Practical and Cost Effective Solution to the Need for Shielding Penetrations Against Photons and Neutrons from Normal and Accident Losses

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Introduction

The Thomas Jefferson National Accelerator Facility (Jefferson Lab) houses a 4 GeV, 200 μA continuous wave (CW) recirculating electron accelerator. This underground accelerator is made up of two superconducting linear accelerators (linacs), two arcs, a beam switch yard (BSY), and three end stations (Figure 1). Each linac has the capability of accelerating electrons to a kinetic energy of 400 MeV. The arcs contain four (on the west) and five (on the east) beamlines to transport the beams of differing energies back into the linacs. The BSY steers the desired beams into the end stations as needed for nuclear physics experiments.

The accerator is connected to the control and diagnostic electronics in the above-ground service buildings via 30 cm and 51 cm diameter penetrations that travel through 4.6 m of soil and concrete. As a result, there exists the potential for personnel exposure to radiation scattering up the penetrations. It was desired that some of these buildings become Uncontrolled Areas, so that persons in the buildings would not require dosimetry. The Jefferson Lab Beam Containment Policy also requires that effective dose rates to workers be limited to 150 mSv in one hour if a maximum beam power loss accident was to continue unabated.

Legal/Policy Requirements

The primary driver for badging requirements is Title 10, Code of Federal Regulations Part 835 (10CFR835), which indicates that radiation dosimetry is required when a member of the public or a declared pregnant Radiation Worker is expected to receive greater than 0.50 mSv-yr^{-1}, or when Radiation Workers are expected to receive greater than 1.00 mSv-yr^{-1}. It is unreasonable to expect that any member of the public (which includes minors and Jefferson Lab staff who are not radiation workers) will spend 1000 hours (half a work year) in any Radiologically Controlled Areas (RCAs) at Jefferson Lab, much less over any subset of penetrations. Therefore, shielding the penetrations to 1.00 mSv-yr^{-1} is adequate for both cases. This effective dose rate averages to 0.002 mSv-h^{-1} for a 2000-hour work year and 25% occupancy factor over the penetration. A 25% occupancy factor over the penetrations is expected to be quite high and thus conservative.

The Jefferson Lab Beam Containment Policy states that in a maximum credible accident scenario, the maximum dose rate outside passive shielding to be expected by anyone at Jefferson Lab should be 150 mSv in one hour if the accident were to continue unabated. Shielding for the penetrations, then, must take this limit into account. Active safety systems are used to shut off mis-steered beam. A very conservative time for beam shutoff during such an accident would be 1 second. This one second exposure would result in a 0.042 mSv total dose if a person happened to be in the very worst spot possible.

Supporting Information

Previous measurements of streaming up penetrations from oblique-angle scattering have yielded the following reduction factors from the bottom of penetrations to the top: neutrons, 0.0005; photons, 0.001. Since at no point in the machine are the beamline components line-of-sight from the top of the penetrations, these factors are used to reduce the source term from the roof of the tunnel to the top of the penetrations.

A cost-effective solution for the shielding was determined to be uniform pea-gravel, based upon preliminary calculations of different types of shielding. Other potential selections were lead, iron, and boron-loaded polyethylene. The gravel is fairly inexpensive and does a good job of shielding both neutrons and photons, as is described below. Pea gravel has an average density of 1.84 g-cm^{-3} - 2.08 g-cm^{-3}, regardless of the grain size*. However, there is essentially no difference when the amount of dry gravel is measured by weight, as was the case at Jefferson Lab.

The photon mass attenuation coefficient was conservatively determined to be at the Compton minimum, 0.0202 cm^2-g^{-1} at 30 MeV for SiO_2. The buildup factor was iteratively determined. Verification tests with an industrial radiography source, Ir-192, (and the appropriate SiO_2 cross sections at the Ir-192 energies) indicate that the method is both appropriate and accurate.

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* **Private conversation with Suresh Chandra, Civil Engineer, Thomas Jefferson National Accelerator Facility**

The neutron removal cross section was then estimated for SiO_2 **not** backed by hydrogenous material. An estimate of the ratio of iron and lead neutron removal cross sections when not backed by hydrogenous material to their hydrogen-backed cross sections (LSU, 1976) was made. Then, the same ratio was estimated for silicon and oxygen by logarithmic interpolation of the atomic weights (the ratio for hydrogen, of course, remains unity):

$$\frac{0.204}{\ln(207)} \rightarrow \frac{0.34}{\ln(56)} \rightarrow \frac{R_{Si}}{\ln(28)} \rightarrow \frac{R_O}{\ln(16)} \rightarrow \frac{1.0}{\ln(1)}$$
$$\therefore \quad R_{Si} = 0.48\,; \; R_O = 0.57$$

Applying the ratios to the hydrogenous-backed removal cross sections and folding in the weight percent of each component yields a removal cross-section for SiO_2:

$$\sigma_{SiO_2} = (0.48)(0.0281\,cm^2\text{-}g^{-1})(0.47) + (0.57)(0.0405\,cm^2\text{-}g^{-1})(0.53)$$
$$= 0.0186\,cm^2\text{-}g^{-1}$$

Extra conservatism is realized because the shielding is in fact surrounded on the sides by hydrogenous material - the concrete and compacted earth around the penetration. It should be noted that most of the dose rate from neutron production at the angles of interest are from giant resonance neutrons, so the removal cross section is valid for these energies. Experimental data with an Am-Be neutron source shows that the calculations are conservative (measurements show that 16" is nearly a tenth-value layer, while calculations show it should only reduce the effective dose rate by a factor of four).

Calculations

The first step in the process was to run a computer code to determine the effective dose rates from an optimal iron target at various energies and angles at one meter over the range of beam energies. Then, a geometry factor was introduced that takes into account the angular distances from the beamlines to the tunnel ceiling and determines a $1/r^2$ distance reduction factor for the various angles from the target. Using the product of these two calculations, one can determine the absolute worst-case angle for dose rates at the bottom of a penetration, regardless of any actual penetration or beamline element location. This number was determined not only to be conservative, but also to reduce calculation time in determining the true penetration locations. The source term is then reduced by the factors mentioned previously to yield a dose rate at the top of the penetration. The depths of pea gravel to bring the dose rates down to 150 mSv-h^{-1} (accident scenario) and 0.002 mSv-h^{-1} (normal losses) were calculated.

The example calculations below will take a given set of data (0.445 GeV, 200 μA, 45°) and show how the calculations are performed.

Target:	iron, 8.0" length, 2.5" radius
Neutron Dose Rate:	6.0×10^3 mSv-kW^{-1}-h^{-1}
Photon Dose Rate:	$10. \times 10^3$ mSv-kW^{-1}-h^{-1}

The $1/r^2$ distance factor is calculated by determining the distance to the ceiling from the various beamline elements. For the arcs, the normal distance from the ceiling of the top beampipe is approximately 0.374 meters. Therefore, the distance from the ceiling at 45° may be calculated using a sine dependence and the factor is calculated as:

$$\frac{(1m)^2}{\left(\frac{0.374m}{\sin(45^o)}\right)^2} = 3.6$$

The dose rates, then, at the tunnel ceiling are:

$$\begin{aligned} Neutron:\ (6.0x\,10^3\,mSv\text{-}kW^{-1}\text{-}h^{-1})(0.445GeV)(200\mu A)(3.6) &= 1.9x\,10^6\,mSv\text{-}h^{-1} \\ Photon:\ (1.0x\,10^4\,mSv\text{-}kW^{-1}\text{-}h^{-1})(0.445GeV)(200\mu A)(3.6) &= 3.2x\,10^6\,mSv\text{-}h^{-1} \end{aligned}$$

Multiplying each component by the penetration reduction factor yields dose rates at the top of the penetration:

$$\begin{aligned} Neutron:\ (1.9x\,10^6\,mSv\text{-}h^{-1})(0.0005) &= 950mSv\text{-}h^{-1} \\ Photon:\ (3.2x\,10^6\,mSv\text{-}h^{-1})(0.001) &= 3200mSv\text{-}h^{-1} \end{aligned}$$

Finally, the calculation for determining the amount of pea gravel to bring the dose rate at the top of the penetration to 150 mSv-h^{-1} is made. The equations used to determine this for the two types of radiation are:

$$neutron:\ \frac{\ln\left(\frac{950mSv\text{-}h^{-1}}{150mSv\text{-}h^{-1}}\right)}{(0.0186\,cm^2\text{-}g^{-1})(1.8423g\text{-}cm^{-3})} = 54cm$$

$$photon:\ \frac{\ln\left(\frac{3200mSv\text{-}h^{-1} * 2.0}{150mSv\text{-}h^{-1}}\right)}{(0.0202\,cm^2\text{-}g^{-1})(1.8423g\text{-}cm^{-3})} = 101cm$$

where 2.0 is used for the buildup factor for photons at the given thickness. However, since we are shielding for both neutron and gamma, the standard exponential reduction equations may be combined and solved iteratively; the depth is determined to be 107 cm (42 inches).

$$(\dot{D}_{photon})(B)(e^{[(-\mu/\rho)_{photon}(\rho)(x)]}) + (\dot{D}_{neutron})(e^{[(-\mu/\rho)_{photon}(\rho)(x)]})$$
$$= (3200 mSv-h^{-1})(2)(e^{[(-0.0202)(1.8423)(x)]}) + (950 mSv-h^{-1})(e^{[(-0.0186)(1.8423)(x)]})$$
$$= 150 mSv-h^{-1}$$

Although a factor of two extra conservatism is often used for neutron scattering in a tube, there are more than likely enough sources of conservatism already in the calculation; the experimental data points to an overall conservatism.

Results

An analysis of the calculations reveals that maximum dose rates occur in the top beamline, with maximum design energy beam - 445 MeV in the East Arc, 845 MeV in the West Arc, 3645 MeV in the North Linac, and 4045 MeV in the South Linac. Then the same considerations must be made: what is the amount of shielding required to keep instantaneous dose rates to less than 150 mSv-h^{-1}, and what is the amount of shielding required to keep normal loss dose rates to workers less than 0.002 mSv-h^{-1}?

For the first scenario, one only needs to perform the calculations above for maximum beam current (200 μA). The second scenario requires a knowledge of what one should consider a "normal" loss. Jefferson Lab's Radiation Control Review (Southeastern, 1987) identifies these normal losses. These normal losses, then, are used for source terms in each of the affected areas.

Since the penetrations are not all empty, it was assumed that the cables, conduits, etc., do not add to the shielding effectiveness and are thus considered empty space. Once again, the method of filling by weight compensates for this empty space. For photons, streaming up conduit or waveguides is at worst a linear function of area (for a two-reflection process, NCRP, 1977); for neutrons, streaming is reduced exponentially as an inverse function of square root of area (Schopper, 1990) Thus, these completely open spaces do not in any way negate the effectiveness of the shielding.

Conclusion

It was recommended that the following minimum thicknesses of pea gravel shielding be used in the various locations to remove the requirement for badging in the service buildings:

North Linac: 70 g cm^{-2}

North Linac spreader: 393 g cm^{-2}

South Linac: 75 g cm^{-2}

South Linac spreader: 397 g cm^{-2}

East Arc: 365 g cm^{-2}

West Arc: 365 g cm^{-2}.

It should be noted that most of the Jefferson Lab workers occupationally exposed under these conditions are also required to make tunnel access during accelerator shutdown. Exposure after shutdown results in most of the effective dose to Jefferson Lab workers.

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