fusible plug device for service pressures between 500 psig (3,540 kPa) and 6,000 psig (41,400 kPa) using a fusible alloy with a nominal yield temperature of 217°F (102.7°C).

Type CG-10

A fusible trigger device that uses a fusible metal alloy to trigger the pressure relief mechanism on the device. These devices should activate within 90 seconds and should not be used for service pressures exceeding 13,100 psig (90,300 kPa).

Type CG-11

A pressure relief valve that opens to relieve excess system pressure and then closes and reseals to prevent further fluid flow once the pressure is below the set relief pressure of the device. These devices are capable of activating and resealing multiple times.

Type CG-12

A combination device incorporating a fusible trigger device and a pressure relief valve that can be activated by either temperature or pressure. These devices are not to be used for service that exceeds 13,100 psi (90,300 kPa).

Through careful examination, it can be observed that each of these Compressed Gas Association (CGA) pressure relief device classifications utilize features found in one or more of the four main categories of PRD, although each have different specifications for safe usage. The CGA has rated these PRDs for acceptable use on DOT (Department of Transportation) specification cylinders for more than 200 gases and cryogenic liquids. Table 3 in the CGA S-1.1 standard [3] should be consulted for the specific requirements regarding the type(s) of PRD that are required for each gas, as well as specific details about the PRD location requirements for compressed gas cylinders. For application-specific sizing and location requirements related to PRD usage for stationary storage vessels, the CGA S-1.3 standard should be consulted.

3 Overview of PRD Failure Incidents

Although PRDs are an important safety measure in the storage of high-pressure gases, they also present their own risks and challenges. To bring perspective to the consequences of these incidents, several failure events specifically involving hydrogen have been analyzed. There have been several recent incidents within the hydrogen industry involving the premature failure of a pressure relief device. The repercussions from these failures vary from no damage or injury to death of personnel and extensive structural damage. These device failures can also have political consequences; hydrogen gas is still viewed by some as an unsafe energy source. Unreliable technology can significantly hinder progress toward public acceptance of hydrogen as a viable energy alternative.

Before analyzing failure incidents, it is necessary to distinguish between the failure modes for a PRD. Two main failure modes are feasible:

- **Type 1 Failure:** A PRD should activate but does not [4]
- **Type 2 Failure:** A PRD activates when it should not [4]

A Type 1 failure has far more hazardous potential than a Type 2 failure because it results in a situation where the internal pressure within a vessel can exceed its MAWP and potentially burst. Fortunately, Type 1 failures are very uncommon. Type 2 failures occur more frequently and typically result from improperly maintained equipment, improper selection or sizing, or compromised structural properties. To understand what can cause a PRD to fail, as well as to describe the resulting aftermath of a device failure, a few sample incidents involving the failure of a device used for hydrogen service are described below. A full incident report for each of these events can be found on the H₂Incidents database at <http://www.h2incidents.org/>.

3.1 PRD Failure Incidents

Tube Trailer Leak Through Over-Pressure-Protection Rupture Disk

A failed rupture disk on a hydrogen delivery tube trailer was detected by an employee at the filling facility. The leak was reported and a response team safely contained the leak and vented

the hydrogen gas through an exhaust tube. The burst disk had been rated for 4,000 psi and had failed around 2,100 psi. Analysis of the failed burst disk, as well as other devices on the trailer, showed the disks were made of a high strength steel alloy that was susceptible to hydrogen embrittlement. There was no equipment damage or personal injury in this event [5].

Unexpected Failure of Rupture Disk on Liquid Hydrogen Tank

A burst disk PRD ruptured prematurely when a cryogenic liquid hydrogen storage tank became slightly over-pressurized due to heating from ambient temperature. Investigation showed that the hydrogen piping was creating back pressure on the disk during manual venting, which caused the PRD to rupture below the set pressure. There was no equipment damage or personal injury in this event [6].

High-Pressure Burst Disk Failure

A burst disk PRD ruptured prematurely at 5,200 psig during a filling operation to 6,000 psig. The failure resulted in a violent release of a vent line that was improperly secured, which caused significant damage to nearby system components. Fortunately, there were no personnel in the area when the disk failed. This device was rated to 10,000 psig; metallurgical analysis showed the rupture disk was composed of pure nickel, a material that is not suitable for hydrogen service. Hydrogen embrittlement in the disk led to stress cracks and eventual failure [7].

Hydrogen Tube Trailer Burst Disk Ruptures Prematurely While Filling

A burst disk on a hydrogen tube trailer ruptured prematurely during the filling process. This resulted in hydrogen gas venting through the exhaust tube as designed. The gas ignited exiting the tube, which caused a flame to shoot out of the tube until the gas leak was contained. The burst disk failed about 1,000 psig below set pressure as a result of improper requalification following an inspection. The percussion from the failed burst disk startled a mechanic working under the trailer, who subsequently sustained minor injury during his hurried exit. No property damage resulted from the incident [8].

Pressure Relief Device Fails at Fueling Station

A pressure relief valve failed at a high-pressure hydrogen storage station, causing the release of hydrogen gas through the vent stack where it ignited and burned for approximately 2.5 hours. Approximately 300 kg of hydrogen was released. The venting equipment functioned as designed; only a canopy, which had been placed over the equipment after the initial installation, was damaged by the flame. The relief valve had failed due to hydrogen embrittlement of the high strength steel used for the nozzle. The event caused the evacuation of local businesses and elementary schools and generated significant attention by local media. No injuries resulted from the failure; the incident resulted in less than \$300 of structural damage, but the station was out of service for several months during the following investigation [9].

Hydrogen Explosion at Coal-Fired Power Plant

The premature failure of a rupture disk device during a routine delivery, and subsequent failure of vent piping, caused the buildup of hydrogen gas and a resulting explosion at a coal-fired power plant. The PRD, which had been recently serviced, did not contain the fusible metal backing that was specified. In addition to the significant structural damage caused by the blast, the delivery driver was killed in the explosion, and 10 others were injured [10].

3.2 Analysis of Failure Incidents

As shown by this brief list of events, there is a wide range of severity that can result from a PRD failure. Often, the incident results in normal operation of the venting equipment and subsequently there is minimal damage or personal injury. However, in cases like the coal-fired power plant, there can be significantly greater consequences from a device failure. It is worth noting that all of the reported PRD failure incidents are of Type 2 failure classification; the PRD fails below set pressure. This implies that all of these cases of PRD failure are a matter of reliability with the PRD designs. These cases were all a result of improper selection, design, or improper servicing. Since issues with hydrogen service are still being discovered, there are still design improvements that need to be made to assure the safe and reliable use of hydrogen as a commercially viable energy alternative. However, as a general statement, pressure relief devices are a reliable last line of protection against an over-pressurization event.

A few major takeaways from this discussion of various hydrogen-related failure incidents include the following:

- Planning and properly executing regular maintenance on PRDs is important to prevent premature activation below the set pressure.
- Proper training is required for anyone who works on or near PRD systems to understand the basic function of PRDs as well as what to expect when a PRD activates. Subsequently, response procedures should be developed in the case of a premature activation.
- It is important to ensure that any device used for hydrogen is composed of a material suitable for hydrogen service (see section 5.1.1 Hydrogen Embrittlement).

Understanding the design and function of these devices will help anyone working with PRDs respond appropriately in the event of a failure. Additionally, by understanding how these devices fail, the systems can be designed to prevent such incidents, resulting in overall safer PRD technology.

4 PRD Codes and Standards

To guide the PRD selection process for each application, there are several codes and standards that should be consulted. Table 3 below provides a useful reference guide for the applicable codes and standards and what relevant information can be found in each.

Table 3. Pressure Relief Device Codes and Standards

Title	Relevant Information
CGA S-1.1 – 2007 Pressure Relief Device Standards Part 1 – Cylinders for Compressed Gases Thirteenth Edition	<u>General</u> <ul style="list-style-type: none"> • PRD Technical Type Definitions • Gas Specific PRD Assignments <u>Compressed Gas Cylinder Specific</u> <ul style="list-style-type: none"> • PRD Type Specific Application Requirements • PRD Design / Construction Requirements • PRD Testing Requirements • PRD Identification/Marking Requirements • PRD Maintenance Requirements • PRD Service Life/Replacement Period Requirements
CGA S-1.2 – 2005 Pressure Relief Device Standards Part 2 – Cargo and Portable Tanks for Compressed Gases Eighth Edition	<u>Portable Compressed Gas Tanks and Cargo Specific</u> <ul style="list-style-type: none"> • PRD Type Specific Application Requirements • PRD Design / Construction Requirements • PRD Testing Requirements • PRD Identification/Marking Requirements • PRD Maintenance Requirements
CGA S-1.3 – 2005 Pressure Relief Device Standards Part 3 – Stationary Storage Containers for Compressed Gases Seventh Edition	<u>Stationary Storage Container Specific</u> <ul style="list-style-type: none"> • PRD Type Specific Application Requirements • PRD Design / Construction Requirements • PRD Testing Requirements • PRD Identification/Marking Requirements • PRD Maintenance Requirements

4.1 Industry Position on PRDs for High-Pressure Gas Storage

High-pressure gas storage vessels generally fall within one of two categories: mobile storage vessels and stationary storage vessels. Mobile vessels and their relief systems must meet the minimum DOT requirements as specified within 49 CFR. Stationary vessels are usually built to ASME requirements but can also be DOT vessels (e.g., a parked tube trailer that is supplying a process). As a generally accepted practice within industry, high-pressure gaseous storage systems are designed with a PRD in direct pneumatic connection to the pressure vessel that meet the requirements of either DOT or ASME code, or as required by the governing CGA standards. These PRDs are seen as providing an additional level of safety to prevent catastrophic failure of a storage vessel. In light of recent incidents involving PRD failure, some stakeholders have asserted the position that PRDs can, in specific scenarios, actually introduce additional and unnecessary failure risk to the system. Their position states that when properly sited to avoid the possibility of engulfing fire, the only credible over-pressure event is the risk of a pressure source (e.g., compressor, pump, regulator) malfunctioning thereby overfilling the vessel and increasing its pressure above the MAWP. ASME code requires the installation of a PRD for scenarios deemed credible by the designer, and such PRDs must be in a position to maintain the pressure in the vessel below MAWP. For an external source of pressure, the PRD must be located either on the vessel or between the pressure source and the vessel, and it must be set at or below the MAWP.

These stakeholders have asserted that for non-liquefied compressed gases, the only credible internal event that would cause an over-pressure situation would be an engulfing fire. ASME codes state that if storage containers are sited in compliance with NFPA codes, such that the possibility of an engulfing flame is minimized, PRDs installed directly in contact with the storage vessel are not required. Therefore, these firms hold the position that PRDs are not necessary on high-pressure gaseous storage vessels that meet NFPA location standards as well as ASME PRD standards for protection from external pressure sources.

Again, this is the position of certain stakeholders within industry; this stance has not yet been universally accepted by the industry as a whole. If enough evidence can be provided to support this opinion, there is potential for the governing codes and standards to be revisited and updated as necessary.

It is important to note that this position pertains only to high-pressure stationary gas storage containers and explicitly excludes cryogenic fluids or other condensed fluids.

5 PRD Applications for Hydrogen

As the world's energy demand continues to grow exponentially, new sources of energy are constantly being explored. Hydrogen could prove to be a very effective alternative fuel to power transportation, backup power, and various other energy needs. While working toward a commercially viable hydrogen infrastructure, a major challenge is the development of safe, effective methods for handling the highly flammable hydrogen gas. As such, it is important to understand the issues with PRD application in a hydrogen environment, as well as the types of PRDs approved for hydrogen service.

5.1 Issues with PRDs Used for Hydrogen Service

Due to its small molecular size and low ignition energy, hydrogen can be challenging to store safely at high pressures. PRDs are implemented as a final safety measure for hydrogen storage containers to prevent over-pressurization incidents. Some issues with PRDs used for hydrogen service include leakage and hydrogen embrittlement, which can lead to device failure.

Unfortunately, due to the frequency of Type 2 failures as shown by the failure event summary (see section 3.1 PRD Failure Incidents), PRDs may not be reliable enough to be applied on a broad commercial scale necessary for the development of hydrogen energy infrastructure.

Studies are underway to understand the failure modes of these devices so that they can be designed to improve reliability. As a result of the frequency of PRD failure there has been recent discussion within industry about the necessity of PRDs on hydrogen storage containers for certain over-pressure scenarios. However, until the codes are updated to reflect a change of policy that might result from these discussions, PRDs should be installed to meet the applicable standards for the particular application, be it mobile or stationary.

5.1.1 Hydrogen Embrittlement

A major consideration when designing components for hydrogen service is the prevention of hydrogen-assisted fracture, which occurs through a process known as hydrogen embrittlement. Hydrogen has a very small molecular size and can easily permeate into most metals. Once diffused, the hydrogen forms areas of embrittlement, such that it weakens or “embrittles” the metal by reducing ductility and promoting cracking. Three main factors that can affect the magnitude of hydrogen embrittlement are material, environmental conditions, and mechanical loads or stresses [11]. Higher-strength steel alloys, which are typically used in high-pressure applications for other gases, are known to experience a greater loss in ductility when used in hydrogen service than lower strength steels do. Minimizing stresses in the element will prevent failure resulting from hydrogen embrittlement, as the metal will still retain some level of ductility. Materials recommended for hydrogen service include 300-series stainless steels, copper, and brass, as they are the least susceptible to hydrogen embrittlement when exposed to the gas for prolonged periods [11].

5.1.2 Flammability

Because hydrogen has a low ignition energy in air (20 μ J), it is important to design relief systems to vent away from personnel and equipment to prevent injury or explosions. Often hydrogen will spontaneously ignite (due to static, particle impingement, or the shock wave from a high pressure release), which can result in the false perception of a serious incident even in the event of a functional pressure relief event. Additionally, hydrogen burns with a pale blue flame that can be

nearly invisible in daylight [12]. As such, PRDs should always be vented up away from areas where hydrogen gas could potentially congregate and create an explosive condition, or where personnel could haphazardly come in contact with an inconspicuous hydrogen flame.

5.2 Acceptable PRDs for Hydrogen Service

PRDs that are acceptable for hydrogen service on DOT compressed gas cylinders are listed in Table 4 (taken from Table 3 of the CGA S-1.1 standard [3]).

Table 4. PRDs for Hydrogen Applications

Device Type	Device Code
CG-1	N
CG-4	J
CG-5	J
CG-7	N
CG-10	J
CG-11	N

The accompanying letter codes J and N are defined as follows:

- J—“For cylinders, this device is required in only one end. For tubes, this device is required at both ends and each device shall be arranged to discharge upwards and unobstructed to the open air in such a manner as to prevent any impingement of escaping gas upon the containers or personnel.” [3]
- N—“This device is required in only one end of tubes. The device shall be arranged to discharge upwards and unobstructed to the open air in such a manner as to prevent any impingement of escaping gas upon the containers or personnel.” [3]

For stationary storage vessels, the PRD application requirements are based on relief flow capacity calculations; there are not specific PRD configuration assignments for usage in a hydrogen environment. To calculate application-specific sizing and configuration requirements for PRDs on a stationary storage vessel, sections 5 and 6 of the CGA S-1.3 should be consulted.

6 Conclusion

PRDs are pertinent safety components for pressurized gas storage systems. The four major types of PRDs can be categorized by the 11 CGA classifications that describe most of the PRDs currently commercially available. Although they are implemented as a safety measure, there is some small additional risk involved with the use of a PRD, specifically when used for hydrogen service. However, as the failure modes for these devices are analyzed, the reliability will improve until the risk of device failure is minimized. The indicated CGA standards provide the minimum requirements for safely designing and implementing PRDs into various compressed gas storage systems. These standards should be consulted when selecting a PRD for a specific design application. PRDs are applied in most types of high-pressure gas storage, but their application in hydrogen is specifically pertinent as the world moves toward a cleaner, more sustainable energy future. As such, PRD design and implementation requirements for hydrogen are still being reviewed and augmented as necessary.

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Appendix

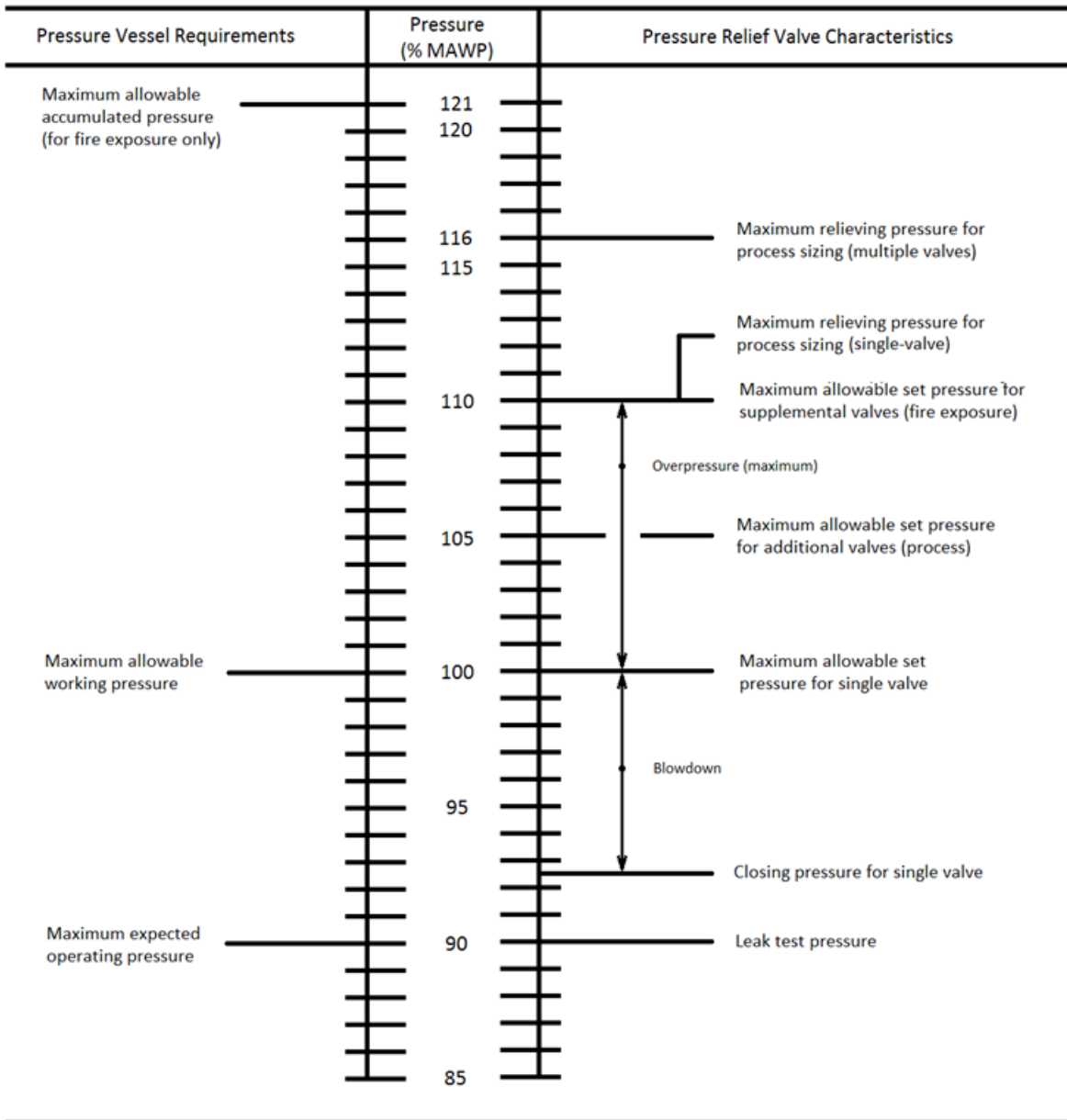


Figure A1. Pressure relief valve activation characteristics

Illustration by Arlen Kostival, NREL 500041

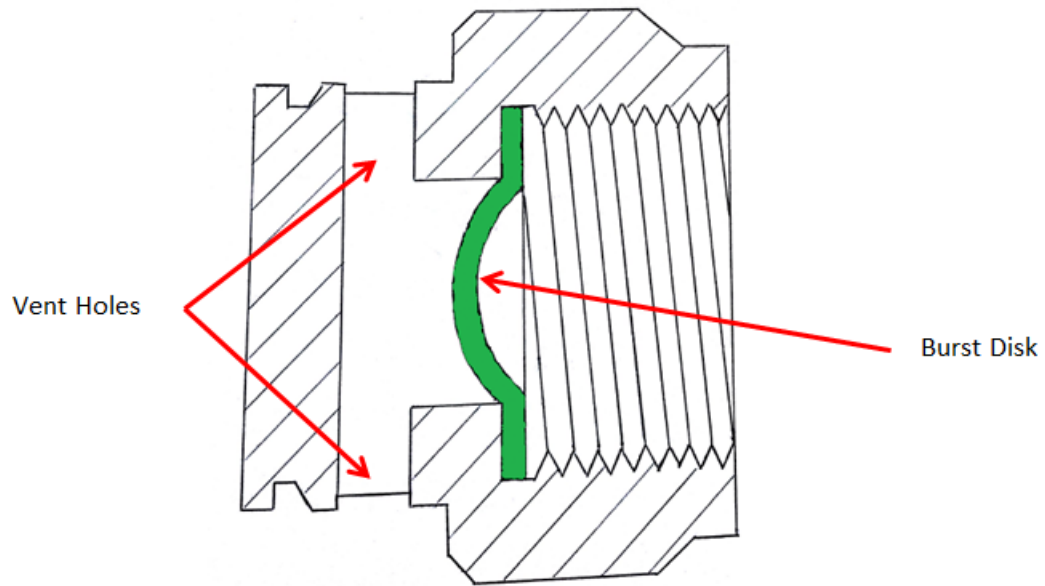


Figure A2. Frangible burst disk device cross-section

Illustration by Arlen Kostival, NREL 500038

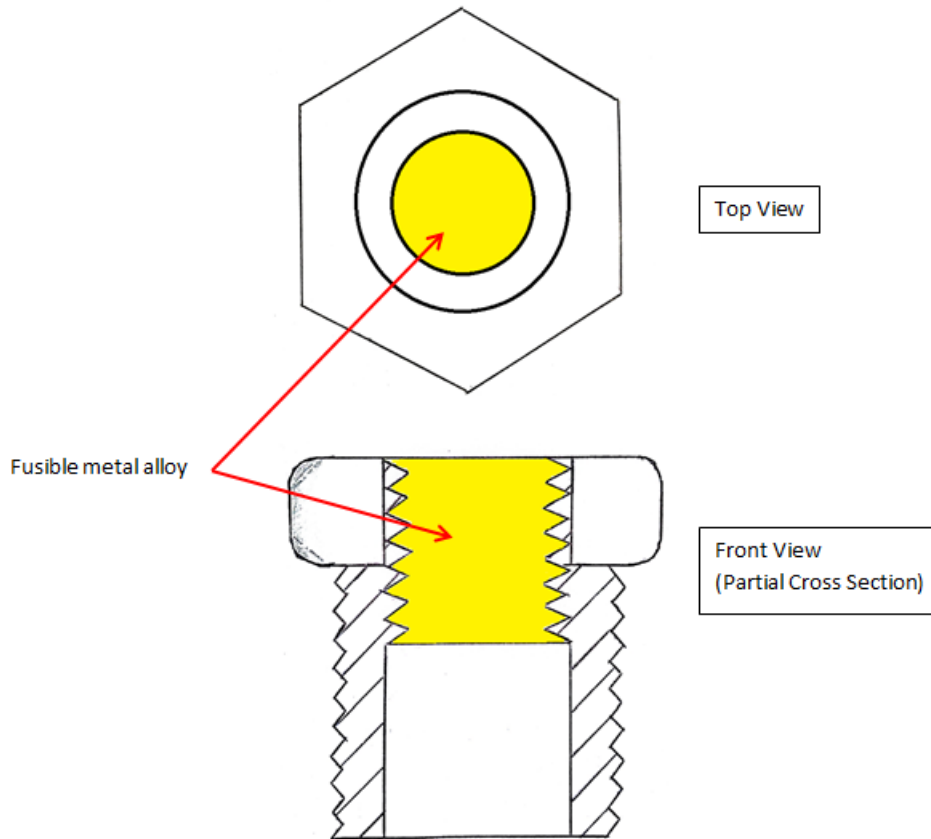


Figure A3. Fusible metal plug device

Illustration by Arlen Kostival, NREL 500040

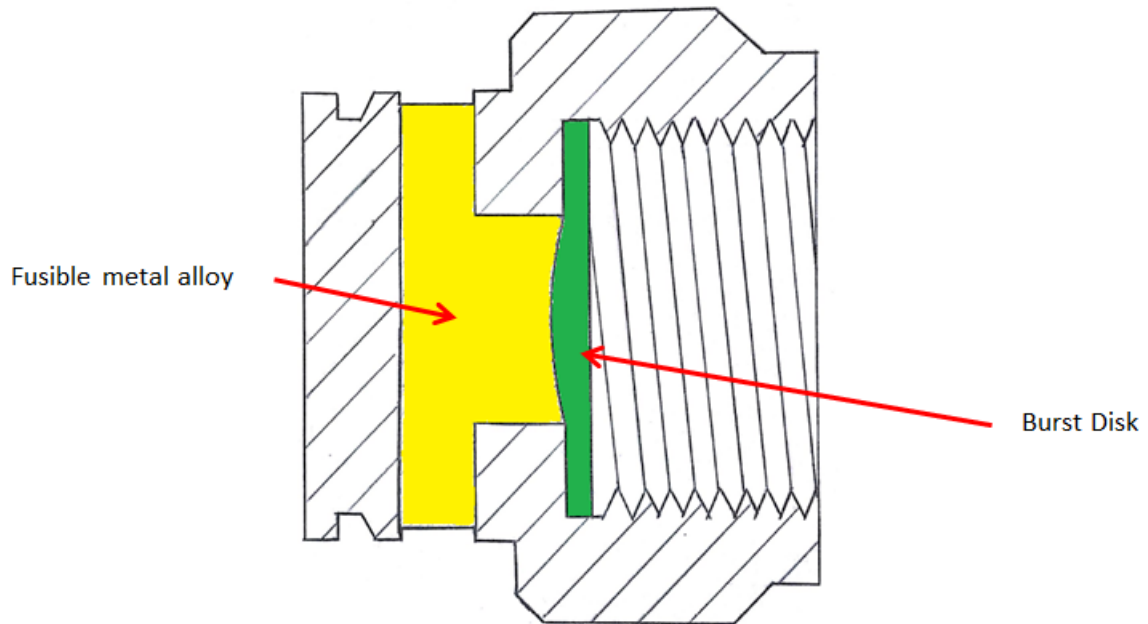


Figure A4. Frangible burst disk and fusible metal plug device cross-section

Illustration by Arlen Kostival, NREL 500039

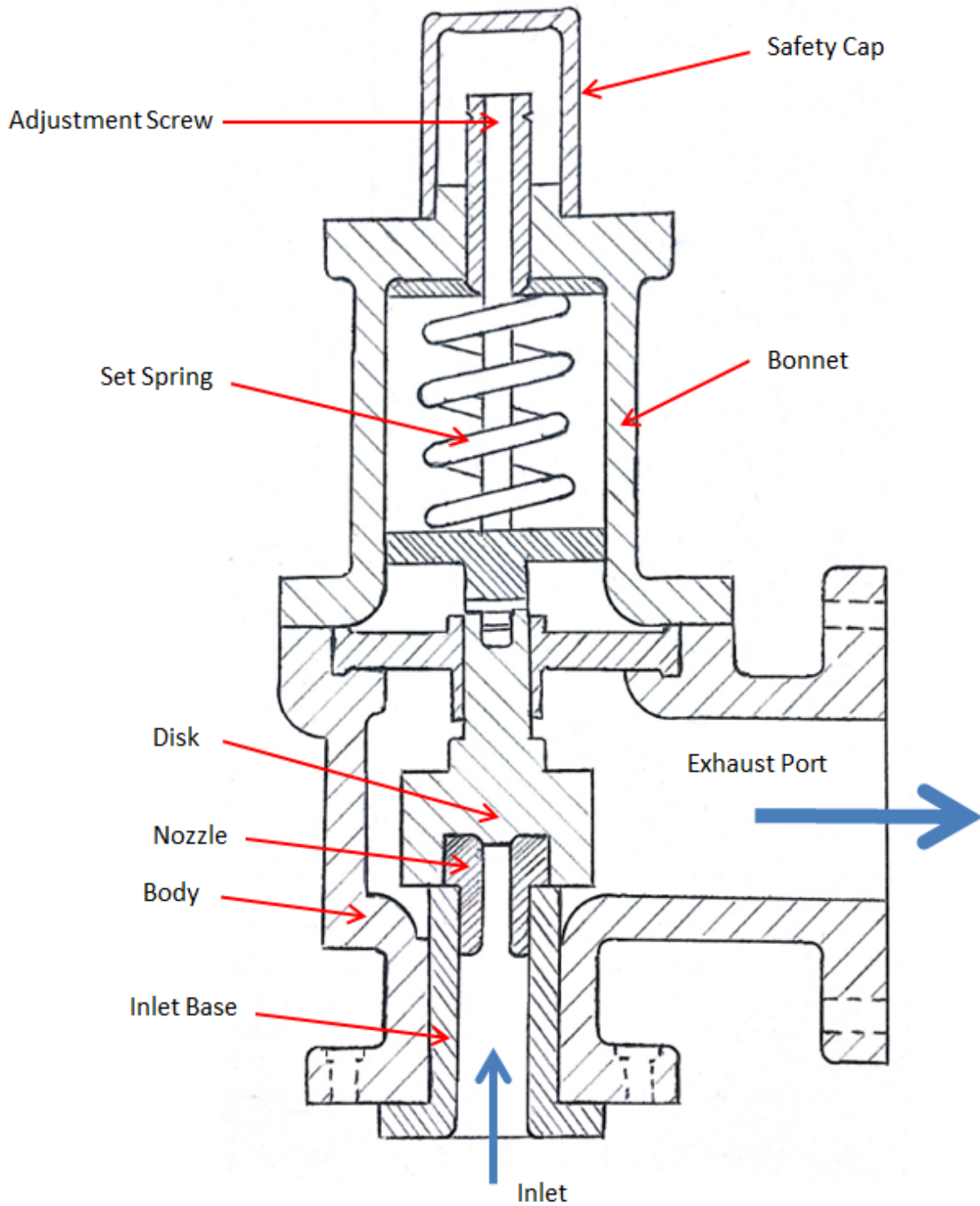


Figure A5. Spring-loaded pressure relief valve device cross-section

Illustration by Arlen Kostival, NREL 500043

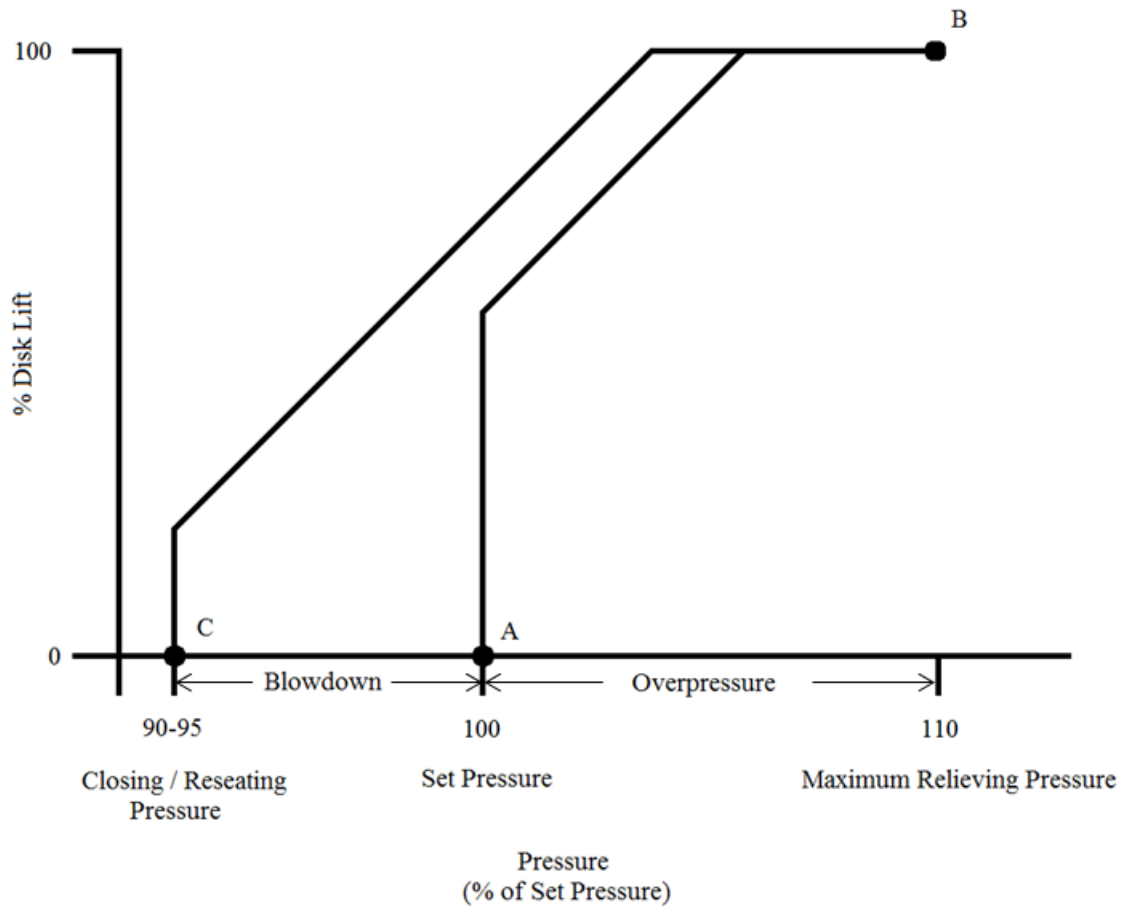


Figure A6. Pressure relief valve operation chart

Illustration by Arlen Kostival, NREL 500042