INCREASING THE USEFUL LIFE OF QUENCH RELIEFS WITH INCONEL BELLOWS

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ABSTRACT

Reliable quench relief valves are an important part of superconducting magnet systems. Fermilab developed bellows-actuated cryogenic quench reliefs which have been in use since the early 1980's. The original design uses a stainless steel bellows. A high frequency, low amplitude vibration during relieving events has resulted in fatigue failures in the original design. To take advantage of the improved resistance to fatigue of Inconel, a nickel-chromium alloy, reliefs using Inconel 625 bellows were made. Design, development, and testing of the new version reliefs will be discussed. Tests show that relief valve lifetimes using Inconel bellows are more than five times greater than when using the original stainless steel bellows. Inconel bellows show great promise in increasing the lifetime of quench relief valves, and thus the reliability of accelerator cryogenic systems.

INTRODUCTION

The superconducting magnets of the Tevatron accelerator are protected from over pressurizing during a magnet quench (when the superconductor ceases to be superconducting) by a quench relief valve. These reliable, cost-effective cryogenic reliefs were developed by Fermilab. Figure 1 shows a cross-sectional drawing of these reliefs. The poppet seating force is provided by the remote pressurization of a bellows-driven actuator. When the pressure force from the magnet side, plus a small spring force, exceeds the force exerted by control pressure (that is, approximately the magnet pressure exceeding the control pressure), the valve opens for relieving with the poppet moving back counter to the flow.[1] This valve design has been in service since the beginning of the Tevatron era in the early 1980's.

While the quench relief valves have proven to be dependable for the Tevatron, their failures still contribute a great deal to accelerator cryogenics system downtime.[2] Valuable operating time could be gained if this portion of cryogenic downtime were reduced.

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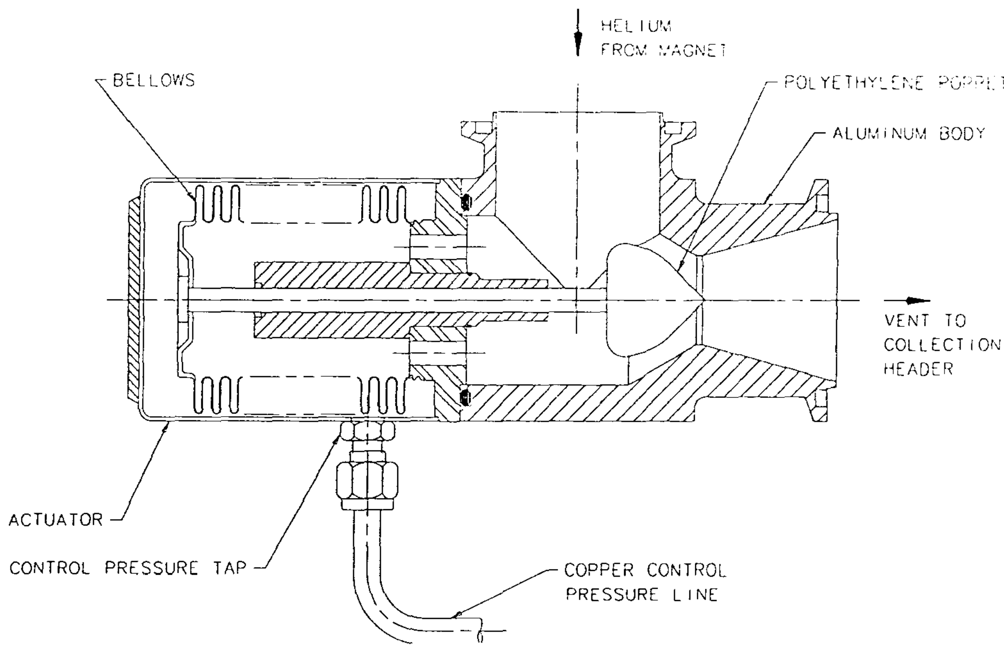

Figure 1: Fermilab's quench relief valve

Let us consider the most common way a valve can fail, a cracked bellows. After many quenches, the thin bellows material can crack due to fatigue. This fatigue process is accelerated by a high frequency chatter of about 95 hz which a quenching bellows experiences.[3] Stress corrosion, such as from chlorides, is not an issue since the bellows is completely enclosed in a helium environment. Initially, a cracked bellows failure manifests itself as a loss of control gas pressure, which subsequently bleeds into the quench suction header. As the crack grows larger upon repeated relieving events, it eventually becomes very difficult or impossible to locally supply enough pressure to hold the cracked bellows closed. It is this group of failures that we intend to reduce with bellows assembly improvements.

BELLOWS DETAILS

The relief valve bellows have previously been made of stainless steel 316. The effect of using bellows made of Inconel 625, a nickel-chromium alloy, will be studied. The intent is to extend the bellows lifetime due to the increased fatigue resistance of Inconel over stainless steel. For comparison, mechanical properties at room temperature of Inconel 625 (annealed sheet) and stainless steel 316 are shown in Table 1.[4,5,6] The impact strength shown is based on Charpy keyhole testing at room temperature. Inconel 625, like austenitic stainless steels, retains its ductility and toughness at low temperatures making it suitable for cryogenic service.

Other bellows actuator modifications were considered to improve the relief lifetimes, such as restricting actuator motion, throttling flow into the high pressure side of the bellows, or replacing the bellows with a sliding piston. Experiments with these schemes revealed that they either did an insufficient job of dampening chatter, were not conservatively safe, or

Table 1. Mechanical properties of competing bellows materials

Material	Tensile Strength	Endurance Limit for Smooth Bar	Modulus of Elasticity	Impact Strength
Inconel 625	931 MPa	620 MPa	207 GPa	66 J
Stainless 316	579 MPa	269 MPa	200 GPa	95 J

were too complicated. One helpful valve improvement was introducing opening/closing hysterisis by rapidly venting control side pressure upon a relieving event, which warrants further developement. For this study, we chose to focus on only improving the bellows material, which will avoid drastic change to the bellows assembly configuration and will retain the relieving characteristics of the original, proven, fast acting, operationally safe design.

Further lifetime improvements to a bellows potentially can be made by having more of the stroke in compression as opposed to tension. Compression is a more desirable way to load a bellows in that it does not promote growth of fatigue cracks the way tension does. The stainless steel bellows design had about 60% of its stroke in tension while the Inconel reliefs have about 35% of stroke in tension. Some lifetime variation between the two designs may be attributable to this. When observing stroke differences within a particular design, such variations appear to be small.

THE WELDING EXPERIENCE

An important aspect of the bellows is how it is joined to the rest of the assembly. Poorly done welds can lead to large heat affected zones which deteriorate mechanical properties. Secure, leak tight joints are required. With an Inconel bellows, the joining of two different materials must be done. Furthermore, there is the potential difficulty of welding the thin bellows material to a thicker piece. These factors must be considered when developing a successful valve assembly.

If the weld joints are not properly designed, successful welding can be difficult or impossible. The key factor is to have a good, tight fit. Our final design calls for a slight interference fit between the straight extended neck of the bellows and its mating parts, the base flange or the cap. TIG fusion welds are used. The welding is done by the bellows manufacturer who prepares the bellows with a sizing die to expand and smooth out the bellows necks for a good fit. In our experience, it is helpful to have these critical bellows welds done by the bellows manufacturer for quality assemblies, utilizing their equipment and expertise.

Some further bellows assemblies were made using electron beam welded joints to study the benefit of improved heat control. The results, in terms of leak tightness, show no better performance than the fusion welds. If the fit is poor, neither welding process will be successful; therefore, the weld quality between the bellows ends and mating parts is ultimately determined by the fit. If the fit is good, the metal dissimilarities are not a factor. Insufficient data was gathered to determine whether or not an electron beam weld for the end assemblies would improve the bellows lifetime.

Another critical weld is on the bellows itself. The bellows we have used are mechanically formed with a longitudinal weld that joins the rolled sheet prior to formation of the convolutions. If an excessive weld bead is left behind, localized stress concentrations occur during bellows movement, causing cracks to initiate at the welded seam. This was learned by observing premature failures at the seam welds in the second batch of Inconel bellows which had unacceptable welds. Thus, our testing of Inconel bellows has been limited to the first batch of bellows with the superior welds, which clearly had smaller weld seams.

Future work involves setting the specifications to obtain more Inconel bellows, either with good welds or seamless bellows that do not have a seam weld.

THE TEST FIXTURE

For testing purposes, room temperature compressed air is used to repeatedly cycle the relief valves. 0.7 MPa is available from a shop air compressor. It is accumulated in a vessel made of 15.2 cm pipe, 2.44 m long. This size allows the accumulated air volume to approximate the volume of helium relieved when a Tevatron dipole quenches. When a sufficient amount of pressure is allowed to build up, a solenoid valve will open exposing the vessels contents to the relief valve inlet. After the volume is expelled, the solenoid closes and pressure again builds for the next cycle. A counter keeps track of the number of cycles. There are pressure gauges on the accumulator vessel, the relief valve inlet, and the relief valve control pressure side. A photograph of the test setup is shown in Fig. 2.

The test fixture is looking for a bellows cracking failure, manifested by seeing high pressure on the control pressure side of the bellows which is connected to the pressure regulated bottle. The only way for high pressure to communicate with the control side is through a bellows crack. If such a rise in pressure is seen, the solenoid valve will cease cycling, freezing the cycle count.

The pressure transducer readings can be recorded with a fast data logging system that stores 16 seconds of readings at 1000 hz. These snapshots can subsequently be retrieved to study the features of one firing event. During a relieving event, most of the volume is carried away in the first two or three seconds.

Due to shop air compressor size and the restriction of the solenoid valve, the maximum pressure achieved in the test rig is not as high as peak pressures seen during magnet quenches, where peak pressures can be around 1.05 MPa.[3] Nonetheless, we are duplicating the motion that occurs and the stresses that result from this motion, giving a good simulation.

RESULTS

Several relief valves were installed on the test fixture and cycled to failure. Pressures during one of these simulated relieving events is shown in Figure 3. How does this compare to an actual quench? For a magnet quench during current accelerator operating energy (900 GeV) peak pressure is 1.05 MPa, achieved 0.28 seconds after the quench, requiring 1.9 seconds to vent down to relief set pressure.[3] Another difference between this simulated quench and an actual quench is that here, as shown in Figure 3, the chattering starts immediately with the relief opening, while during an actual quench the chattering only begins after the relief valve inlet pressure has been lowered to near the set relieving pressure. This is explained by the fact that the test fixture room temperature flow is initially choked before the relief inlet by the 1.6 cm orifice of the solenoid valve. There is little pressure drop before the valve inlet when installed on magnets, which have a 3.0 cm tube for the cold flow leading up to the relief, so flow is not choked until the throat of the relief.

Since these data were taken at 1000 hz, a shorter segment of time can be closely looked at to better resolve the oscillations in relief inlet pressure that occur when the set pressure is approached. This is shown in Figure 4. A high frequency, low amplitude vibration of about 96 hz is seen. This duplicates valve flutter seen during actual quenches, which agrees with the second harmonic of the valve assembly's natural frequency as calculated assuming a lumped mass on a spring with mass.[3]

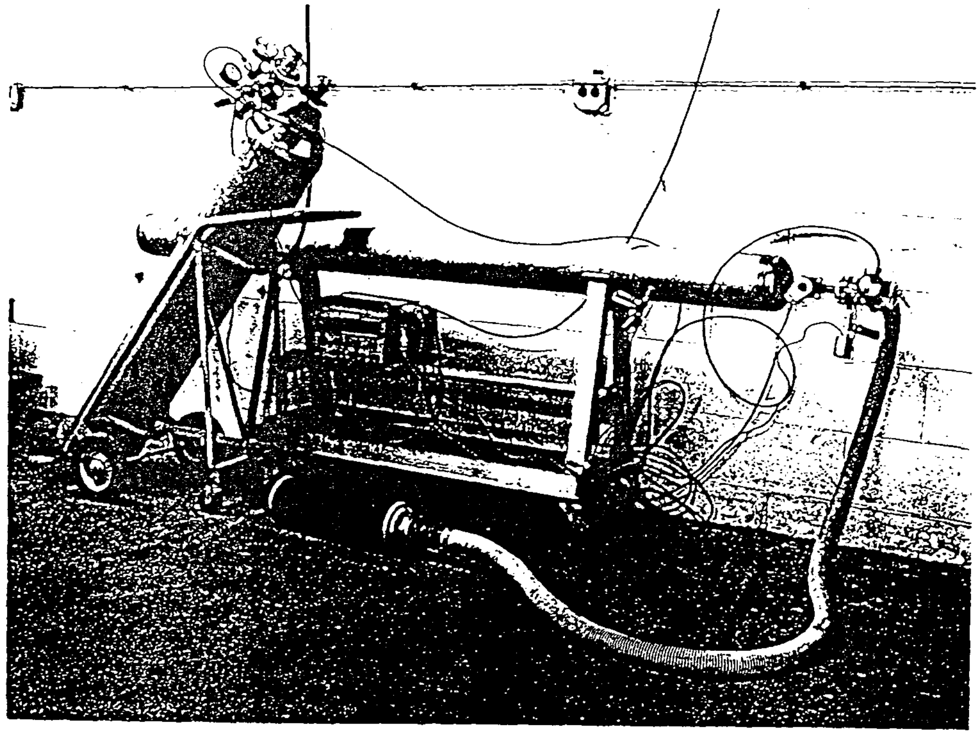

Figure 2: Test fixture for simulating quench relieving events

In order to compare performance, we will keep track of the number of relief events before a bellows crack occurs. Notice that this count is not the same as the number of loading cycles on the bellows due to the high frequency oscillations that each relieving event brings. Ultimately the important design parameter for operations is how many quenches a relief can survive. While the test fixture does not exactly duplicate a quench, it allows for meaningful head-to-head comparison of competing designs.

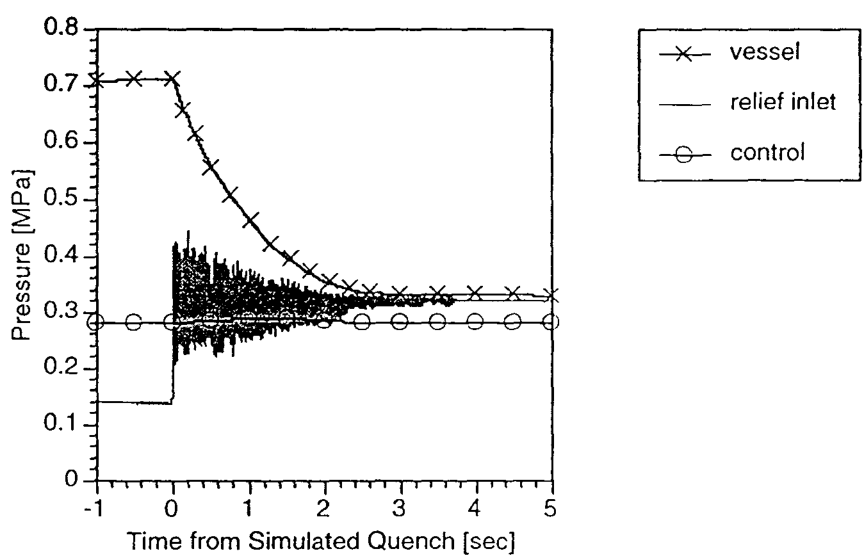

Figure 3: Pressures during one simulated quench

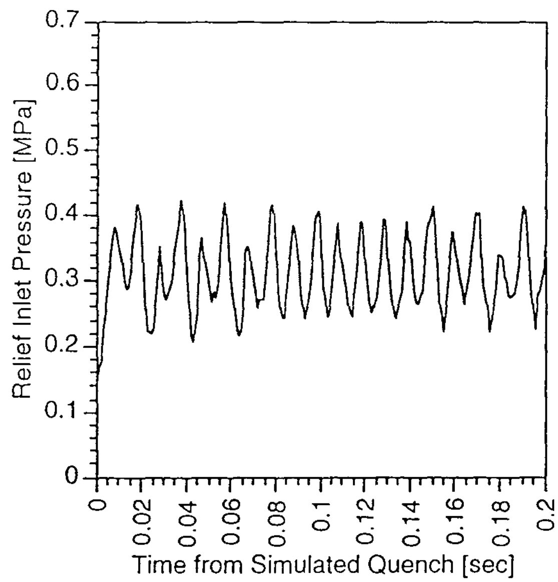

Figure 4: Oscillations in relief inlet pressure during one simulated quench event

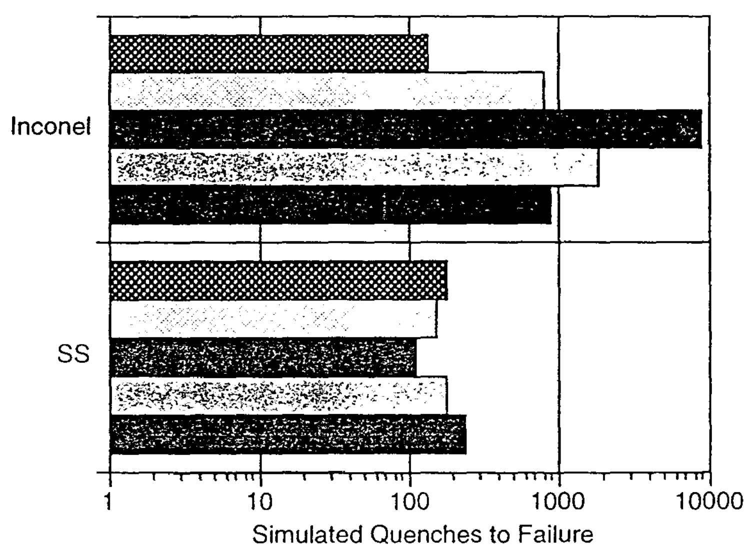

Figure 5: Lifetime of various relief valves before bellows failure

The events-to-failure for tested relief valves are shown in Fig 5. Each article tested is represented with one bar. One can see how the Inconel bellows reliefs outperform those with stainless steel bellows. In one peculiar case, an Inconel bellows sample had a lifetime approaching 10,000 relieving events. This was attributed to the fact that in this case the pressure switch to detect bellows cracking and stop the count was not set with enough sensitivity, causing cycling to erroneously continue after failure until a larger crack had developed. The actual initial failure point was most likely more in line with the others of this type. In the limited testing of Inconel bellows done here, the scatter seen in the lifetime results will be addressed by future testing.

CONCLUSIONS

Experience was gained in the design of improved relief valve bellows assemblies. Tests have shown that the new Inconel bellows relief valves have over five times the life (in terms of relieving events) than the original stainless steel style, lasting typically 900 relief events compared to about 170. Inconel bellows can increase the lifetime of quench relief valves, and thus, the reliability of the accelerator cryogenic system.

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