

Don't let  
the cold  
catch you  
out



## **Matt Byers, Baker Hughes, USA, outlines the engineering best practices used today to optimise the design of pressure relief valves operating under cryogenic conditions.**

**P**ressure relief valves (PRVs) are a necessary requirement for overpressure protection within the LNG industry.

However, not all PRVs are created equally when it comes to performance within cryogenic applications, and design temperatures as low as -320°F (-196°C). These applications require PRVs with enhanced sealing features to address the cryogenic conditions and perform their safety function.

PRVs are the last line of defence to protect equipment and personnel from an overpressure event. Construction materials, trim designs, and anti-galling measures are all critical components of a PRV design, as they help to address their challenging applications. Common PRV problems in these applications that need to be addressed include:

- **Seat leakage:** Thermal stress from low temperature causes material deflection. This deflection on a seating surface can result in leakage while the valve is closed, or immediately following a relief event.
- **Galling of bearing/guiding surfaces:** Anti-seize grease, commonly used in non-cryogenic applications to prevent galling, quickly deteriorates under cryogenic temperatures. This results in galling-induced wear between the metallic components, which leads to seat leakage, valve simmer, and 'hang-up' of guiding surfaces as the valve attempts to re-seat following a relief event.
- **Process loss and fugitive emissions:** Seat damage as a result of prolonged seat leakage, premature opening as a result of major seat leakage, or the PRV not fully closing after a relief event, due to excessive galling, can all lead to unwanted and costly release, or fugitive emission, of process fluid (Figure 1).

End users have been implementing local fixes to reduce or delay the impact to their operation through reactive PRV maintenance. However, the severity of cryogenic requirements in the LNG industry

extend further than the typical relief valve countermeasures that are commonly used today.

### **Reactive PRV maintenance**

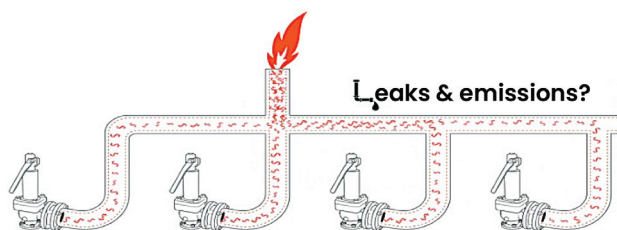
The traditional approach to managing PRV field issues has been a 'good enough' strategy of reactive maintenance. With reactive maintenance, most PRVs follow a regular service interval ranging between every six months to every three years, set by local site policies and best practices. While this approach may serve to maintain operations, it does not always properly analyse root cause failure modes and implement full corrective actions. Unfortunately, this approach has drawbacks due to the unpredictable nature of system operation and PRV performance status before and after a relief event.

### **Unplanned outages**

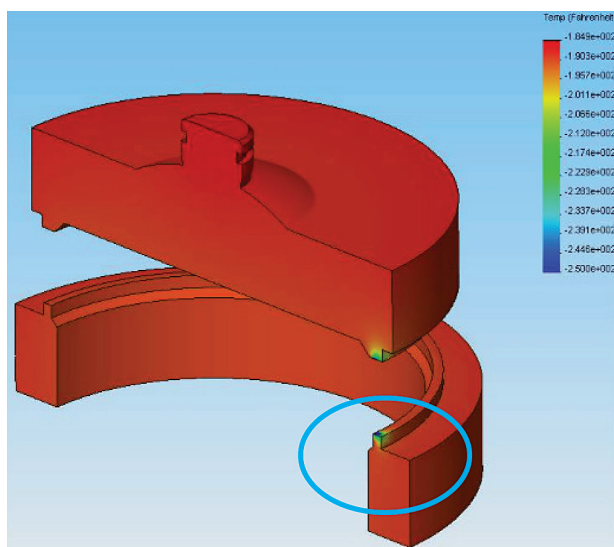
Under harsh, long-term conditions it is difficult to predict with certainty if, or when, a PRV is going to open, how long it will open, how stable it will perform under the overpressure conditions, and, most importantly, will it reclose and be leak-tight afterwards? For these reasons, operators can often find their PRVs in an undesirable state, leading to unplanned outages for correction. These outages put operators in a major bind and cause entire supply chains to scramble in attempt to source critical service, parts, and/or replacement PRVs to get the system back up and running.

This urgent scenario is not a cheap exercise for anyone involved when considering the premium costs including air freight, expedite fees, and overtime labour. Plants would benefit from better utilisation of their resources and spending if they could be redeployed for true system corrective maintenance, as opposed to high cost expedited repairs.

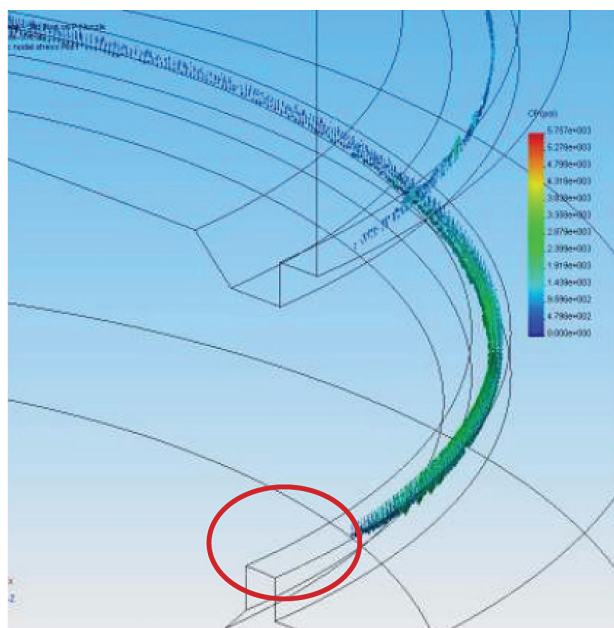




**Figure 1.** Seat leakage of pressure relief valves (PRV) causes process loss and fugitive emissions.



**Figure 2.** Temperature distribution with leak path simulation.



**Figure 3.** Contact pressure distribution, standard PRV nozzle and standard PRV disc.

## Maintenance guesswork

PRV maintenance can be next to impossible to accurately predict. If you ask a PRV manufacturer “How often should I service my PRV?”, the answer is resoundingly the same: “It depends...” In defence of the manufacturers, they are not dodging the question, because it truly does depend.

Factors to consider when developing a PRV service interval plan include the following: the criticality of the service; how often the PRV is expected to cycle; the amount of debris and particulate in the line; the stability of the PRV during an overpressure event; and countless other variables. As a result, end users tend to err on the side of caution and service their PRVs more often than required. Furthermore, too often do operators throw away precious dollars to service PRVs which do not require service. But better safe than sorry, right?

## Innovative design solutions

Cryogenic PRV applications require optimised design solutions with countermeasures for seat leakage and galling prevention to address commonly known failure modes and prevent unplanned downtime, PRV repair, and reduced fugitive emissions. Time is money, right? The correct PRV for the correct application, with design features proven and tested, can save you time and money by providing reliable cryogenic overpressure protection.

The typical failure mode of a PRV operating with cryogenic media is seat leakage after valve actuation, or when the operating pressure is close to set pressure. Once an initial valve seat leak, or simmer, is established, icing can build on the seat, which causes leakage to progressively worsen as the PRV begins to visually resemble a ball of frost after an extended period of time. These leaks can be stopped when the valve body and inlet flange are heated with an external heating element to eliminate the icing, thus allowing proper re-seating.

The finite element analysis (FEA) outlined in the following sections has been used to replicate this failure mode. As the process media escapes through a microleak flow path, the fluid undergoes an isoenthalpic pressure drop that produces a localised reduction in temperature. Simulations show liquefied methane operating at 90% of set pressure, with a fluid temperature of  $-190^{\circ}\text{F}$ , yielding a localised temperature reduction as low as  $-250^{\circ}\text{F}$ . A thermal FEA simulates this leak path in a very small area between the nozzle and the disc shown in Figure 2. The thermal analysis simulates the temperature profile of a leaking valve and is the input for performing the static FEA to understand its impact on the seat tightness of the valve. At 90% of set pressure, it was demonstrated that there were no contact forces between the disc and nozzle, not only at the leak path but also in the area immediately adjacent to the leak path as shown in Figure 3.

## Leveraging innovation

High temperature PRV design innovations have evolved over the last 100 years, mostly on steam applications, from their yoke/side rod constructions to their disc designs. Many of today's PRVs designed for steam have unique disc designs which leverage thermal expansion principles to provide leak-tight performance at elevated temperatures. However, the industry has not seen the same innovation for low temperature cryogenic applications, where the same thermal expansion principles apply and can be even more prevalent. What if the disc was designed to leverage the same thermal expansion principles that have demonstrated and successfully proven leak-tight performance on high temperature gas and steam applications? These high temperature disc designs have a thermolip feature, which uses the temperature differential between the process fluid and ambient temperature in the body bowl to cause a downward

deflection, providing more contact stress on the nozzle seat and creating greater seat tightness at elevated temperatures. An FEA was performed on a high temperature disc with a thermolip feature using high temperature and cryogenic temperature boundary conditions to analyse the deflection performance. As shown in Figure 4, the deflections due to temperature are different and opposite for the high temperature and cryogenic temperature tests.

The design concept of the high temperature disc uses the differential temperature to provide downward axial deflection. This same concept has been applied to design a reversed thermolip disc as shown in Figure 5, which would produce the same leak-tight performance at cryogenic temperature as has been proven with high temperature discs at elevated temperatures.

## Thermal analysis results

The boundary conditions used for the FEA of the low temperature disc are the same conditions as applied to the previously mentioned analysis of using a standard PRV disc and nozzle.

The FEA results shown in Figure 6 demonstrate that the disc and nozzle temperatures reached the full fluid temperature. The plot shows the temperature distribution on the Cryodisc and nozzle components as a leak path is simulated. The analysis shows the temperature drops across the leak path.

## Thermal stress and contact analysis

These same loads are used for both the benchmark study and for the standard PRV disc and nozzle. Figure 7 shows the uniform contact pressure distribution around the seating area between the Cryodisc design and the nozzle. The lower the coefficient of thermal expansion, the greater the improved performance of the Cryodisc thermolip. The reversed thermolip maintains contact pressure in the leak region even as a microleak develops.

## API 526 spring-loaded PRV cryogenic valve testing

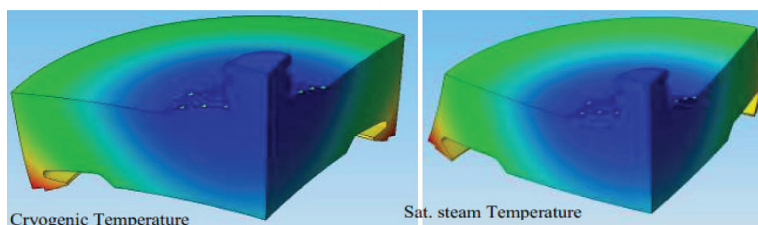
Liquid nitrogen was supplied to the PRV nozzle with a cloud of gaseous nitrogen at the disc-seat region. This is undertaken to best represent field conditions where vaporisation of the liquid natural gas in the nozzle is expected.

## Verifying FEA results with actual test results

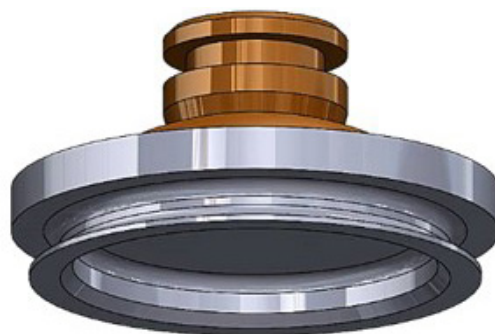
In order to verify the FEA results, actual cryogenic testing using liquid nitrogen with test temperatures down to  $-320^{\circ}\text{F}$  ( $-196^{\circ}\text{C}$ ) was performed on various PRVs. The test results summarised in Table 1 are the average of multiple API 526 spring-loaded PRV sizes in F and J orifices tested with a set pressure of 100 psig.

The seat leakage, based on API 527 bubbles/minute criteria, for the standard disc show the leakage rates considerably worsen over time, eventually exceeding the acceptable leakage rate. This quantifies the FEA results of the standard disc showing no contact pressure in the leak path. As the leakage rate worsens over time, the PRV will experience seat damage, simmer, and unwanted fugitive emissions.

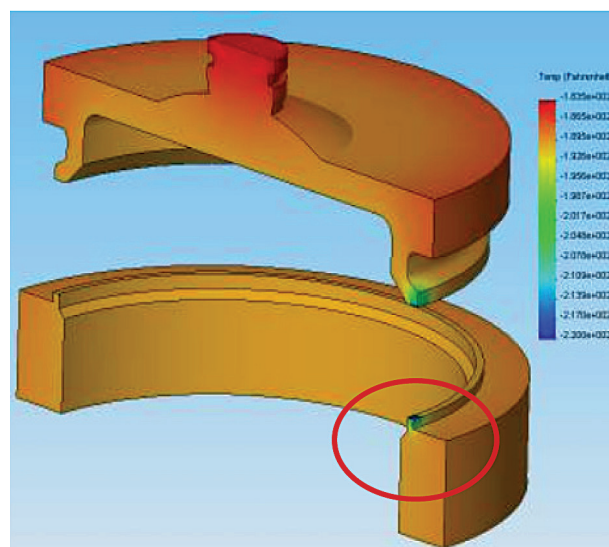
Comparably, the seat leakage results using the Cryodisc show the leakage rate improving over time, developing a tighter seal, and the leakage rates are well within the API 527 acceptable bubbles/minute criteria. Based on test results, the FEA results for the Cryodisc can be confirmed that contact pressure increases as



**Figure 4.** Deflections of a high temperature disc designed with a thermolip under cryogenic and saturated steam conditions. Deflections magnified for illustration.



**Figure 5.** Cryodisc design with reverse thermolip and titanium nitride (TiN) coating.



**Figure 6.** Temperature distribution with leak path simulation.

the low temperature causes the thermolip to deflect axially downward, increasing the contact pressure on the nozzle.

The enhanced seat tightness due to the Cryodisc thermolip design is proven through FEA and validated through actual lab testing. A PRV that can maintain seat tightness on LNG will have the knock-on effect of reducing unplanned downtime, PRV repair costs, process loss, and excessive fugitive emissions.

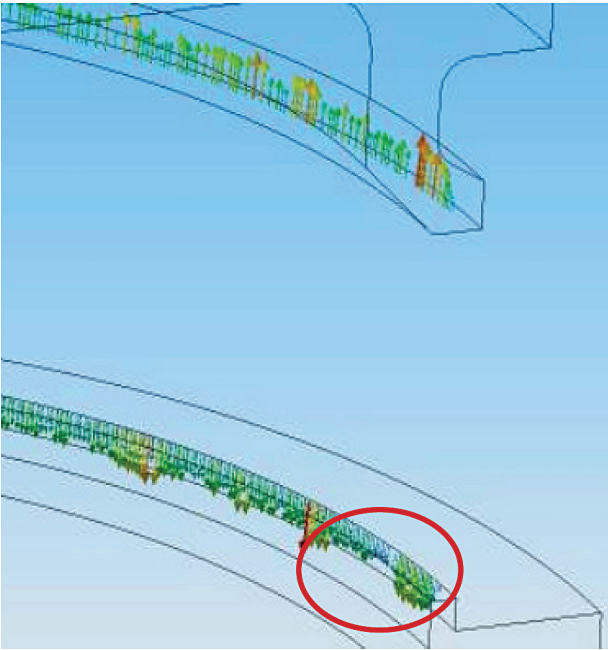
## Galling of bearing and guiding surfaces

Titanium nitride (TiN) coating is an extremely hard ceramic material (harder than carbide or chrome) applied to improve the substrate's surface properties. It is applied as a thin coating,

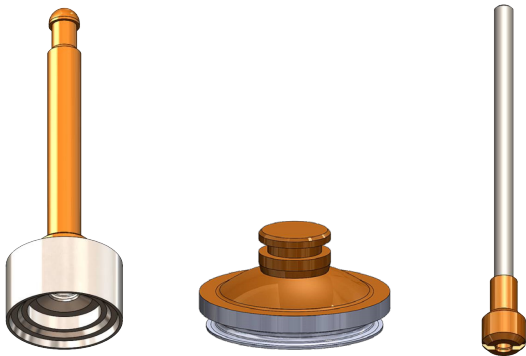


less than 4  $\mu\text{m}$ , and is used to harden and protect metal to metal bearing surfaces, sliding/guiding surfaces, and for cutting tools. This coating can eliminate galling, microwelding, seizing, and adhesive wear on the critical PRV components. It has a low friction, can enhance corrosion resistance, and has erosion resistance.

Cryogenic PRV testing was performed at the Houston Advanced Research Center (HARC) in the US, with the PRVs submerged in liquid nitrogen. Testing was performed on various sizes and set pressures of API 526 spring-loaded PRVs and it was discovered that after multiple cycles under full cryogenic



**Figure 7.** Contact pressure distribution, Cryodisc and standard PRV nozzle.



**Figure 8.** Disc holder, Cryodisc, and spindle TiN coated on sliding and bearing surfaces.

conditions, the valves exhibited hanging while closing and seat leakage above API 527 allowable leakage rates. During the PRV teardown, galling was noticed on bearing surfaces and guiding surfaces, such as the spindle to disc holder, disc holder to disc, guide inside diameter, and disc holder outside diameter. TiN coating was applied to all bearing surfaces of the bearing components, IDs and ODs of guiding components, and repeated cryogenic testing was performed.

The test results showed impressive improvements in seat leakage resulting from the elimination of galling of the bearing and guiding surfaces of these components after cycle testing of the PRVs under these conditions. The valves showed smooth opening and closing, without hanging and with tight shut-off.

Based on these results, TiN coating on the critical bearing and guiding components of the PRV can improve seat tightness after a relief event on LNG, and can reduce unplanned downtime, PRV repair costs, process loss, and excessive fugitive emissions.

### Conclusion

This article has outlined the engineering best practices being used today in order to optimise the design of PRVs used under cryogenic conditions, specifically for critical LNG overpressure protection needs. Based on advanced engineering techniques such as FEA combined with actual PRV test results, we have learned that not all PRVs are created equally when it comes to performance within cryogenic applications, and design temperatures as low as  $-320^{\circ}\text{F}$  ( $-196^{\circ}\text{C}$ ).

These challenging applications demand proper materials of construction, enhanced cryogenic seat sealing technology, and anti-galling measures to ensure reliable overpressure protection before and after a relief event.

Time is money when it comes to unplanned downtime, and saving money on PRV repairs can add up fast. Choosing the right PRV for the right application, with design features that are proven and tested, can save time and money by providing reliable cryogenic overpressure protection. **LNG**

Table 1. Standard PRV trim vs low temperature PRV trim leak performance						
API 526 F & J Orifices	Leak pressure (% of set)	API 527 acceptable leakage (bpm)	Standard disc		Cryodisc	
			Time (min.)	Leak rate (bpm)	Time (min.)	Leak rate (bpm)
			14	20	15	18
			15	52	24	15
			20	250	46	2