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Shielding and Activation Simulations and Calculations for the Adelphi Pelletron Accelerator Facility

by James J. Carroll, Jarrod C. Marsh, and Christopher J. Chiara

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DEVCOM Army Research Laboratory

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14. ABSTRACT The Adelphi Pelletron Experimental (APEX) Facility at ARL's Adelphi Laboratory Center is a new research asset whose development and operations have been supported by the Defense Threat Reduction Agency (DTRA). APEX is a unique facility within the DoD that provides the ability to make nuclear data measurements and investigate the effect of ionizing radiation on materials. In addition, APEX is in the National Capital Region and can facilitate training for local scientists, U.S. Army, and DTRA staff about these measurements and their limitations. The core of APEX is a tandem van de Graaff ion accelerator of the Pelletron type, which has been used by the U.S. Navy for several decades before its transfer to ARL in 2017. APEX includes two ion sources that can provide ions suitable for acceleration of most elements. The initial focus of research with the Pelletron is geared toward improving the quantity and quality of nuclear data on the interactions of fast neutrons with materials. This report describes analyses of 1) the radiation shielding provided by the APEX Test Cell and 2) possible activation of facility and beamline materials as needed to obtain an Army Radiation Authorization for Pelletron operations.					
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1. Introduction

The Adelphi Pelletron Experimental (APEX) Facility at the U.S. Army Combat Capabilities Development Command (DEVCOM) Army Research Laboratory (ARL)'s Adelphi Laboratory Center (ALC) is a new ARL research asset whose development and operations have been supported by the Defense Threat Reduction Agency (DTRA). APEX is a unique facility within the DoD that provides the ability to make nuclear data measurements and investigate the effect of ionizing radiation on materials. In addition, APEX is in the National Capital Region and can facilitate training for local scientists, Army (FA52), and DTRA staff about these measurements and their limitations. The core of APEX is a tandem van de Graaff ion accelerator of the Pelletron type, manufactured by National Electrostatics Corporation (NEC). This Pelletron was used by the U.S. Navy for several decades before its transfer to ARL in 2017, and considerable effort and funding has been expended on its reassembly, upgrades, and testing. APEX includes two ion sources: a Source of Negative Ions by Cesium Sputtering (SNICS), which can provide ions suitable for acceleration of most elements, and a Toroidal Volume Ion Source (TORVIS), which is designed as a high-current source of negative hydrogen ions. The initial focus of research with the Pelletron is on improving the quantity and quality of nuclear data on the interactions of fast neutrons with materials.

Before operating the Pelletron in APEX, it was necessary to obtain a U.S. Army Radiation Authorization (ARA). Preparation of this ARA application began in April 2023. ARL nuclear physics subject matter experts (SMEs) worked closely with the ARL Radiation Safety Officer (RSO) on a draft application. Those SMEs performed simulations of the radiation environment provided by the Pelletron at that time. Much later, in summer 2024, the RSO indicated new concerns regarding the possible activation of structural and beamline materials by fast neutrons, despite the anticipated neutron flux being many orders of magnitude smaller than that of nuclear reactors where this concern is more typical. The ARL nuclear physics SMEs performed a detailed analysis of possible activation and had that analysis reviewed by the Defense Health Agency's Public Health Office. The shielding and activation analyses were included as part of the successful ARA application (awarded in May 2025) and appear hereafter for archival record.

2. Benchmarking

Radiation-transport codes like Geant4 and Monte Carlo N-Particle Transport (MCNP) are highly regarded and used worldwide by the nuclear physics and nuclear engineering communities. Nevertheless, the results of simulations from

such codes must be properly benchmarked against real-world physical measurements to ensure their accuracy. The reason harkens back to the adage of GIGO (garbage in, garbage out) because all radiation-transport codes rely on input cross-section data for calculating nuclear reaction rates and the interactions of radiation with matter. Considering this, ARL nuclear physics SMEs in the Nuclide Science Team took a conservative approach to drawing firm conclusions based on simulation results regarding radiation shielding and potential activation in the ARL/ALC Building 500 Test Cell due to operation of the tandem van de Graaff accelerator (an NEC 9SDH-2 Pelletron). The Pelletron has a maximum terminal voltage of 3 MV and can accelerate protons with energies up to 6 MeV. The near-term intent is to use these protons to irradiate a natural beryllium target (the “primary” target, 100% ^9Be) to produce fast neutrons. The fast neutrons would then be used to perform basic nuclear data/cross-section measurements on other materials. For the $^9\text{Be}(p, n)$ reaction, $Q = -1.8504$ MeV so that the maximum possible energy of neutrons produced from 6-MeV protons is approximately 4.13 MeV. The nominal maximum proton current through the Pelletron is 100 μA , although in historical practice at the Naval Surface Warfare Center, Carderock Division, this current could not be achieved with this accelerator.

The Nuclide Science Team generally performs radiation-transport simulations with custom codes built from the Geant4 (2025) toolkit. This open-source code was developed by the European Organization for Nuclear Research (CERN) and is maintained and updated by a large community of users. Cross sections for nuclear physics reactions and interactions of radiation with matter are incorporated into a Geant4 simulation by inclusion of appropriate “physics lists.” One of the most highly recommended physics lists for neutron interactions with matter, and thus for radiation-safety simulations, and which is most in agreement with MCNP simulations and measurements (see Lu et al. 2021), is the QGSP_BIC_AllHP package that includes the latest information from the TALYS-based Evaluated Nuclear Data Library (TENDL). Geant4 simulations with the QGSP_BIC_AllHP physics list were used for ARL analyses. Herein, the term “Geant4” will be used for ARL simulations even where referenced works (such as Lu et al. [2021]) also used Geant4.

Benchmarking the Geant4 simulation results through comparison with measurements is not yet possible at ALC. Instead, Nuclide Science Team members performed measurements at the University of Kentucky Accelerator Laboratory (UKAL), bombarding Be, B, Li, and Ta targets with protons in February 2024 for this purpose. A 3- μA current of 5-MeV protons from their accelerator, their maximum safely achievable current at that energy, was used for these measurements. A Thermo Scientific RadEye X neutron survey meter was used to

determine the effective dose rate of 5.12 rem/h at 2 min in the forward direction from a thick Be target (sufficient to stop all protons; a thick target was used in all Geant4 simulations).

The current version of Geant4 has a built-in capability for scoring radiation dose in multiple volumes, but it has a known flaw when scoring neutron dose with the QGSP_BIC_AllHP physics list. For ARL analyses, Geant4 was used with this physics list to simulate the total fluence and energy spectrum of neutrons incident on a scoring volume corresponding to the position of the survey meter at UKAL from 3 μ A of 5-MeV protons. Then the fluence per unit dose equivalent from Table 1004(b).2 of 10CFR20.1004 (NRC 2005) was used to obtain an effective dose rate from the Geant4 simulation of 5.77 rem/h. This Geant4 result is within approximately 11% of the UKAL measurement, and it was considered to be in good agreement.

Another benchmark was made to Figure F1 in the National Council on Radiation Protection 51 guidelines (NCRP 1977).^{*} This plot gives the neutron fluence rates (thus, the neutron flux) from various (p, n) reactions for thick targets. The units of the plot are atypical and unexplained, but a review of Figure 5 in the source document (Burrill 1963) for Figure F1 finds units that are more clearly applicable. For 5-MeV protons incident on a thick Be target, approximately 1.4×10^8 n/(s μ A sr) is depicted. This gives a production estimate of 2.81×10^{-4} n/p, for neutrons emitted into all angles, from this reaction using 5-MeV protons.[†] The value obtained by Geant4 simulation for the same beam parameters is 2.9×10^{-4} n/p, within approximately 3% of the NCRP 51 value. An MCNP simulation performed for comparison gave 2.6×10^{-4} n/p, in reasonable agreement with the Geant4 value. The value from Figure 4 in Lu et al. (2021) is larger at approximately 5×10^{-4} n/p for a thick Be target and 5-MeV protons but within a factor of 2 of the Geant4 results; the results from the Geant4 simulations are adopted because their corresponding dose values agree well with the UKAL measurements.

Simulations that are initiated with a given number of protons (each being a “history” for the simulation, which tracks all interactions of that particle and any other particles or photons it creates) are not as effective at achieving statistical accuracy in the results for produced neutrons because only approximately one of every few thousand protons causes emission of a neutron. Statistical accuracy

^{*} Note: NCRP 144 (2003) was intended to expand on and update NCRP 51 (1977), but it does not contain information for proton energies below 10 MeV for $^9\text{Be}(p, n)$ reactions, and, therefore, it is not quantitatively useful for the Pelletron. Table 2.3 of NCRP 144 does provide a qualitative assessment of the general potential for radiation exposure from particle accelerator components systems for proton energies less than 10 MeV: “beam delivery,” “target/user,” and “beam stop” are designated as “moderate,” whereas “ion source” and “accelerator” are designated as “low” potential.

[†] Note that 6.25×10^{12} protons $\Leftrightarrow$ 1 μ A s.

improves with an increase in the number of scored, or counted, particles (neutrons, in this case). Most proton interactions are purely electromagnetic with atomic electrons during stopping of the protons in the thick Be target. Geant4 simulations are limited to a practical maximum of approximately 10^9 initial particles to be tracked, and a simulation running 10^9 proton histories will only create approximately 10^6 neutrons, proceeding to track those neutrons as they scatter and are absorbed within the large Test Cell. Computational resources are more effectively used for consideration of the effects of neutrons by starting directly with neutron histories and scaling to proton currents based on the above n/p value. This allocates all 10^9 simulated histories to neutron tracks, increasing the statistical accuracy of the results. Each simulation run starting with 10^9 neutrons requires approximately 72 h to complete due to all the neutron-scattering interactions in the large Test Cell; thus, iterative evaluation of different shielding configurations, for example, is a lengthy process. This was worthwhile to achieve more trustworthy effective dose results. Of course, starting with neutrons requires that the neutron output from protons of a given energy incident on a thick Be target be properly benchmarked, to include neutron energy and angular distributions in addition to the numbers of neutrons produced per incident proton.

Figure 1 shows a comparison between the angular distribution of neutrons produced by 5-MeV protons determined from the Geant4 simulations and the distribution obtained in Lu et al. (2021). The general shape of the angular distribution from the Geant4 simulations agrees within errors with the simulation results of Lu et al. (2021). Very limited angular-distribution information is given in NCRP 51 (1977) Table F.4 for the ${}^9\text{Be}(p, n)$ reaction and indicates that neutron emission per steradian at 90° is 67% of that at 0° for 2.5-MeV neutrons (which would be produced by 4.56-MeV protons). For the Geant4 results of Figure 1, based on 5-MeV protons, the neutron emission per steradian at 90° is approximately 43% of that emitted at 0° . Notwithstanding the sparse information from NCRP 51 (1977), the Geant4 angular distribution is well benchmarked in comparison with Lu et al. (2021).

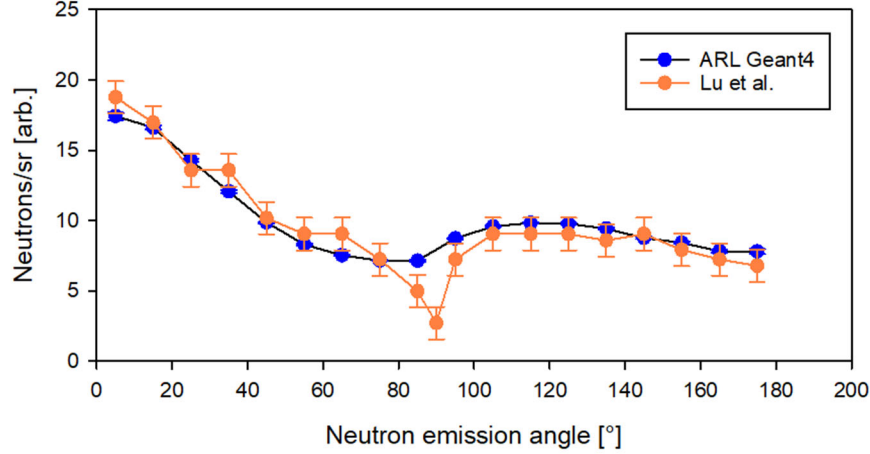


Figure 1. Angular distribution of neutrons produced from a thick Be target by 5-MeV protons from (blue) Geant4 simulations and (orange) (Figure 7(b) in Lu et al. [2021]). Error bars for the Geant4 simulations, from counting statistics, are smaller than the symbols. Error bars for the results from Lu et al. (2021) reflect the process of extracting values from Figure 7 therein. The vertical scale is arbitrary, normalized to account for the different units for the Geant4 results and those from Lu et al. (2021)—the relative emission to different angles is the important comparison here while the total number of neutrons produced has already been benchmarked above.

Figure 2 shows a polar plot of the angular distributions for neutrons emitted per steradian due to irradiation of a thick Be target by 5-MeV protons (relevant to the UKAL measurements) and by 6-MeV protons (relevant to determine the maximum effects expected from the Pelletron).

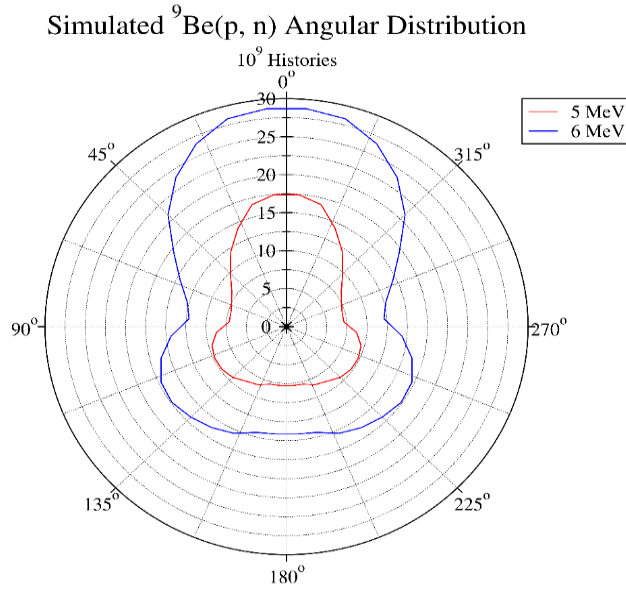


Figure 2. Polar plot of angular distributions (neutrons emitted per steradian) from the Geant4 simulations from 5- and 6-MeV protons incident on a thick Be target. The radial scale is arbitrary because the relative emission into different directions is the key point.

The simulated energy spectrum of the emitted neutrons (summed over all directions) is shown in Figure 3. These are compared with the results of Lu et al. (2021) (earlier version of Geant4 and physics list, with unspecified directionality but likely emission into all directions). The spectra have been normalized to the total number of emitted neutrons. The effective dose, calculated using 1004(b).2 of 10CFR20.1004 for the Geant4 spectrum, is within approximately 8% of the value obtained from the spectrum from Lu et al. (2021), so the difference in shapes of the energy spectra does not appear to significantly affect dose estimates.

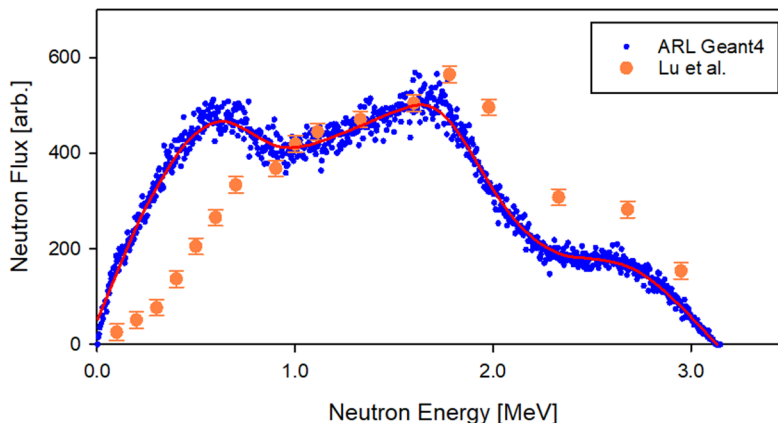


Figure 3. Neutron flux in arbitrary units produced by 5-MeV protons on a thick Be target vs. neutron kinetic energy in MeV from Geant4 simulation into all solid angles (blue circles). The orange circles are taken from the simulations of Figure 5 in Lu et al. (2021), angular information unknown but likely into all directions. The smoothed red line serves to guide the eye to the Geant4 results. The spectra have been normalized to the same total number of emitted neutrons. Note that Howard et al. (2001) do not include results for all angles.

Figure 4 shows a similar comparison between Geant4 simulations for neutrons emitted within 10° of the forward direction (direction of the proton beam) and the measurements given in Figure 11 in Howard et al. (2001). Again, the spectra agree qualitatively, and the differences do not significantly affect effective dose-rate estimates obtained with the Geant4 spectrum. Finally, the Geant4 simulations included the entire geometry and materials of the Test Cell (including air), so that the resulting spectra better reflect the actual scattering of neutrons produced by the Pelletron.

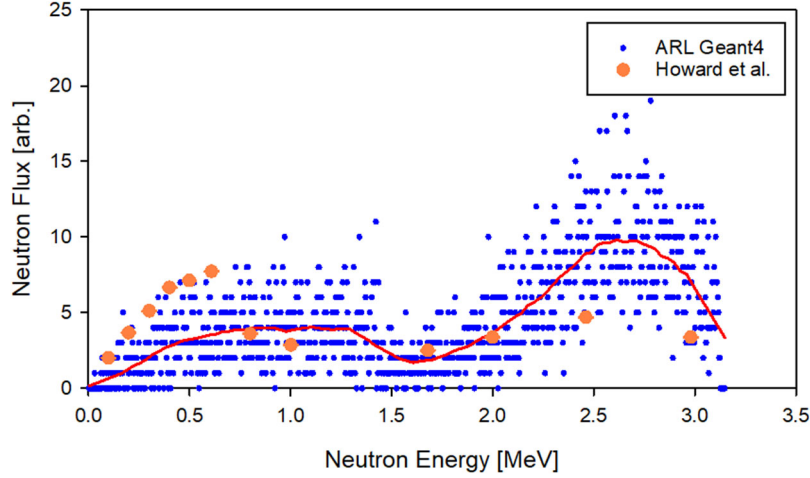


Figure 4. Neutron flux (arbitrary units) produced by 5-MeV protons on a thick Be target vs. neutron kinetic energy in MeV from (blue circles) Geant4 simulation into less than 10° around the forward beam direction and (orange circles) from Howard et al. (2001) Figure 11 at 0° . The smoothed red line serves to guide the eye to the Geant4 results. The spectra have been normalized to the same total number of emitted neutrons. Note that Lu et al. (2021) do not include results specified for forward angles.

Geant4 simulations seem to be reliable for determination of estimated activation and shielding (based on effective dose values) in the Test Cell to within conservatively 20%, as summarized in Table 1. The accuracy of simulations can be enhanced by using neutrons as the initial particles instead of protons, based on the neutron angular and energy distributions and the n/p value, as described above. For activation and shielding calculations, neutrons based on 6-MeV protons are used to represent the maximum operating conditions for the Pelletron.

Table 1. Benchmark summary.

Result	Established accuracy	Benchmarked by
Total neutron production by protons (n/p)	11%; 3%	Effective dose rate measured at UKAL for 5-MeV protons; MCNP simulation
Neutron angular distribution	20%	Angular distribution from Lu et al. (2021)
Neutron energy distribution	8%	Effective dose rate compared with that calculated from Lu et al. (2021) distribution

3. Activation Estimates

Hereafter, input to the simulations assumes a 6-MeV proton beam with a 100- μ A current incident upon a thick Be target. These inputs were used to predict the activation and shielding for realistic, maximum output conditions for the Pelletron. A proton energy of 5 MeV was used in the Benchmarking section, to facilitate

comparison with available measurements at UKAL and relevant literature, much of which is given per μA proton current.

Neutrons produced via the ${}^9\text{Be}(p, n)$ reaction and scattered in the Test Cell could, in principle, activate some materials. The Nuclide Science Team has considered activation estimates for concrete of the Test Cell, beamline components nearest the neutron-production location, and the Be primary target itself.

3.1 Concrete in Test Cell

There are several references available regarding measured activation of concrete by neutrons in reactor environments (e.g., Žagar and Ravnik 2000) or from proton accelerators at higher energies than the Pelletron (e.g., Fujibuchi et al. 2015). The neutron spectrum in a reactor is very different from that created by protons on a Be target in the Test Cell, and the total neutron flux within a reactor is many orders-of-magnitude larger, so the present analysis was guided by the Fujibuchi et al. (2015) approach. In that work, the long-lived radioisotopes ${}^{60}\text{Co}$ (half-life of 5.271 years) and ${}^{152}\text{Eu}$ (half-life of 13.517 years) were detected from their gamma-ray emission in concrete in a medical cyclotron vault, and the measured activation was compared with the respective International Atomic Energy Agency (IAEA) Clearance Levels (CLs) (IAEA 2023). The CLs define the “activity concentration” beyond which activated material must be considered radioactive waste for remediation. The Army has established Screening Levels for Clearance (SLCs) (DOA 2023) that are activities per unit mass beyond which materials must be considered to be contaminated. A distinction between the SLCs and the CLs is that the latter standard gives separate limits for both “moderate” amounts of material (total material less than approximately 1 metric ton) and “bulk” amounts of material (in excess of approximately 1 metric ton). The CLs for the same activated material can be significantly different depending on whether the quantity in the setting under consideration is designated as moderate or bulk. For the radioisotopes considered herein, the “volume” SLCs mirror the “bulk” CLs and apply for their quantities.

A new Geant4 simulation was performed for 10^9 initial 6-MeV protons, the nominal maximum energy achievable with the Pelletron. The number of neutrons emitted per incident proton from the primary target was 5.3×10^{-4} , allowing a calibration of the number of neutrons emitted to the proton current and irradiation duration. That simulation also determined the angular and energy distributions of emitted neutrons resulting from protons incident on the Be target.

A simulation was then performed with 10^9 neutron histories using the previously determined energy spectrum and angular distribution from 6-MeV protons, with the neutrons emitted directly from the Be target’s location within the Test Cell. Some

neutrons from that location and some scattered in the Test Cell were incident on a 1-ft cubic volume of concrete within the floor 4 ft below the neutron-production location (the concrete walls and ceiling are at distances of at least 14 ft so the focus here is on the floor). Capture of thermal neutrons is generally the dominant means of activating materials (Glascock and Neff 2003), and this was confirmed by calculations of the contributions from neutron resonance values taken from Mughabghab (2006); thermal capture cross sections were also obtained from that encyclopedic reference. The production of an activated radioisotope was calculated from the cross sections and the Geant4 spectrum of thermal neutrons incident on the concrete volume of interest according to the general equation

$$N_{act} = N_{target} \int \frac{d\phi(E)}{dE} \sigma(E) dE, \quad (1)$$

where N_{act} is the number of nuclei of the activated radioisotope, N_{target} is the number of target nuclei available for neutron capture, $d\phi(E)/dE$ is the fluence of thermal neutrons in the thermal (Maxwellian) spectrum, and $\sigma(E)$ is the cross section for thermal-neutron capture. Equation 1 becomes slightly modified when the cross section from Mughabghab (2006) is given at the nominal thermal energy of $E_{th} = 0.0253$ eV (corresponding to the most probable neutron speed of 2200 m/s) so that the energy-dependent cross section, $\sigma(E)$, is obtained by scaling the 2200-m/s value by a factor of $\sqrt{E_n/E_{th}}$ (Révay and Belgia 2004). When the cross section is given as averaged over the Maxwellian spectrum, the spectral density of the neutron fluence becomes the total fluence in the thermal spectrum. In each instance, the neutron spectra at the position of the potentially activated materials were determined from the Geant4 simulations.

The capture cross section of ^{59}Co is 37.18 b (Mughabghab 2006), and this is the 2200-m/s value. Cobalt is present (with 100% abundance of ^{59}Co) within standard concrete at a level of approximately 0.65 $\mu\text{g/g}$ concrete (Goh et al. 1986) (note that NCRP 51 [1977] Table H.2 does not provide information on these important trace constituents of concrete), and the density of ordinary concrete was taken to be 2.4 g/cm^3 . The produced ^{60}Co activity concentration in the concrete volume is estimated to be 1.1×10^{-3} Bq g^{-1} , assuming operation of the Pelletron for 6 h/day, 5 days/week, for 35 weeks in a year, and at an operating current of 100 μA . The produced activity decays according to its 5.271-year half-life (ENSDF 2025) so that the activity concentration remaining after any given operational duration must include a correction for the decay during a production period T_{irr} given by

$$AC_{irr} = \frac{R_{prod} T_{1/2}}{\ln(2)} [1 - e^{-T_{irr} \ln(2)/T_{1/2}}], \quad (2)$$

where $R_{prod} = 1.1 \times 10^{-3}$ Bq g^{-1} year $^{-1}$ and AC_{irr} is the specific activity at the end of the production period. The activity concentration of ^{60}Co in the concrete volume of

interest would be $9.9 \times 10^{-4} \text{ Bq g}^{-1}$ after 100 years if the Pelletron was operated at 100- μA current of 6-MeV protons, never approaching the SLC for this radioisotope of 0.1 Bq g^{-1} .

Activation of ^{152}Eu was analyzed in a similar manner, where the concentration of this element in concrete was estimated (Yoshida et al. 2020) to be up to approximately 0.7 ppm of Eu in the natural material of concrete aggregate compared with 8 ppm for cobalt. Taking the above cobalt concentration in concrete of $0.65 \mu\text{g/g}$ concrete and correcting for the molar mass of europium and cobalt, the europium concentration is estimated to be $0.15 \mu\text{g/g}$ concrete. Assuming the same Pelletron operation duration per year as described above and a current of 100 μA of 6-MeV protons, the activity concentration of produced ^{152}Eu after 1 year would be $2.7 \times 10^{-3} \text{ Bq g}^{-1}$. The activity concentration after 100 years of Pelletron operation would be $5.3 \times 10^{-2} \text{ Bq g}^{-1}$, below the SLC of 0.1 Bq g^{-1} .

IAEA (2023) describes how an effective activation concentration should be calculated when multiple activated radioisotopes are present in a material. Following that prescription, the effective SLC = 1.1 Bq g^{-1} , and this should be compared with the summed activity concentrations of the individual activated radioisotopes. The summed activity concentrations present after 100 years of Pelletron operation would reach only 0.67 Bq g^{-1} . Long-term activation of the concrete is not a significant consideration for the Pelletron.

Žagar and Ravník (2000) also consider the total contribution to the specific activity of concrete in a decommissioned nuclear reactor due to other activated radioisotopes. The shorter-lived radioisotopes that contribute the most to the total concrete activity are ^{42}K (half-life of 12.355 h) and ^{47}Ca (half-life of 4.536 days), so they are considered here only as related to activity when personnel enter the Test Cell after daily irradiations. The ^{42}K is produced by neutron capture (thermal cross section 1.46 b^9) (Mughabghab 2006) on ^{41}K present (6.73% natural abundance) within the concrete, where the total potassium content is 1.3% by weight (according to NIST [2025]). Taking daily operation of 100 μA of 6-MeV protons for 6 h, the produced activity of ^{42}K within the subject 1 ft-cubic volume of concrete directly under the primary target will be approximately $3.2 \mu\text{Ci}$ (exempt quantity = $10 \mu\text{Ci}$) (NRC 1993) Considering its decay, the ^{42}K will saturate by the end of a week of full Pelletron operation at $3.78 \mu\text{Ci}$, remaining well below the exempt limit, and will be down to less than $0.1 \mu\text{Ci}$ before operations resume the next week.

The thermal cross section for ^{46}Ca is 0.74 b (Mughabghab 2006), this isotope is 0.004% abundant in natural calcium, and calcium appears at 4.4% by weight in concrete. The produced daily activity of ^{47}Ca within the subject concrete volume will be below 1 nCi (exempt quantity = $10 \mu\text{Ci}$ [NRC 1993]).

Long-term activation of concrete due to the Pelletron, even operated at 100- μ A current of 6-MeV protons, is not significant with respect to material remediation or contamination concerns as defined by the CLs and the SLCs. Short-term activation of concrete due to the Pelletron, operated at 100 μ A of 6-MeV protons, is likewise not a hazard to personnel.

3.2 Beamline Components

The largest-mass beamline component close to the neutron-emission point is a switching electromagnet, which can be used to divert the proton beam to different targets—although in place, it will not be used in the foreseeable future, and the protons will pass undeflected through its central beamline. The largest components of the switching magnet are an iron magnet core and copper conductors. The volume of the magnet is approximately $1.82 \times 10^5 \text{ cm}^3$ and is estimated to be 70% iron and 25% copper (the remainder is empty for the beamline).

For iron, activations of the radioisotopes ^{55}Fe (half-life of 2.744 years, abundance of 5.85% for ^{54}Fe) and ^{59}Fe (half-life of 44.49 days, abundance of 0.28% for ^{58}Fe) were considered. The mass of the iron content is over 1 metric ton so the bulk CL = 1000 Bq g $^{-1}$ was used, which is identical for the SLC. The thermal capture cross section of ^{54}Fe is 2.25 b (Mughabghab 2006) and the thermal neutron spectrum was determined from Geant4 within the volume of the switching magnet. The produced activity concentration of ^{55}Fe in the magnet during 1 year of operation with 6-MeV protons at 100 μ A will be 5.94 Bq g $^{-1}$ and 26 Bq g $^{-1}$ after 100 years of such operation, far below the corresponding SLC. For ^{59}Fe , with thermal neutron cross section of 1.32 b (Mughabghab 2006), the produced activity concentration after 100 years will be 0.6 Bq g $^{-1}$ for the same operating conditions, less than its SLC = 1 Bq g $^{-1}$.

The activation per day of ^{55}Fe and ^{59}Fe in the switching magnet will be approximately 1.5 and 0.7 μ Ci, respectively, within the entire iron volume of the magnet. For comparison, the exempt limits are 100 and 10 μ Ci, respectively (NRC 1993). Decay of ^{55}Fe occurs by electron capture to stable ^{55}Mn , accompanied by a gamma ray at 126 keV (with very low probability) and characteristic X-rays below 6 keV (ENSDF 2025). Self-shielding of the iron magnet will greatly inhibit the passage of these gamma rays so ^{55}Fe activity is not likely to be a significant hazard but will be monitored. Decay of ^{59}Fe occurs by β^- emission to stable ^{59}Co : mean beta energies are 80.64 and 149.21 keV for the principal (98%) decay branches (ENSDF 2025), and at such energies they will produce bremsstrahlung inefficiently (see Segrè 1982). The decays are accompanied by characteristic X-rays (below 7 keV) and gamma rays with the strongest being at 1099 and 1292 keV (ENSDF

2025). Self-shielding within the magnet will be less effective but still significant; the activity of the magnet will be monitored.

Copper has two stable isotopes, ^{63}Cu (69.2% abundance, thermal neutron cross section of 4.5 b (Mughabghab 2006) and ^{65}Cu (30.9% abundance, thermal neutron cross section of 2.17 b (Mughabghab 2006), which can be activated to produce ^{64}Cu (half-life of 12.7 h) and ^{66}Cu (half-life of 5.12 min). The estimated activities at the end of each day are 40 μCi and 37 mCi, respectively, within the approximately 2-metric ton magnet. The value for ^{66}Cu exceeds its exempt limit of 0.1 μCi . After the end of daily 6-h operations, the activity of ^{66}Cu will decrease to the exempt limit in 111 min; its activity will reduce to 0 μCi before the next day's operation. After 1 week's operation, the activity of ^{64}Cu will be 78 μCi , down to 3 μCi before operations begin on Monday morning.

The activation of the switching magnet should be monitored upon entry into the Test Cell and entry should be delayed as necessary to prevent exposure. However, activations of iron and copper radioisotopes in the switching magnet do not present concerns regarding levels that would require remediation as radioactive waste.

3.3 Be Neutron-Production Target

The $^9\text{Be}(p, n)$ reaction produces ^9B with a half-life shorter than 10^{-17} s (ENSDF 2025). The ^9B decays by proton emission into ^8Be , which has a half-life shorter than 10^{-15} s, and which subsequently decays into a pair of stable ^4He nuclei. A variety of other reactions on Be are also energetically possible for 6-MeV protons (Howard et al. 2001), for example, (p, γ) , (p, α) , and $(p, 2\alpha d)$, but all produce stable final nuclei or radioisotopes with half-lives shorter than 10^{-12} s. Thus, direct proton activation of a Be target is not important for operations in the Test Cell.

Activation of the Be primary target itself can also occur due to neutrons produced within that target. The effect of fast neutrons in the range of a few MeV has been considered (in the context of using Be as a neutron detector) in Talebitaher et al. (2011). The reaction in question is $^9\text{Be}(n, \alpha)$ and produces ^6He , which has a half-life of less than 1 s and decays into stable ^6Li . This is not considered significant for the Test Cell because it takes on the order of 90 s to open the 50-ton door to enter, at which point any ^6He produced will have undergone decay for more than 90 half-lives.

Thermal neutron capture by ^9Be (cross section averaged over the Maxwellian spectrum = 8.49 mb (Mughabghab 2006) produces ^{10}Be that beta decays with a half-life of 1.5×10^6 years (ENSDF 2025) into stable ^{10}B . Geant4 simulations indicate a total rate of 3.3×10^{11} n/s at all energies into all directions from 6-MeV

protons at 100 μA . Of those, a fraction of less than 5×10^{-5} are within the thermal range (these are directly produced within the Be target; scattered thermal neutrons from the Test Cell walls were not included). Thus, the rate of thermal neutron production would be less than 1.7×10^7 n/s. To provide an order-of-magnitude estimate for the resulting production rate of ^{10}Be activity within the Be target itself, a simple calculation was made for an equivalent-mass Be sphere with neutron production from its center. The primary target is a disk 0.25 mm thick and 2.54 cm in diameter, with a mass of 0.23 g. A sphere of the same mass and standard beryllium density would have a radius of 0.31 cm. Target nuclei of ^9Be within different concentric spherical shells of thickness dr would be subject to different neutron fluxes over the area given the surface of each shell, with the number of ^{10}Be nuclei produced in each shell, dN_{act} , being given by Equation 1. The total number of ^{10}Be nuclei produced per second was then obtained by integrating the shell contributions from $r = 0 - 0.31$ cm, and this gave approximately 5.6×10^3 ^{10}Be /s. This is equivalent to a rate for production of ^{10}Be activity of 2.2×10^{-21} Ci/s of beam-on time at 100 μA , requiring more than 1 million years to produce the Nuclear Regulatory Commission exempt activity of 0.1 μCi (NRC 1993) if the Pelletron was operated every second of every year at 100 μA . Due to these calculations, the Nuclide Science Team estimates that activation of a Be primary target is not a significant hazard for Pelletron operations.

4. Shielding

4.1 Test Cell and Surrounding Configuration

The ALC Building 500 Test Cell (Room 133) is, in general, a very robust shielded facility that was used until several years ago to house and operate two X-ray-producing electron linacs. Before approximately 1996, the Test Cell was used as a location within which X-rays from the Aurora pulsed-power device (bremsstrahlung up to 12 MeV endpoint energy) were used to irradiate materials. With some notable exceptions, its walls are approximately 11-ft thick (several feet thick high-density concrete on outer boundaries of the walls with packed earthen fill). Only packed earth lies below the concrete floor of the Test Cell, and the ceiling of the Test Cell is concrete covered with packed earth.

Access to the Test Cell is through three doors: a 15-ton concrete plug door, a 50-ton concrete rolling door, and a 110-ton concrete rolling door. A general diagram of the Test Cell is given in Figure 5, which shows the positions of these doors. The area beyond the 15-ton door is within the building and restricted by a locked door located approximately 18 ft higher, which opens to the outside world. The 110-ton door opens to a ramp in the outside world by which large items can be

brought to the 110-ton door entrance. The 50-ton door opens to an area of the interior of Building 500 (the “staging area”), which is next to the Control Room. Control of access to the Test Cell is achieved by locking the 15- and 110-ton doors and monitoring (locking is possible) the 50-ton door. All doors are incorporated into a radiation interlock system that prevents operation of the Pelletron if any door is open.

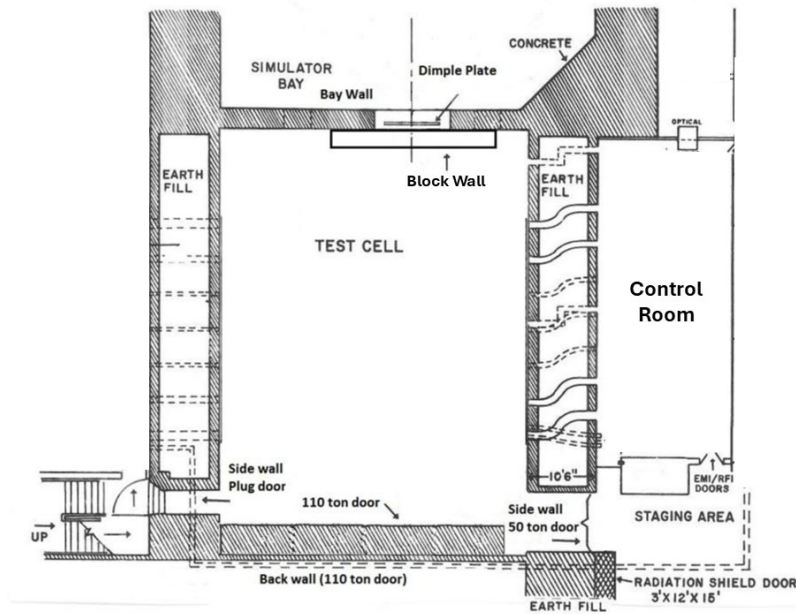


Figure 5. Top-down view of the ALC Building 500 Test Cell. Key features are the 15-ton “side wall” plug door, the 110-ton rolling door, the side wall 50-ton door, the “Dimple Plate,” the Block Wall, and two passthroughs/apertures for HVAC ducting in the “Bay Wall.” The sides of those passthroughs are indicated by dashed lines through the Bay Wall on either side of the Dimple Plate.

As constructed in the 1970s, no radiation generator was placed inside the Test Cell. Instead, the large Aurora pulsed-power electron accelerator was placed in the “SIMULATOR BAY” (current terminology is the “High Bay,” Room 134), and radiation produced by that device was introduced into the Test Cell through a location labeled in Figure 5 as the Dimple Plate. No personnel were present in the High Bay during operation of Aurora, and the mass of the very large Aurora accelerator itself contributed significantly to the total effective shielding in the direction of the High Bay. Thus, the Bay Wall between the Test Cell and the High Bay was constructed with the thinnest of the Test Cell walls at 3 ft of concrete. Also located on the Bay Wall are two passthroughs 14 ft above the Test Cell floor for HVAC structures. Figure 6 shows the Bay Wall viewed from inside the Test Cell, where a supply duct and return vent on the left occupy the leftmost passthrough and are clearly visible. The Dimple Plate is obscured in the photograph by a large Block Wall consisting of blocks composed of either solid concrete or steel-shot-

impregnated concrete. At the top right of the Block Wall, note the concrete blocks that are stacked on the top of a tall support structure—those blocks were positioned there prior to 2011 before installation and operation of the electron linacs. Moreover, those blocks provided photon shielding for the return vent of the right-hand passthrough but no shielding of the supply duct coming through that passthrough above the return vent. A similar set of blocks was positioned in front of the left return vent for linac operations, but they were removed during installation of the Pelletron components (see the lower leftmost part of Figure 6). The large cream-painted objects are approximately 6-ton bending magnets used to turn the Pelletron's ion beam by 90° , as required by the geometry of the Test Cell. Although the presence of concrete-block shielding for the return vents and the Dimple Plate were required during operation of the electron linacs (for bremsstrahlung production), this was not automatically the case for the anticipated fast neutrons produced by the Pelletron, prompting the following analysis.



Figure 6. Inside the Test Cell looking in the direction of the Bay Wall. A ventilation supply duct and return vent structure are in the top left part of the Bay Wall that occupies a left passthrough, whereas a similar structure in the top right part of the Bay Wall is obstructed by a set of concrete blocks. A similar block structure was in front of the left return vent only, but it had to be removed during installation of the Pelletron beamline components. The large concrete Block Wall was erected before operation of the electron linacs to reduce radiation passing through the Dimple Plate. The Pelletron beamline carries ions (right) toward the Bay Wall, turns them left past the Block Wall, then again turns the ions away from the Bay Wall toward the camera.

Figure 7 shows the High Bay looking toward the Bay Wall. Locations on the floor of the High Bay are used on a routine basis for a variety of projects and could be occupied during Pelletron operations. The mezzanine under the Dimple Plate could likewise be occupied, although this is rare because that location is only used for storage. Finally, the raised platform closest to the Dimple Plate could be occupied,

although that only occurs for placement of radiation-monitoring equipment, and access is only by climbing up a ladder and navigating either over or through the platform railing. The passthroughs and the Dimple Plate were considered as potential “weak points” in the Test Cell shielding.



Figure 7. Inside the High Bay looking in the direction of the Bay Wall. Legacy radiation-warning signs can be seen on the position of ducts in the High Bay corresponding to the position of the passthroughs seen in Figure 6. The Dimple Plate is seen in the rectangular recess. Since the removal of Aurora in 1996, the High Bay has been adapted to use for a variety of projects, including construction of a mezzanine (gray flooring surrounded by yellow railing) and, on top of that, a platform just in front of the Dimple Plate. The mezzanine is used only for storage, and the platform is only used to monitor radiation levels on the High Bay side of the Dimple Plate. The better-lit area below the mezzanine is used by personnel on a routine basis for work on unrelated projects.

4.2 Effective Dose Simulations

Geant4 simulations were conducted to evaluate the Test Cell shielding and the potential need for additional shielding near its weak points. The simulations were launched with anywhere from 10^8 to 10^9 neutrons, depending on the statistical-accuracy needs of the particular results; each 10^9 -neutron simulation took approximately 3 days to complete, and many simulations were conducted to study different configurations and compositions of additional shielding. The Test Cell walls were fully modeled, including cable passthroughs (“S” tubes, shown in Figure

5) between the Test Cell and the adjacent Control Room, and the doors, floor, and ceiling. The Dimple Plate and Block Wall as well as the passthroughs were also included in the model. Neutrons were launched with the appropriate energy and angular distributions from the position where the primary (Be) target will be located (shown in Figure 8), as would be produced from 6-MeV protons. Phantoms of 1 cubic foot size were placed at various locations (shown in Figure 8) outside the Test Cell, and the Geant4 simulation recorded the numbers of neutrons entering each phantom and their energies. As described above, values from Table 1004(b).2 of 10CFR20.1004 (NRC 2005) were then used to determine the effective neutron dose rates per Pelletron proton current at the locations of each phantom. Gamma-ray effective dose rates contributed approximately $10^{-8}\%$ of the total effective dose rates, so scoring of gamma rays was subsequently turned off for most simulations because their inclusion significantly increased the run times.

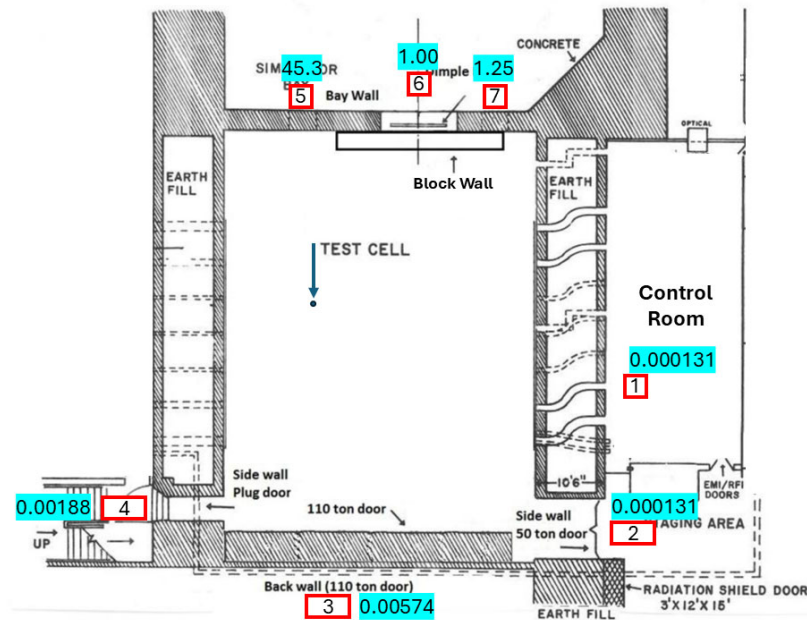


Figure 8. Top-down view of the “bare” Test Cell showing the locations of phantoms 1–7, red boxes, for registering effective dose rates. The effective dose rates in units of $\text{mrem h}^{-1} \mu\text{A}^{-1}$ are the blue-highlighted values next to their respective phantoms. The neutron-emission location (primary Be target) is indicated by the dot within the Test Cell, and the direction of the proton beam is shown by the arrow near the emission point that is aimed toward the 110-ton door.

Figure 8 specifically shows the effective dose rates for a bare configuration for the Test Cell, without any shielding for the left passthrough and excluding the existing concrete blocks in front of the rightmost return vent, but with the Block Wall present. In addition, phantoms not shown in Figure 8 were scored at locations above the rooftop directly over the two HVAC passthroughs in the Bay Wall, no neutrons were recorded to be incident on those phantoms, and, therefore, the neutron

effective dose rates there were estimated to be zero. Several conclusions can immediately be drawn from these results:

- The effective dose rate in the Control Room, at the operator position (Control Panel of the Pelletron, phantom #1), is not expected to exceed about 13 $\mu\text{rem/h}$ even with the Pelletron operated at 100- μA proton current. The area-occupancy factor during Pelletron operations is assumed to be 1 (see NCRP 51 [1977] Section 4.2.3 and Appendix B.6), so that the effective dose rate there is not further reduced. Shielding from the bare Test Cell is sufficient.
- The effective dose rate just outside the 50-ton door (phantom #2) is not expected to exceed approximately 13 $\mu\text{rem/h}$ even with the Pelletron operated at 100- μA proton current. An area-occupancy factor of 1/16 would be most appropriate for this location, but even a value of 1/4 further reduces the effective dose rate to approximately 3 $\mu\text{rem/h}$. Shielding from the bare Test Cell is sufficient.
- The effective dose rate just outside the 110-ton door (phantom #3) is not expected to exceed approximately 0.6 mrem/h even with the Pelletron operating at 100- μA proton current. An area-occupancy factor of 1/16 would be appropriate for this location, further reducing the effective dose rate to approximately 40 $\mu\text{rem/h}$. Shielding from the bare Test Cell is sufficient.
- The effective dose rate just outside the 15-ton door (phantom #4) is not expected to exceed approximately 0.2 mrem/h even with the Pelletron operating at 100- μA proton current. An area-occupancy factor of zero is appropriate for this location because access to that location is controlled by a locked door far above it. Shielding from the bare Test Cell is sufficient.

The expected weak points of the Test Cell did allow higher effective dose rates on the High Bay side of the Bay Wall near the HVAC passthroughs and the Dimple Plate. The largest of these values was for the phantom beyond the left passthrough, which is approximately 4.5 rem/h during Pelletron operations at 100- μA proton current for the bare configuration of the Test Cell. However, the actual locations of those phantoms as viewed from the High Bay (see Figure 7) are of critical importance. Figure 9 depicts the locations of phantoms #5, #6, and #7 as viewed from the High Bay side and the effective dose rates at those locations and the resulting values on the mezzanine and platform seen in Figure 7. For the values on the mezzanine and High Bay floor, emission of radiation from the positions of phantoms #5, #6, and #7 is considered as though they will be point sources; however, they will not be point sources because they are locations where radiation from within the Test Cell will enter the High Bay in a more outward-directed

manner, so the values determined on the Mezzanine and the floor of the High Bay are upper bounds. The impact of effective dose rates along the mezzanine was considered first.

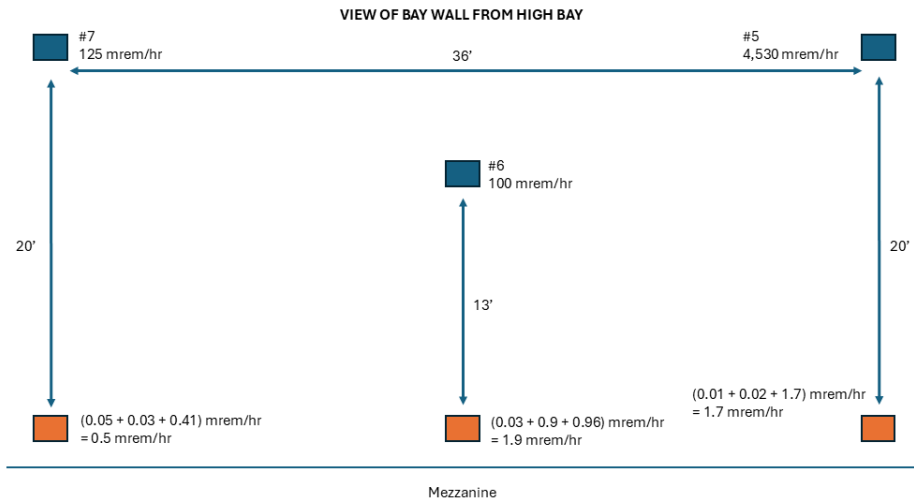


Figure 9. Schematic of the Bay Wall viewed from the High Bay, showing the position of the phantoms outside the left (#5) and right (#7) passthroughs and the Dimple Plate (#6), with effective dose rates from the Geant4 simulation for Pelletron operations at 100 μ A of 6-MeV protons and the bare Test Cell configuration. The positions at chest level on the mezzanine directly below each phantom and their effective dose rates unreduced by occupation factors are also shown. The contributions on the mezzanine from distance-corrected values from each of the #7, #6, and #5 effective dose rates are shown separately.

Although the estimated effective dose rates for a proton current of 100 μ A recorded in the phantoms #5 and #7 (the HVAC passthroughs) are significant on their face (particularly for #5 because there is no additional shielding for the left vent in the bare Test Cell), the occupancy factors for those locations will be zero during Pelletron operations. The only way to reach the right passthrough from the High Bay side is by crane, lift, or a tall ladder brought to that location, and access would require coordination with the RSO and Pelletron operators. The left passthrough location on the High Bay side of the Bay Wall can be reached by a fixed ladder and catwalk designed for use in maintenance of the HVAC system. The closest approach to the left passthrough is approximately 10 ft; the ladder used to reach that location would need to be locked out at its bottom to ensure an occupancy factor of zero during Pelletron operations. However, radiation at the locations of the passthroughs would cause an effective dose rate on the mezzanine; the vertical distance from the passthrough phantoms to chest height of a person on the mezzanine just below was measured to be approximately 20 ft. Correcting for the distance to phantom #7 and assuming an effective area of 2 ft² for dose absorption by a person at chest height gives an effective dose rate of 50 μ rem/h on the mezzanine just below it, and the total effective dose rate at the position of a person

on the mezzanine just below phantom #7 due to both passthroughs and the Dimple Plate is approximately 0.5 mrem/h. Consideration of the occupancy factor of 1/16 for the mezzanine further reduces this effective dose rate to approximately 30 μ rem/h. The greatest contributor at this position, despite the greater distance, comes from the left passthrough (phantom #5), which contributes 82% of the effective dose rate.

Similarly, the total effective dose rate on the mezzanine 13 ft immediately below phantom #6 (platform outside the Dimple Plate) was 1.9 mrem/h, which was further reduced to approximately 0.1 mrem/h when considering the occupancy factor of 1/16. Radiation at phantom #5 contributes 51% of the effective dose on the mezzanine below the platform. Likewise, the effective dose rate on the mezzanine directly below phantom #5 is 1.7 mrem/h (completely dominated by the radiation from that passthrough), which was reduced to approximately 0.1 mrem/h for the mezzanine occupancy factor of 1/16.

The effective dose rate at the position of a person on the platform was directly given by phantom #6 as 100 mrem/h. During Pelletron operations, the occupancy factor for this location must be maintained at zero, and the ladder from mezzanine to the platform must be locked at its bottom to ensure no personnel can climb toward the position of phantom #6. Considering occupancy factors and the Geant4 results, no personnel will be exposed to more than 1 mrem/h effective dose rate on the mezzanine or platform. The floor of the High Bay is used by ARL staff on a routine basis, but it is another 14 ft below the mezzanine; the effective dose rate on the floor of the High Bay, using an occupancy factor of 1, could reach approximately 0.6 mrem/h directly under phantom #5 (the left passthrough). Thus, no further reduction of the effective dose rate is needed for locations in the High Bay. However, further reduction can be achieved by limiting the Pelletron proton current or by augmenting the Test Cell shielding for the left vent and ductwork; the latter is preferable because the proton current required to maximize research output from the Pelletron cannot be determined at this time.

Several materials can be used to shield the left passthrough, and the focus was on doing so from within the Test Cell due to the difficulty in mounting shielding on the High Bay side of the Bay Wall for such high locations. Concrete is common for radiation shielding, and concrete blocks were used inside the Test Cell during the electron–linac era to shield the left return vent although not the supply duct. In principle, a new structure could be erected, and concrete blocks could be used again for the left passthrough (supply duct and return vent), but this would introduce considerable weight above the beamline components and a major damage risk to the Pelletron. NCRP 51 (1977), Appendix F.6 indicates that the half-value thickness for ordinary concrete is approximately 25 cm for thermal neutrons and

approximately 42 cm for fast neutrons (near 4 MeV). In contrast, Subramanian et al. (2018) indicate that the measured half-value thickness for non-borated high-density polyethylene (HDPE) is approximately 17 cm for thermal neutrons and approximately 20 cm for fast neutrons, whereas for 30% borated HDPE, the values are 6 and 15 cm, respectively. Thus, even non-borated HDPE is superior to concrete for efficacy of neutron shielding while also being much lighter (0.94 g/cm^3 for HDPE vs. 2.4 g/cm^3 for concrete). The weight is particularly critical when the configuration of additional shielding for the left passthrough is considered. Scattering of thermal neutrons would allow them to reach a region behind a simple flat plate or wall of shielding material so that material must, as much as possible, surround the entire left passthrough; this means covering the bottom, front, and right side (as seen from inside the Test Cell) of the left passthrough, yet leaving open the left side of new shielding to allow exit for the supply duct and for entrance of air toward the vent. Obviously, this configuration could lead to extremely heavy shielding, depending on the selected material, situated above the Pelletron beamline.

Geant4 simulations agree with the literature (Subramanian et al. 2018) on the superior performance of non-borated HDPE over concrete for a given thickness. Taking a 7.5-inch-thick non-borated HDPE shield constructed in the above configuration, the resulting effective dose rates on the High Bay side of the Bay Wall at the previously defined phantom positions are given in Table 2.

Table 2. Effective neutron dose rates for positions on the High Bay side of the Bay Wall from a Geant4 simulation with non-borated HDPE additional shielding inside the Test Cell for the left passthrough: a current of 100 μ A of 6-MeV protons was assumed.

Location	Effective dose rate (mrem/h) w/o occupancy factor reduction	Effective dose rate (mrem/h) w/o occupancy factor reduction, as defined above
Phantom #5	58	0 ^a
Mezzanine below phantom #5	0.05	0.003
Phantom #6 (platform)	131 ^b	0 ^a
Mezzanine below phantom #6	0.9	0.06
Phantom #7	114 ^c	0 ^a
Mezzanine below phantom #7	0.08	0.005
High Bay floor	0.006	0.006

^a Requires lockout of ladder at its bottom.

^b Approximately 26% difference between this and the 100 obtained for the bare Test Cell simulation, similar to the 20% from the simulation benchmarking.

^c Approximately 10% difference between this and the 125 obtained for the bare Test Cell simulation, consistent with the 20% from the simulation benchmarking.

The modeled 7.5-inch-thick non-borated HDPE left-passthrough shield reduces the effective dose at phantom #5 by a factor of 0.013 from that occurring for the bare Test Cell, significantly outperforming 7.5-inch-thick concrete, which provides a reduction by a factor of just 0.054. At the same time, the weight of the shield would be reduced by 60% by using non-borated HDPE instead of concrete.

Another simulation was conducted in which possible left-passthrough shielding of 7.5-inch non-borated HDPE was replaced by a similar shape with 1-inch-thick 5%-borated HDPE. This did not change the effective dose rates to positions #6 or #7 outside the 20% uncertainty expected for the Geant4 simulations. At position #5, the effective dose rate without consideration of occupancy was approximately 1.5 rem/h for a Pelletron proton current of 100 μ A, compared with 4.5 rem/h for the bare Test Cell and 58 mrem/h using 7.5-inch non-borated HDPE. Again, zero occupancy directly at position #5 must be maintained. The effective dose rate without consideration of occupancy on the mezzanine just below location #5 is reduced to 5.4 mrem/h, which is further reduced to approximately 0.3 mrem/h when including an appropriate occupancy factor of 1/16. The gamma-ray effective dose rate, without consideration of occupancy, at location #5 was less than 1 nrem/h when the 1-inch-thick 5%-borated HDPE shielding is included for the left passthrough and for a 100- μ A current of 6-MeV protons; the gamma-ray effective dose rate was determined to be insignificant compared with the rate due to neutrons

at this location, despite the expected production of gamma rays from the boron and hydrogen.

Geant4 simulations, benchmarked as described above, indicate that no additional shielding is necessary for the left passthrough. However, reasonable additional shielding of the left passthrough can be achieved using 5%-borated HDPE in a configuration that encloses the underside, right side, and front of the left passthrough as viewed from inside the Test Cell. This minimizes the weight of shielding material that must be supported or suspended above Pelletron beamline components. Table 3 summarizes the conclusions from the simulations.

Table 3. Recommendations for shielding during Pelletron operations up to 100- μ A current of up to 6-MeV protons for production of neutrons from a Be target.

Left passthrough	Existing shielding of the Test Cell is sufficient. A configuration of 1-inch-thick 5%-borated HDPE could reasonably be added. ^a
Platform outside Dimple Plate on High Bay side of the Bay Wall	Ladder locked out at its bottom to maintain zero occupancy of the platform during operations.
Ladder to maintenance area 10 ft from left passthrough on High Bay side of the Bay Wall	Ladder locked out at its bottom to maintain zero occupancy of the maintenance level during operations.
Mezzanine	Monitor to ensure anticipated occupancy level. Control access if necessary.
Control Room	Existing shielding of the Test Cell is sufficient.
Exterior of Test Cell other than the Bay Wall and Control Room	Existing shielding of the Test Cell is sufficient.

^a This proposed additional shielding was constructed and installed.

5. Summary and Conclusion

Analyses of the radiation shielding for the APEX Facility Test Cell and the potential activation of primary structural and beamline components were performed. The analysis indicated that no supplemental shielding was necessary to protect staff outside the Test Cell, but that a specifically proposed supplemental shield could further reduce the effective radiation dose on the High Bay side of the Bay Wall. Use of this supplemental shield was adopted.

The analysis indicated no expectations of significant activations of structural or beamline components by fast neutrons from the Pelletron. The amounts of activation expected under the most optimistic operational parameters were far below the Army Screening Levels for Clearance.

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List of Symbols, Abbreviations, and Acronyms

ALC	Adelphi Laboratory Center
APEX	Adelphi Pelletron Experimental
ARA	Army Radiation Authorization
ARL	Army Research Laboratory
b	Barn
CERN	European Organization for Nuclear Research
CL	Clearance Level
DEVCOM	U.S. Army Combat Capabilities Development Command
DTRA	Defense Threat Reduction Agency
GIGO	Garbage In, Garbage Out
HDPE	High-Density Polyethylene
HVAC	Heating, Ventilation, and Air Conditioning
IAEA	International Atomic Energy Agency
mb	Millibarns
MCNP	Monte Carlo N-Particle Transport
NCRP	National Council on Radiation Protection
NEC	National Electrostatics Corporation
RSO	Radiation Safety Officer
SLC	Screening Levels for Clearance
SME	Subject Matter Expert
SNICS	Source of Negative Ions by Cesium Sputtering
TENDL	TALYS-Based Evaluated Nuclear Data Library
TORVIS	Toroidal Volume Ion Source
UKAL	University of Kentucky Accelerator Laboratory

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