



**Fermilab**

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Radiological Consequences of a Lithium Lens Rupture

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We consider the radiological consequences of a rupture of the lithium lens cylinder. Because of the low atomic number of lithium ( $Z=3$ ) there are only two radioisotopes of potential concern. These are  $^3\text{H}$  ( $T_{1/2} = 12.3$  years) and  $^7\text{Be}$  ( $T_{1/2} = 53.3$  days).

I. Tritium Production in the Lithium Lens

Two tritium production mechanisms are possible in natural lithium metal. The first is by direct interaction of the 120 GeV proton beam with the lens material and production by high energy secondary particles produced in the  $\bar{p}$  production target immediately upstream. The second is production by thermal neutrons via the  $^6\text{Li}(n,\alpha)^3\text{H}$  reaction. Direct production by high energy particles can be estimated as follows:

1. Assume a target thickness,  $t$ , of lithium given by

$$t = 0.534 \text{ gm}\cdot\text{cm}^{-3} * 15 \text{ cm} \approx 8 \text{ gm}\cdot\text{cm}^{-2}$$

2. Assume a tritium production cross section due to high energy particles of 30 mb. This choice is based on typical  $^3\text{H}$  production cross sections in other low Z elements (e.g.,  $^4\text{He}$ , C,O,N).
3. Assume a beam intensity and repetition rate of  $3 \times 10^{12}$  protons per 2 seconds, and neglect production by secondaries since the target and lens are thin (in terms of interaction lengths).
4. The production rate, R, is then given by

$$R = 30 \text{ mb} * \frac{10^{-27} \text{ cm}^2}{\text{mb}} * 8 \frac{\text{gm}}{\text{cm}^2} * \frac{6.02 \times 10^{23}}{7 \text{ gm}} * \frac{3 \times 10^{12}}{2 \text{ sec}}$$

$$R = 3.1 \times 10^{10} \text{ sec}^{-1}$$

After a six month irradiation (and neglecting decay during irradiation since  $T_{1/2} \approx 12.3$  years) the tritium activity will be

$$A = \lambda \cdot R \cdot T = \frac{3.1 \times 10^{10} \text{ sec}^{-1} * 1.6 \times 10^7 \text{ sec}}{17.7 \text{ yrs} * 3.2 \times 10^7 \text{ sec/yr}} * \frac{1 \text{ Ci}}{3.7 \times 10^{10} \text{ sec}^{-1}}$$

$$A = 24 \text{ mCi}$$

where  $\lambda = \ln 2 / T_{1/2}$  and T is the irradiation time.

An alternative estimate can be obtained by using the results of a CASIM calculation by Yurista for the target vault geometry.<sup>1</sup> This has the advantage that production by secondaries is included through the proper treatment of the high energy cascade, however the conversion factor from star density in lithium to tritium concentration is not known. It is

reasonable to assume, however, that the conversion factor is not too different from that in soil, since the  $^3\text{H}$  production cross sections are generally similar in all low Z materials, ranging from 10 to 30 mb. Note that the conversion factor used below is derived from a measurement of leachable  $^3\text{H}$  in soil. The amount actually produced is probably somewhat more. Thus,

$$A = 1.4 \times 10^{-2} \frac{\text{stars}}{\text{cm}^3 \text{ proton}} * 47 \text{ cm}^3 * \frac{3 \times 10^{12}}{2 \text{ sec}} * 1.6 \times 10^7 \text{ sec} * \frac{3.7 \times 10^{-9} \text{ pCi}}{\text{star}}$$

A = 58 mCi
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The two results agree to within a factor of about two. Given the assumptions and uncertainties involved this should be considered reasonable agreement.

## II. $^3\text{H}$ Production by $^6\text{Li}(n,\alpha)^3\text{H}$

Thermal neutrons incident on the lithium of the lens can produce tritium through the  $^6\text{Li}(n,\alpha)^3\text{H}$  reaction. The cross section for this reaction is 940b, about 30000 times larger than the cross section used to calculate direct tritium production via high energy particles. Thus, although the isotopic abundance of  $^6\text{Li}$  in natural lithium is only 7.5%, thermal neutron production of  $^3\text{H}$  may dominate.

The absorption length,  $\ell$ , of a thermal neutron in natural lithium is estimated as

$$\frac{1}{\ell} = n\sigma = \frac{6.02 \times 10^{23}}{7 \text{ gm}} * 0.534 \frac{\text{gm}_3}{\text{cm}^3} * 0.075 * 940\text{b} * \frac{10^{-24} \text{ cm}^2}{\text{b}}$$

$$\ell \approx 0.31 \text{ cm}$$

Since  $\ell$  is small compared to the characteristic dimensions of the lithium cylinder ( $r=1\text{cm}$ ,  $L=15\text{cm}$ ) we can assume that all thermal neutrons incident on the lithium will interact to form tritium. The problem then reduces to estimating the thermal neutron flux incident on the lithium cylinder.

The true thermal flux is very difficult to estimate since it can depend sensitively on the details of shielding geometry, the presence of moderating material, etc. We make a crude order of magnitude estimate using the results of Armstrong and Barish,<sup>2</sup> who calculated the thermal fluence at the inner surface of a 2.2 meter radius concrete tunnel when a 3 GeV proton beam was lost uniformly inside an iron cylinder of  $40 \text{ gm/cm}^2$  radius located on the tunnel axis. Scaling their results linearly with bombarding energy and correcting for the different absorption lengths of tungsten and iron we estimate the thermal neutron flux,  $\Phi$ , to be

$$\Phi = \frac{5.5 \times 10^{-2} \text{ n/cm}^2}{\text{interacting proton/cm}_{\text{Fe}}} * \frac{1.5 \times 10^{12} \text{ interacting protons/2 sec}}{5 \text{ cm}_w * \frac{1.7 \text{ cm}_{\text{Fe}}}{1.0 \text{ cm}_w}} * \frac{120 \text{ GeV}}{3 \text{ GeV}}$$

$$\Phi = 1.9 \times 10^{11} \text{ n} \cdot \text{cm}^{-2} \cdot \text{sec}^{-1}$$

We have assumed that half the incident 120 GeV protons interact inelastically in the tungsten target to eventually give rise to thermal neutrons, and neglect similar interactions in the lithium itself. Converting to a tritium production rate by multiplying by the lens surface area we get

$$R = \phi \cdot A = 1.9 \times 10^{11} \text{ n} \cdot \text{cm}^{-2} \cdot \text{sec}^{-1} * 100 \text{ cm}^2$$

$$R = 1.9 \times 10^{13} \text{ sec}^{-1}$$

After a six month irradiation the total tritium activity is

$$A = \lambda \cdot R \cdot T = \frac{1}{5.66 \times 10^8} \text{ sec} * 1.9 \times 10^{13} \text{ sec}^{-1} * 1.6 \times 10^7 \text{ sec}$$

$$A = 5.4 \times 10^{11} \text{ sec}^{-1} = 15 \text{ Ci}$$

Note that the long lifetime for  $^3\text{H}$  decay means that the equilibrium  $^3\text{H}$  concentration will not be reached in the lens, and that the activity produced will increase approximately linearly with the irradiation time for times short compared to the half-life.

### III. $^7\text{Be}$ Production

The half-life of  $^7\text{Be}$  (53.3 days) is of the order of typical irradiation times. Thus, it can be assumed that  $^7\text{Be}$  production in the lithium will reach equilibrium in a typical three-to-six month collider run. The equilibrium activity is then given by the production rate

$$A_{\text{eq}} = \sigma \cdot I \cdot t$$

where  $\sigma$  is the  ${}^7\text{Be}$  production cross section,  $I$  the beam intensity and  $t$  the target (lens) thickness. The resulting activity is

$$A_{\text{eq}} = 30 \text{ mb} * \frac{10^{-27} \text{ cm}^2}{\text{mb}} * \frac{3 \times 10^{12}}{2 \text{ sec}} * 8 \frac{\text{gm}_2}{\text{cm}^2} * \frac{6.02 \times 10^{23}}{7 \text{ gm}}$$

$$A_{\text{eq}} = 3.1 \times 10^{10} \text{ sec}^{-1} = 0.84 \text{ Ci}$$

where we assume a 30 mb production cross section at 120 GeV and again neglect production by secondaries. Based on the CASIM calculation discussed previously, secondaries may result in a factor of two or so change in the result, depending on the conversion factor from star density to  ${}^7\text{Be}$  activity in lithium.

#### IV. Radiological Consequences

The scenarios of a lens rupture are discussed in detail in  $\bar{p}$  Note 373 by G. Dugan.<sup>3</sup> Under normal running the lens material remains solid and the radioactivity will be contained within the lens. In this sense the lens is no different than other low Z materials such as Be or BeO used as targets and beam dumps elsewhere at the lab.

The complicating factor is the repetitive pulsing of the lens, which causes heating of the lens cylinder and axial loads due to magnetic forces. Should the lens cooling fail and the pulsing continue, a rupture of the cooling jacket could occur, possibly ejecting some material (principally lithium, water, or lithium compounds) into the vault or cooling water

lines. Similar results can occur if the end windows fracture. If the lithium exceeds its melting point, additional high temperature reactions could occur. The lens monitoring and interlock system has been designed, therefore, to sense a lens failure prior to melting (within 6 pulses or twelve seconds), preventing the high temperature reactions. Details of the monitoring and interlock system are contained in  $\bar{p}$  Note 443 by J. Krider.

We consider here the release into the vault, and ultimately the AP-1 enclosure, of the entire inventory of tritium or  $^7\text{Be}$ , even though such a complete release is highly unlikely. It would require a failure of the lens itself, a failure of the lens monitoring and interlock system and a means to completely liberate the tritium and  $^7\text{Be}$  contained within the lithium. A more likely situation is that a combination of tritiated Li compounds, tritiated water and hydrogen gas would occur with some of the solid material also containing  $^7\text{Be}$ . Hence the concentrations discussed below represent a worst case situation.

A.  $^3\text{H}$  Concentration (on-site)

If we suppose that 100% of the tritium is released into the vault and that none combines to form stable compounds or particulates that are trapped by the HEPA filter, then the total tritium concentration may be estimated.

The airflow through the vault is 2000 cfm, so that if the entire release is assumed to occur in one minute the localized, short-term concentration in the AP-1 enclosure and at the AP-1 exhaust stack will be about

$$\frac{15 \text{ Ci}}{2000 \text{ ft}^3} \approx \frac{0.26 \text{ } \mu\text{Ci}}{\text{ml}}$$

A worker in the AP-1 enclosure or one breathing the exhaust stack air at a typical rate of 20 liters per minute during the assumed one minute release would then inhale ~5200  $\mu\text{Ci}$ , assuming that all the tritium is in the form of water vapor and that it is completely absorbed and uniformly distributed in the body. The total  $\beta$  dose resulting from this uptake would be ~400 mrad.

B.  $^3\text{H}$  Concentration (off-site)

Typical dilution factors using a Gaussian plume diffusion model in the atmosphere would result in a reduction in concentration at the site boundary of  $5 \times 10^4$  (Ref. 5). The localized, "fence-post" concentration for this short-term, batch release would then be

$$\frac{0.26 \text{ } \mu\text{Ci}}{\text{ml} \times 5 \times 10^4} = 5.2 \frac{\text{pCi}}{\text{ml}}$$

The maximum tritium uptake by an individual at that location would be about 0.1  $\mu\text{Ci}$ , resulting in an internal  $\beta$  dose of ~.008 mrad, an insignificant amount and well below allowable limits.

### C. Measurements

It is important to re-emphasize that the  $^3\text{H}$  activity and concentrations derived here depend directly on the assumed thermal neutron flux, together with the area of lithium exposed to that flux and the irradiation time. There is considerable uncertainty in the actual value of the flux inside the target vault. The flux might be reduced from the assumed value due to the presence of Fe shielding in the vault, since Fe is a poor moderator. The lens transformer may provide some shielding of the lens cylinder to reduce the effective area of lithium that is exposed. On the other hand, a specific lens may eventually be irradiated for longer than the six month interval assumed here, resulting in higher tritium activity.

It would be useful to measure the thermal neutron flux within the vault during targeting of 120 GeV protons for  $\bar{p}$  production. This could be accomplished by using gold activation foils placed within the vault. After suitable irradiation the foils could be removed and their activity measured to determine the thermal flux near the lens.

The use of isotopically enriched  $^7\text{Li}$  could also reduce tritium production by thermal neutrons, provided that the abundance of  $^6\text{Li}$  atoms is reduced sufficiently to increase the absorption length beyond the characteristic dimensions of the lithium cylinder. Conversely, the use of "pure"  $^6\text{Li}$  will not result in a still larger tritium production rate, since all incident thermal neutrons are already absorbed by the  $^6\text{Li}$  in natural

lithium.

D. <sup>7</sup>Be Concentrations

Using the same one minute release time and 2000 cfm flow rate we obtain a <sup>7</sup>Be concentration of

$$\frac{840 \text{ mCi}}{2000 \text{ ft}^3} = \frac{0.015 \text{ } \mu\text{Ci}}{\text{ml}}$$

for a one minute release, assuming all <sup>7</sup>Be is released into the air. The maximum permissible <sup>7</sup>Be airborne concentration for occupational exposures is 1 pCi per ml, based on an assumed 2000 hour work year. Taking the ratio of assumed exposure times (1 minute versus 2000 hours), this implies a maximum permissible airborne concentration for the one minute exposure of 0.12  $\mu$ Ci per ml. Thus, the potential <sup>7</sup>Be airborne concentration is about ten times below the concentration guide.<sup>5</sup>

Off-site concentrations are even further below the time-weighted MPC for the general population. Using the same dilution factor of  $5 \times 10^4$  as was used for <sup>3</sup>H, the short term off-site concentration would be

$$\frac{.015 \text{ } \mu\text{Ci}}{\text{ml} \times 5 \times 10^4} = \frac{0.3 \text{ pCi}}{\text{ml}}$$

The time-weighted MPC, based on an assumed exposure time of one minute and occupancy time of 168 hours per week is

$$.013 \frac{\text{pCi}}{\text{ml}} * \frac{52 \text{ weeks} \times 168 \text{ hrs/week} \times 60 \text{ mins/hour}}{1 \text{ minute}} \approx \frac{6800 \text{ pCi}}{\text{ml}}$$

Thus the off-site release is about 0.004% of the concentration guide.

## V. Summary and Conclusions

1. A non-negligible tritium inventory may build up within the lithium lens due to thermal neutron capture on  $^6\text{Li}$ . The production rate will be equal to the thermal neutron flux incident on the lens. Estimates for this flux within the target vault are very uncertain. It could be measured by gold foil activation to better determine if tritium is a real concern in the event of a lens rupture. Order of magnitude estimates indicate that short-term airborne concentrations may result in internal whole body  $\beta$  doses of ~400 mrem, if all the tritium is released into the air in the form of water vapor within the AP-1 enclosure. Off-site doses and concentrations are well below allowed limits.

A more likely result is that some tritiated lithium compounds, water, and hydrogen gas will form within the vault and less than the full inventory will be released. In the event of a lens rupture it should be assumed that any lithium compounds that contain hydrogen may also contain tritium. Tritium, a low energy beta emitter, will not be detectable with the usual survey

instrumentation. Until the production rate of tritium can be determined with better certainty, pulse testing of an activated lens within the vault should not be done with people in the AP-1 enclosure.

2. The potential airborne  $^7\text{Be}$  concentration remains well below the MPC both on and off-site. However,  $^7\text{Be}$  does represent an external  $\gamma$ -ray hazard and source of contamination. Experience has shown that  $^7\text{Be}$  will probably "plate out" on the duct work and within the vault, or be trapped by the HEPA filter.  $^7\text{Be}$  emits a 478 keV  $\gamma$ -ray about 10% of the time and can therefore be detected with portable survey instruments. In the event of a lens rupture there could be as much as 840 mCi of  $^7\text{Be}$  spread throughout the vault and the air pathway leading to the HEPA filter. In the event of a perforation of the filter or duct work, some of this activity could be released into the AP-1 enclosure either as airborne activity or particulates.

References

1. P. Yurista, private communication.
2. T. W. Armstrong and J. Barish, Nucl. Science and Eng. 38 (1969) 265.
3. G. Dugan, "Lithium Lens Catastrophe Theory,"  $\bar{p}$  Note 373, April, 1983.
4. J. Krider, "Lithium Lens Interlocks,"  $\bar{p}$  Note 443, December 18, 1985.
5. Fermilab Radiation Guide - Chapter 13.