CONSEQUENCES OF A LITHIUM LENS FAILURE

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I. Summary.

This note reviews the calculations presented in pbar notes#373 and 454 on the failure mechanisms and radiological consequences of a lithium lens rupture, with emphasis on the proton lens. Consequences of a failure of the proton lens are similar to, but less severe than, a failure of the already-existing collection lens. Safety measures taken in the case of the proton lens comparable to those already in place for the collection lens should be adequate.

II. Failure Mechanisms.

A. Simple Fracture of the Cooling Jacket.

This can be considered to be a "normal" failure. Failure of containment by the cooling jacket is detected by measuring the pressure buildup and conductivity increase in the cooling water[1]. Li that comes in contact with the cooling water combines with the water according to the reaction

$$\mathrm{Li} + \mathrm{H_2O} \rightarrow \mathrm{LiOH} + \tfrac{1}{2}\mathrm{H_2} + 52.9\,kcal.$$

The reaction proceeds relatively slowly at normal temperatures. If all the lithium in the proton lens (6g) reacts with water, 46 kcal will be liberated. This is a negligible amount of energy, if evenly distributed over the entire volume of cooling water. The threshold for detection (<0.1 g of lithium) represents an even smaller release of <760 cal. Typically conductivity and pressure rise on the time scale of hours, indicating a very slow reaction rate (<1mg/min). The most important requirement in this case is sensitive continuous measurement of the pressure and conductivity of the cooling water, in a manner similar to the collection lens.

B. Loss of Coolant Accident.

If the flow of cooling water to the lens ceases, a rapid temperature increase of the lithium ensues. The increased stress quickly breaks the cooling jacket, bringing hot lithium into contact with water. The expected sequence of events is similar to that for the collection lens, which has been spelled out by Dugan.[2] The major differences between the two lenses are the greatly reduced amount of lithium in the proton lens, and the smaller amount of energy in the current pulse.

The proton lens has been designed to operate at a peak field of 100 kG. Although we expect typical operation to be at 80 kG, calculations will be presented here for the (more strenuous) design point. The energy delivered to the lens by ohmic heating from the current pulse is 95 calories. There are about 6 g of lithium in the proton lens, and 5 g of cooling water in the cooling jacket. Normally, the core temperature will cycle between a peak of 100 °C just after a pulse to 35 °C just before the next pulse (1.5-sec rep rate). But in the absence of cooling the temperature will rise $\Delta T = Q/mc = 95/(6x.8) = 20$ °C per pulse if the septum is dry, or $\Delta T = Q/mc = 95/(6x.8 + 5x1) = 10$ °C if (static) water remains in the cooling jacket. As the temperature rises, stress on the cooling jacket (52 ksi max. under normal conditions) increases at a rate which is difficult to determine because of the large fraction of lithium in the end region "reservoir" that absorbs much of the heat from the small lithium core. However, in just a few pulses it will clearly surpass the strength of the titanium septum (endurance limit=140 ksi). Failure then proceeds in the same way as in the collection lens, but much slower: the cooling jacket breaks (this requires a few pulses), the cooling water inside the septum boils (100 pulses or less, depending on the rate of the Li+H_2O reaction), the lithium melts (about 10 pulses), and finally the molten lithium burns in the open air, while continuing to heat up monotonically. Figure 1 shows the progression for the proton lens, and (for comparison) the collection lens. *The rate of temperature rise is much slower for the proton lens than for the collection lens.* Hence a monitoring system that is adequate for the collection lens should also be adequate for the proton lens.

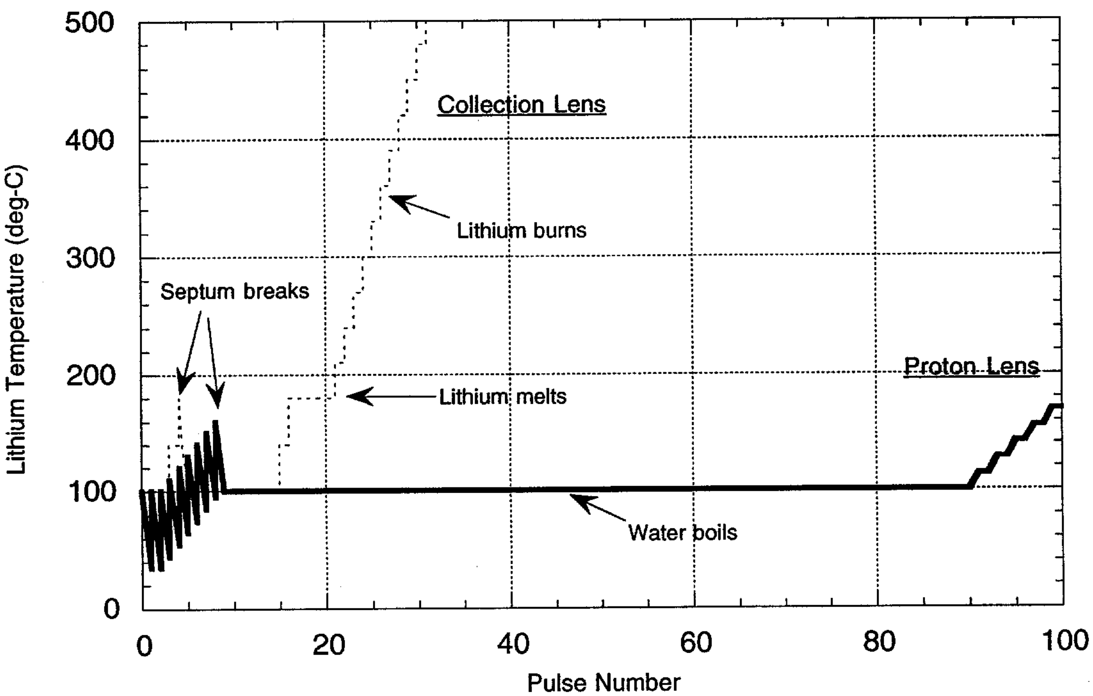

Figure 1. Temperatures in collection lens and proton lens upon loss of coolant flow. The accident occurs on pulse #2.

C. Fracture of the Beryllium Window.

Dugan considers the worst-case scenario to be progressive partial failure of the window, causing poor thermal contact between the lithium and the titanium septum. The lithium could heat up to molten temperature. If at this point the titanium septum should fail, simultaneous complete failure of the window will allow ejection of molten lithium and water into the target vault.

Again, the same process proceeds at a slower pace in the proton lens than in the collection lens. The energy required to melt 6 g of lithium at an initial temperature of 35 °C is 1300 cal. This requires 14 pulses at 95 cal/pulse. Hence, in the absence of any cooling, the lithium melts in 14 pulses (vs. 6 pulses for the collection lens); subsequent septum failure allows the cooling water to come in contact with the lithium, keeping it at 100°C for up to 100 pulses.

III. Radiological Consequences.

Following pbar note#454[3] we now estimate the buildup of radioactive ^3H and ^7Be in the proton lens.

Freeman has shown that the predominant mechanism for tritium production is by thermal neutrons via the $^6Li(n,\alpha)^3H$ reaction. The cross section for this reaction is 940 b. The thermal neutron flux is very difficult to determine in the real target vault geometry. Freeman makes a rough estimate which, after correcting for increased bombardment rates (5×10^{12} protons at a 1.5-sec rep rate) and for a 7-cm Ni target, yields an estimate for the thermal neutron flux $\phi = 5 \times 10^{11}$ neutrons/cm^2/sec. In natural lithium the isotopic abundance of ^6Li is 7.5%, so that the absorption length of a thermal neutron is about 3 mm. This length is the same as the radius of the proton lens, hence a large fraction, f, of the thermal neutrons interact with the ^6Li to form tritium. For simplicity, assume the fraction f=1. Then the tritium production rate is determined by multiplying the thermal neutron flux by the the lens surface area,

$$R = \phi \bullet A = 5 \times 10^{11} \times 40 \text{ cm}^2 = 2 \times 10^{13} \text{ sec}^{-1}.$$

The energy released in the reaction is 4.8 MeV. At a reaction rate of 2×10^{13} /sec, the nuclear power is 15 Watts. This is small compared to the ohmic heating of the lens (260 Watts). After 6 months continuous operation, the total tritium activity is

$$A = \lambda \bullet R \bullet T = 1.767 \times 10^{-9} \times 2 \times 10^{13} \times 1.6 \times 10^{7} \text{sec}$$
$$= 5.6 \times 10^{11} \text{ sec}^{-1} = 15 \text{ Ci}.$$

The tritium activity in the collection lens would be roughly 40 Ci under the same conditions and assumptions.

The production of ^7Be by 120 GeV protons incident on the lithium has a cross section of 30 mb. Because of the relatively short half life (53 days), the resulting equilibrium activity is given by the production rate $A = 3.6 \times 10^{10} \text{ sec}^{-1} = 1$ Ci.

IV. Conclusions.

In the extremely unlikely event that both lenses simultaneously suffer a worst-case accident, the total inventory of released materials could increase about 40% over the case in which only the collection lens is present. In addition, because of the projected increase in production beam intensity and rep rate, the activity will increase by a factor of 2.2 over that predicted by Freeman. In view of a potential overall factor of 3 increase in activity, his conclusions can be updated as follows:

1. Short-term concentration in the AP-1 enclosure after a 1-minute release of 100% of the tritium could result in a total β dose to a worker of ~1.2 rad. Thus pulse testing of an activated lens within the vault should not be done with people in the AP-1 enclosure.
2. Maximum tritium uptake by a person offsite remains negligible (~.024 mrad).
3. Potential ^{7}Be airborne concentration could be 0.045 μCi /ml. This is below the maximum permissible airborne concentration for a single one-minute exposure of 0.12 μCi/ml.
4. Offsite concentrations of ^{7}Be are negligible.

Dugan recommends that lithium lens failure be sensed such as to minimize the formation of molten lithium. For the collection lens this criterion requires that lens failure be sensed within 2 pulses (3 sec.). Applying this criterion to the proton lens would require that failure be sensed within 14 pulses (21 sec.). The relaxed requirement makes the sensing problem much less severe for the proton lens.

The most serious radiological problem is the tritium inventory which builds up within the lithium lenses due to thermal neutron capture on ^{6}Li. Radiological consequences will not be qualitatively changed by the introduction of a proton lens. The thermal neutron flux is not well known, and in fact may differ significantly between the proton lens and the collection lens. Freeman suggests measuring this flux by gold foil activation. Such a measurement is clearly useful, both to better quantify radiological effects of an accident, and also to determine the upper limit to the useful lifetime of the lenses due to buildup of helium and tritium within the lenses (see Appendix). Two steps could be taken to reduce the extent of tritium buildup: first, the use of isotopically pure ^{7}Li; second, the installation of boron-rich neutron shields near the lenses.

The use of isotopically pure ^{6}Li would not result in a significantly enhanced tritium production because there is already sufficient ^{6}Li in natural lithium to absorb nearly all thermal neutrons incident on the lenses. The advantage of ^{6}Li is the reduction of beam absorption in the lenses by about 1.3%.

Appendix.

Helium and tritium from the ^{6}Li(n,α)^{3}H reaction build up over time, possibly affecting the operation of the lens. This is a complicated issue, with several potential implications for long-term operation. The importance of the buildup of these reaction products depends on the mechanical and metallurgical properties of the lithium and the titanium containment vessel. Swelling of the lens is expected, due to the pressure of the contained helium gas. If the tritium remains in a gaseous state, it will add to the pressure increase in the lens. It may also migrate to the titanium walls,[4] since titanium has a great affinity for hydrogen. Hydrogen embrittlement of the titanium walls may be an additional important effect of the tritium on the lens. There is some evidence, for example, that hydrogen tends to concentrate in the strain field near the tip of a crack, thereby assisting in crack growth.

Swelling of the lens from helium and tritium production may be estimated by considering the pressure increase in the lithium, which has a bulk modulus of

$$B_T = -V\left(\frac{\partial P}{\partial V}\right) = 1.156\text{x}10^6\,\text{psi}. \qquad \text{A.1}$$

The gas will obey the relation

$$P\,dV_{gas} = NkT, \qquad \text{A.2}$$

and since $dV_{gas} = -dV_{lithium}$ and $P_{lithium} = P_{gas}$, we can combine expressions A.1 and A.2 to determine the resulting pressure increase

$$P = \left(\frac{NkT\,B_T}{V_{lens}}\right)^{1/2}. \qquad \text{A.3}$$

Assuming that in six months $3.2\text{x}10^{20}$ alpha particles, and $1.6\text{x}10^{20}$ H_2 molecules are produced and trapped in the lens, then $N=4.8\text{x}10^{20}$, and the pressure increase is

$$P = \left(\frac{4.8\text{x}10^{20} \bullet 1.6\text{x}10^{-19} \bullet .026\,\text{eV} \bullet 7.86\text{x}10^{9}\,\text{Pa}}{1.2\text{x}10^{-5}\,\text{m}^3}\right)^{1/2} = 3.62\text{x}10^7\,\text{Pa} = 5.2\text{kpsi}.$$

This pressure increase is comparable to, and adds to, the pressures present under normal operation. For example, the hoop stress s_t developed by this pressure is given by[5]

$$s_t = P\left(\frac{r_o^2 + r_i^2}{r_o^2 - r_i^2}\right) = 19\,\text{kpsi}, \qquad \text{A.4}$$

where r_o and r_i refer to the outer and inner radii of the titanium cylinder. (The hoop stress developed in the collection lens under the same assumptions is 27 kpsi.) If the pressure continues to grow, it will eventually rupture the beryllium window and/or the titanium septum, in combination with the normal cyclical stresses in the lens. One may speculate that gas-filled voids in the lithium metal may act as scattering centers to affect the conductivity of the lithium. Thus long-term changes in the focusing strength of the lens could provide some indication of the stress buildup.

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1 S. O'Day, pbar note#533.
2 G. Dugan, pbar note#373, 4/24/83.
3 W. S. Freeman, pbar note#454, 3/6/86.
4 G. Alefeld and J. Volkl, eds., Hydrogen in Metals, Vols. I and II, Springer-Verlag, 1978.
5 J. P. Den Hartog, Strength of Materials, Dover, 1949, p. 143.