Pressure Relief Devices for Hydrogen Vehicles

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PRD Introduction

- A PRD is a safety device that protects against failure of a pressure containment system by releasing gas or liquid.
- Failure can occur from excessive pressure or temperature.
- Overpressure can arise from valve failure, operator error, phase change, reaction, or heating.
- Excessive temperature is usually associated with an impinging fire.

PRD History

- PRDs were invented in 1682.
- In 1905 – 1911, 1300 U.S. deaths occurred in boiler explosions.
- PRD use has been widespread ever since.
- Several million PRDs are in use in the U.S.
- Hydrogen and CNG vehicles could greatly increase the number of PRDs in use.

PRD Triggering

- Hydrogen vehicle containers require PRDs primarily to protect against impinging fires.
- Modern composite tanks are good thermal insulators and they weaken at high temperatures.
- Fuel pressure is not expect to increase significantly during an impinging fire. A container may not be filled with hydrogen at the time of the fire.

- PRDs can be triggered by pressure, temperature, or a combination.
- Most hydrogen and CNG vehicle containers are protected by temperature activated PRDs.

PRD Failures

- Type 1 failures are when a PRD should vent but does not.
- Type 1 failures are usually associated with blockage by dirt or ice.
- PRDs are the final safety device. Type 1 failures are very hazardous.

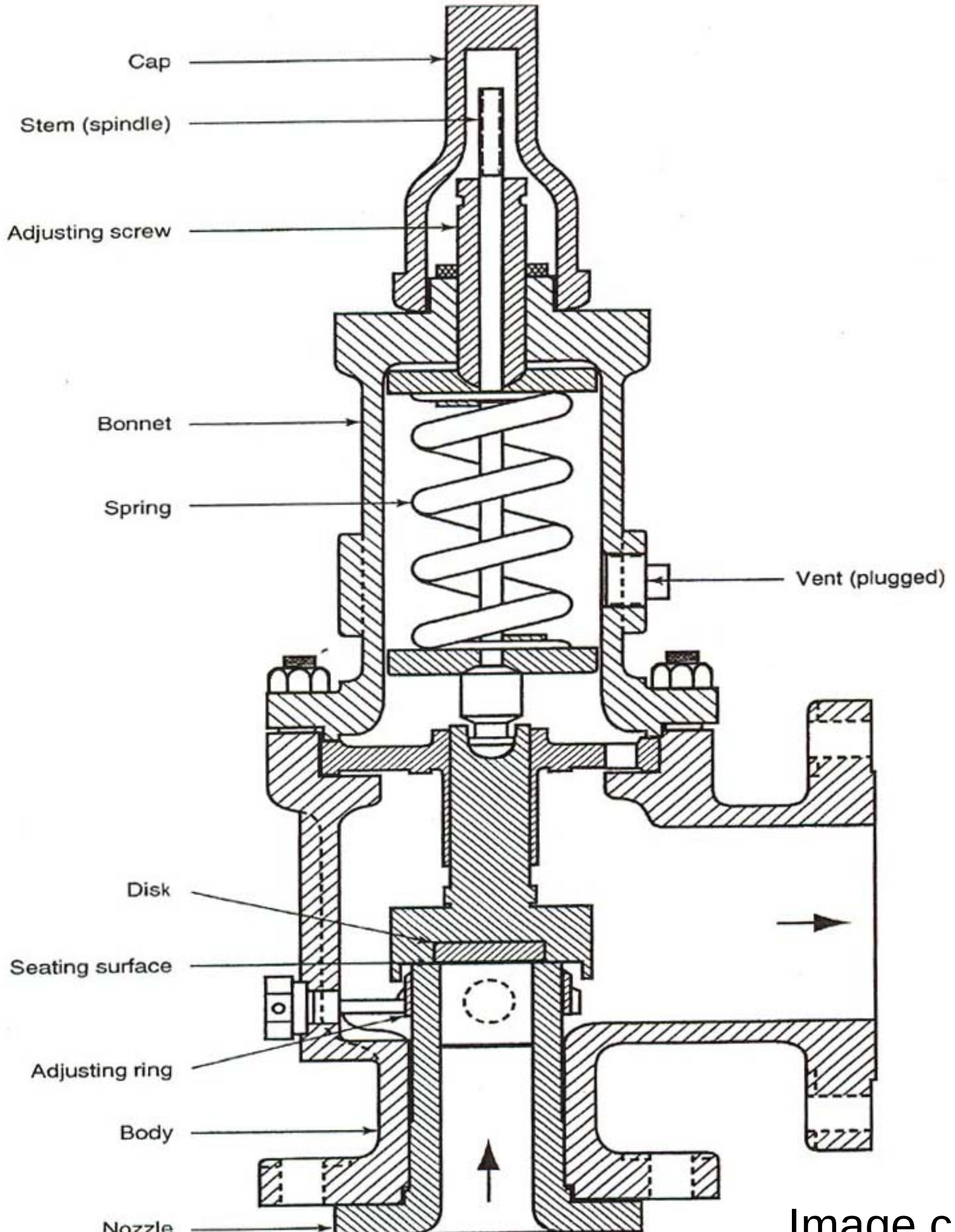
- Type 2 failures are when a PRD should not vent but does.
- Type 2 failures can arise from impact, ice formation, or worn PRD components.

PRD Types

- ❖ PRDs are made for diverse fluids, conditions, and flow passage sizes.
- ❖ The two main categories are reclosable and nonreclosable.
- ❖ Reclosable PRDs can be reused.
- ❖ They are not used for hydrogen vehicle containers because:

- they do not vent fully,
- they restrict the flow rate, and
- they are pressure activated.

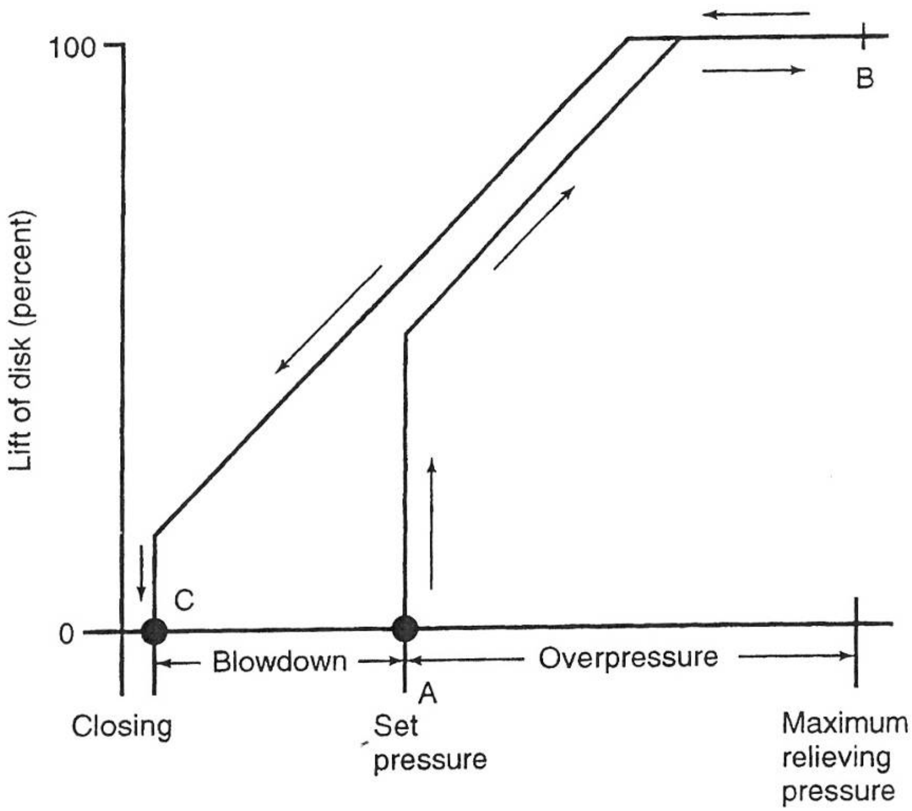
Typical Spring-Loaded Pressure Relief Valve



- ❖ Inflow and outflow are indicated by arrows.
- ❖ Sealing is between disk and seat.
- ❖ Adjusting screw controls spring tension.
- ❖ Cap prevents tampering.

Image credit: Malek (2006).

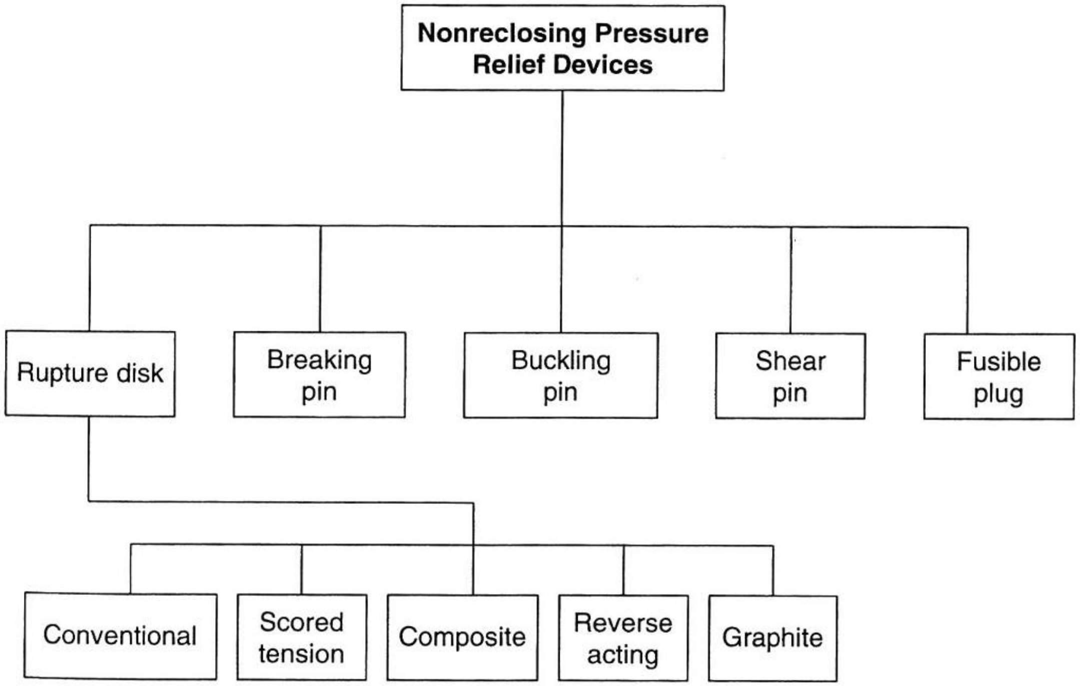
PRV Area and Pressure



- Flow area generally increases with upstream pressure.
- Hysteresis occurs between increasing and decreasing pressure.

Image credit: Malek (2006).

Nonreclosable PRDs



- These are used where activation requires a fully-opened PRD and complete venting.
- These can be temperature activated.
- Replacement is required after activation.

Image credit: Malek (2006).

Rupture Disks

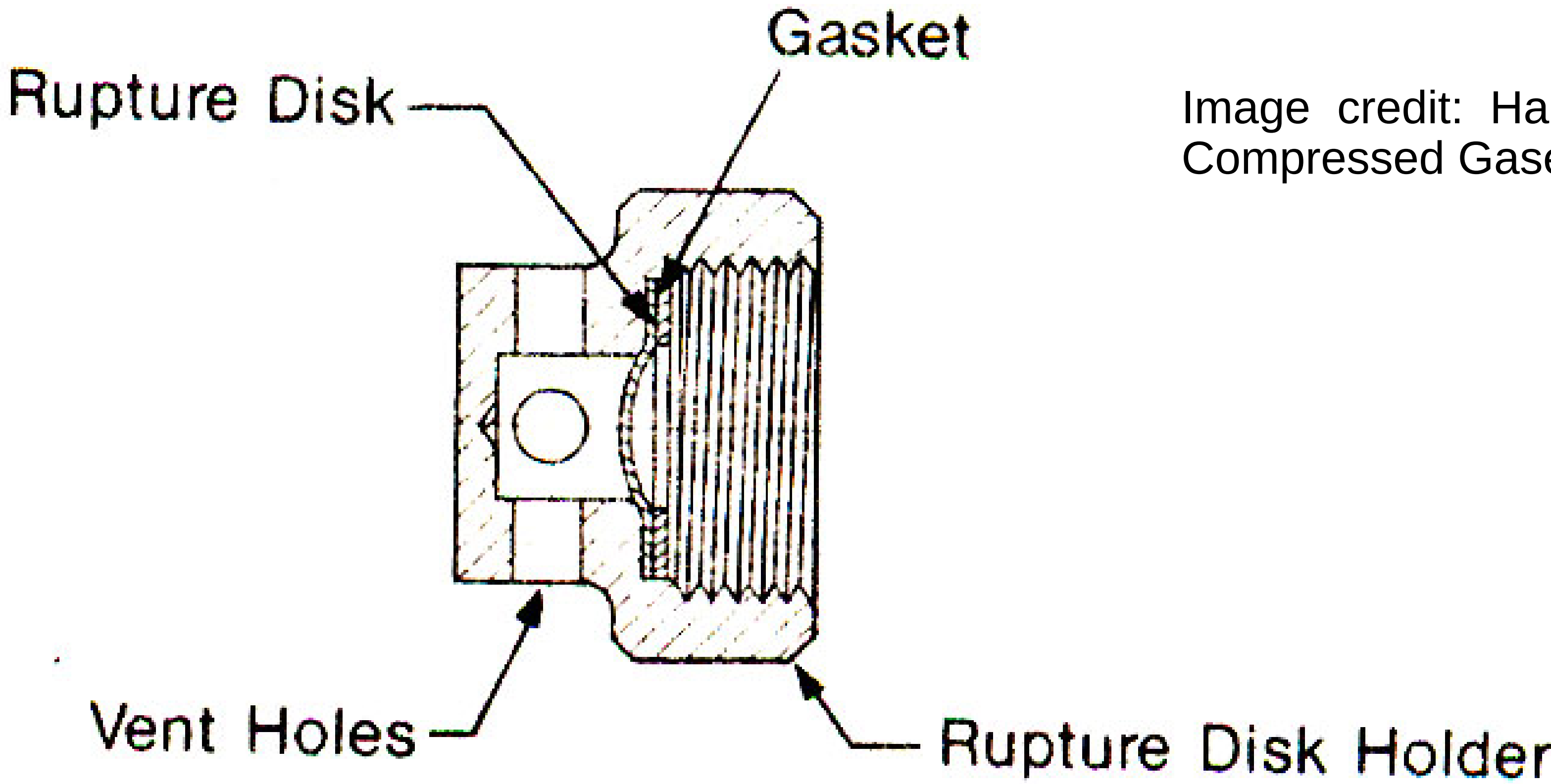
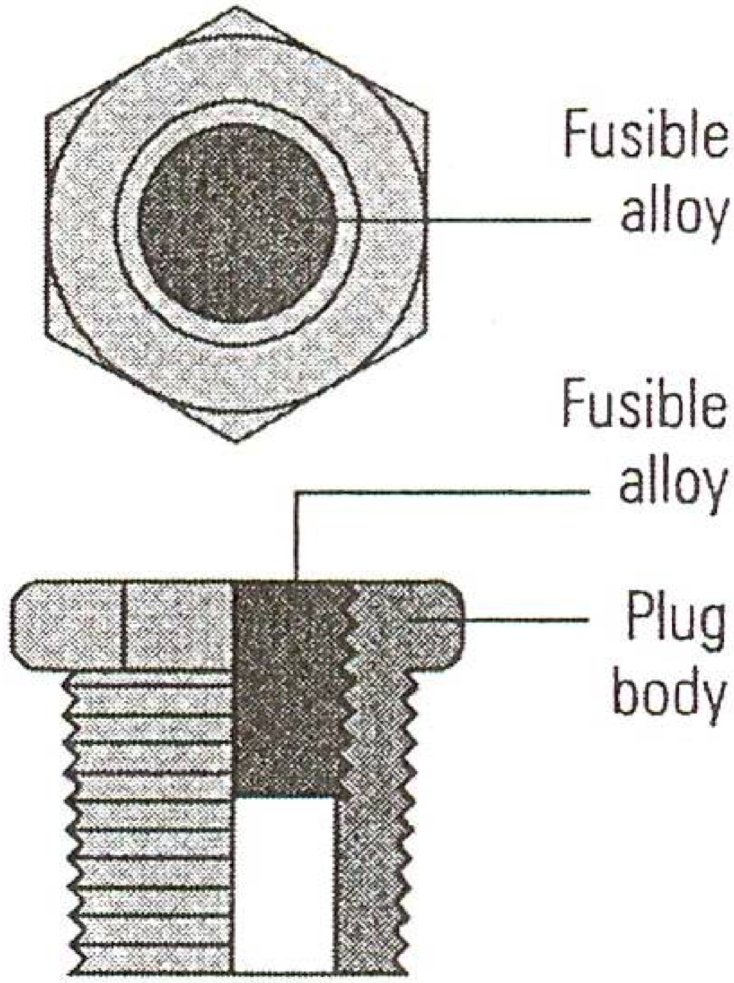


Image credit: Handbook of Compressed Gases (1990).

- These are also called burst disks.
- They are activated by high pressure.
- Potential drawbacks include shrapnel and sensitivity to corrosion.

Fusible Metal PRDs



❖ These are thermally activated.

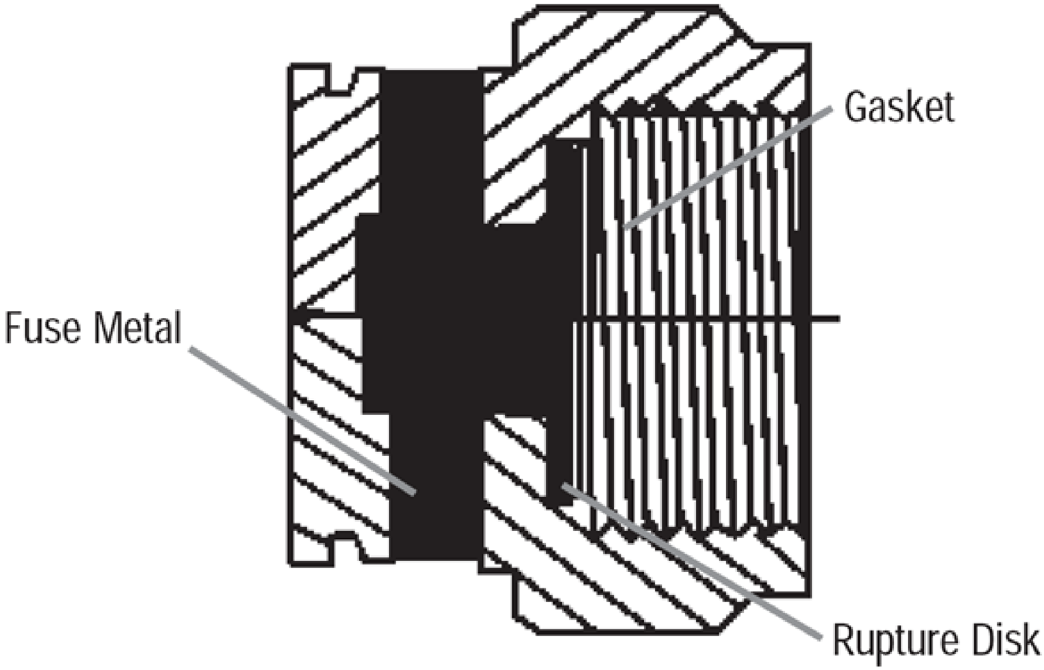
❖ Eutectic metal alloys are the fuse.

❖ CGA type CG-2 activate at 74 °C and are limited to 34 barg.

❖ CGA type CG-3 activate at 100 °C.

Image credit: Malek (2006).

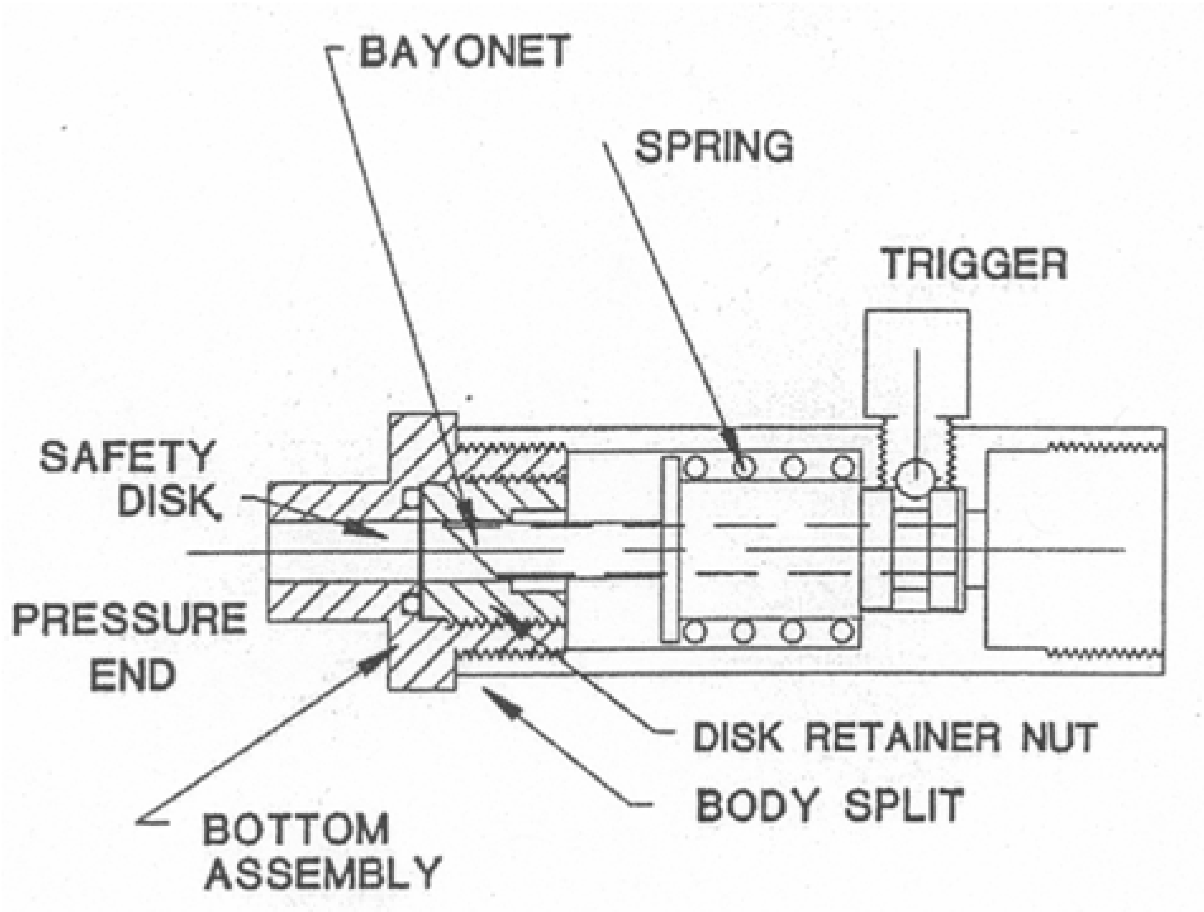
Combination PRDs



- A combination fusible plug and rupture disk PRD is shown.
- Activation requires simultaneous high T and high p.
- Fuse metal protects rupture disk from external corrosion.

Image credit: Air Products (2008).

Bayonet PRD



- Response time is reduced if fuse metal is directly exposed to hot gas.
- A Mirada bayonet PRD is shown.
- Gas vents from right to left through the hollow bayonet.

Image credit: Rolander et al. (2003).

PRD with Fuse Metal and Poppet

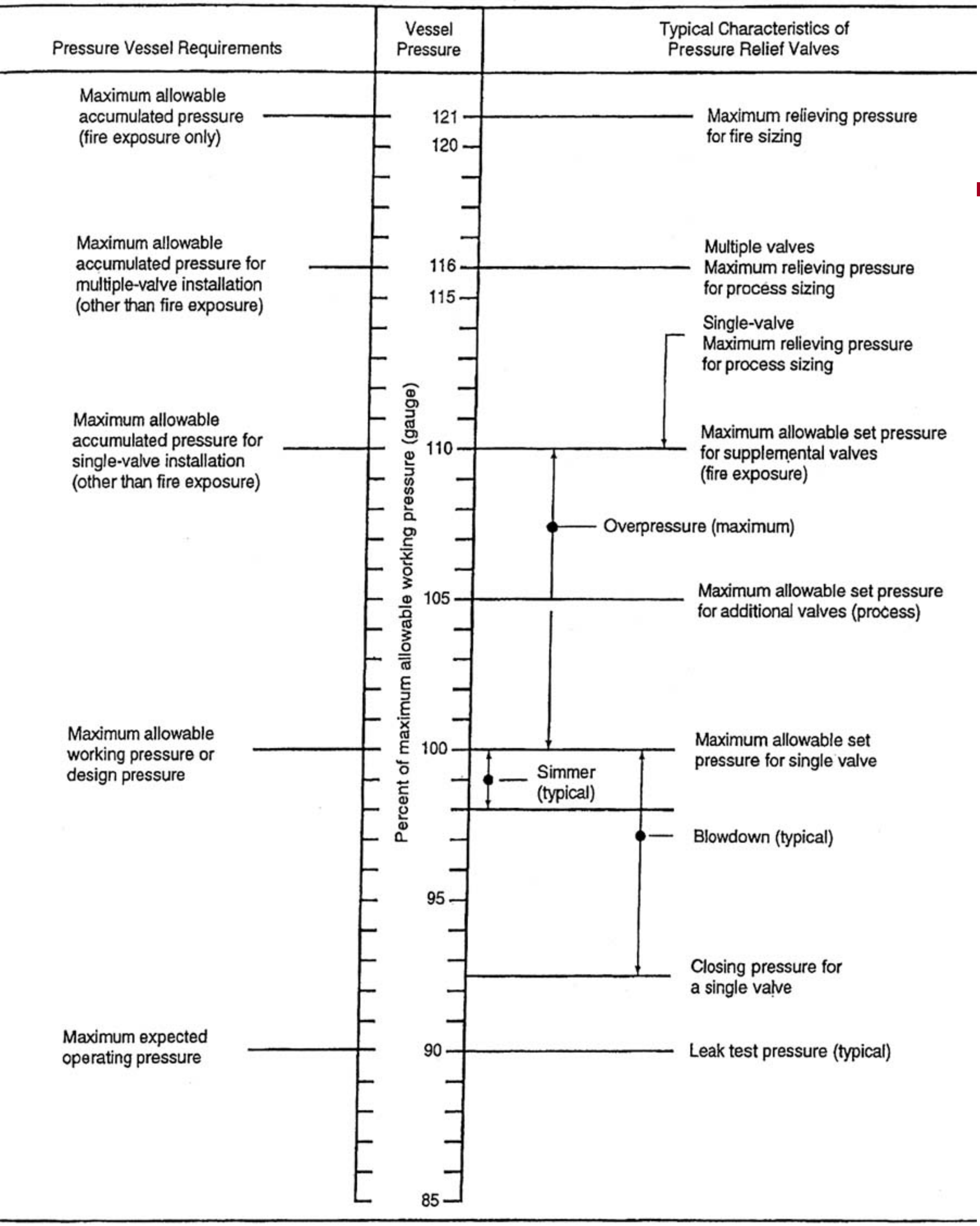
- ❖ A brass safety plug for CNG buses is shown.
- ❖ When metal melts poppet moves upward, opening O-ring seals.
- ❖ Gas vents radially.

Image credit: Rotarex (2008).

Glass Bulb PRD

- ❖ Technology is similar to automatic fire sprinklers.
- ❖ Hollow glass bulb contains liquid.
- ❖ Bulb breaks at 110 °C, opening the O-ring seal.
- ❖ Gas vents radially.

Image credit: Rotarex (2008).



Pressure Activation

- Most PRDs activate at the MAWP.
- Service pressure is not exceeded under normal operations.
- Accumulated pressure is that above MAWP.

Image credit: Malek (2006).

PRD Sizing

$$\frac{p}{p_0} = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}}$$

$$\frac{T}{T_0} = \frac{2}{k+1}$$

$$\rho = \frac{p\,MW}{R_u\,T}$$

$$c = \left(\frac{R_u\,T\,k}{MW}\right)^{1/2}$$

$$m = \rho\,c\,A$$

- Isentropic choked flow is assumed here.
- For isentropic H_2 discharge, choking occurs at 0.91 barg.

$$m = A\,p_o\left(\frac{k\,MW}{T_0\,R_u}\right)^{1/2}\left(\frac{2}{k+1}\right)^{\frac{k+1}{2(k-1)}}$$

Discharge Time

$$m = A\ p_o \left(\frac{k\ MW}{T_0\ R_u}\right)^{1/2} \left(\frac{2}{k+1}\right)^{\frac{k+1}{2(k-1)}}$$

$$d\,\rho_0 = -\,(\,m / V\,)\,dt$$

$$t = \frac{V}{A}\left(\frac{MW}{k\ R_u\ T_0}\right)^{1/2} \left(\frac{2}{k+1}\right)^{\frac{-(k+1)}{2(k-1)}} ln\left(\frac{p_{01}}{p_{02}}\right)$$

PRD Vent Lines

- Many PRDs have no provision for connecting a vent line.
- Many hydrogen and CNG vehicles do not have PRD vent lines.
- When used, vent lines are required not to restrict the flow.
- They require covers to prevent blockage by water or dirt.
- They must vent outside the vehicle.
- They must be securely fastened.

Summary of Vehicle PRD Codes

Standard	Title	Country	Year
CGA S-1.1	Pressure relief device standards - part I - cylinders for compressed gases	U.S.	2007
CSA HGV2	Standard for compressed hydrogen gas vehicle fuel containers (draft)	Canada, U.S.	draft
CSA HPRD1	Pressure relief devices for compressed hydrogen vehicle fuel containers (draft)	Canada, U.S.	draft
CSA NGV2	Standard for natural gas vehicle containers	Australia, Japan, Mexico, U.S.	2007
FMVSS 304	Compressed natural gas fuel container integrity	U.S.	2003
ISO 11439	Gas cylinders – high pressure cylinders for the on-board storage of natural gas as a fuel for automotive vehicles	International	2000
ISO 15869	Gaseous hydrogen and hydrogen blends - land vehicle fuel containers (draft)	International	draft
NFPA 52	Vehicle fuel systems code	U.S.	2006
SAE J2578	Recommended practice for general fuel cell vehicle safety	U.S.	2002
SAE J2579	Technical information report for fuel systems in fuel cell and other hydrogen vehicles	U.S.	2008

NFPA 52

- Vehicle Fuel Systems Code.
- Requires PRDs on CNG containers in vehicles.
- Requires PRDs to be thermally activated.
- NFPA 52 discussed PRDs for manifolded containers.
- Matching requirements for hydrogen vehicles are planned.
- NFPA 2, Hydrogen Technologies Code, is scheduled for release in 2010.

FMVSS 304

- In U.S., CNG vehicle containers must meet FMVSS 304.
- This is similar to NGV2, ISO 11439, ISO 15869, CSA B51, KHK, and TUV.
- Similar requirements are planned for hydrogen vehicle containers.
- Pressure cycling test – 18,000 cycles up to 123% of service pressure.
- Burst test – 3.5 times service pressure. This will be 2400 barg for hydrogen.
- Bonfire test.

FMVSS 304 Bonfire Test

- One container each at 98% and 24% of service pressure.
- Horizontal placement above linear fire source such as diesel pool, 1.65 m long.
- Average temperature 25 mm below the container of at least 430 °C.
- PRD shielded with steel box.

- To pass test, in 20 mins container must either vent down to 6.9 barg or not rupture.

- Many have recommended an improved bonfire test.

HPRD1

- This is CSA America's draft *Pressure Relief Devices for Compressed Hydrogen Vehicle Fuel Containers*.
- It will cover thermally and pressure activated nonreclosable PRDs.
- Its tests will include:

- pressure cycling (16,750 cycles)
- long-term creep thermal cycling (-40 – 85 °C)
- salt corrosion resistance
- copper corrosion resistance (using ammonia)
- impact
- leakage (0.2 scc/hr or less)
- bench top activation
- flow capacity

PRD Practice in Hydrogen Vehicles

- Most existing or planned hydrogen highway vehicles involve compressed gas at up to 690 barg.
- Most PRDs will continue to be thermally activated.
- High pressure hydrogen releases can be expected to ignite.
- The direction of venting is important.

Hydrogen Vehicle PRD Research

- Swain (2001) tests comparing hydrogen and gasoline vehicle fires.
- Suzuki et al. (2006) PRD vent orientation tests.
- Tumura et al. (2006) bonfire tests.
- Sekine et al. (2008) bonfire tests.

Hydrogen Vehicle PRD Case Studies

- ❖ Many hazards are similar to CNG vehicles, which are in wider service.
- ❖ Two CNG bus fires resulted in safe venting by the PRDs.
- ❖ A CNG Ford Crown Victoria in a fire experienced a container rupture in 2003.
- ❖ A CNG Honda Civic ruptured in 2007 (below).

Image credit: Seattle FD (2007).

Vehicle PRD Recommendations

- Valve caps can reduce type 1 and type 2 PRD failures. However these still occur in compressed gas vehicles.
- Collisions can contribute to type 1 and type 2 PRD failures.
- Localized fires may be more hazardous than bonfire-type fires. Responding to such fires may require electronic PRDs.
- Explosive squib valves may aid firefighters responding to hydrogen vehicle fires and collisions.
- Intumescent paint or other cylinder insulation should be pursued.