LITHIUM COLLECTION LENS FILLING PROCESS FOR FERMILAB ANTIPROTON SOURCE

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Abstract

The most critical step in fabrication of the lithium collection lens is the introduction of molten lithium into the core of the lens. A preload (hydrostatic compressive stress) of approximately 2500 psi is desired within the solid lithium for proper lens operation. Instrumentation that is accurate at temperatures well above the melting temperature of lithium (180.6 ºC) must be used to monitor the pressure during the fill to achieve the desired preload. Measurements from recent lens fills show that as the lens cools, the preload decreases by approximately 50 psi/ºC on average. This paper shows that this apparent thermal expansion modulus can be determined analytically as well as numerically. These results are then compared to measured values.

INTRODUCTION

The lithium collection lens[3] used at Fermilab (Figure 1) is a pulsed device with a one-centimeter radius. Operating at up to 1000 Tesla per meter, it is used to focus an 8 GeV antiproton beam coming off of a target. It is cycled approximately once every two seconds and has a life expectancy of between 5-10 million pulses. A positive preload of approximately 2500 psi is necessary to combat the "magnetic pinch" that occurs during each pulse on the lithium during operation. The preload prevents electrical arcing, which can occur if the lithium separates from the titanium septum. There are a few plausible mechanisms that are thought to cause failure. The prevailing theory suggests that the titanium septum fails in fatigue at locations of high stress reversal. Ideally, the preload of the lens should be such that it eliminates the stress reversal and reduces the magnitude of the stress during operation.

Accurately measuring the preload at elevated temperatures has been a problem in the past. The instrumentation experienced large thermal zero-shifts and had a small signal to noise ratio, which resulted in a large uncertainty on the preload. This has hindered the development of any reliable trends that might suggest an optimal preload for future lenses. New advances in pressure transducer technology have made it possible to measure the pressure of solid and liquid lithium up to 400 ºC with an accuracy of better than 0.25%. In addition, a more accurate data acquisition system has been implemented, and software was created to show the long-term pressure vs. temperature relationship in real time. This allows us to predict how much the preload will decrease as the lens cools and adjust accordingly during a fill. Better instrumentation along with a better understanding of this phenomenon has made it possible to achieve the target preload within the desired tolerance.

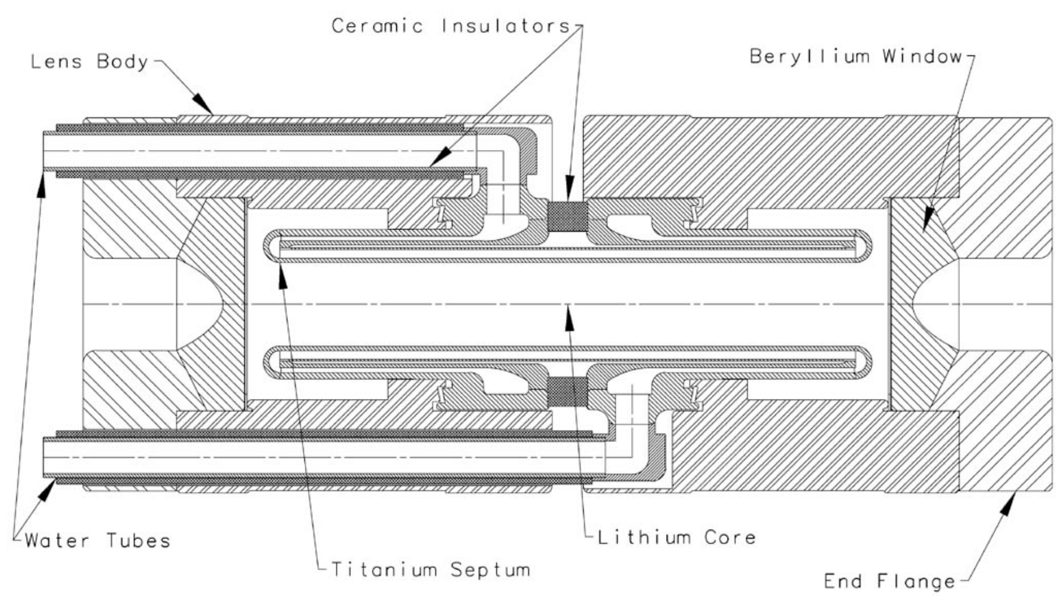

Figure 1. Cross-Sectional View of the Lithium Collection Lens used at Fermilab

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THE FILLING PROCESS

The lens is connected to a reservoir of molten lithium through two stop-cocks (metal-on-metal valves), which are open during most of the fill. This allows lithium to flow into or out of the lens. The reservoir of molten lithium is contained within a bellows assembly, which transmits pressure from a hydraulic ram to the lithium. Initially, the lens is injected with molten lithium at a pressure of about 500 psi. As the temperature decreases and the lithium solidifies, the pressure drops dramatically as the lithium thermally contracts. The bellows pressure is adjusted to compensate for the thermal contraction. As the lens temperature drops from the solidus point down to 100 ºC, the lithium pressure is slowly increased to 6000 psi. As it continues to cool from 100 ºC down to 40 ºC, the bellows pressure is adjusted in an attempt to arrive at the desired preload of approximately 2500 psi. The stop-cocks are generally closed at about 40 ºC, after which temperature the preload cannot be changed by adjusting the bellows pressure. The lens will continue to cool until it reaches room temperature, when the final preload measurement is made.

INSTRUMENTATION

There have been three forms of instrumentation used to measure the preload. The first involved miniature pressure transducers from Entran®. This transducer was originally specified because it worked well in space-restricted areas. Since it was entirely enclosed in the lens body, the wires could be cut and the transducer would then be left in the lens body for installation into the transformer assembly. The primary limitation of this transducer is that most strain gauge based instrumentation has a realistic temperature limit[5] of between 120–150 ºC. Above this temperature, the epoxy bonding the strain gauges to the measurement diaphragm within the transducer begins to break down. Large zero-shifts can occur and have been observed at these elevated temperatures. Zero-shifts of this nature cannot be measured nor compensated for. The uncertainty associated with this type of zero-shift error is on the order of +/- 1000 psi.

The second type of instrumentation used was strain gauges, which measured the circumferential strain on the outside of the lens body. High temperature strain gauges, developed by Vishay Micromeasurements Group, were installed; which are reliable at temperatures up to 260 ºC. The internal pressure was calculated by correlating the strain with a pre-determined calibration curve. Since the radius to thickness ratio of the lens body is approximately two, it is considered a thick walled cylinder. Unfortunately, this contributes to a signal to (thermal) noise ratio of approximately one. Ideally, it should be ten or higher. Statistical error analysis[4] suggests an uncertainty for our application on the order of +/- 500 psi for conditions such as this.

Because of the large uncertainties associated with the miniature pressure transducers and the strain gauges, it was necessary to find a better method of instrumentation that could more accurately measure the preload. Dynisco Instruments has developed a variety of robust Melt Pressure Transducers that have been specifically designed for the harsh and rugged environments of the Extrusion and Polymer Processing Industries. Their pressure transducers have a unique design that removes the instrumentation diaphragm from the heat source. The pressure diaphragm can then be exposed to temperatures up to 400 ºC without concern of thermal shifts. The design transmits the pressure to the instrumentation diaphragm through a mercury-filled capillary tube. The strain gauges on the instrumentation diaphragm then operate in a much cooler atmosphere. Therefore, the transducer can output a much more accurate signal. The uncertainty is less than 0.25% of the full-scale output, which is generally less than 25 psi.

Our experience has shown that these pressure transducers were not only more accurate, but also more robust during installation. In addition, thermal calibration time is minimal because the thermal output is small and very repeatable. We now conduct the filling process with a total of four Dynisco pressure transducers: one measuring the molten lithium pressure, and one measuring the hydraulic ram pressure, and two measuring the preload.

LITHIUM MATERIAL PROPERTIES

Most metals have a linear coefficient of thermal expansion (α) of between 10-25 μ/ºC. Lithium has one of the highest linear CTE's of any metal: α_{Li} = 46-56 μ/ºC from 20-180 ºC. This contributes to a large loss in preload as the lens cools.

While the thermal properties of lithium are well known and trusted, the mechanical properties are not. Very little data is available; thus, the confidence for that data is low. Lithium is too soft to be used in structural engineering, so there has not been any great need to accurately determine the mechanical properties. Values for the elastic modulus (E_{Li}) have been reported[2,6,7] anywhere from 280 – 1131 ksi at room temperature. There is only one known set of temperature dependant data[7], so that data at 35 ºC will be used for the remainder of this discussion.

Given that E_{Li} = 896 ksi and Poisson's Ratio (ν_{Li}) is equals to 0.36, the bulk modulus (K_{Li}) can be calculated, and is equal to 1067 ksi. It is interesting to note that E_{Li} decreases significantly as the temperature increases from 20-180 ºC. This is because the homologous temperature ($T_H = T_{abs}/T_{melt}$) is greater than 0.65. Steady state creep that is analogous to viscous flow occurs at $T_H > 0.7$, or $T_{Li} > 45$ ºC.

THERMAL EXPANSION MODULUS

The bulk modulus (K) is a relationship that expresses change in pressure with respect to volumetric strain ($\Delta V / V$). Compressibility (X) is then defined as the inverse of the bulk modulus:

$$X \equiv \frac{1}{K} \equiv \frac{\Delta V}{V \Delta P} \quad (1)$$

The volumetric coefficient of thermal expansion (β) is simply three times the linear coefficient of thermal expansion: $\beta_{Li} = 3\alpha_{Li}$ = 142 µ/ºC at 35 ºC.

$$\Delta l = l \alpha \Delta T \qquad \Delta V = V \beta \Delta T \quad (2)$$

By combining equations (1) and (2), a very important material property is derived that is called the Thermal Expansion Modulus (TEM):

$$\frac{\Delta P}{\Delta T} = \frac{\beta}{X} \qquad TEM = \frac{\beta}{X} \quad (3)$$

This is purely a theoretical relationship that describes the increase in pressure of lithium in a completely rigid container. Based on the material properties mentioned before, TEM_{Li} = 151 psi/ºC. In practice, though, no container is completely rigid. Because the containment vessel will flex with pressure, the actual loss of preload is a function of the stiffness of the vessel. Therefore, a loss of 151 psi/ºC is the theoretical maximum that can be expected at 35 ºC.

PRELOAD RATE

The preload rate (PR) describes the change in pressure for lithium in an elastic containment vessel. For a simple cylinder, it can be shown[1] that:

$$PR = \frac{\Delta P}{\Delta T} = \frac{\beta_{Li}}{X_{Li} + \frac{2R}{E\,t}} \quad (4)$$

Here, R is the inner radius of the tube and t is the wall thickness. Test data on a simple titanium tube (E_{Ti} = 16.5 Msi) has confirmed the validity of this relationship. A 7/8" tube with t_{Ti} = 0.061" resulted in a PR of 87-95 psi/ºC from 100 ºC down to 20 ºC. Equation (4) predicts 84 psi/ºC at 35 ºC.

Because the lithium cavity in the lens is not a simple cylinder, theoretically predicting the lens preload rate is very complicated. For the cylinder part of the septum, equation (4) predicts that PR = 67 psi/ºC, given R_{Ti} = 1.0 cm and t_{Ti} = 0.040". Finite Element Analysis has been used to investigate this further. Figure 2 shows a contour plot of the hydrostatic pressure over 1 ºC. As one would expect, the preload rate is not uniform throughout the lithium cavity. An axi-symmetric weighted average of the PR in this model is about 71 psi/ºC at 35 ºC.

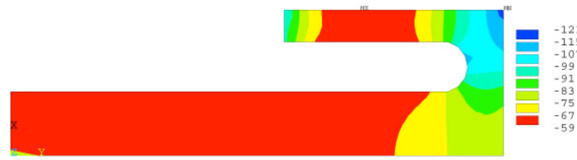

Figure 2. Axisymmetric model of the Preload Rate

It is interesting that this model does not agree with the empirical results. After the stop-cocks are closed, the measured PR for the lens is about 46-48 psi/ºC.

There are two plausible explanations for this discrepancy. First, it could be caused by a temperature differential between the lithium and the lens body. The effective PR drops sharply if the lithium is cooler than the lens body, by even 1-2 ºC. A differential of up to 4 ºC has been observed. Secondly, it is also possible that the E_{Li} mentioned is not correct. An E_{Li} of 500-600 ksi would better correlate with the empirical results, and is well within the range of published data. Most likely, it is a combination of both explanations.

The PR as previously discussed is for a constant volume. During most of the filling process, however, the stop-cocks are open; this will be referred to as PR'. Liquid or solid lithium can flow into or out of the lens, depending on the pressure differential between the lens and the bellows. While the nominal PR' during this phase is 50 psi/ºC, the short term PR' varies from 20-70 psi/ºC. The pressure gradient is necessary to cause the short term PR' to increase or decrease proportionally, in an attempt to achieve the desired preload at room temperature.

CONCLUSIONS

With better instrumentation, we have been able to more accurately measure the preload of the lithium during the filling process. Developing the TEM and PR relationships has helped us to predict, and therefore better control the final preload. Further FEA and a more accurate E_{Li} is necessary to increase our understanding of this phenomenon.

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