UNIVERSITY OF MASSACHUSETTS LOWELL
CAPSTONE PROJECT DRAFT
DEPARTMENT OF PHYSICS & APPLIED PHYSICS

Shielding Verification of Simulated Facility Dose Profiles for UMLRR 5 MW Upgrade

Fluence to Dose Shielding Verification Study

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Spring 2026

Abstract

The University of Massachusetts Lowell Research Reactor (UMLRR) is planning to undergo a power upgrade from 1 MW to 5 MW. This project estimates facility dose profiles and future shielding requirements for the upgraded configuration by utilizing Monte Carlo N-Particle (MCNP) fluence models for the 1 MW configuration and developing a custom Python-based physics engine. The methodology employs linear fluence scaling, material-specific attenuation modeling with Berger buildup factors for photons, tabulated dose conversion factors for neutrons, and numerical root-finding algorithms to determine necessary shielding improvements. A combined neutron–photon dose framework is used to solve for the concrete thickness required to meet a regulatory target of 0.002 rem hr^{-1}. At 5 MW, the required ordinary concrete thicknesses are 196.43 cm (6.44 ft) for the beam port and 195.03 cm (6.40 ft) for the thermal column. Reference calculations at 1 MW yield 170.31 cm and 166.37 cm, respectively, confirming a 26–29 cm increase due to the upgrade. These results provide a manual, transparent verification of future MCNP-based dosimetry studies, maintaining regulatory compliance of dose limits and operational safety for the upgraded facility.

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1 Introduction

1.1 Background

The University of Massachusetts Lowell Research Reactor (UMLRR) is a 1 MW open-pool reactor located on the North Campus of the University of Massachusetts Lowell [1]. Construction was completed in 1974, and the reactor achieved first criticality in 1975. Since that time, the UMLRR has served as a platform for education and research in nuclear engineering, physics, and radiological protection sciences. The facility now hosts a variety of neutron and gamma irradiation capabilities, including reactor-based beam facilities and Cobalt-60 irradiation sources [1].

In recent years, planning has begun for a power upgrade from 1 MW to 5 MW. Such an upgrade requires new fuel assemblies, upgraded coolant systems, and, most critically for this study, revised shielding configurations for the reactor-based irradiation facilities. The increased neutron and photon fluence rates at 5 MW will produce proportionally higher dose rates at facility boundaries, and existing shielding must be evaluated to ensure continued compliance with regulatory dose limits.

1.2 Problem Statement

The power upgrade will principally affect the dose output of two irradiation facilities at the UMLRR: the beam port and the thermal column.

The beamport is a 6-inch diameter channel penetrating the pool wall and directed toward the reactor core [1]. It is equipped with movable shielding elements — a lead shield and a ferric-concrete plug—and the surrounding irradiation area is enclosed by concrete and borated polyethylene to attenuate the beam and scattered radiation during operations. The beam port produces a mixed neutron-photon field spanning a broad range of energies, with a notably hard neutron spectrum and a photon spectrum exhibiting a prominent iron capture gamma peak near 7.65 MeV, generated by neutron capture in the steel structural components of the reactor [2]. The current beam port shielding stack, in the beam direction, consists of approximately two feet of borated polyethylene, followed by two feet of concrete, followed by two inchs of borated polyethylene [1].

Safety regulations for the UMLRR mandate that either the concrete plug or the lead shield remain in place during reactor operations [1]. This analysis focuses on the configuration in which the lead shield is engaged and the concrete plug is fully withdrawn. This setup is prioritized because it represents a standard operating state and yields a higher fluence profile than the inverse configuration (plug in, shield out). Scenarios in which both shielding components are in place are excluded, as they produce lower fluence and dose levels. By analyzing the "shield in, plug out" configuration, this study adopts a conservative approach, bounding the expected dose profiles under normal operating conditions. The layout of the beamport facility can be seen in Figure 1.

The thermal column is a facility designed to produce a collimated beam composed predominantly of lower-energy, thermal neutrons. It employs a combination of lead and graphite to moderate higher-energy neutrons emerging from the core and to shape the output beam [1]. Although the thermal column has a higher total neutron flux than the beam port [3], the softer energy spectrum results in a substantially lower neutron dose rate. The photon spectrum at the thermal column exit is similar in shape to that of the beam port, though

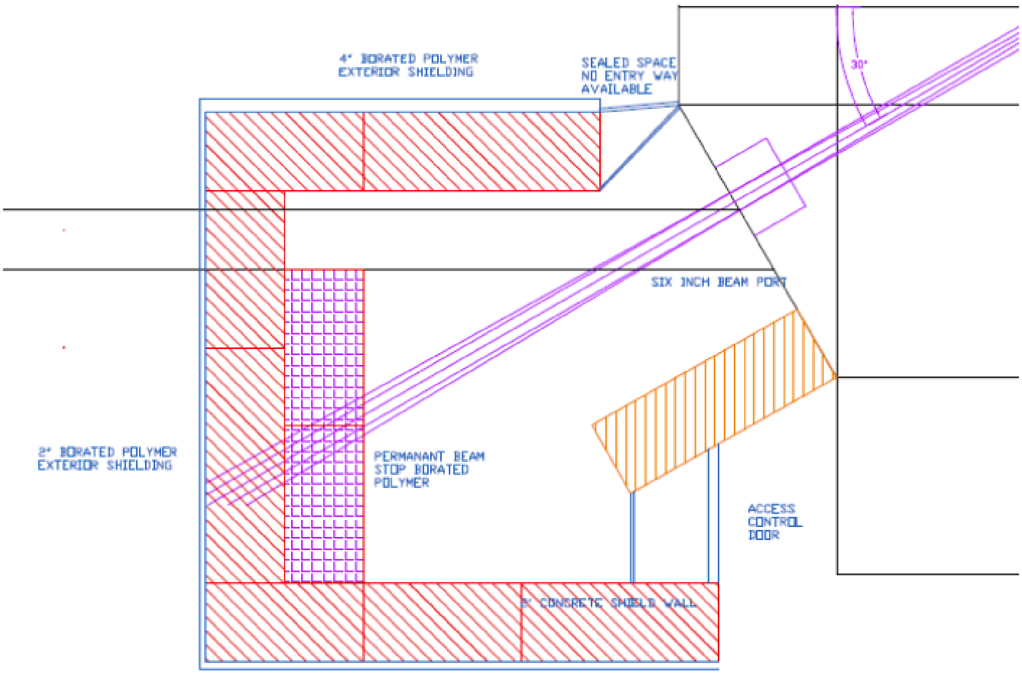

Figure 1. Plan view of the beam port facility showing the six-inch beam port channel, borated polyethylene shielding layers, concrete shield wall, and access control door [1].

the relative contribution of photons to the total dose is larger due to the reduced neutron dose. The thermal column data used in this study correspond to the face of the door port; the internal cavity geometry does not include a collimator [3]. The thermal column is currently shielded by a movable array of barium carbonate concrete bricks, approximately two feet in total thickness [1]. A diagram of the inner cavity of the thermal column under the conditions of this study can be found in Figure 2.

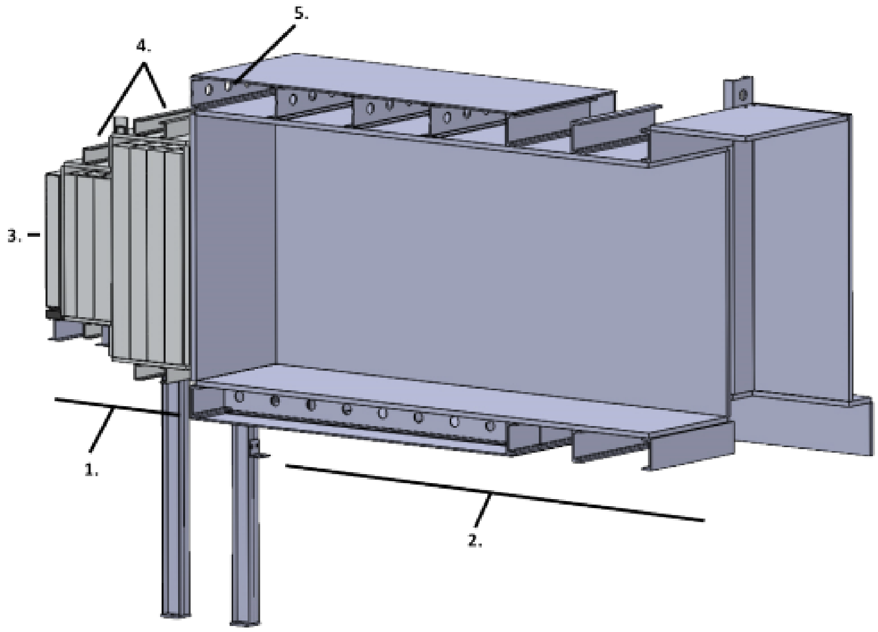

Figure 2. Isometric view of the thermal column assembly showing the thermal column extension, thermal column case, lead gamma shield, aluminum-encased graphite, and coolant flow path [1].

1.3 Shielding Model Assumptions

The actual shielding configurations at both facilities employ multi-material stacks or specific composites. The beam port uses borated polyethylene layers with a concrete core, while the thermal column uses barium carbonate concrete bricks. However, published buildup factor data, attenuation coefficients, and neutron dose conversion factors are most readily available for ordinary concrete [4, 5]. The Berger buildup parameters used in the photon calculation and the Wyckoff–Chilton dose conversion factor tables used in the neutron calculation are both derived specifically for ordinary concrete slabs.

For this reason, the analysis models both facilities as if shielded entirely by ordinary concrete with density $\rho = 2.30$ g cm^{-3}. This simplification has different implications for each facility. At the beam port, the calculation neglects the neutron-moderating effectiveness of the borated polyethylene layers, which are specifically designed to thermalize and capture neutrons via the $^{10}\mathrm{B}(n, \alpha)$ reaction. The concrete-only model therefore overestimates the neutron shielding thickness required, since the borated polyethylene is more effective per unit thickness for neutron attenuation than ordinary concrete. For photon shielding, the concrete-only assumption is more representative, since concrete is the primary photon attenuator in the beam port stack. At the thermal column, the use of ordinary concrete rather than barium carbonate concrete underestimates the actual shielding performance, because barium concrete has a higher effective atomic number and density, providing superior photon attenuation. In both cases, the concrete-only model yields a conservative result for the required shielding thickness.

1.4 Objectives

The objectives of this study are to develop a computational tool capable of calculating dose profiles from MCNP-generated fluence maps for both neutron and photon fields, incorporating material-specific attenuation physics and buildup corrections based on published data from Shultis and Faw [4] and Wyckoff and Chilton [5], to quantify the equivalent ordinary concrete shielding thickness required to reduce combined neutron and photon dose rates below the regulatory target of $H_{\text{max}} = 0.002$ rem hr^{-1} (2 mrem hr^{-1}) for each facility at any power level (specifically 5 MW), and to compare individual and combined shielding requirements between the two facilities and assess the implications of the power upgrade for existing shielding infrastructure.

2 Theoretical Framework

The dosimetry and shielding methodology used in this study follows the framework presented in Shultis and Faw [4], supplemented by neutron dose data from Wyckoff and Chilton [5]. The approach is consistent with the independent calculations performed for this project [6].

2.1 Power Scaling

For a reactor operating at steady state, the neutron and photon fluence rates at any point outside the core are, to first order, linearly proportional to the thermal power. Under this approximation, the fluence at 5 MW is estimated as

$$\Phi_{\text{5MW}} \approx 5 \times \Phi_{\text{1MW}} \,. \tag{1}$$

This linear scaling law assumes that the spatial and energy distributions of the fluence are independent of power level, i.e., that the core geometry, fuel loading pattern, and neutron spectrum shape do not change significantly between 1 MW and 5 MW [1]. In practice, modest spectral hardening or softening may occur due to temperature-dependent feedback effects (e.g., Doppler broadening, moderator density changes), but these second order corrections are neglected in this analysis. The linear approximation, although not without its issues, is standard practice for preliminary shielding assessments of research reactor upgrades and provides a conservative upper bound when the spectrum does not harden or soften appreciably with increasing power.

2.2 Photon Dosimetry

2.2.1 Unshielded Exposure Rate

The radiological quantity used for photon dose assessment is exposure, measured in roentgens (R). Following the formulation in Shultis and Faw [4] and [6] , for the i-th photon energy bin, the unshielded exposure rate at the location of interest is

$$\dot{X}(E_i) = \phi_\gamma(E_i)\, \Gamma(E_i) \,, \tag{2}$$

where $\phi_\gamma(E_i)$ is the photon fluence rate (photons cm^{-2} s^{-1}) for energy E_i, and $\Gamma(E_i)$ is the unshielded exposure rate per unit fluence rate for that energy. The quantity $\Gamma(E_i)$ is defined as

$$\Gamma(E_i) = E_i \left(\frac{\mu_{\rm en}}{\rho}\right)_{{\rm air},\,i} \frac{q}{W} \times \{\text{unit conversions}\}\ , \tag{3}$$

where E_i is the photon energy in MeV, $(\mu_{\rm en}/\rho)_{{\rm air},\,i}$ is the mass energy-absorption coefficient for air ($\text{cm}^2\ \text{g}^{-1}$) at energy E_i, $q = 1.602 \times 10^{-19}$ C is the electronic charge, and $W = 33.97 \times 10^{-6}$ MeV is the mean energy per ion pair in air [6]. The unit conversion factors are

$$\left(\frac{10^3\ \text{g}}{1\ \text{kg}}\right)\left(\frac{3600\ \text{s}}{1\ \text{hr}}\right)\left(\frac{1\ \text{R}}{2.58 \times 10^{-4}\ \text{C kg}^{-1}}\right)\ , \tag{4}$$

which yield $\Gamma(E_i)$ in units of R cm^2 s γ^{-1} hr^{-1}. The combined numerical value of $(q/W) \times \{\text{conversions}\}$ evaluates to approximately 6.684×10^{-5} R s g MeV^{-1} hr^{-1}.

It is assumed throughout this analysis that the photon exposure rate in R hr^{-1} is numerically equivalent to the deep dose equivalent rate in rem hr^{-1} (i.e., 1 R $\approx$ 1 rem), which is a standard approximation for photons in the energy range relevant to reactor shielding [4, 6].

2.2.2 Shielded Exposure Rate and the Berger Buildup Factor

When a concrete shield of thickness x is introduced, the transmitted exposure rate for the i-th photon energy is attenuated but enhanced by photon buildup due, for example, to Compton scattering within the shield. The shielded exposure rate is

$$\dot{X}(E_i, x) = \dot{X}(E_i) \cdot g(E_i, x)\,, \tag{5}$$

where $g(E_i, x)$ is the dimensionless transmission function [4]. This function accounts for both the primary (uncollided) photons that penetrate the shield and the secondary (scattered) photons produced by interactions of the incident beam within the shielding material.

The transmission function is modeled using the Berger form of the buildup factor [4]:

$$g(E_i, x) = e^{-\mu(E_i)\,x}\left[1 + a(E_i)\,\mu(E_i)\,x\ \cdot e^{b(E_i)\,\mu(E_i)\,x}\right]\ , \tag{6}$$

where $\mu(E_i)$ is the linear attenuation coefficient for concrete (cm^{-1}) at energy E_i, obtained by multiplying the mass attenuation coefficient (μ/ρ, total minus coherent) from Shultis and Faw Table C.7 [4] by the concrete density $\rho = 2.30$ g cm^{-3}. The parameters $a(E_i)$ and $b(E_i)$ are energy-dependent Berger buildup coefficients for air kerma in concrete, also tabulated in Shultis and Faw [4]. The Berger formulation captures the initial rise of the buildup factor at small shield thicknesses and its eventual saturation, providing a more accurate representation of photon transmission through thick shields than simple exponential attenuation alone. For typical gamma energies in the 0.5–2.0 MeV range within low to medium Z materials such as concrete, the buildup corrected dose rate exceeds a pure exponential extrapolation by roughly an order of magnitude at intermediate thicknesses because the simple exponential model fails to account for the significant accumulation of, for example, Compton-scattered secondary photons.

The total shielded photon exposure rate at thickness x is the sum over all energy photon bins:

$$\dot{X}(x) = \sum_{i=1}^{n_\gamma} \dot{X}(E_i, x)\,. \tag{7}$$

2.3 Neutron Dosimetry

2.3.1 Dose Conversion Factor Approach

The conventional approach for neutron dosimetry through concrete shields is to convert the neutron fluence rate at a location of interest into a dose equivalent quantity using tabulated dose conversion factors that inherently account for neutron transport, scattering, and secondary photon production within the shield [4, 5]. For the i-th neutron energy group, the deep dose equivalent rate behind a concrete shield of thickness x is

$$\dot{H}_n(E_i, x) = \phi_n(E_i)\, f_n(E_i, x)\,, \tag{8}$$

where $\phi_n(E_i)$ is the neutron fluence rate (neutrons cm^{-2} s^{-1}) for the i-th energy group, and $f_n(E_i, x)$ is the deep dose equivalent per unit neutron fluence rate for that energy group, accounting for a concrete shield thickness x. The function $f_n(E_i, x)$ is tabulated in Table 8.9 of Shultis and Faw [4] and is referred to as the dose conversion factor (DCF). The neutron DCF values were derived from detailed transport calculations through concrete slabs and incorporate the effects of neutron scattering, moderation, and secondary photon production [4, 5]. The original experimental and computational basis for these DCF tables was established by Wyckoff and Chilton [5], who computed dose rates from practical neutron energy distributions incident on concrete shielding slabs for a range of thicknesses.

The total neutron deep dose equivalent rate at thickness x is

$$\dot{H}_n(x) = \sum_{i=1}^{n_n} \dot{H}_n(E_i, x)\,, \tag{9}$$

where $n_n = 23$ energy groups are used, spanning from thermal energies (< 0.4 eV) to 20 MeV, following the group structure defined in Shultis and Faw [4]. The tabulated DCF data are given as a function of mass thickness (g cm^{-2}), which is converted to linear thickness (cm) by dividing by the concrete density ρ.

2.3.2 Typos in Published DCF Data

During the course of this work, four typographical errors were identified in the Shultis and Faw Table 8.9 DCF values [4]. The errors were discovered by comparison with the original Wyckoff and Chilton data [5]. One of these affects the dose calculations in the energy range relevant to this study: for the 15–25 MeV energy group at a concrete mass thickness of 500 g cm^{-2}, the listed value of 1.4×10^{-16} Sv cm^2 should be 1.4×10^{-15} Sv cm^2. The remaining three errors pertain to energies above 20 MeV (the 25–40, 40–60, and 60–80 MeV groups at mass thicknesses of 450–700 g cm^{-2}) and do not affect the present analysis because the MCNP-generated neutron spectra contain negligible fluence above 20 MeV. The corrected values from Wyckoff and Chilton [5] were used in all calculations.

2.4 Combined Neutron–Photon Dosimetry

Under the assumption of numerical equivalence between photon exposure rate (R hr^{-1}) and deep dose equivalent rate (rem hr^{-1}) [4, 6], the total deep dose equivalent rate at the location of interest behind a concrete shield of thickness x is

$$\dot{H}_d(x) = \dot{H}_n(x) + \dot{X}(x)\,, \tag{10}$$

where $\dot{H}_n(x)$ is the neutron contribution (rem hr^{-1}) and $\dot{X}(x)$ is the photon contribution (R hr^{-1} $\approx$ rem hr^{-1}). This combined framework follows a reasonable methodology [6] for the UMLRR shielding analysis. Given a regulatory limiting value H_{max} on the far side of the shield, the required shield thickness x^* is determined by solving

$$\dot{H}_d(x^*) = H_{\text{max}} \,. \tag{11}$$

For this study, $H_{\text{max}} = 0.002$ rem hr^{-1} (2 mrem hr^{-1}).

3 Computational Methodology

3.1 Software Architecture

The computational tool was developed in Python and utilizes a modular architecture organized around shared physics engines and facility-specific configurations. The principal libraries employed are `NumPy` for vectorized numerical computation of dose rates across energy bins, `pandas` for loading and managing CSV-formatted fluence and coefficient data, and `SciPy` for interpolation of tabulated coefficients and for numerical root-finding using Brents Method [7].

The code is structured so that the photon and neutron dose calculation modules are shared across all facilities, while facility-specific parameters—fluence data file paths, neutron fluence arrays, angle of incidence, and power scaling factor—are defined in an easily modifiable configuration dictionary. This design allows new facilities or configurations to be added without modifying the physics engine, and permits parametric studies (e.g., sweeping power from 1 to 5 MW) with a single function call.

3.2 Data Acquisition and Pre-Processing

3.2.1 Photon Fluence Data

Photon fluence spectra for both facilities were obtained from MCNP simulations performed by Konomi [2, 3]. The beam port photon data comprise 281 energy–fluence rate pairs spanning 0.01 to 20 MeV, provided at the 1 MW operating power. The thermal column photon data span a comparable energy range. In both cases, photon energies below 0.01 MeV were filtered out during loading under the assumption that their contributions to dose and shielding requirements are negligible at the concrete thicknesses of interest [6].

The photon fluence data were stored as CSV files with two columns (energy in MeV, fluence rate in γ cm^{-2} s^{-1}). At runtime, the fluence rates are multiplied by the power scaling factor p (Eq. 1), allowing dose calculations at any power level.

3.2.2 Neutron Fluence Data

Neutron fluence data for both facilities were also provided by Konomi from MCNP simulations [2, 3]. The original neutron fluence data provided by Konomi was in 640 energy bins using the SAND-II structure (1×10^{-10} to 20 MeV)[8], and these data then were re-binned into 23 energy groups to coincide with the bin structure in Wyckoff and Chilton (Table 8.9 of [4]), which itself derives from the Wyckoff and Chilton data [5].

The beam port neutron spectrum is characterized by a hard spectrum with significant contributions from fast-neutron energy groups, reflecting the direct line of sight to the reactor core through the lead shield. The total beam port neutron fluence is 7.93×10^6 n cm^{-2} s^{-1} [2]. The thermal column neutron spectrum is dominated by the thermal group ($E < 0.4$ eV), with a total fluence of 1.37×10^7 n cm^{-2} s^{-1} [3], reflecting the moderating effect of the graphite column. Despite the higher total neutron fluence at the thermal column, the preponderance of low-energy neutrons results in a much lower unshielded dose rate than the beam port.

As with the photon data, neutron fluence arrays are scaled by the power factor p at runtime.

3.2.3 Published Data

Four sets of published tabulated coefficients are loaded at initialization of the program and shared across both facility calculations for photon and neutron dose calculations.

The mass energy-absorption coefficients for air, $(\mu_{\text{en}}/\rho)_{\text{air}}$, are taken from Appendix C (Table C.7) of Shultis and Faw [4]. These give the fraction of photon energy deposited per unit mass density thickness of air as a function of photon energy and are used in the computation of the exposure rate conversion factor $\Gamma(E_i)$ (Eq. 3).

The mass attenuation coefficients for concrete, $(\mu/\rho)_{\text{concrete}}$, are also from Shultis and Faw Table C.7 [4]. Multiplying by the assumed concrete density $\rho = 2.30$ g cm^{-3} yields the linear attenuation coefficient $\mu(E_i)$ (cm^{-1}) used in the Berger transmission function (Eq. 6). The "total-minus-coherent" convention used by Shultis and Faw excludes coherent (also known as Rayleigh) scattering, which does not contribute to energy deposition or effective attenuation over a wide range of photon energies.

The Berger buildup parameters for air kerma in concrete, $a(E_i)$ and $b(E_i)$, are energy-dependent parameters tabulated in Shultis and Faw [4] Appendix E that define the Berger form of the buildup used in Eq. 6. The parameter a governs the magnitude of the buildup contribution and decreases with increasing energy, while b controls the growth rate of the buildup with thickness and transitions from negative values at low energies (where photoelectric absorption dominates) to small positive values at higher energies where Compton scattering dominates.

Finally, the neutron dose conversion factors, $f_n(E_i, x)$, are tabulated in Table 8.9 of Shultis and Faw [4], with original data from Wyckoff and Chilton [5]. These DCF values give the deep dose equivalent rate per unit neutron fluence rate as a function of both energy group and concrete mass density thickness (g cm^{-2}).

3.3 Interpolation Techniques

The tabulated coefficient data are provided at discrete energy and thickness values, while the dose calculations require evaluation at arbitrary energies and thicknesses. As such, different interpolation strategies are employed for the different physical quantities used.

The mass energy-absorption coefficient $(\mu_{\text{en}}/\rho)_{\text{air}}$ and the linear attenuation coefficient μ are interpolated as functions of photon energy using natural cubic splines (`scipy.interpolate.CubicSpline`), ensuring C^2 continuity across the energy range. Cubic splines are preferred over linear interpolation because both coefficients exhibit strong curvature at low photon energies (below ∼0.1 MeV), where photoelectric absorption produces a steep energy dependence; linear interpolation would underestimate the coefficient values between tabulated points in this region. The Berger buildup parameters $a(E_i)$ and $b(E_i)$ vary more slowly with energy and are interpolated linearly. These interpolation techniques were consistent with the independent calculations performed for this project [6].

The neutron DCF values $f_n(E_i, x)$ from Shultis and Faw Table 8.9 [4] span many orders of magnitude and decrease approximately exponentially with thickness. To avoid negative interpolated values, interpolation is performed in the logarithmic domain: for each energy group, $\ln[f_n(E_i, x)]$ is interpolated linearly as a function of thickness (cm), and the result was exponentiated:

$$f_n(E_i, x) = \exp[\text{interp}(\ln f_n(E_i, x_j),\ x_j,\ x)] \ , \tag{12}$$

where x_j are the tabulated thickness values converted from g cm^{-2} to cm by dividing by $\rho = 2.30$ g cm^{-3}.

3.4 Dose Rate Computation

For a given concrete thickness x, the photon exposure rate $\dot{X}(x)$ was computed by summing over all n_γ energy bins in the fluence spectrum. For each bin, the interpolated coefficients $\mu(E_i)$, $(\mu_{\text{en}}/\rho)_{\text{air},i}$, $a(E_i)$, and $b(E_i)$ were evaluated, the unshielded exposure rate $\dot{X}(E_i)$ is computed from Eqs. 2 and 3, the transmission function $g(E_i, x)$ was evaluated from Eq. 6, and the shielded contribution was accumulated. Negative interpolated coefficient values (which can occur at the extrapolation boundaries of the cubic spline) are clipped to zero to prevent unphysical results. This vectorized computation was performed using `NumPy` array operations for efficiency, allowing the entire energy spectrum to be processed in a single function call.

The neutron dose rate $\dot{H}_n(x)$ was computed by accounting for all 23 energy groups. For each group, the DCF at thickness x was evaluated using the log-linear interpolation model (Eq. 12), multiplied by the power-scaled neutron fluence rate for that group, and accumulated. Error handling was implemented to skip energy groups for which the DCF evaluation fails (e.g., due to extrapolation beyond the tabulated thickness range), ensuring accuracy and robustness for thick-shield calculations. The combined dose rate $\dot{H}_d(x)$ is the sum of the photon and neutron contributions (Eq. 10), and serves as the objective function input to the root-finding algorithm.

3.5 Root-Finding Algorithm

The required shielding thickness x^* satisfying Eq. 11 is found by solving the objective function

$$f(x) = \dot{H}_d(x) - H_{\text{max}} = 0 \tag{13}$$

using Brent's method, implemented as `scipy.optimize.brentq` [7]. Brent's method is a hybrid root-finding algorithm that combines the guaranteed convergence of bisection with the superlinear convergence speed of the secant method and inverse quadratic interpolation. Given a bracketing interval $[a, b]$ where $f(a)$ and $f(b)$ have opposite signs, the algorithm is guaranteed to find a root to machine precision [7].

The search interval is $[0, x_{\max}]$ with $x_{\max} = 500$ cm. Before calling the solver, the code verifies that $\dot{H}_d(0) > H_{\max}$ (shielding is needed) and that $\dot{H}_d(x_{\max}) < H_{\max}$ (the target is achievable within the search range). If the first condition is not met, the required thickness is zero; if the second is not met, a warning is issued and $x_{\max}$ is returned as a lower bound.

The same root-finding approach is applied independently to the photon-only dose function $\dot{X}(x)$ and the neutron-only dose function $\dot{H}_n(x)$ to determine the individual shielding requirements. These serve as consistency checks: the combined requirement must always exceed the larger of the two individual requirements, since at the thickness that reduces one component to $H_{\max}$, the other component still contributes a nonzero residual dose.

3.6 Geometric Corrections

The beam port channel intersects the concrete shield wall at a nominal angle of $\alpha = 60°$ measured from the wall surface [1]. Because the beam is incident on the wall obliquely, the perpendicular wall thickness needed to provide a given path length of shielding material is less than the path length itself. If the root-finding algorithm yields a required path length t_{path} through the shield, the corresponding perpendicular wall thickness is

$$t_{\text{wall}} = t_{\text{path}} \cdot \sin(\alpha)\,, \tag{14}$$

where α is the angle between the beam axis and the wall surface. For the beam port, $\alpha = 60°$ and $\sin(60°) \approx 0.866$. The thermal column beam is normal to the shielding wall ($\alpha = 90°$) [1], so no geometric correction is required.

4 Results

This section presents the computed dose rates and shielding requirements for both facilities. The 1 MW results serve as a baseline for comparison and validation, while the 5 MW results represent the primary deliverable of this study. All results assume ordinary concrete ($\rho = 2.3$ g cm^{-3}) and a regulatory target dose rate of $H_{\max} = 0.002$ rem hr^{-1}.

4.1 Unshielded Dose Rates

The unshielded (zero-thickness) dose rates at the exit face of each facility were computed by summing the energy-bin contributions from the MCNP fluence spectra [2, 3]. Table 1 summarizes the results at both power levels, and the dependence of dose rate on power level is plotted in Fig. 3 and 4.

At the beam port, the unshielded field is overwhelmingly neutron-dominated, with neutrons accounting for approximately 97.5% of the combined dose at $x = 0$. This is primarily due to the lead shielding in place in the beam port in the considered configuration, as well as the hard neutron spectrum emerging from the beam port [2], which includes significant contributions from fast-neutron energy groups with high dose conversion factors [4, 5]. At the thermal column, photons contribute a larger share (∼22.5%) of the unshielded combined dose, despite the thermal column having a higher total neutron fluence [3]. This occurs because the thermal column neutron spectrum is much softer, dominated by the thermal group, which carries a lower dose conversion factor per unit fluence than the

Table 1. Unshielded dose rates at $x = 0$ cm for both facilities.

Facility	**Component**	**1 MW (rem hr^{-1})**	**5 MW (rem hr^{-1})**
Beam Port	Photon	1.50×10^1	7.50×10^1
	Neutron	5.93×10^2	2.96×10^3
	Combined	6.08×10^2	3.04×10^3
Thermal Column	Photon	1.99×10^1	9.95×10^1
	Neutron	6.84×10^1	3.42×10^2
	Combined	8.83×10^1	4.42×10^2

fast-neutron groups that dominate the beam port spectrum [4]. As expected, all 5 MW values follow directly from the linear scaling in Eq. 1.

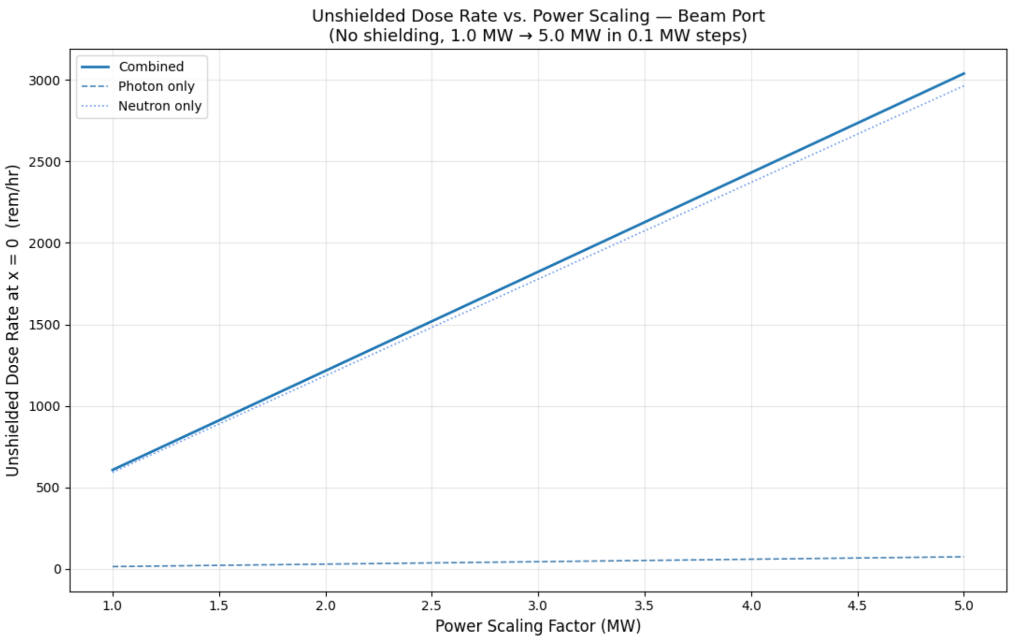

Figure 3. Unshielded dose rate at $x = 0$ cm as a function of reactor power for the Beam Port, illustrating linear scaling from 1 MW to 5 MW.

4.2 Shielding Requirements at 5 MW

Table 2 presents the individual (photon-only, neutron-only) and combined shielding requirements at 5 MW. Plots of dose rate vs. concrete thickness are provided in Figure 5 and Figure 6.

The beam port requires 196.43 cm (6.44 ft) of ordinary concrete to reduce the combined 5 MW dose rate to 0.002 rem hr^{-1}. After the 60° geometric correction (Eq. 14), the effective perpendicular thickness is $t_{\text{eff}} = 196.43 \times \sin(60°) = 170.12$ cm (5.58 ft). The thermal column requires 195.03 cm (6.40 ft) with the beam perpendicular to the shielding wall, so no geometric correction applies.

At the beam port thickness of 196.43 cm, the photon contribution is 1.39×10^{-3} R hr^{-1} (69.7% of the regulatory limit) and the neutron contribution is 6.07×10^{-4} rem hr^{-1} (30.3%). At the thermal column thickness of 195.03 cm, the photon contribution is 1.76×10^{-3} R hr^{-1}

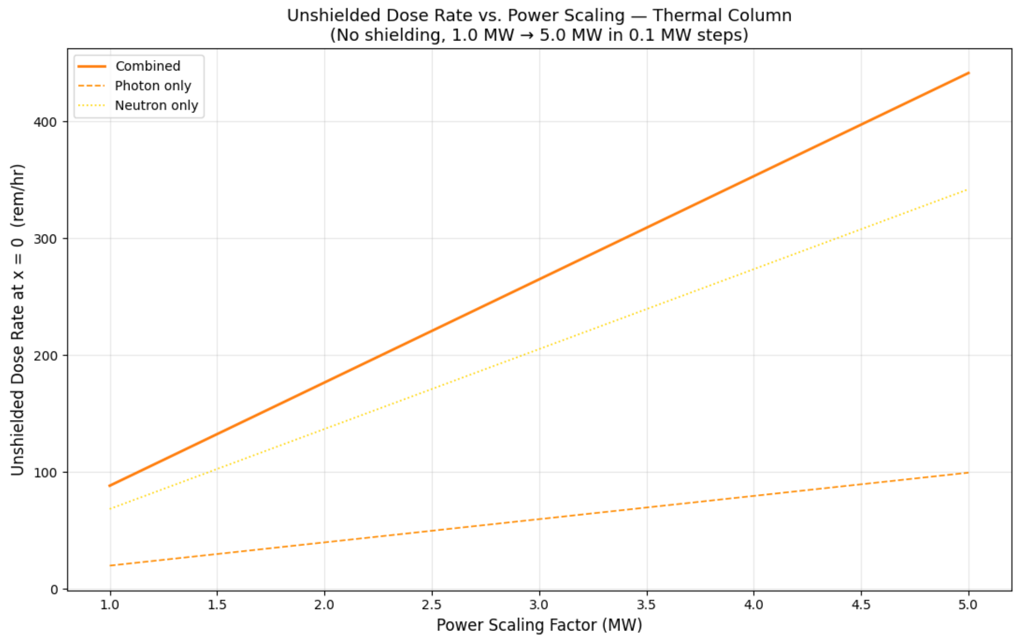

Figure 4. Unshielded dose rate at $x = 0$ cm as a function of reactor power for the Thermal Column

Table 2. Shielding requirements at 5 MW ($H_{\text{max}} = 0.002$ rem hr^{-1}, ordinary concrete).

Facility	**Photon only** (cm)	**Neutron only** (cm)	**Combined** (cm)	**Angle correction**
Beam Port	189.98	179.83	196.43	$t_{\text{eff}} = 170.12$ cm at 60°
Thermal Column	192.67	161.39	195.03	N/A (perpendicular)

(87.8%) and the neutron contribution is 2.44×10^{-4} rem hr^{-1} (12.2%). In both cases, the residual dose at the shielding boundary is dominated by photons, reflecting the fact that neutrons attenuate more efficiently through concrete than high-energy photons [4].

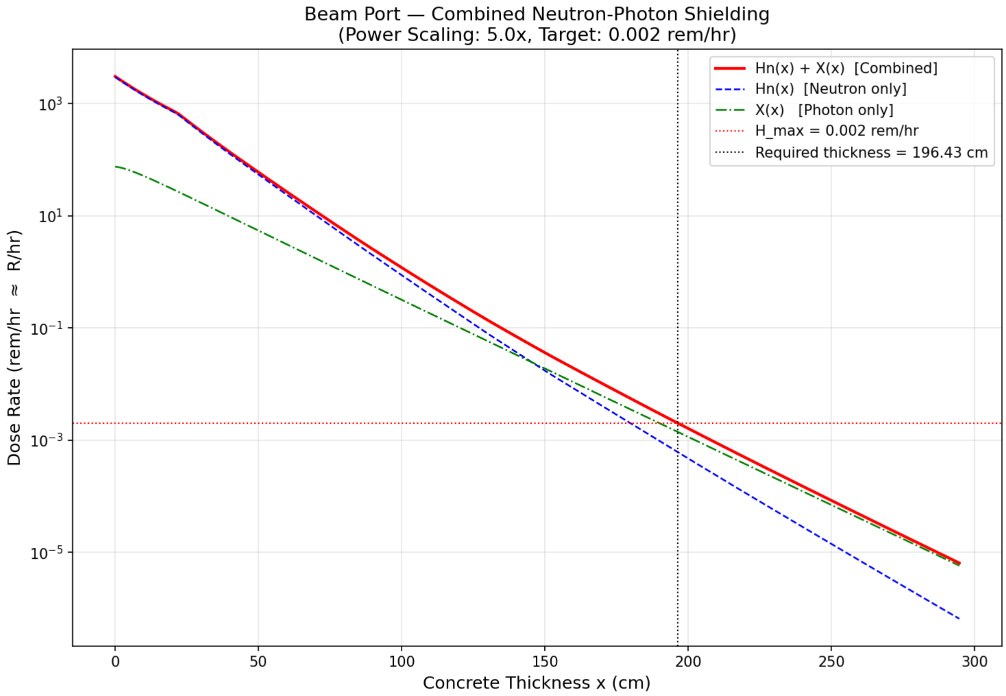

Figure 5. Combined neutron–photon shielding curve for the beam port at 5 MW. The crossover between neutron and photon curves near $x \approx 150$ cm explains the photon-dominated residual dose at the solution thickness of 196.43 cm.

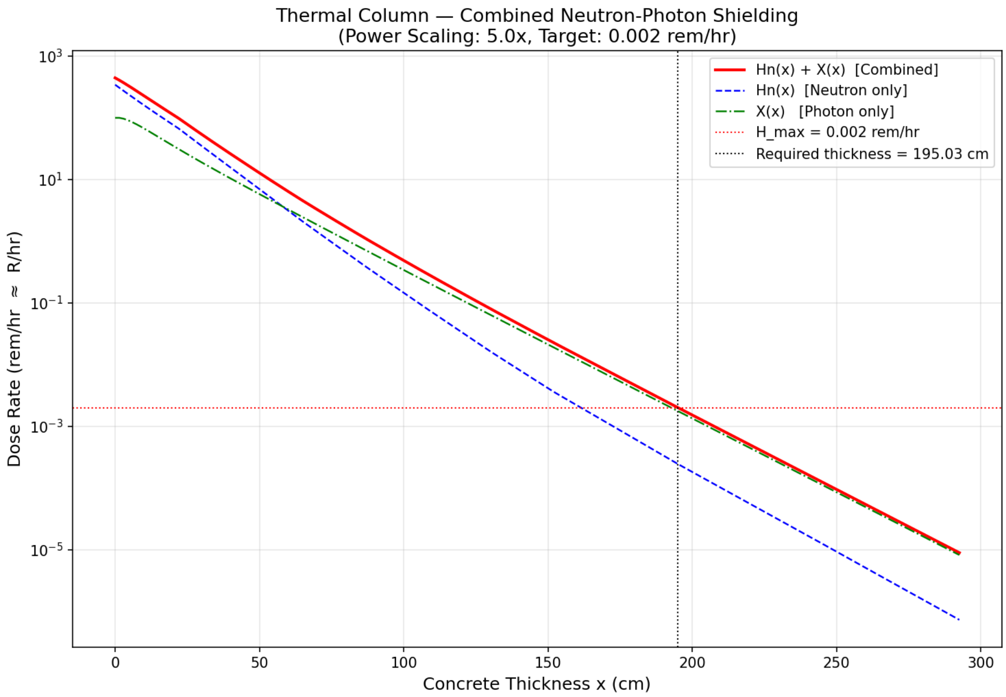

Figure 6. Combined neutron–photon shielding curve for the thermal column at 5 MW. The photon curve dominates the total dose at all thicknesses beyond ~60 cm, and the required thickness is 195.03 cm.

4.3 Comparison with 1 MW Baseline

For reference, Table 3 compares the combined shielding requirements at 1 MW and 5 MW. Plots of dose rate vs. concrete thickness are provided in Figure 7 and Figure 8.

Table 3. Combined shielding requirements at 1 MW and 5 MW.

Facility	1 MW (cm)	5 MW (cm)	Increase (cm)	5 MW effective (cm)
Beam Port	170.31	196.43	26.12	170.12 (at 60°)
Thermal Column	166.37	195.03	28.66	195.03

The fivefold increase in source fluence requires only 26–29 cm of additional concrete, a consequence of the exponential nature of radiation attenuation: a factor-of-five increase in dose corresponds to approximately $\log_2(5) \approx 2.3$ additional half-value layers.

At 1 MW, the beam port dose breakdown at the solution thickness (170.31 cm) is approximately 60% photon and 40% neutron, while at 5 MW (196.43 cm) it shifts to 70%/30%. This trend reflects the increasing photon dominance at greater shield depths. The thermal column shows an even stronger photon dominance at both power levels (85% at 1 MW, 88% at 5 MW), consistent with its softer neutron spectrum attenuating more rapidly through concrete.

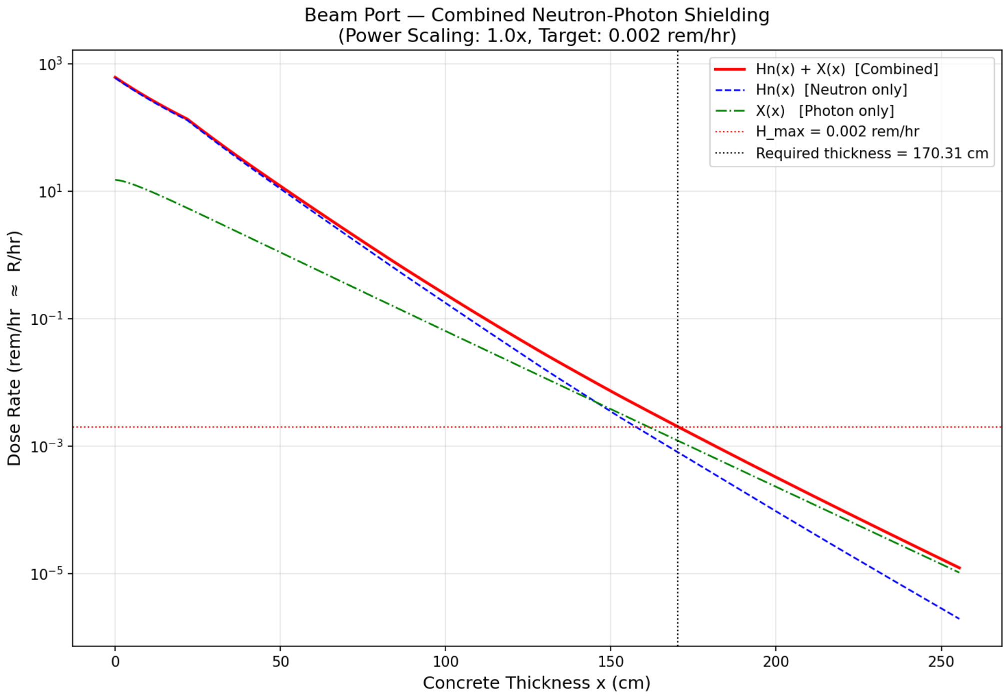

Figure 7. Combined neutron–photon shielding curve for the beam port at 1 MW. The required ordinary concrete thickness is 170.31 cm, with the neutron–photon crossover occurring near $x \approx 130$ cm.

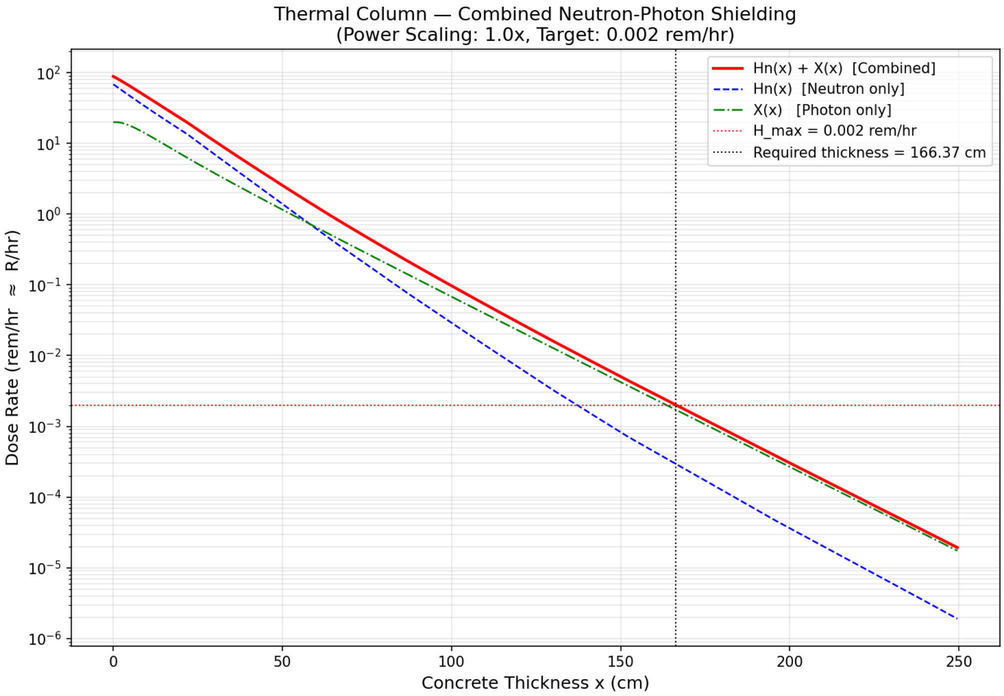

Figure 8. Combined neutron–photon shielding curve for the thermal column at 1 MW. The required ordinary concrete thickness is 166.37 cm, with photon dominance evident at all thicknesses beyond ∼50 cm.

A notable feature of the 5 MW results is the near-convergence of the two facilities' combined requirements: the beam port requires 196.43 cm while the thermal column requires 195.03 cm, a difference of only 1.4 cm. At 1 MW the difference was 3.9 cm. This convergence occurs because both facilities become increasingly photon-dominated at depth, and their photon spectra have similar effective attenuation characteristics in concrete.

5 Discussion

5.1 Comparison with Installed Shielding

The beam port is currently shielded by a layered stack consisting of approximately two feet (∼61 cm) of borated polyethylene, two feet (∼61 cm) of concrete, and one inch (∼2.5 cm) of borated polyethylene, for a total physical thickness of approximately 124.5 cm [1]. The thermal column employs a movable shield of barium carbonate concrete bricks approximately two feet (∼61 cm) thick [1].

The 5 MW combined shielding requirement computed in this study, 196.43 cm for the beam port and 195.03 cm for the thermal column, substantially exceeds the installed thicknesses at both facilities. However, this comparison must be interpreted with care. The present calculation models both shields as pure ordinary concrete, which does not capture the neutron-moderating and absorbing effectiveness of the borated polyethylene at the beam port or the superior photon attenuation of the barium concrete at the thermal column. The computed concrete-equivalent thicknesses therefore represent upper bounds on the actual shielding needed, and the true adequacy of the installed shielding depends on a material-specific analysis that accounts for the actual multi-layer composition.

Once material-specific attenuation data are available for borated polyethylene and barium carbonate concrete, a more refined comparison can be made. Additional facility measurements or MCNP models of the actual shielding stacks would allow direct verification of the installed shielding adequacy at 5 MW.

5.2 Shielding Physics at Depth

The two facilities exhibit very different shielding behaviors, driven by the hardness of their respective neutron spectra [2, 3]. At the beam port, the unshielded dose is neutron-dominated (97.5% at $x = 0$), but the neutron dose attenuates more rapidly through concrete than the photon dose. This produces a crossover near $x \approx 130$–150 cm (depending on power level), beyond which the photon field becomes the dominant contributor. This crossover has practical implications: additional concrete beyond this point provides diminishing returns for neutron attenuation but remains effective for photon reduction. The prominent iron capture gamma line near 7.65 MeV in the beam port photon spectrum [2] is a significant contributor to the shielding requirement at depth, as high-energy photons penetrate concrete more effectively due to the lower mass attenuation coefficients at high energies [4].

At the thermal column, photons dominate the residual dose at all thicknesses beyond $\sim$50 cm. The softer neutron spectrum, while contributing a higher total fluence [3], results in a lower dose per unit fluence and more rapid attenuation through concrete [4, 5]. The combined 5 MW shielding requirement (195.03 cm) is only 2.4 cm above the photon-only requirement (192.67 cm), indicating the concrete is a more effective shield for low-energy neutrons than for the photons emerging from these facilities.

5.3 Assumptions and Limitations

Several assumptions and simplifications should be noted when interpreting these results.

The fluence is assumed to scale linearly with reactor power (Eq. 1), neglecting potential spectral hardening or softening due to temperature-dependent nuclear cross-section effects at higher power. If the neutron spectrum hardens at 5 MW, the actual shielding requirement could be somewhat higher than predicted; conversely, spectral softening would reduce the requirement.

A uniform density of $\rho = 2.30$ g cm^{-3} is assumed for ordinary concrete. As discussed in Section 1.3, the actual facility shielding employs borated polyethylene (beam port) and barium carbonate concrete (thermal column), neither of which is modeled here. The concrete-only assumption yields conservative results, since the actual materials provide equal or superior attenuation per unit thickness for the radiation types present.

The assumption that 1 R $\approx$ 1 rem for photons [4] is reasonable in the energy range of interest (0.01–10 MeV) but may be less accurate at specific photon energies. The neutron DCF table [4] covers energies up to 20 MeV, and the MCNP spectra are predominantly below 10 MeV [2, 3], so the table coverage is adequate. The broad-beam geometry implicit in the buildup factors [4] and DCF tables [5] accounts for scattered radiation arriving at non-normal angles, though the beam port geometric correction at 60° is applied separately.

Finally, the thermal column data are taken from the face of the door port without a collimator in place [3]. If a collimator is used in practice, the beam divergence and energy spectrum at the shielding face may differ from the values used here.

6 Conclusion

A Python based computational tool was developed for calculating combined neutron and photon dose profiles through concrete shielding, using MCNP generated fluence spectra [2, 3] as input. The tool implements Berger buildup factors for photon transmission [4], tabulated dose conversion factors for neutron attenuation from Wyckoff and Chilton [4, 5], and Brent's method for numerical root-finding [7]. The methodology follows typical conventions for radiation shielding [6] for the UMLRR facility.

At 5 MW, the beam port requires 196.43 cm (6.44 ft) of equivalent ordinary concrete to reduce the combined dose rate to 0.002 rem hr^{-1}, with an effective perpendicular thickness of 170.12 cm (5.58 ft) after the 60° angle correction. The thermal column requires 195.03 cm (6.40 ft). Both facilities are photon-dominated at the shielding boundary, with photons accounting for 69.7% and 87.8% of the residual dose at the beam port and thermal column, respectively. The 5 MW requirements exceed the 1 MW baseline values by 26–29 cm, and the two facilities converge to within 1.4 cm of each other at 5 MW due to the common dominance of photon attenuation at depth.

These computed concrete-equivalent thicknesses substantially exceed the physical dimensions of the current installed shielding at both facilities. However, the actual multi-material shielding stacks —borated polyethylene and concrete at the beam port and barium carbonate concrete at the thermal column—provide better attenuation compared to ordinary concrete alone, particularly for neutrons. A material-specific analysis incorporating the actual shielding compositions will be necessary to determine the precise adequacy of the installed shielding for operations at 5 MW.

This tool provides a flexible and transparent method for comparable MCNP shielding simulations and can be readily extended to additional facilities or shielding materials as the UMLRR upgrade planning progresses.

References

[1] UMass Lowell Research Reactor. "Final Safety Analysis Report". Tech. rep. FSAR., (pages 3–6, 12, 17).

[2] Ksenofon Konomi. "Fluence of Photons and Neutrons of Beam Port Simulation Results". In-house computational results. Unpublished internal work. (Pages 3, 9, 10, 12, 18, 19).

[3] Ksenofon Konomi. "Fluence of Neutrons of Thermal Column Simulation Results". In-house computational results. Unpublished internal work. (Pages 3, 4, 9, 10, 12, 18, 19).

[4] J. Kenneth Shultis and Richard E. Faw. "Radiation Shielding"., (pages 5–14, 18, 19).

[5] J. M. Wyckoff and A. B. Chilton. “Dose due to practical neutron energy distributions incident on concrete shielding slabs”. In: *Dose Calculations: Proceedings of the Third International Congress of the International Radiation Protection Association*. CONF-7309076-P1. Washington, DC: 1973, pp. 694–699 (pages 5, 6, 8–10, 12, 18, 19).

[6] Mark Tries. “Mathcad files for neutron and photon dose”. Unpublished computational files. Provided by author. (Pages 6–9, 11, 19).

[7] SciPy Developers. “scipy.optimize.brentq”. Online documentation. Accessed: URL: https://docs.scipy.org/doc/scipy/reference/generated/scipy.optimize.brentq.html (pages 9, 11, 19).

[8] ASTM International. “Standard Practice for Characterizing Neutron Fluence Spectra in Terms of an Equivalent Monoenergetic Neutron Fluence for Radiation-Hardness Testing of Electronics”. Tech. rep. E722-19. ASTM International, 2019. DOI: 10.1520/E0722-19. URL: https://www.astm.org/e0722-19.html (page 9).

A Python Code

This project was originally developed across approximately 20 individual Python scripts encompassing data parsing, formatting, testing, graphing, and shielding calculations. For presentation purposes, the most critical components have been consolidated into a single combined script that computes the shielding requirements and generates the associated figures.

```python
import numpy as np
import pandas as pd
import matplotlib.pyplot as plt
from scipy.interpolate import CubicSpline, interp1d
from scipy.optimize import brentq
import os

POWER_SCALING       = 5.0
RHO_CONCRETE        = 2.30
TARGET_DOSE_RATE    = 0.002
MAX_THICKNESS       = 500.0

Q_CHARGE        = 1.602e-19
W_VALUE_AIR     = 33.97e-6
ROENTGEN_CONV   = 2.58e-4

DOSE_CONVERSION_FACTOR = (Q_CHARGE / W_VALUE_AIR) * 1000 * (1 / ROENTGEN_CONV) * 3600

AIR_COEFF_CSV       = r'path/to/photon_mass_energy_absorption_coeff_air.csv'
CONCRETE_COEFF_CSV  = r'path/to/linear_attenuation_coeff_concrete.csv'
BERGER_CSV          = r'path/to/berger_buildup_parameters_air_kerma_concrete.csv'
SHULTIS_CSV         = r'path/to/neutron_energy_DCF.csv'

FACILITIES = {
    "Beam Port": {
        "angle_of_incidence": 60.0,
        "photon_fluence_csv": r'path/to/beam_port_photon_fluence.csv',
        "neutron_fluence_unscaled": np.array([
            1.85e+06, 8.25e+04, 7.20e+04, 1.22e+05, 8.00e+04,
            1.08e+05, 1.24e+05, 1.40e+05, 3.69e+05, 7.69e+05,
            1.30e+06, 1.27e+06, 5.38e+05, 6.88e+04, 2.34e+05,
            1.62e+05, 1.60e+05, 1.91e+05, 1.88e+05, 4.68e+04,
            4.48e+04, 1.28e+03, 2.06e+02
        ]),
        "plot_save_path": r'path/to/output/beam_port_combined_shielding.png',
    },
    "Thermal Column": {
        "angle_of_incidence": 90.0,
        "photon_fluence_csv": r'path/to/thermal_column_photon_fluence.csv',
        "neutron_fluence_unscaled": np.array([
            1.37e+07, 6.69e+04, 5.92e+04, 6.98e+04, 4.57e+04,
            5.73e+04, 7.19e+04, 5.36e+04, 9.25e+04, 4.66e+04,
            2.67e+04, 1.75e+04, 8.16e+03, 1.65e+03, 4.47e+03,
            4.23e+03, 5.75e+03, 1.41e+04, 1.78e+04, 1.51e+03,
            3.18e+02, 2.39e+01, 7.22e-02
        ]),
```

```python
        "plot_save_path": r'path/to/output/thermal_column_combined_shielding.png',
    },
}


def load_photon_fluence(csv_path, power_scaling):
    df = pd.read_csv(csv_path)
    df.columns = ['Energy_MeV', 'FluenceRate']
    df['FluenceRate'] = df['FluenceRate'] * power_scaling
    df = df[df['Energy_MeV'] >= 0.01]
    return df


def load_shared_photon_coefficients():
    df_air = pd.read_csv(AIR_COEFF_CSV)
    df_air.columns = ['Energy_MeV', 'MuEnRho_Air']

    df_concrete = pd.read_csv(CONCRETE_COEFF_CSV)
    df_concrete.columns = ['Energy_MeV', 'Mu_Concrete_Mass']

    df_coeffs = pd.merge(df_air, df_concrete, on='Energy_MeV')

    df_berger = pd.read_csv(BERGER_CSV)
    df_berger.columns = ['Energy_MeV', 'a', 'b']

    return df_coeffs, df_berger


def build_photon_interpolators(df_coeffs, df_berger):
    cs_mu_en_rho = CubicSpline(df_coeffs['Energy_MeV'], df_coeffs['MuEnRho_Air'])
    concrete_linear_mu = df_coeffs['Mu_Concrete_Mass'] * RHO_CONCRETE
    cs_mu_concrete = CubicSpline(df_coeffs['Energy_MeV'], concrete_linear_mu)
    interp_a = interp1d(df_berger['Energy_MeV'], df_berger['a'], kind='linear', fill_value="extrapolate")
    interp_b = interp1d(df_berger['Energy_MeV'], df_berger['b'], kind='linear', fill_value="extrapolate")
    return cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b


def photon_dose_rate(thickness_cm, energies, fluence_rates,
                     cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b):
    mu           = np.maximum(cs_mu_concrete(energies), 0)
    mu_en        = np.maximum(cs_mu_en_rho(energies), 0)
    a            = interp_a(energies)
    b            = interp_b(energies)
    gamma        = energies * mu_en * DOSE_CONVERSION_FACTOR
    rl           = mu * thickness_cm
    transmission = np.exp(-rl) * (1 + a * rl * np.exp(b * rl))
    return np.sum(gamma * fluence_rates * transmission)


def build_dcf_model(T_raw, DCF_raw, rho):
    T_cm    = np.asarray(T_raw, dtype=float) / rho
    DCF     = np.asarray(DCF_raw, dtype=float) * 100.0 * 3600.0
    interp_ln = interp1d(T_cm, np.log(DCF), kind='linear',
                         fill_value="extrapolate", assume_sorted=False)
```

```
    def dcf_of_thickness(x_cm):
        return np.exp(interp_ln(np.asarray(x_cm, dtype=float)))
    return dcf_of_thickness


def load_neutron_dcf_functions():
    df = pd.read_csv(SHULTIS_CSV)
    energy_col = "Energy Interval (MeV)" if "Energy Interval (MeV)" in df.columns else df.columns[0]
    ignore_cols = [energy_col] + [c for c in df.columns if c.startswith("Unnamed")]
    thickness_cols = [c for c in df.columns if c not in ignore_cols]

    T_mass   = np.array(thickness_cols, dtype=float)
    sort_idx = np.argsort(T_mass)
    T_mass   = T_mass[sort_idx]
    thickness_cols_sorted = [thickness_cols[i] for i in sort_idx]

    energies   = df[energy_col].to_numpy(dtype=float)
    n_energies = len(df)

    dcf_functions = []
    for i in range(n_energies):
        row_dcf    = df.loc[i, thickness_cols_sorted].to_numpy(dtype=float)
        valid_mask = np.isfinite(row_dcf)
        T_valid    = T_mass[valid_mask]
        DCF_valid  = row_dcf[valid_mask]
        if T_valid.size < 2:
            dcf_functions.append(lambda x: 0.0)
            continue
        dcf_functions.append(build_dcf_model(T_valid, DCF_valid, RHO_CONCRETE))

    return energies, n_energies, dcf_functions


def neutron_dose_rate(thickness_cm, dcf_functions, fluence_rate):
    total = 0.0
    for fn, phi in zip(dcf_functions, fluence_rate):
        try:
            total += fn(thickness_cm) * phi
        except Exception:
            pass
    return total


def combined_dose_rate(thickness_cm,
                       E_photon, Phi_photon,
                       cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b,
                       dcf_functions, fluence_neutron):
    X  = photon_dose_rate(thickness_cm, E_photon, Phi_photon,
                          cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b)
    Hn = neutron_dose_rate(thickness_cm, dcf_functions, fluence_neutron)
    return Hn + X


def solve_combined_shielding(target,
                              E_photon, Phi_photon,
                              cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b,
```

```
                              dcf_functions, fluence_neutron,
                              max_thickness=MAX_THICKNESS):
    def objective(x):
        return combined_dose_rate(x, E_photon, Phi_photon,
                                  cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b,
                                  dcf_functions, fluence_neutron) - target

    dose_at_0 = combined_dose_rate(0.0, E_photon, Phi_photon,
                                   cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b,
                                   dcf_functions, fluence_neutron)
    if dose_at_0 <= target:
        print("  No shielding needed     unshielded dose is already below target.")
        return 0.0

    dose_at_max = combined_dose_rate(max_thickness, E_photon, Phi_photon,
                                     cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b,
                                     dcf_functions, fluence_neutron)
    if dose_at_max > target:
        print(f"  WARNING: Target not achievable within {max_thickness} cm. "
              f"Dose at max thickness: {dose_at_max:.4e}")
        return max_thickness

    return brentq(objective, 0.0, max_thickness)


def plot_combined(facility_name, required_thickness,
                  E_photon, Phi_photon,
                  cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b,
                  dcf_functions, fluence_neutron,
                  power_scaling,
                  save_path=None):
    x_vals = np.linspace(0, min(required_thickness * 1.5, MAX_THICKNESS), 200)

    y_photon  = np.array([photon_dose_rate(x, E_photon, Phi_photon,
                          cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b)
                          for x in x_vals])
    y_neutron = np.array([neutron_dose_rate(x, dcf_functions, fluence_neutron) for x in x_vals])
    y_total   = y_photon + y_neutron

    fig, ax = plt.subplots(figsize=(10, 7))
    ax.semilogy(x_vals, y_total,   'r-',  linewidth=2,   label='Hn(x) + X(x)  [Combined]')
    ax.semilogy(x_vals, y_neutron, 'b--', linewidth=1.2, label='Hn(x)  [Neutron only]')
    ax.semilogy(x_vals, y_photon,  'g-.', linewidth=1.2, label='X(x)   [Photon only]')
    ax.axhline(TARGET_DOSE_RATE, color='r', linestyle=':', linewidth=1,
               label=f'H_max = {TARGET_DOSE_RATE} rem/hr')
    ax.axvline(required_thickness, color='k', linestyle=':', linewidth=1,
               label=f'Required thickness = {required_thickness:.2f} cm')
    ax.set_xlabel('Concrete Thickness x (cm)', fontsize=12)
    ax.set_ylabel('Dose Rate (rem/hr       R/hr)', fontsize=12)
    ax.set_title(f'{facility_name}     Combined Neutron-Photon Shielding\n'
```

```python
                 f'(Power Scaling: {power_scaling}x, Target: {TARGET_DOSE_RATE} rem/hr)',
                 fontsize=13)
    ax.legend(fontsize=10)
    ax.grid(True, which='both', alpha=0.3)
    plt.tight_layout()

    if save_path:
        os.makedirs(os.path.dirname(save_path), exist_ok=True)
        plt.savefig(save_path, dpi=150)
        print(f"  Plot saved to {save_path}")
    plt.show()


def plot_unshielded_vs_power(facility_name, config,
                             cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b,
                             dcf_functions,
                             save_path=None):
    power_range = np.arange(1.0, 5.01, 0.1)
    palette = {
        "Beam Port":      {"combined": "tab:blue",   "photon": "steelblue",   "neutron": "cornflowerblue"},
        "Thermal Column": {"combined": "tab:orange",  "photon": "darkorange", "neutron": "gold"},
    }
    cols = palette.get(facility_name, {"combined": "black", "photon": "grey", "neutron": "silver"})

    df_base     = load_photon_fluence(config["photon_fluence_csv"], 1.0)
    E_base      = df_base['Energy_MeV'].values
    Phi_base    = df_base['FluenceRate'].values
    neutron_raw = config["neutron_fluence_unscaled"]

    total_doses, photon_doses, neutron_doses = [], [], []
    for p in power_range:
        ph0 = photon_dose_rate(0, E_base, Phi_base * p,
                               cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b)
        n0  = neutron_dose_rate(0, dcf_functions, neutron_raw * p)
        photon_doses.append(ph0)
        neutron_doses.append(n0)
        total_doses.append(ph0 + n0)

    fig, ax = plt.subplots(figsize=(11, 7))
    ax.plot(power_range, total_doses,   color=cols["combined"], linewidth=2, linestyle='-',  label='Combined')
    ax.plot(power_range, photon_doses,  color=cols["photon"],   linewidth=1.2, linestyle='--', label='Photon only')
    ax.plot(power_range, neutron_doses, color=cols["neutron"],  linewidth=1.2, linestyle=':',  label='Neutron only')

    ax.set_xlabel('Power Scaling Factor (MW)', fontsize=12)
    ax.set_ylabel('Unshielded Dose Rate at x = 0  (rem/hr)', fontsize=12)
    ax.set_title(f'Unshielded Dose Rate vs. Power Scaling     {facility_name}\n'
                 '(No shielding, 1.0 MW     5.0 MW in 0.1 MW steps)', fontsize=13)
    ax.set_xticks(np.arange(1.0, 5.1, 0.5))
```

```python
    ax.legend(fontsize=10)
    ax.grid(True, which='both', alpha=0.3)
    plt.tight_layout()

    if save_path:
        os.makedirs(os.path.dirname(save_path), exist_ok=True)
        plt.savefig(save_path, dpi=150)
        print(f"  Power-scaling plot saved to {save_path}")
    plt.show()


def run_facility(facility_name, config,
                 cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b,
                 dcf_functions, n_energies_neutron):
    power       = POWER_SCALING
    angle       = config["angle_of_incidence"]
    neutron_raw = config["neutron_fluence_unscaled"]
    save_path   = config.get("plot_save_path", None)

    print(f"\n{'='*80}")
    print(f"   {facility_name.upper()}")
    print(f"{'='*80}")

    df_photon = load_photon_fluence(config["photon_fluence_csv"], power)
    E_photon   = df_photon['Energy_MeV'].values
    Phi_photon = df_photon['FluenceRate'].values

    if len(neutron_raw) != n_energies_neutron:
        print(f"  WARNING: Neutron fluence array length ({len(neutron_raw)}) "
              f"!= Shultis CSV rows ({n_energies_neutron})")
    fluence_neutron = neutron_raw * power

    photon_0  = photon_dose_rate(0, E_photon, Phi_photon,
                                 cs_mu_en_rho, cs_mu_concrete, interp_a,
    interp_b)
    neutron_0 = neutron_dose_rate(0, dcf_functions, fluence_neutron)
    total_0   = photon_0 + neutron_0

    required_thickness = solve_combined_shielding(
        TARGET_DOSE_RATE,
        E_photon, Phi_photon,
        cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b,
        dcf_functions, fluence_neutron
    )

    effective_thickness    = required_thickness * np.sin(np.radians(angle))
    required_thickness_ft  = required_thickness / 30.48
    effective_thickness_ft = effective_thickness / 30.48

    def solve_photon_only(target):
        def obj(x):
            return photon_dose_rate(x, E_photon, Phi_photon,
                                    cs_mu_en_rho, cs_mu_concrete, interp_a,
    interp_b) - target
        return brentq(obj, 0, MAX_THICKNESS)

    def solve_neutron_only(target):
        def obj(x):
```

```
            return neutron_dose_rate(x, dcf_functions, fluence_neutron) - target
        return brentq(obj, 0, MAX_THICKNESS)

    photon_only_thickness  = solve_photon_only(TARGET_DOSE_RATE)
    neutron_only_thickness = solve_neutron_only(TARGET_DOSE_RATE)

    print(f"  Power Scaling Factor:          {power}x")
    print(f"  Target Dose Rate (H_max):      {TARGET_DOSE_RATE} rem/hr")
    print(f"  Concrete Density:              {RHO_CONCRETE} g/cm^3")
    print(f"  Angle of Incidence:            {angle} degrees")
    print("-" * 80)
    print(f"\n  UNSHIELDED DOSE RATES (x = 0 cm):")
    print(f"    Photon X(0):                 {photon_0:.6e} R/hr")
    print(f"    Neutron Hn(0):               {neutron_0:.6e} rem/hr")
    print(f"    Combined H_d(0):             {total_0:.6e} rem/hr")
    print(f"\n  INDIVIDUAL SHIELDING (each to {TARGET_DOSE_RATE} rem/hr alone):")
    print(f"    Photon only:                 {photon_only_thickness:.2f} cm  /  {photon_only_thickness/30.48:.2f} ft")
    print(f"    Neutron only:                {neutron_only_thickness:.2f} cm  /  {neutron_only_thickness/30.48:.2f} ft")
    print(f"\n  COMBINED SHIELDING (Hn(x) + X(x) = {TARGET_DOSE_RATE} rem/hr):")
    print(f"    Required linear thickness:   {required_thickness:.2f} cm  /  {required_thickness_ft:.2f} ft")

    if angle < 90.0:
        print(f"    Effective thickness at {angle} degrees:  {effective_thickness:.2f} cm  /  {effective_thickness_ft:.2f} ft")
    else:
        print(f"    (Perpendicular incidence    no angle correction needed)")

    photon_at_sol  = photon_dose_rate(required_thickness, E_photon, Phi_photon,
                                      cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b)
    neutron_at_sol = neutron_dose_rate(required_thickness, dcf_functions, fluence_neutron)

    print(f"\n  DOSE BREAKDOWN AT SOLUTION THICKNESS ({required_thickness:.2f} cm):")
    print(f"    Photon contribution:         {photon_at_sol:.6e} R/hr  ({100*photon_at_sol/TARGET_DOSE_RATE:.1f}% of limit)")
    print(f"    Neutron contribution:        {neutron_at_sol:.6e} rem/hr  ({100*neutron_at_sol/TARGET_DOSE_RATE:.1f}% of limit)")
    print(f"    Total:                       {photon_at_sol+neutron_at_sol:.6e} rem/hr")
    print("=" * 80)

    plot_combined(facility_name, required_thickness,
                  E_photon, Phi_photon,
                  cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b,
                  dcf_functions, fluence_neutron,
                  power,
                  save_path=save_path)


if __name__ == "__main__":
```

```
    print("Loading shared coefficient data...")
    df_coeffs, df_berger = load_shared_photon_coefficients()
    cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b = build_photon_interpolators(df_coeffs, df_berger)

    print("Loading Shultis neutron DCF table...")
    energies_neutron, n_energies_neutron, dcf_fns = load_neutron_dcf_functions()

    for name, config in FACILITIES.items():
        run_facility(name, config,
                     cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b,
                     dcf_fns, n_energies_neutron)

    POWER_SCAN_SAVES = {
        "Beam Port":      r'path/to/output/beam_port_unshielded_dose_vs_power.png',
        "Thermal Column": r'path/to/output/thermal_column_unshielded_dose_vs_power.png',
    }
    print("\nGenerating unshielded dose rate vs. power scaling plots...")
    for name, config in FACILITIES.items():
        plot_unshielded_vs_power(name, config,
                                 cs_mu_en_rho, cs_mu_concrete, interp_a, interp_b,
                                 dcf_fns,
                                 save_path=POWER_SCAN_SAVES[name])

    print("\n\nAll facilities complete.")
```