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Optimization Analysis Plan for the PRO-X and NCNR Collaboration on the NNS Research Reactor Project

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Executive Summary

The National Institute of Standards and Technology (NIST), through the NIST Center for Neutron Research (NCNR), and the U.S. Department of Energy's National Nuclear Security Administration (NNSA), through Argonne National Laboratory, are collaborating to apply the Proliferation Resistance Optimization (PRO-X) framework to the conceptual design of the proposed NIST Neutron Source (NNS) research reactor. This effort is intended to integrate proliferation resistance into early design decisions while supporting mission performance, safety, and project practicality, thereby advancing nonproliferation and reactor mission objectives together rather than treating them as competing priorities.

The NNS is being developed to replace the aging National Bureau of Standards Reactor and to sustain and expand an essential national capability in neutron measurement science. The proposed facility is a 20 MW pool-type research reactor with a compact core, heavy-water reflector, cold neutron sources, thermal beam capabilities, and irradiation facilities. Because the project remains in conceptual design, this collaboration provides a timely opportunity to influence major design choices before engineering, licensing, and procurement decisions become fixed.

This analysis plan establishes a structured, multi-objective approach for comparing design candidates with a baseline design. The optimization focuses on three complementary objectives: strengthening proliferation resistance by reducing the production, accumulation, accessibility, and attractiveness of special fissionable material; preserving or enhancing reactor mission performance; and maintaining adequate safety margins under representative operating conditions. The work is intended to inform design refinement and decision-making during the pre-licensing stage, not to provide final regulatory analyses.

The principal areas of analysis include fuel system selection, fuel assembly design, fuel management and shuffling strategies, power-peaking mitigation, cooling-capacity rightsizing, and the configuration of key experimental capabilities. Across these areas, optimization emphasizes practical and implementable design improvements that align reactor capabilities with declared mission needs while avoiding unnecessary excess in material inventory, fissile material throughput, power, cooling capacity, or facility complexity.

For NIST and NNSA stakeholders, this effort provides a clear and traceable technical basis for high-consequence design and procurement decisions. The expected outcomes include comparative assessments and decision-ready recommendations that support conceptual design refinement, strengthen future vendor engagement, and help ensure that nonproliferation objectives are incorporated directly into project requirements and acquisition planning.

This collaboration is intended to strengthen the NNS project while design changes remain most feasible. By integrating proliferation resistance early and systematically with performance and safety considerations, the effort supports development of a more secure, efficient, and mission-effective reactor design that advances both national scientific capability and U.S. nonproliferation objectives. Beyond the NNS project, the PRO-X/NCNR collaboration establishes a practical, mission-driven model for future partnerships between NNSA and reactor developers, supporting NNSA's broader nonproliferation goals by demonstrating how proliferation resistance can be enhanced while supporting reactor mission performance, safety, and operational effectiveness.

1. Introduction

In October 2024, the U.S. Department of Commerce’s National Institute of Standards and Technology (NIST) and the U.S. Department of Energy’s National Nuclear Security Administration (NNSA) signed a Memorandum of Understanding (MOU) establishing a framework for technical collaboration on the proliferation resistance (PR) optimization of the new NIST Neutron Source (NNS) research reactor. The MOU reflects a shared commitment to strengthening nonproliferation outcomes by integrating proliferation resistance considerations directly into the design and operation of the NNS.

Under the MOU, NIST identified their Center for Neutron Research (NCNR) as the implementing organization for NIST, while NNSA designated Argonne National Laboratory (Argonne) to carry out technical activities on their behalf. The collaboration focuses on applying the Proliferation Resistance Optimization (PRO-X) program framework to the design optimization of the proposed new research reactor to be constructed by NIST, with the objective of enhancing proliferation resistance while supporting mission performance, safety, and project constraints. The approaches and insights developed through this effort are also intended to inform the conceptual design of the NNS as bid specifications are developed for future procurement.

This document describes the optimization approach developed in support of this collaboration and provides a structured framework for integrating proliferation resistance considerations into near-term design decisions for the NNS reactor.

1.1 Overview of PRO-X and PRO-RR

The Proliferation Resistance Optimization (PRO-X) program, led by NNSA, seeks to minimize the production, accumulation, and accessibility of special fissionable material (SFM) while supporting peaceful-use missions and assuring adequate safety. Within this effort, PRO-RR applies the PRO-X approach specifically to research reactor systems.

PRO-X is most effective when applied early in a project’s design lifecycle, before major technical, operational, and procurement decisions become fixed. Rather than relying on late-stage modifications or add-on measures, the approach uses technical analysis and engineering judgment to identify practical design options within the specific mission, design maturity, and constraints of each reactor project. The process seeks win-win opportunities for design improvements that simultaneously strengthen proliferation resistance, improve mission performance and efficiency, and preserve safety and overall project practicality.

PRO-RR applies the PRO-X framework tailored to the technical and operational characteristics of each research reactor project.

1.2 Overview of the NIST NNS Project

NCNR houses the National Bureau of Standards Reactor (NBSR), an aging 20 MW high performance research reactor, primarily used for out-of-core neutron scattering and irradiation experiments and for in-core neutron activation (NAA) analysis experiments. The NBSR supports NCNR's mission of ensuring the availability of neutron measurement capabilities for U.S. researchers from various sectors, and it has been a critical pillar in providing that capability to the nation since 1967. Despite upgrades, demand for neutron scattering research now exceeds NCNR's existing capacity, fulfilling only a third of the requested beam time. This growing demand, coupled with the notable aging of NBSR, underscores the need for a replacement reactor.

The NNS (Figure 1-1) is being developed by NCNR to replace the NBSR as the center's primary reactor-based source for out-of-core neutron measurements and to provide modernized and improved NAA measurement facilities. The NNS was designed with expanded instrument capacity and flexibility to support future neutron science needs, which were thoroughly explored in NIST SP 2100-07 [1]. The NNS design borrows from more recent demonstrated technologies for high performance research reactors in the world, making use of significantly more advanced knowledge-based technologies that were not available when the NBSR was originally developed.

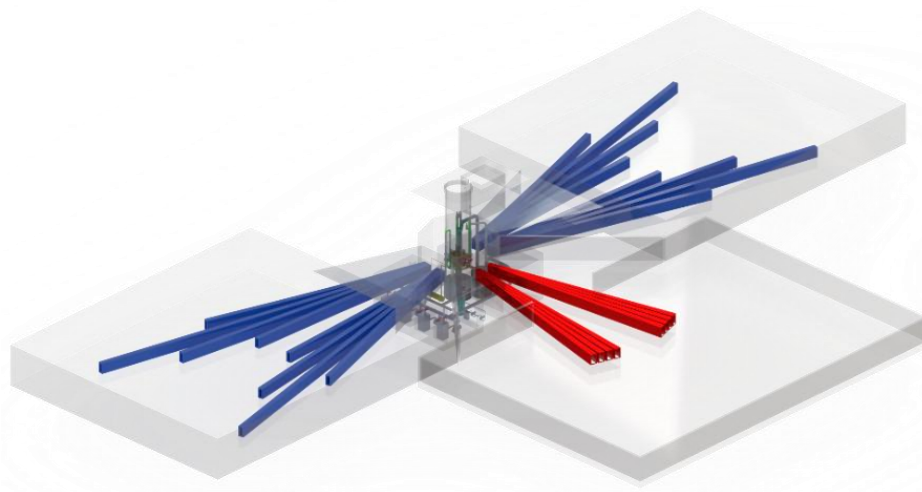


Figure 1-1 Rendering of the NNS facility layout showing the two cold neutron guide halls (blue) and one thermal guide hall (red) surrounding the reactor.

The NNS reactor (Figure 1-2) is conceptualized as a compact core moderated and cooled by light water, surrounded by a heavy water reflector tank within an open pool of light water. The heavy water tank contains two state-of-the-art liquid deuterium (LD_2) cold neutron sources, each supplying the demand of one of the two guide halls. The cold sources are designed to be vertically accessible to more effectively accommodate upgrades when future ones are available or needed. The compact core consists of a 3×3 rectangular lattice of nine total fuel assemblies, each nominally fueled with 21 curved fuel plates containing U-10Mo alloy of high assay low-enriched uranium (HALEU). The core is cooled with forced convection upflow and incorporates passive safety features such as flap valves that automatically establish a flow path between the core and the pool in the case of a loss of coolant accident.

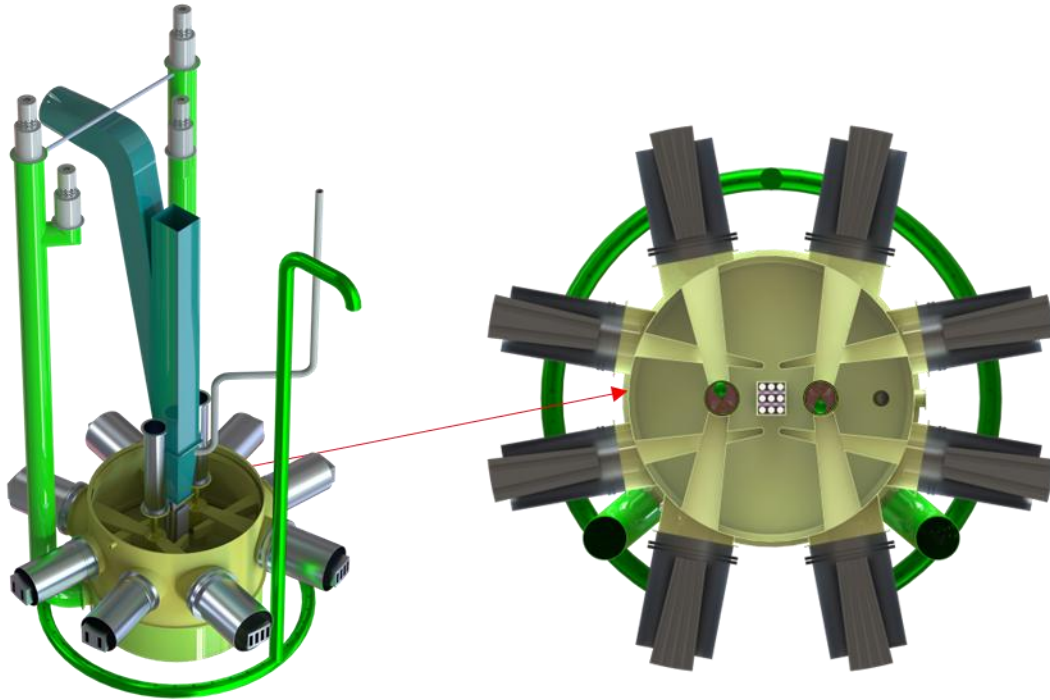


Figure 1-2. An illustration of the NNS reactor showing the core, the two cold sources, the reflector tank, and some of the relevant piping connected.

The NNS project has successfully passed the pre-conceptual design phase and is currently in the conceptual phase, where design choices are still being refined before progression to the engineering design phase. The conceptual design phase focuses on verification and, when possible, validation of the models, assessment of fuel alternatives, the incorporation of more experimental capabilities like rabbit tubes, and the progression of the acquisition, including the issuance of the Request for Information (RFI) and drafting of the Statement of Work (SOW) for bidding in the market. The NCNR is looking forward to working with Argonne National Laboratory and NNSA on the progression of this vital project to American measurement and nuclear technology infrastructure.

Because the NNS project is still in conceptual design, optimization can have significant practical influence on the reactor's evolving configuration. Key decisions related to fuel options, fuel management, experimental capabilities, system sizing, and procurement inputs are still being developed, creating an opportunity to identify design improvements before major engineering and acquisition decisions become more fixed. The next section defines the purpose, scope, and boundaries of that optimization effort.

1.3 Expected Outcomes and Benefits of the Partnership

This collaboration leverages the combined expertise of NIST NCNR and the NNSA PRO-RR technical team to optimize the NNS reactor design for performance, safety, and proliferation resistance while contributing to the timely, cost-effective development of the NNS. NNS will

benefit from a stronger technical basis for evaluating design options¹ as well as clearer engineering constraints and proliferation resistance considerations to inform future vendor engagement.

Reactor facility optimization systematically identifies and compares design options that reduce the use, production, attractiveness, and accessibility of SFM. This includes approaches that improve annual fuel utilization, reduce unnecessary fuel throughput, minimize fuel inventory consistent with mission requirements, manage excess reactivity, promote flatter power and flux distributions, and right-size core power, cooling capacity, and irradiation volumes to declared mission needs.

From a reactor project perspective, optimization supports design progression from the established conceptual configuration toward a more detailed and implementable design. Structured evaluation of the combined space of performance, proliferation resistance, and safety enables clearer prioritization of design options, more focused analysis, and early identification of features that offer “win-win” benefits. This clarifies priorities for additional analysis and supports more effective vendor engagement. It also reduces downstream technical and schedule risk by helping avoid over-designed systems and unnecessary conservatism.

The optimization also supports design realism by aligning nonproliferation objectives with long-term usability, maintainability, and regulatory expectations. It favors design options that enhance detectability of anomalies, limit excess capacity beyond mission requirements, and support stable, reliable, and economical operation.

The outcome of this partnership will include:

- Providing a technical basis for strengthening proliferation resistance in the NNS reactor design,
- Improving the technical basis for design decisions affecting performance and safety,
- Clarifying engineering constraints and proliferation resistance objectives for future vendor engagement,
- Supporting more effective conceptual design refinement,
- Supporting cost-efficient project delivery.

¹ For the purpose of describing the optimization analysis plan, the terms used are: **Design Option**, a broad possible choice or alternative in the design space, **Design Variant**, a modified version of a baseline or reference design, and **Candidate Design**, a design that is sufficiently defined to be evaluated against the mission objectives and constraints.

2. Purpose and Scope

This section explains the rationale for performing this work during the conceptual design phase and identifies the scope and boundaries of the optimization effort conducted under the PRO-X collaboration between NCNR and Argonne.

2.1 Strategic Significance

The optimization effort informs high-consequence design choices during the conceptual design phase, when the reactor design can still evolve. Its purpose is to integrate proliferation resistance into early design decisions for NNS, through practical, implementable improvements that remain consistent with mission, safety, and project objectives. Figure 2-1 illustrates the decreasing flexibility to influence major design choices as the project progresses from conceptual design into later phases. Conducting this work during conceptual design allows for near-term design refinement without disrupting established project assumptions, schedules, or regulatory pathways. It also supports informed decision making by project leadership as NNS progresses toward procurement and vendor engagement.

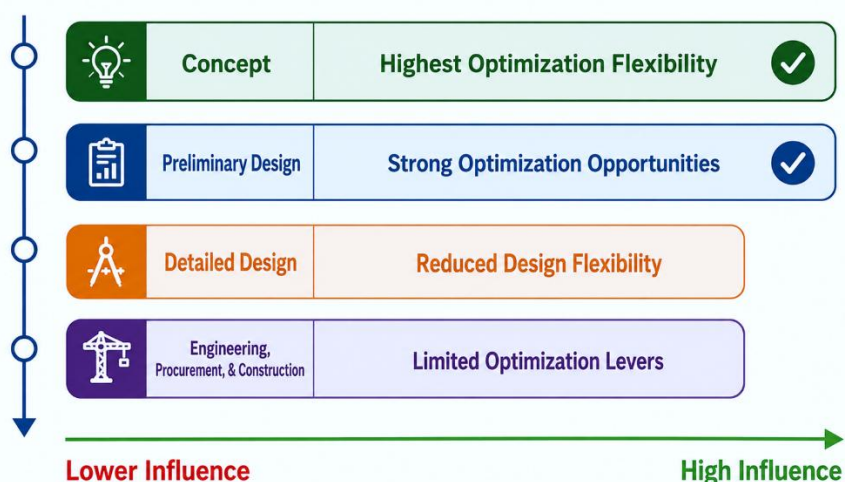


Figure 2-1. PRO-X impact by project phase.

2.2 Scope, Boundaries, and Exclusions

The optimization activity focuses on identifying and evaluating design options that strengthen proliferation resistance while supporting peaceful-use missions. It is performed within a defined design space shaped by project maturity, licensing expectations, operational limits, and procurement constraints. Analyses examine the integrated behavior of the whole reactor system and address fuel management, irradiation capability, cooling capacity, operating cycles, and material inventories.

The following are outside the scope of this work: formal calculations for regulatory submittals; development or qualification of new fuels or assembly designs; and detailed mechanical, structural, or balance-of-plant design or analysis. The overall control system concept selected by NCNR is treated as fixed, but limited evaluation of operational strategies within the conceptual framework may be considered (such as control grouping or programming approaches). Detailed control hardware design or alternative control system architectures are also excluded. For cooling systems, scope is limited to establishing appropriate cooling capacity requirements for the primary reactor cooling system and individual irradiation positions (in-core and ex-core); detailed mechanical design of cooling systems is excluded.

Neutronic analyses will characterize reactivity behavior, power and flux distributions, fuel utilization, and nuclear material inventories to quantify impacts on mission performance, proliferation resistance, and safety. Particular emphasis will be placed on multi-cycle and equilibrium-cycle behavior to ensure that candidate designs are assessed under representative operating conditions. Calculations are conducted with enough fidelity to support consistent comparison among candidate designs and identification of trends, not the establishment of licensing margins or final design parameters.

Steady-state thermal-hydraulics analyses will be used to assess whether candidate designs provide sufficient margin to thermal safety limits. These analyses are intended to support viability screening and design refinement during the conceptual phase. Transient accident analysis is outside the scope of this effort because the primary objective is to compare candidate configurations under representative steady-state operating conditions. Nevertheless, steady-state results can provide useful screening information by identifying designs that approach established thermal-hydraulic limits. Comprehensive analyses required for licensing and preparation of regulatory documents are outside of scope, but targeted code-to-code comparisons may be included as a supplementary activity to support the technical basis for NCNR's future regulatory discussions.

Together, the optimization analyses provide a coherent, physics-based foundation for evaluating proliferation resistance, performance, and safety consistent with the intent of a pre-licensing optimization effort. Modeling methodologies, uncertainty treatment, and licensing-grade analyses are addressed separately in dedicated analysis plans or in downstream project phases.

3. Optimization Framework

To support the NNS optimization study, this section defines the technical framework used to evaluate candidate designs. The framework is designed to enable consistent assessment of candidate designs using a common basis while accounting for realistic project constraints. It also ensures that proliferation resistance is considered together with reactor performance and safety so that opportunities to improve multiple objectives simultaneously can be identified.

3.1 Optimization Philosophy and System Rightsizing

The optimization study for NNS is anchored in a facility-level rightsizing philosophy that seeks an appropriate balance among mission effectiveness, proliferation resistance, safety, and overall project practicality. For a neutron source reactor, the objective is not simply to maximize reactor power, but to provide the neutron and gamma environments needed to support a broad range of user missions. In this context, rightsizing means selecting core and plant capabilities—such as irradiation capacity, cycle length, and heat removal capability—so they are adequate to satisfy mission, functional and safety needs, while avoiding capability that is not justified by those needs. This rightsizing approach helps limit unnecessary complexity, oversized systems, and avoidable material throughput that could otherwise increase proliferation concerns or complicate implementation.

Consistent with this philosophy, optimization focuses on identifying practical design improvements that remain feasible within the defined optimization space. Proliferation resistance is addressed by considering opportunities to reduce SFM generation and diversion pathways as well as design features that can improve the detectability of anomalous or off-normal conditions. The comparative evaluation approach is described in Section 3.3.

3.2 NNS Baseline Design Definition

All optimization analyses are anchored to a formally identified baseline design for the NNS. This baseline represents the current level of design maturity for the project and captures the principal design decisions made to date, including the selected reactor concept, core layout, reactivity control strategy, and reliance on a fuel assembly design consistent with the U.S. High Performance Research Reactor (USHPRR) conversion program plan for U-10Mo fuel. Establishing this baseline is important because it creates a consistent and traceable benchmark against which proposed design changes can be assessed. It enables candidate options to be compared on a common basis, helps distinguish incremental improvements from more fundamental departures, and supports a transparent evaluation of benefits, tradeoffs, and implementation impacts within the optimization study.

The baseline NNS configuration is a 20 MW pool-type research reactor featuring a compact core cooled by light water and positioned within a vertical core chimney. Surrounding the chimney is a heavy-water reflector tank that contains two cold neutron sources and neutron beam tubes. These reactor components are located at the bottom of a reactor pool filled with demineralized light water.

Figure 3-1 illustrates the reflector tank internals, including the central core, cold sources, and beam tubes.

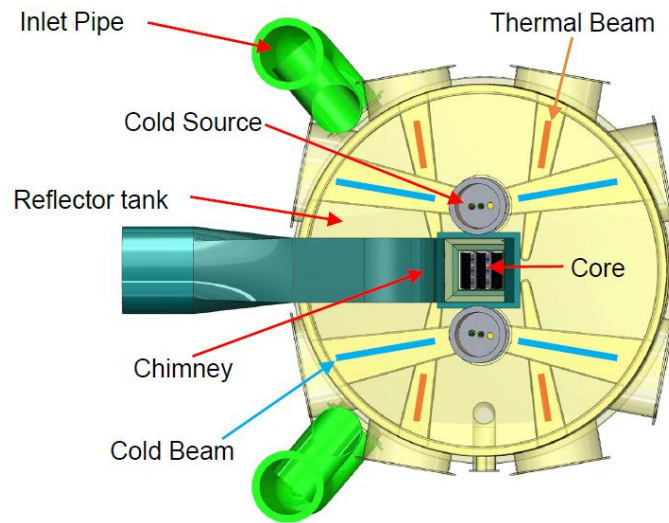


Figure 3-1 Reflector tank with core, cold sources, and beam tubes. [2]

The baseline core design, designated Box9, consists of nine fuel assemblies arranged in a compact 3×3 array and controlled by six hafnium control blades as shown in Figure 3-2. Light water flows upward through the core, serving both as the primary coolant and as the neutron moderator, before being routed to the primary cooling system for heat removal. This compact layout establishes the baseline geometry for neutronic, thermal-hydraulic, and safety analyses used throughout the optimization study.

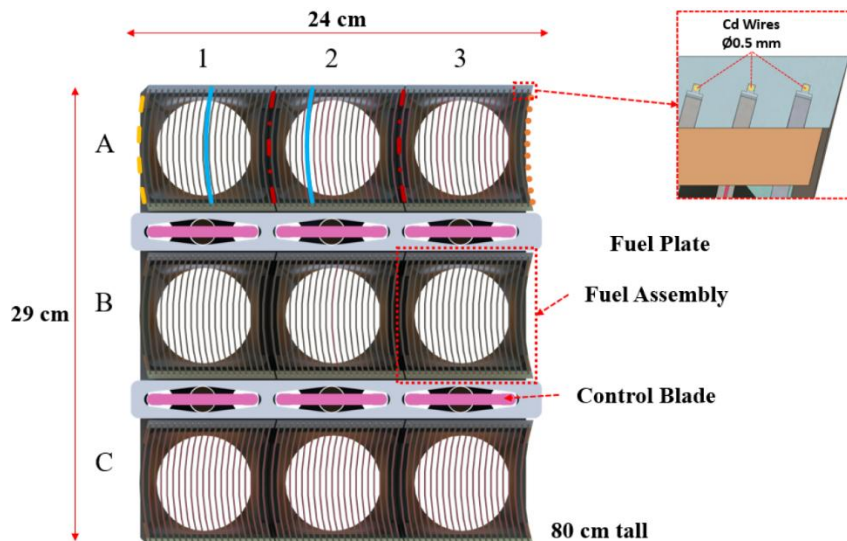


Figure 3-2. Planar view of the NNS core. [2]

Each fuel assembly has an approximately square cross section and contains 21 curved fuel plates. The baseline fuel form is based on U-10Mo foil with zirconium interlayers and aluminum cladding.

Burnable poison is also included in the baseline assembly as cadmium wires to assist in controlling excess reactivity and limiting power peaking, especially for fresh fuel.

The baseline core follows a three-batch fuel management strategy. During each operating cycle, three fresh fuel assemblies are inserted into the core, while assemblies that have already been irradiated are relocated to new positions. Each assembly remains in the core for three cycles before discharge. This approach provides a consistent and practical loading pattern for equilibrium operation and serves as the baseline fuel management scheme for the optimization effort.

Figure 3-3 provides a visual illustration of the fuel management scheme: Three fresh assemblies (identified as A-a2, B-b2, and C-c2 and green in the figure) are loaded each cycle and then moved to another position (A'-c1, B'-b3, and C'-a1, yellow) in the next cycle and then in the third and last cycle moved to a final position (A''-a3, B''-b1, and C''-c3, red). The figure also uses row/column coordinates to locate the position of the assemblies.

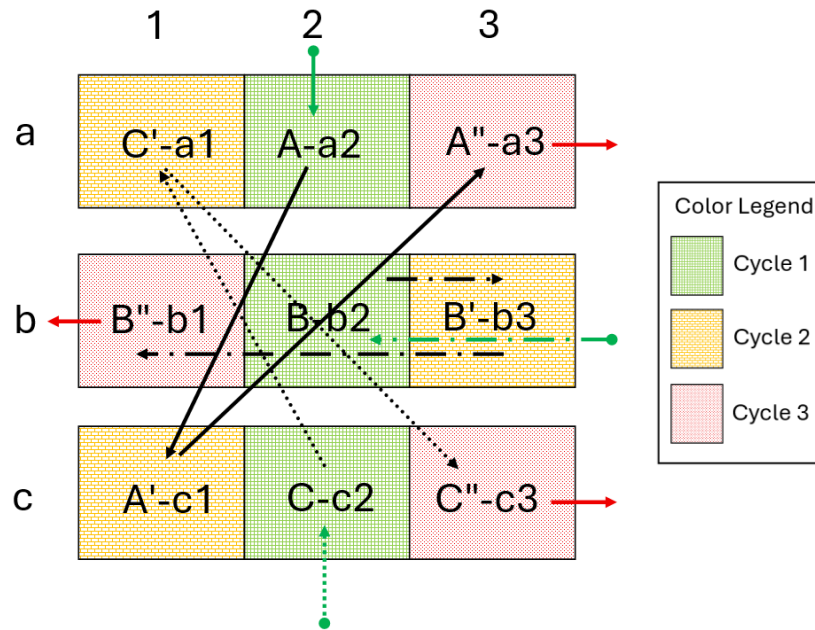


Figure 3-3. NNS fuel shuffling scheme. [2]

For analytical purposes, each fuel cycle is represented using a sequence of depletion state points spanning startup (SU), beginning of cycle (BOC), intermediate burnup conditions (MOC), and end of cycle (EOC). These state points provide the basis for evaluating reactivity behavior, required control blade positions, power peaking trends, and isotopic changes over the course of irradiation. Q2 and Q4 are two additional intermediate state points to decrease the possible errors that may result from long burnup steps. Figure 3-4 provides a visual description of the cycle states and cycle state points.

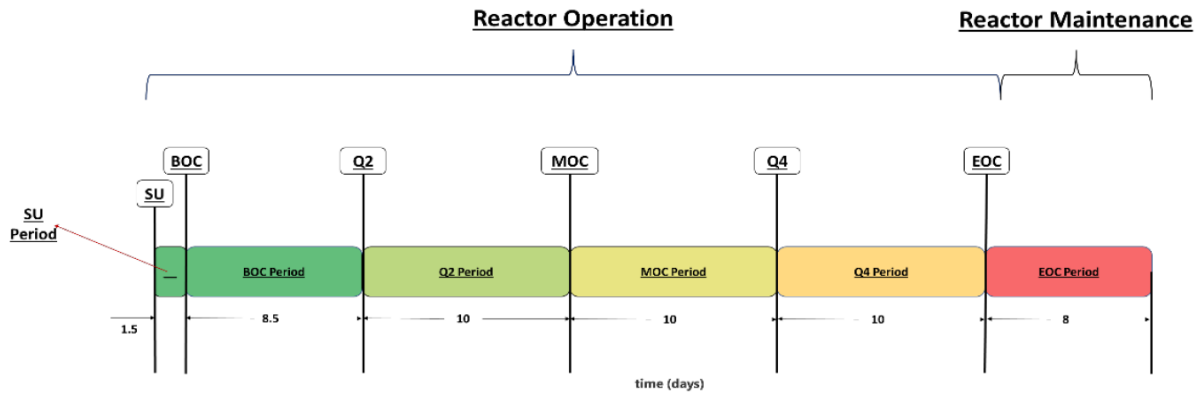


Figure 3-4. Cycle states and cycle state points. [2]

3.3 Comparative Evaluation Approach

Design alternatives are compared to the baseline design within a multi-objective framework, using a traceable set of metrics tied to proliferation resistance, reactor and experimental performance, and adequate safety margins. This comparison provides the basis for identifying practical design improvements within the pre-licensing scope of the optimization effort.

Comparisons focus on key operational and utilization aspects of the reactor, including fuel management strategies, irradiation capability, cooling capacity requirements, operating cycles, and nuclear material inventories. This approach ensures that candidate designs are considered within realistic project constraints, while still capturing the coupled neutronic, thermal-hydraulic, and operational impacts.

Comparisons are supported by physics-based neutronics and thermal-hydraulics analyses applied at a level of fidelity sufficient to quantify the impacts of design options on defined metrics and to provide a transparent technical basis for recommendations. Neutronics analyses are used to quantify reactivity behavior, power and flux distributions, fuel utilization and cycle characteristics, and inventories and isotopic composition of SFM. Thermal-hydraulic analyses are used, as needed, to assess feasibility within established operational and safety envelopes and to quantify margins to key limiting phenomena under representative steady-state conditions.

Mandatory constraints identified in Section 5 are treated as screening conditions. Candidate designs that cannot satisfy the mandatory constraints are not pursued, while design variants that satisfy those constraints are compared based on their demonstrated impacts on the applicable metrics and objectives.

4. Optimization Objectives and Metrics

This section presents the objectives used to direct the optimization effort and outlines the metrics applied to compare design alternatives. The selected metrics represent attributes relevant to proliferation resistance, mission performance, and safety at the conceptual design stage. They are intended to support structured comparison among design options, rather than to establish prescriptive acceptance criteria or provide the formal design analyses required for licensing and safety documentation.

4.1 Proliferation Resistance Objectives

A primary objective of PRO-X is to reduce the production, accumulation, and attractiveness of special fissionable material associated with reactor operation. This objective is evaluated here using metrics directly related to total plutonium production and plutonium isotopic composition.

Plutonium is generated in reactors through neutron capture in U-238. Higher burnup, resulting from longer cycle lengths and/or higher power density, generally increases total plutonium production but also raises the Pu-240 fraction, making the plutonium less attractive for misuse. Lower burnup, associated with lower power density and shorter cycles, produces less plutonium overall but with a higher Pu-239 fraction. Accordingly, two complementary proliferation resistance metrics are used: total plutonium production and plutonium isotopic composition, which together reflect both material quantity and attractiveness. Plutonium quality is characterized by the fractions of Pu-239 and Pu-240 in the total plutonium inventory of discharged fuel assemblies. These values are derived from discharged-fuel compositions calculated through core depletion analyses for each candidate configuration and are used to compare alternatives against the baseline.

The number of fresh fuel assemblies and mass of HALEU used per year are also of significance to proliferation resistance. Because of their importance to the economics of effective reactor operation, the focus on these two metrics is described as performance objectives. This is a clear example of “win-win” optimization where proliferation resistance and performance goals are in complete alignment.

4.2 Performance Objectives

The optimization framework considers proliferation resistance together with reactor performance and safe, practical, and efficient operation. For NNS, performance must be evaluated in terms of its ability to fulfill the neutron science mission, including support for cold neutron sources, thermal beam instruments, neutron guides, irradiation facilities, and future experimental expansion, while maintaining effective core operation and fuel management.

Performance is therefore assessed using metrics that capture both core utilization and experimental capability. These include fuel utilization measures and neutron flux characteristics at relevant experimental locations derived from cycle depletion behavior.

The following subsections describe the principal performance objectives and associated comparison metrics.

4.2.1 Core Design and Fuel Utilization

Improved fuel utilization offers both environmental and economic benefits. Higher discharge burnup reduces the number of fuel assemblies consumed per unit of useful neutron production, thereby lowering spent fuel generation. It also reduces fresh fuel demand and associated fuel cycle costs.

A desirable feature of the core design is a more uniform burnup distribution across the fuel. In research reactors, this can be promoted through core layouts and shuffling strategies that flatten neutron flux and better balance power generation. Within the performance objectives for NNS, the following metrics are used to evaluate fuel utilization and the effectiveness of alternative fuel management schemes:

- **Fresh fuel consumed annually.** The number of fresh fuel assemblies required per year, which is a major contributor to operating cost and directly affects the number of spent assemblies requiring storage and disposition.
- **Cycle length.** Longer operating cycles, when supported by appropriate shuffling strategies, generally enable higher burnup and improved fuel utilization.
- **Annual equivalent full-power days.** The number of days per year that the reactor can operate at full power and deliver experimental flux.
- **Assembly-average discharge burnup.** The total burnup of discharged fuel assemblies in a cycle divided by the number of discharged assemblies.
- **Peak-to-average plate burnup.** For a given fuel assembly, the ratio of the highest plate burnup to the average plate burnup at end of cycle.
- **Peak-to-average segment burnup.** In the depletion model, each plate is subdivided laterally and axially to represent local power peaking and to track the local burnup of fissile material. This metric is the ratio of the maximum local segment burnup to the average segment burnup in the assembly.
- **Fuel handling operations per cycle.** The number of fuel handling operations is of interest to both operational simplicity and proliferation resistance. Comparisons of shuffling schemes consider this metric.

These metrics are obtained from cycle-specific and equilibrium-cycle depletion analyses and are applied consistently across candidate fuel management options.

4.2.2 Cold Neutron Sources (CNS)

The performance objectives for the cold neutron source system are centered on establishing NNS as a competitive continuous neutron source facility for cold neutron science while preserving flexibility for future growth.

A principal objective is to achieve the peak unperturbed thermal neutron flux in the reflector region. At the NNS design power of 20 MW, the target value for this metric is at least $5 \times 10^{14} \text{ cm}^{-2} \cdot \text{s}^{-1}$. Because CNS performance depends strongly on the thermal neutron flux available in the reflector, candidate reactor and reflector configurations are compared in part with their ability to achieve this objective.

The reactor should also provide sufficient reflector volume and geometric flexibility to accommodate multiple large-volume cold neutron sources, multiple beam tubes viewing each source, and the associated guide layout. CNS configurations and locations should maximize source brightness while remaining compatible with practical cooling requirements and safe, stable operation.

In addition to reflector flux, the CNS performance objectives include the ability to accommodate multiple CNS units, support efficient beam extraction and guide layout, provide capacity for a large cold neutron instrument suite, and maintain flexibility for future expansion, installation, maintenance, and safe operation. These broader considerations are retained because they materially affect the suitability of a given reactor/reflector configuration as a practical CNS platform.

4.2.3 Experimental Capabilities Other than CNS

Beyond the cold neutron source mission, the reactor should support a broad set of experimental capabilities that include thermal neutron beams, thermal neutron guides, and near-core irradiation facilities. These capabilities should be incorporated in a way that preserves the primary neutron science mission, satisfies measurement needs for standard reference materials work at NIST, expands user access, and avoids significant adverse impacts on CNS performance or overall reactor operation.

For thermal neutron applications, a key objective is to preserve at least the current suite of NBSR thermal neutron beam instruments while maintaining the option to add additional thermal neutron capabilities. The design should therefore accommodate a minimum of six thermal neutron instruments and allow for future expansion where practicable. Thermal beam tubes and, where advantageous, thermal neutron guides should be arranged to maximize usable flux for thermal neutron instruments, improve instrument siting flexibility, and reduce, where possible, background conditions in experimental areas.

The placement and geometry of thermal beam tubes should be selected so that beam entrances are positioned as close as practical to the reflector flux peak, while avoiding unacceptable interference with the cold neutron system. Thermal beam provisions should be designed such that their impact on flux in the cold sources is minimized. This establishes a performance objective of balancing thermal beam capability against preservation of CNS effectiveness. Accordingly, thermal beam

options are evaluated based on usable neutron flux, beam quality, and impact on cold source performance.

The reactor should also include near-core irradiation facilities of varying size and function, including pneumatic rabbit tubes, and experiment tubes located in the reflector tank region. These facilities should support irradiation and pneumatic transfer applications with negligible detriment to the cold and thermal neutron beam missions. Accordingly, an important performance objective is to provide useful irradiation capability without materially degrading neutron beam performance or reducing reactor availability. Relevant evaluation criteria include neutron flux, spectrum, irradiation volume, and flux uniformity at the irradiation location.

In particular, to support neutron activation analysis, NNS will require two rabbit tubes favoring thermal neutron energies, at least one larger rabbit tube to accommodate atypical sample shapes, and, if possible, at least one rabbit tube favoring epithermal or fast neutron energies. Their locations and spectral characteristics should provide effective irradiation performance while remaining compatible with reflector-space constraints and without materially reducing the effectiveness of beam-based experimental systems.

To support specialized neutron science experiments requiring very low neutron energies, the reflector tank layout should retain the option for a future ultra-cold neutron source (UCNS), so long as it does not impose disproportionate penalties on reflector performance, facility complexity, or reactor operability.

Collectively, these capabilities should broaden the scientific utility of the facility and complement the primary neutron science missions.

4.3 Safety Objectives

Safety-related objectives focus on assuring adequate thermal-hydraulic margins during steady-state operation, consistent with established research reactor design best practices and licensing requirements. Although research reactors are designed to deliver neutron flux rather than thermal power, the safe removal of heat from the core must always be assured.

NCNR identified the fuel-temperature limit based on plate blistering temperature as a safety criterion and also evaluated margins to safety-related boiling phenomena: the critical heat flux (CHF), onset of flow instability (OFI), and onset of nucleate boiling (ONB) [NIST-TN-2323]. These phenomena define practical limits on fuel heat removal and therefore provide meaningful indicators of operating margin.

Within the optimization framework, candidate core design configurations are compared using safety-related metrics associated with these phenomena, including:

- The critical heat flux ratio (CHFR),
- The onset of flow instability ratio (OFIR),
- The onset of nucleate boiling ratio (ONBR),
- The maximum fuel temperature, and

- The maximum cladding temperature.

These safety metrics are evaluated using thermal-hydraulic analyses based on representative steady-state operating conditions for each candidate configuration. Transient and accident analysis is outside the scope of this optimization effort (see Section 2.2); the existing NCNR pre-conceptual transient and accident analyses [3] provide an existing safety basis against which the applicability of candidate variants can be considered. Mandatory safety and licensing requirements are treated as fixed constraints, as discussed in Section 5.4. The purpose of the optimization effort is not to establish licensing limits, but to identify design options that maintain adequate margins to established safety criteria while supporting improved proliferation resistance and mission performance.

Nuclear criticality safety considers the “shutdown margin”, i.e., the margin available for the NNS to safely shutdown with its most reactive safety/control blade fully withdrawn. Neutronic safety is treated in these studies by the concept of an “excess reactivity budget”, i.e., the space between excess reactivity of the uncontrolled core and an adequate shutdown margin. Thus, experimental device configuration and fuel management strategy include excess reactivity as part of the objective and constraint comparisons.

4.4 Multi-Objective Optimization

Research reactor optimization involves balancing multiple objectives that must be considered together rather than reduced to a single performance measure. The PRO-X framework supports comparison of candidate designs using quantified metrics across all objectives.

Design choices that influence proliferation resistance, mission performance, and safety margins are often interdependent and nonlinear, so some options can improve multiple objectives simultaneously. The objective of the optimization framework is to identify configurations where these effects are aligned or can be balanced within realistic project constraints, while making those relationships explicit to support informed decision making. Such opportunities may arise when improvements in reactor performance also reduce operational costs and special fissionable material throughput, thereby strengthening both proliferation resistance and economic performance.

Candidate options are compared to the baseline design using the metrics described in this section and the constraints identified in Section 5. Those constraints are treated as fixed screening conditions, and required mission performance is maintained to ensure that the reactor fulfills its intended functions. Proliferation resistance remains an explicit consideration throughout the evaluation, favoring solutions that reduce material attractiveness, improve fuel utilization and material management, or enhance detectability without introducing undue complexity or operational burden.

This multi-objective framework and the relationships among the key objectives are illustrated in Figure 4-1.

The outcome of the multi-objective optimization is a traceable characterization of how feasible candidate designs perform relative to the baseline and to one another across the defined objectives, rather than selection of a preferred design based on a single metric.



Figure 4-1. PRO-X multi-objective optimization.

5. Constraints and Fixed Requirements

This section identifies the constraints that bound the optimization space and ensure that proposed design options remain realistic and executable. These constraints include prior design decisions, fabrication and qualification limitations, operational considerations, licensing and safety requirements, and schedule- and procurement-driven factors. They are treated as fixed conditions for the optimization effort and are not subject to relaxation through design trade studies.

5.1 Prior Design Decisions and Fixed Architectural Features

The optimization effort, described in Section 6, is bounded by prior project decisions that establish the basic NNS reactor architecture. These decisions — which are not themselves subject to optimization — include the use of a compact light water-cooled and -moderated core with a heavy-water reflector tank, and the general mission emphasis on cold and thermal neutron beam capability. The overall control concept selected by NNCN, e.g., the use of control blades, is treated as fixed, although evaluation of material alternatives, operating strategies, and design refinements within that framework may be considered as the design matures. Candidate designs may refine the baseline design, but they are not intended to revisit the basic reactor concept or replace major architectural decisions already adopted by the project.

5.2 Fabrication and Qualification Constraints

Candidate designs must remain consistent with fabrication feasibility and the qualification status of key components. The optimization effort does not include development or qualification of new materials, fuel forms, or assembly concepts, and therefore focuses on configurations that are compatible with established or realistically supportable qualification pathways. These constraints affect the range of allowable design parameters that may be considered. Fabrication practicality is also relevant to proposed changes in assembly-level and component-level design features. Options that would depend on unqualified concepts or unrealistic fabrication assumptions are outside the bounded optimization space for this effort.

5.3 Operational Limits

Operational limits also constrain the optimization space. Candidate configurations must support the intended mission within practical operating conditions, including the nominal reactor power level, expected operating cycle structure, fuel management approach, irradiation services, and stable routine operation. Designs with excessive operational complexity, unstable control behavior, impractical cooling demands, or capabilities beyond those justified by mission requirements are not favored. Operational limits are considered together with performance requirements and proliferation resistance objectives to ensure that candidate options remain operable, maintainable, licensable, and compatible with the expected operating envelope of the facility. Candidate options that would introduce unacceptable operational burden or compromise the stability and predictability of routine reactor operation are outside the bounded optimization space for this effort.

5.4 Licensing and Safety Constraints

NNS will likely be regulated by the NRC and its requirements associated with the construction permit (CP) and operating license (OL) process. Licensing and safety requirements impose non-negotiable constraints on the design space by establishing acceptable operating conditions, safety margins, and design requirements that candidate configurations must satisfy. These constraints influence allowable operating power, cooling capacity, fuel design, core configuration, and other features that affect reactor safety and licensing. Candidate designs must remain consistent with applicable regulatory requirements, the project's licensing basis, and the safety envelope established by prior NCNR analyses.

5.5 RFI/RFP and Supply Chain Constraints

Procurement and supply-chain considerations may impose additional constraints on the design space as the project progresses. Feedback from the RFI process may identify new design, fabrication, or implementation limits that should be incorporated into subsequent specifications for the RFP. Vendor proposals may introduce additional constraints associated with their design approaches, fabrication capabilities, or construction methods. In later project phases, supply-chain availability and quality-program requirements may further constrain material and component selections.

6. NNS Research Reactor Design Optimization Variables

This section identifies and describes the principal design variables available for optimizing the NNS reactor, examining how each influences both proliferation resistance and reactor performance. Each variable represents an engineering degree of freedom whose adjustment propagates through the coupled neutronics, thermal-hydraulics, and safety analyses, requiring systematic evaluation against the dual objectives of strengthened proliferation resistance and sustained mission capability.

The principal design variables are organized into four categories: fuel system and assembly design (Section 6.1), fuel management including shuffling and power peaking mitigation (Section 6.2), experimental facilities including cold sources, beam tubes, rabbit tubes, and an optional ultracold neutron source (Section 6.3), and cooling capacity for the core and irradiation facilities (Section 6.4). Table 6-1 summarizes the relationships between the principal design variables and their associated proliferation resistance and performance benefits.

Table 6-1. Optimization design variables and their proliferation resistance and performance benefits

Design Variable	Proliferation Resistance Benefit	Performance Benefit
Fuel system and fuel assembly design (e.g., U-10Mo monolithic versus U ₃ Si ₂ -Al dispersion; Box9 versus expanded footprint)	Enables systematic evaluation of how fuel form, uranium density, absorber integration, and assembly geometry affect fissile inventory, annual fresh fuel throughput, spent fuel generation and attractiveness, plutonium production, and material attractiveness—supporting selection of a fuel system that strengthens intrinsic proliferation resistance while remaining within the HALEU design space.	Enables evaluation of how fuel form and assembly geometry affect compact-core feasibility, cycle length, power distributions, control requirements, thermal-hydraulic margins, and neutron delivery to experimental facilities—supporting selection of a fuel system that best satisfies mission and operating objectives.

Design Variable	Proliferation Resistance Benefit	Performance Benefit
Fuel management strategy (fuel shuffling and loading patterns)	Reduces throughput of fresh and spent fuel, supports more uniform discharge burnup and less attractive discharge isotopics, minimizes standing fissile inventory and annual plutonium production, and promotes predictable operating behavior that improves material accountancy and detectability of undeclared activity.	Improves fuel utilization and discharge burnup uniformity, supports the target cycle length, reduces annual fuel demand, flattens power distributions, and helps maintain stable control blade requirements across the fuel cycle.
Fuel assembly features to limit power peaking (discrete burnable absorbers, poison wires, integral absorber concepts, water displacers)	Reduces excess reactivity and moderates the need for large fresh-fuel reactivity loadings; promotes more uniform burnup and can reduce fuel throughput and standing fissile inventory, thereby improving PR-related material flow characteristics.	Mitigates radial and local peaking, improves critical heat flux and cladding temperature margins, reduces reactivity swing, and can preserve or extend cycle length while supporting compact-core operation.
Cold neutron source configuration (number, location, diameter, height, cavity geometry, orientation)	Helps identify configurations that support CNS performance without unnecessary increases in core size, fissile inventory, or fresh fuel demand.	Maximizes cold neutron brightness, usable cold neutron current, and guide illumination while balancing spectral quality, heat load, and compact-core coupling; supports high-value cold neutron mission capability.

Design Variable	Proliferation Resistance Benefit	Performance Benefit
Thermal beam tube and waveguide configuration	Defines thermal beam access consistent with the declared neutron mission while limiting unnecessary reflector displacement and excess neutron leakage paths that could otherwise drive compensatory increases in core reactivity demand.	Provides high-quality thermal beams for diffraction, spectroscopy, imaging, and related applications; allows optimization of beam brightness, background, and instrument placement through tangential tube arrangement and guided delivery where beneficial.
Rabbit tube configuration (thermal, epithermal, fast, and bulk irradiation positions)	Aligns the number, location, sizing, and capacity of irradiation positions with the intended analytical mission while considering material access and operational pathways.	Provides irradiation capability for neutron activation analysis and related analytical services with spectrum, flux uniformity, and access matched to mission needs while minimizing interference with primary beam and cold source systems.
Optional ultracold neutron source integration	Supports evaluation of future UCNS capability as a coupled reflector-region design variable, including its implications for core size, fissile inventory, and other mission systems.	Enables potential future ultracold neutron capability for fundamental physics while preserving flexibility to optimize placement so that primary cold and thermal neutron performance is not degraded.

Design Variable	Proliferation Resistance Benefit	Performance Benefit
Cooling capacity for core and irradiation facilities (CNS, UCNS)	Avoids unnecessary excess cooling capacity beyond that required for safe operation and the declared mission, thereby reducing opportunities for undeclared power uprates and limiting excess capability that could support non-mission irradiation activities.	Rightsizing cooling capacity reduces both capital and operating cost.

The baseline NNS configuration described in Section 3.2 serves as the reference point from which optimization proceeds. Quantitative design space boundaries are provided in Appendix A.1.

6.1 Fuel System Selection and Fuel Assembly Design

Fuel material selection simultaneously impacts proliferation resistance attractiveness, core compactness, cycle length, power peaking, and the feasibility of the Box9 footprint. Three candidates are currently under consideration:

1. **U-10Mo monolithic fuel** (baseline): U-Mo alloy foils with Zr interlayer, clad in Al-6061. Undergoing qualification under the USHPRR Conversion Program [2, Sec. 3.2.2].
2. **U₃Si₂-Al dispersion fuel** (alternative): U-silicide particles in an Al matrix, clad in Al-6061. Well-established qualification basis at approved fuel densities; power levels and temperatures; expanded envelope currently being tested by the EU. Feasibility being considered in [2] and supporting analyses by Celikten, Weiss, and Sahin (2023).
3. **U-7Mo/Al dispersion fuel** (alternative): γ -phase U-7wt%Mo particles in an Al matrix, clad in Al-6061. Higher uranium loading than U₃Si₂-Al but susceptible to adverse fuel-matrix interaction layer growth; mitigated by Si addition to the matrix. Extensively irradiation-tested but not yet fully qualified in operation for high-performance reactor conversion.

6.1.1 Uranium Density and Core Compactness

The candidate fuel systems provide different achievable uranium densities and therefore may lead to different core, assembly, and fuel-management configurations. The baseline U-10Mo design supports the current compact nine-assembly core. Alternative dispersion fuels may require

adjustments to assembly geometry, fuel loading, core footprint, or operating strategy to achieve the NNS cycle-length and flux objectives. These interactions make fuel-system selection a primary coupled optimization variable.

6.1.2 Coupled Design Considerations for the Dispersion Fuel Alternatives

If U_3Si_2 or U-7Mo dispersion fuel is selected as the preferred fuel-system option, potential compensating modifications may need to be considered including:

- **More fuel assemblies** (e.g., 4×3 or 4×4 array): may increase available ^{235}U inventory and support longer cycle lengths, but would also enlarge the core and could reduce some of the reflector-flux advantages associated with the compact baseline design [2, Fig. 3].
- **Larger assembly cross-sections** while retaining the 3×3 array: preserves grid plate geometry and overall core arrangement but increases core size, with corresponding impacts on core and reflector performance.
- **More plates per assembly or thicker fuel meat**, subject to thermal-hydraulic constraints on coolant channel width [2, Table 5-2].
- **Shorter cycle length**, which may make it more difficult to satisfy the operational and mission-performance requirements established for the NNS. [2, Requirement R4.1].

From a proliferation resistance perspective, a larger core may increase fissile inventory and annual fresh fuel throughput—both relevant to the proliferation resistance assessment. The relative ease of direct recovery of uranium from the different fresh fuel forms may also inform proliferation resistance.

6.1.3 Fuel Assembly Geometry Variables

Regardless of fuel type, the fuel assembly geometry presents multiple optimization variables including the number of plates per assembly, fuel meat and cladding thicknesses, active fuel height, burnable absorber configuration, and coolant channel geometry.

Changes propagate through neutronics, thermal-hydraulics, and safety analyses. For example, thicker fuel meat improves U-235 loading but narrows coolant channels, potentially degrading thermal margins.

6.1.4 Grid Plate Implications

For the baseline U-10Mo case, the 3×3 footprint defines the baseline Box9 core arrangement. For U_3Si_2 , departures from that footprint may need to be considered to maintain required cycle length and performance. Departures from the baseline footprint will be assessed for their impacts on the thermal-flux objective at the CNS locations, fissile inventory, plutonium production, and other applicable metrics. Changes to core geometry also alter the preferred shuffling pattern (Section

6.2.1), burnable absorber effectiveness (Section 6.2.2), and the geometric relationship with experimental facilities (Section 6.3).

The quantitative parameters and baseline values for the fuel assembly geometry variables are provided in Appendix A.2.

6.2 Fuel Management Optimization

Fuel management encompasses loading, shuffling, and discharge strategies which directly affect cycle length, power peaking, burnup uniformity, fissile inventory, plutonium production, and fresh fuel throughput—all central to both proliferation resistance and performance.

6.2.1 *Fuel Shuffling Strategy*

The baseline design employs a three-batch, in-out loading scheme in which three fresh assemblies are loaded into the center column for each cycle and progressively moved to peripheral positions over three cycles before discharge. This scheme achieves the target cycle length and capacity factor.

However, several characteristics of the baseline scheme motivate evaluation of alternative fuel management approaches. Alternative loading and shuffling strategies will be examined to assess their impacts on fuel utilization, reactor performance, and proliferation resistance relative to the baseline fuel management strategy.

Alternative fuel management schemes are proposed for evaluation:

Alternative A (Out-In Loading) places fresh fuel at the periphery and moves burned fuel inward toward the center. This reduces the material attractiveness of the discharged fuel assemblies, enables additional burnup from the highest-flux center positions, and may improve the burnup uniformity of discharged assemblies. However, the ability to sustain the target cycle length and the effect on control blade worth must be verified.

Alternative B (Scatter Loading) distributes fresh fuel across non-adjacent positions rather than concentrating it in a single column. This approach may reduce core power tilt, improve power uniformity, and distribute fissile material more uniformly. However, these potential benefits and the associated impacts on operational complexity and cycle behavior should be evaluated.

The detailed shuffling pathways, baseline characteristics motivating the alternatives, and evaluation metrics are provided in Appendix A.3.

These two alternatives are not exhaustive; additional shuffling schemes—including rotated loading patterns and configurations tailored to optimize ex-core performance such as cold source spectrum and rabbit tube irradiation conditions—will also be considered as the fuel management study progresses.

6.2.2 Fuel Assembly Features to Limit Power Peaking

Reducing power peaking increases the thermal safety margins and supports more uniform burnup, which benefits both safety and PR. The baseline design incorporates cadmium burnable absorber wires that effectively suppress fresh-fuel reactivity early in the cycle but deplete rapidly, causing a mid-cycle power shift to second-cycle assemblies indicated by preliminary analysis.

Four categories of peaking mitigation features are considered as optimization variables:

- **Discrete burnable absorbers** (baseline cadmium wires), with optimization of wire material, diameter, placement, and number per assembly.
- **Integral burnable absorbers** (applicable to dispersion fuel), where absorber particles are distributed throughout the fuel matrix for more spatially uniform flux suppression.
- **Alternative poison wires** using materials with different depletion characteristics to provide more gradual and sustained reactivity suppression over the assembly lifetime.
- **Water displacers** that reduce local moderation in the outermost coolant channels to mitigate peripheral plate peaking.

Each option is evaluated against criteria including reactivity swing reduction, peak-to-average power ratio, impacts on thermal margins, and cycle length preservation. The quantitative peaking values, baseline thermal margins, and evaluation criteria are provided in Appendix A.4.

6.3 Experimental Capabilities

The experimental facilities are coupled optimization variables whose locations, geometries, and performance requirements interact with core neutronics, reflector perturbations, and proliferation resistance considerations. The NNS is mission-driven, with its primary function being the delivery of cold and thermal neutron beams. Experimental facilities are evaluated together with the core and reflector to support scientific throughput while accounting for proliferation resistance and safety considerations.

6.3.1 Cold Neutron Sources

The CNSs are central to the primary neutron-science mission of the NNS. The compact core design produces a substantially higher peak thermal flux in the reflector than its predecessor NBSR at equivalent power, because the flux peaks *outside* the fuel where CNS thimbles can access it [5]. Changes that increase the size of the core may alter this favorable flux distribution and therefore affect CNS performance.

The cold source configuration presents multiple optimization variables including the number of sources, their location relative to the core, moderator vessel diameter and height, and re-entrant cavity geometry. Each variable involves interactions between cold neutron brightness, spectral quality, nuclear heat load, and the degree of reflector perturbation.

Core–CNS Interaction

The CNSs displace reflector volume and introduce cryogenic materials that perturb the local flux environment, affecting adjacent beam tubes and nearby fuel. These interactions are assessed using applicable CNS performance objectives, including the impact of thermal beam tube placement on CNS flux.

From a proliferation resistance perspective, the cold source configuration supports mission performance without requiring unnecessary increases in core size or fissile inventory, favoring efficient use of the compact HALEU core. The quantitative performance metrics, baseline parameters, and interaction data are provided in Appendix A.5.

6.3.2 Thermal Neutron Beam Tubes/Waveguides

The baseline design includes multiple thermal beam tubes arranged tangentially to the core. This arrangement allows the tubes to view the reflector thermal flux region while limiting direct line-of-sight to the fuel, thereby reducing the fast-neutron and high-energy gamma contributions. This configuration can potentially provide substantially higher thermal brightness than the predecessor facility at equivalent power.

Optimization variables include the tube cant angle, cross-section dimensions, and the use of supermirror thermal neutron guides for instruments located far from the biological shield. Key interaction considerations include cumulative reflector displacement from all beam penetrations, neutron streaming through shield penetrations, and the effect of nearby beam tubes on fuel assembly power distribution. Beam penetrations are also physical protection considerations whose number and provisions should be evaluated within the facility protection assessment.

The quantitative brightness comparisons, guide performance data, and position optimization results are provided in Appendix A.6.

6.3.3 Pneumatic/Hydraulic Rabbit Tubes

Rabbit tubes support neutron activation analysis and related analytical services that are central to the NIST measurement mission. No baseline positions are established in the preconceptual design; locations remain open design variables. Mission requirements for neutron activation analysis define the desired flux, spectral, and operational characteristics for candidate rabbit tube locations.

Operating experience from the predecessor facility provides important benchmarks regarding flux gradients, spectral characterization, temporal stability, and gamma heating constraints. These benchmarks help define the requirements and candidate locations for rabbit tube optimization.

Candidate rabbit-tube configurations may include positions optimized for different irradiation spectra and flux conditions, while avoiding interference with the primary beam and cold source systems. The rabbit tube layout is coupled to the neutron detector positioning, as detector response should not be materially affected by rabbit loading and unloading operations.

Key optimization considerations include competition for reflector space with beam and cold source systems, the cumulative reactivity impact of multiple tubes on the core excess reactivity budget, the relationship between flux magnitude and gradient steepness at different radial positions, and proliferation resistance considerations associated with providing material insertion and retrieval pathways in high-flux regions. Tube sizing and sample capacity should align with the requirements of the intended analytical mission.

The quantitative flux data, spectral parameters, reactivity impact, proposed layout, and NAA requirements table are provided in Appendix A.7.

6.3.4 Ultracold Neutron Source

An ultracold neutron source is proposed as an optional capability for fundamental physics experiments. The UCNS is treated as a coupled design variable, because the converter vessel and its cryogenic infrastructure can significantly perturb local moderation and reflector conditions.

The proposed location is within the heavy water reflector, on a side of the core that does not compete with the cold neutron sources. The UCNS is not expected to directly compete geometrically with the currently identified cold-source and primary beam facilities. Several design couplings must still be considered, including the converter vessel displacement of reflector volume, local neutronic effects, cryogenic system integration, and additional shield penetrations for neutron extraction.

Since future UCNS capability is desired, the impact of a UCNS-sized perturbation is to be evaluated in computational models from the conceptual design phase onward, even if construction is deferred. This ensures that the reflector tank geometry, beam tube layout, and shutdown systems accommodate a future UCNS without fundamental redesign.

The quantitative performance parameters, proposed location details, and coupled design considerations are provided in Appendix A.8.

6.4 Cooling Capacity Optimization for Core and Irradiation Positions

Cooling capacity is a critical design parameter that intersects proliferation resistance, reactor safety, and operational robustness under expected operating conditions. The pre-conceptual baseline Box9 design includes a primary cooling system design based on NBSR components but permits optimization as the design matures [3].

The optimization effort addresses rightsizing of the primary cooling system that serves the core and irradiation positions, together with the separate cooling systems that serve the two CNS and that would serve a potential UCNS. The objective is to match cooling capacity to the optimized configuration so that the declared mission is supported with adequate thermal margins and without unnecessary excess capacity that could support undeclared power uprates or non-mission irradiation activities. The rightsizing is informed by upstream design choices in fuel system, fuel

plate and assembly geometry, fuel management strategy, core layout, and power peaking mitigation.

From a safety perspective, sufficient cooling capacity must be maintained to maintain adequate margins against the thermal-hydraulic screening metrics identified in Section 4.3, and rightsizing changes must not diminish the passive natural circulation feature in the pre-conceptual design. From a proliferation resistance perspective, avoiding unnecessary excess cooling capacity that does not support the declared mission helps reduce opportunities for misuse of the reactor and associated experimental facilities, and may provide operational indicators of departures from declared operating conditions.

The scope of this evaluation is limited to establishing cooling capacity requirements, including total flow and heat removal capability for the primary cooling system and for the cold source cryogenic systems. As established in Section 2.2, detailed mechanical design of the primary cooling system, of the cold source cryogenic infrastructure, and of auxiliary and balance of plant cooling systems is outside the scope of this effort.

7. Implementation

This section describes how the optimization effort will be carried out across the collaborating organizations. It defines each organization's focus and lays out the approach for analyzing and down-selecting design features to arrive at optimized designs.

7.1 Areas of Focus for Each Organization

7.1.1 *NCNR (NIST)*

NCNR owns the development of the NNS design. They define the NNS mission space and operational objectives with the performance requirements and technical specifications needed to support them. NCNR will document the capabilities needed to support the neutron science work planned at NNS, including any specific requirements related to the irradiation locations and conditions (rabbits, neutron spectrum, and flux). These are reflected in the optimization plan as performance objectives (Section 4.2). NCNR will also specify any fixed prior design features and architecture, which will be reflected as design constraints (Section 5.1). This includes mission-driven requirements that shape core configuration, experimental facility needs, reflector features, and other architectural assumptions that bound the design space for the optimization effort. Additionally, NCNR will also provide concurrent data and documentation where appropriate to support the optimization processes. This includes (but is not limited to) alternative models, alternative analyses, reviews, technical basis evaluations, clarifications on acceptance criteria or regulatory requirements, and benchmarking data sets.

7.1.2 *Argonne National Laboratory*

Argonne supports the ongoing NNS design effort through independent analyses, verification activities, and assessment of design alternatives. Acting as an extension of the design team, Argonne explores a broader set of design options and parameter variations than would typically be practical within a single organization and identifies potential engineering solutions within the multi-objective PRO-X framework (Figure 4-1). Argonne's independent neutronics and thermal-hydraulic analyses assess the implications of various design configurations and variables to identify opportunities to strengthen proliferation resistance and improve performance. Fuel management strategies and other design considerations are also explored to inform ongoing design refinement. Argonne's cross-verification of analysis approaches provides additional technical confidence in the analytical methods used to support the NNS design effort. Together, these activities provide technical insight that informs NCNR's evolving reactor design framework and supports subsequent design decisions as the project advances.

7.2 Prioritization of Optimization Efforts

The optimization topics identified in Section 6 will be pursued with differing levels of emphasis as the conceptual reactor design continues to evolve. While certain topics may warrant greater

attention, these activities are not intended to proceed in a strictly sequential manner. Several lines of inquiry will advance in parallel, and insights gained in one area could inform analyses in others. This approach reflects the coupled nature of the design variables (Figure 4-1). Throughout this process, the analyses will seek to identify design options that strengthen proliferation resistance while supporting reactor performance and adequate safety margins.

Early emphasis is placed on technical areas that establish the basic behavior of the core and strongly influence later optimization choices. These include fuel-system selection, core compactness, and major assembly-design features, because they directly affect cycle length, reflector performance, power distribution, thermal margins, and the feasibility of the baseline core configuration (Section 6.1). These analyses establish the initial understanding of core behavior, fuel utilization characteristics, and the associated implications for proliferation resistance.

As viable core and fuel-system options are established, fuel management becomes a major line of inquiry. Alternative loading, shuffling, and discharge strategies are then used to improve understanding of cycle behavior, burnup uniformity, power peaking, fissile inventory, fresh fuel throughput, and associated proliferation resistance considerations (Section 6.2). These studies also help clarify the role of control blade usage and related operating strategies as the core configuration becomes more clearly defined.

Evaluation of cooling system requirements proceeds in parallel with these efforts (Section 6.4). As neutronics and fuel-management analyses provide improved understanding of power distributions and thermal loads, cooling requirements for the core and irradiation facilities can be refined accordingly. This allows cooling capacity to be aligned with the expected operating envelope of the optimized configuration rather than carried forward with unnecessary excess.

The design and placement of irradiation positions, beam tubes, and other experimental facilities (Section 6.3) are likewise refined iteratively as mission needs and core behavior become better defined. These studies examine how facility location, geometry, and associated cooling or shielding provisions affect neutron flux conditions, reflector performance, and interactions with other mission systems.

Some design refinements, such as alternative burnable poison configurations or control programming strategies, are best evaluated after the primary aspects of the core configuration and fuel management approach are better established. These later-stage studies can then focus on improving peaking behavior, reactivity behavior, thermal margins, and operational stability within a more clearly defined design context.

The optional ultracold neutron source requested by NCNR is treated within this same prioritization framework as an additional coupled design variable rather than as an automatic add-on. Its evaluation depends on how earlier core and reflector choices define the available geometric, neutronic, and operational margin.

7.3 Structured Decision Approach

The structured decision approach supports technically sound, transparent, and defensible decision-making throughout the design optimization. It uses an iterative process to refine candidate designs as new insights emerge. Key features are:

- Baseline design – evaluate all options against a chosen reference design
- Iteration – refine design based on new results and information
- Parallel lines of inquiry – assess coupled technical areas simultaneously
- Screening – eliminate non-viable options
- Down-selection – eliminate underperforming options to focus on the most promising
- Win-win focus – favor solutions that improve multiple objectives simultaneously

Starting with the declared requirements and constraints and using the baseline design as a reference, adjustable design features and ranges of associated variable values are identified, potentially creating a large set of candidate designs. The structured decision approach enables efficient examination of this set through staged assessments that progressively screen and down-select weaker candidates, focusing analysis on the most promising ones before introducing additional variables and new studies.

Design candidates are evaluated against the baseline design and each other, but each variable is not evaluated in the same way, with the same weight, or at the same stage. As described in Section 7.2, early focus on primary variables supports efficient down-selection and accelerates progression toward an optimized design. Each evaluation provides insights that may refine or extend the design space with new lines of inquiry.

The process can be visualized as the expansion and reduction of a candidate matrix, as shown in Figure 7-1. In this example, five candidates with one variable parameter are represented as a 5×1 matrix. These candidates are evaluated against defined criteria (Section 4). Options that pass (green) move to the next stage of analysis, while those that fail are excluded from further consideration (grey crosshatch). Results from one stage of analysis inform the selection of additional parameter values and the incorporation of additional variables (outlined in blue). The matrix expands as additional variables or values are added and is reduced when options are screened out. External factors such as an emergent logistical barrier may fix a variable or eliminate individual candidates at any point (red “X”). Different evaluation criteria may be used at each stage, and later analyses may focus on the strongest remaining cases (the excluded lower performing options are marked with “-”).

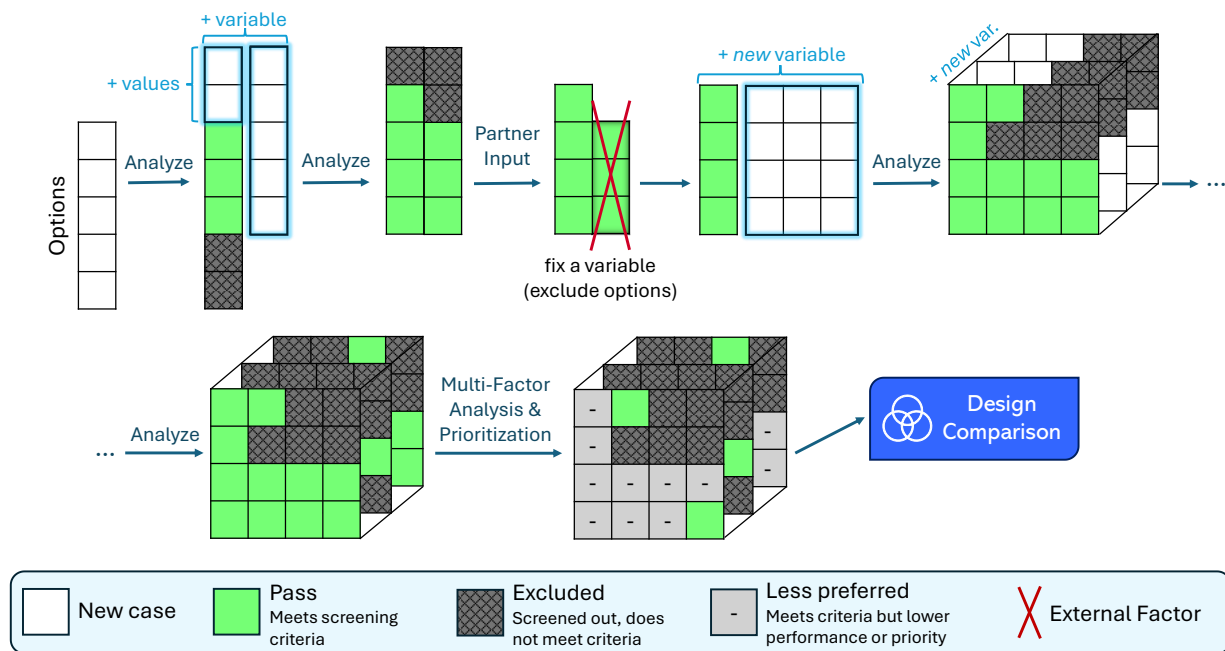


Figure 7-1. Simplified evolution of a design matrix.

In practice, many design variables are strongly coupled, so the process is not linear. Instead, it proceeds iteratively through multiple parallel lines of inquiry. As system interactions become better understood, analyses and parameter values may be adjusted. As mission goals and performance needs are refined by NCNR, variables may be constrained and evaluation criteria may change, expanding or reducing the candidate matrix.

Candidates that are screened out are documented with the basis for exclusion so decisions remain transparent and can be revisited if constraints or criteria change. Dependencies or interactions between design choices are also documented.

At early stages of the analysis, candidate options must first satisfy required mission-performance and safety conditions to remain under consideration. Among options that meet these conditions, subsequent down-selection will favor those that provide the most beneficial combination of proliferation resistance, operability, and resource utilization. An example would be two fuel-management options that both satisfy cycle-length and safety requirements, but differ in fresh fuel throughput, discharge burnup, or fissile inventory. In such cases, the option with stronger proliferation resistance characteristics or more efficient resource use may be carried forward for additional refinement.

The optimization effort proceeds as a sequence of assessments and decisions where high-impact variables receive early emphasis and multiple lines of inquiry inform one another. As the project advances, it will produce better-informed design recommendations and decision-support products, translating optimization insights into actionable design, system integration, and procurement guidance. A simplified view of the process is shown in Figure 7-2.

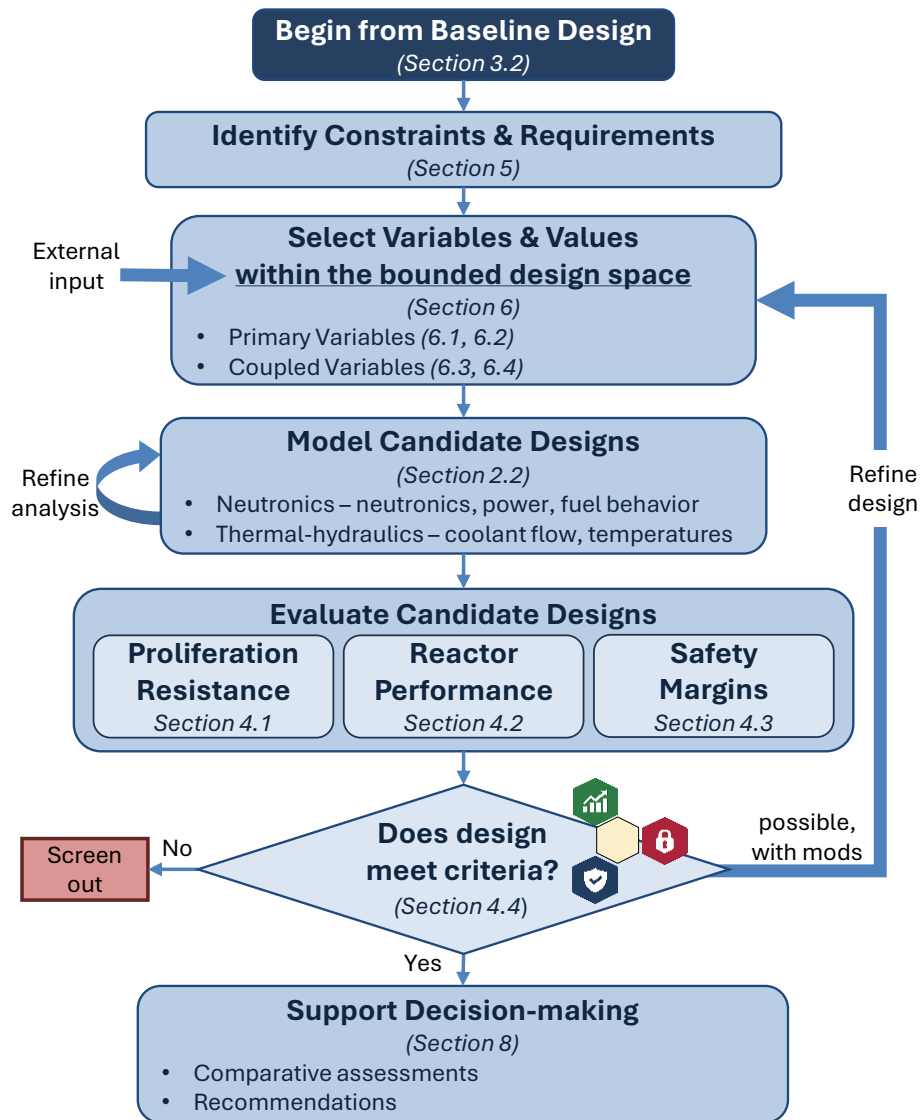


Figure 7-2. PRO-X design optimization process.

8. Expected Outputs and Path Forward

This section summarizes the expected outputs of the optimization effort and explains how they support subsequent project activities. It describes how results will inform conceptual design refinement, RFI/RFP activities, and engagement during future project phases.

8.1 Expected Technical and Decision Support Outputs

This collaborative project is intended to produce a focused set of technical and decision-support outputs that enable informed design decisions for the NNS during the transition from conceptual design toward procurement and detailed design. The outputs emphasize clarity, traceability, and relevance to project decision making rather than exhaustive analysis.

Key deliverables include a clearly defined baseline design and a set of candidate designs, together with comparative assessments of their impacts on proliferation resistance, mission performance, and safety margins. Results will be synthesized into decision-ready products—such as summaries of the feasible design space, comparative tables, and sensitivity observations—that highlight where design choices provide clear benefits, involve important tradeoffs, or warrant further investigation.

In addition, the project will produce concise technical recommendations that capture the implications of the optimization results for key reactor design features. These recommendations will summarize findings related to topics such as promising fuel assembly design paths, fuel management approaches, irradiation facility characteristics, and cooling capacity expectations, based on the comparative analyses performed in this study. The recommendations will be structured so they can be used directly in conceptual design updates, procurement documentation, and vendor engagement discussions, while remaining consistent with the pre-licensing nature of the work. Collectively, these outputs will support design down-selection, prioritization, and later project decisions.

8.2 Integration into Conceptual Design Updates

The results of this optimization effort are intended to be directly integrated into ongoing conceptual design updates for the NNS. Rather than generating standalone studies, the work is structured to inform the controlled refinement of the project baseline by adapting assumptions, constraints, and design choices already under consideration.

Integration is expected to occur through coordination among the technical team and is led by NCNR. NCNR will also be the primary interface with the future prime contractor supporting overall facility engineering and implementation. Within this structure, optimization outcomes provide a technical basis for updates to conceptual core descriptions, interface definitions, and design envelopes relevant to both core and facility-level systems.

This approach supports consistent reflection of proliferation resistance, performance, and safety considerations across core and facility design elements while preserving alignment with project's licensing strategies and previously established design constraints.

8.3 Support for RFI/RFP Issuance and Evaluation of Responses from the Vendor Community

The Request for Information (RFI) issued by NIST is the initial opportunity to receive documented feedback from the research reactor vendor community regarding the NNS project. This feedback leverages their commercial experience to help develop a robust Request for Proposals (RFP). To maximize the value of the RFI, the project should provide sufficient performance requirements and design constraints to support actionable vendor feedback.

The combined NIST/PRO-RR effort will help ensure that proliferation resistance considerations are reflected in the conceptual design requirements and constraints alongside mission performance and safety objectives. Additionally, the PRO-RR team will work with NIST to explicitly incorporate proliferation resistance objectives into the RFI and in assessing how vendor responses address them alongside the project's technical requirements and design constraints. This process also provides an opportunity to emphasize mission performance and utilization objectives rather than relying on reactor power alone as a measure of capability.

The RFP is the beginning of the procurement process for the NNS project at NIST. The RFP will be developed and managed by the NIST team and their contracting office. It should describe, to the extent possible, the technical performance requirements, design constraints, proliferation resistance considerations, and other requirements that vendors must satisfy.

The PRO-RR team will support NIST by reviewing the draft RFP prior to issuance and will work with NIST in responding to any requests for additional information (RAIs) from the vendors as they evaluate the RFP. Once proposals are received from the vendor community, the PRO-RR team will assist the NIST team in assessing how the proposals address the proliferation resistance considerations of the NNS project.

8.4 Engagement with Selected Research Reactor Vendor

The framework and results developed through this optimization effort provide a technical basis for supporting design decisions as the NNS project progresses through procurement, detailed design, and implementation. As a result, continued PRO-RR engagement is expected to focus on targeted technical questions where independent analysis or technical assessment may be beneficial rather than on ongoing optimization of the evolving design.

Continued PRO-RR engagement may also include technical consultation with NCNR during design refinement and support for interpretation of vendor or contractor feedback received through NCNR-led procurement and engineering processes. In addition, the framework may assist NCNR in evaluating proliferation resistance considerations associated with design updates. It may also provide context for addressing questions that arise during interactions with the U.S. Nuclear

Regulatory Commission (NRC) as part of the regulatory review process. In such cases, the role of the PRO-RR effort would be advisory in nature, providing analytical insight where helpful while maintaining alignment with NCNR's responsibilities for design authority, licensing activities, and formal design calculations that support licensing and safety documentation.

Acknowledgement

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Appendix A. Technical Basis for Section 6

This appendix provides the quantitative parameters, baseline values, figure and table cross-references, and supports technical data for each subsection of Section 6. The structure mirrors the main body.

A.1. NNS Design Space Boundaries

The optimization study is conducted within a defined design space that establishes the fixed constraints and adjustable parameters for the NNS reactor configuration. These boundaries specify the reactor power level, core geometry, reflector and moderator concepts, fuel enrichment, cold neutron source placement, and mission-driven irradiation requirements. Together, they define the envelope within which all design variables identified in Section 6 are evaluated, ensuring that proposed modifications remain physically realizable, safety-compliant, and consistent with the declared facility mission. The specific boundaries are as follows:

- **Reactor power:** Up to 20 MW thermal [2, Sec. 2.1].
- **Core footprint:** 3×3 grid plate (baseline); expandable if required by fuel selection.
- **Reflector concept:** D₂O reflector tank with H₂O reactor pool (baseline) [2, Sec. 3.2.4].
- **Fuel plate envelope:** Fixed for U-10Mo; adjustable for alternative fuel.
- **CNS locations:** Baseline at (±45 cm, 0 cm) from core center [4, Sec. 2.1.1]; justified modifications permitted.
- **Enrichment:** HALEU, 19.75 wt% U-235.
- **Cycle length:** ≥ 40 days [2, Requirement R4.1].
- **Peak unperturbed thermal flux:** ≥ $5 \times 10^{14} \text{ cm}^{-2}\text{s}^{-1}$ at CNS locations [2, Requirement R1.2].
- **Irradiation mission:** Per NIST SP 1327 [2], Sections 2.1 and 9.4.

A.2. Fuel System Selection and Fuel Assembly Design

Uranium Density and Core Compactness

U-10Mo provides 15.4 g/cm³ uranium density, yielding 728 g ²³⁵U per fresh assembly (34.7 g/plate × 21 plates) [5, Sec. 2]. The equilibrium core at startup contains ~32.2 kg uranium and ~92 g plutonium [5, Sec. 2]. The dispersion fuel candidates have lower uranium density. For example, U₃Si₂-Al achieves only ~5 g/cm³, roughly 1/3 of U-10Mo loading per plate for identical geometry.

Preliminary scoping analyses indicate that maintaining the target cycle length within the baseline nine-assembly Box9 configuration may require compensating design changes if U_3Si_2 fuel is selected.

Fuel Assembly Geometry Variables

Regardless of fuel type, the following parameters are optimization variables:

Parameter	Baseline Value	Reference
Plates per assembly	21	[2, Sec. 3.2.2; 3, Sec. 2]
Fuel meat thickness	0.025 cm	[5, Fig. 8]
Cladding thickness	0.0415 cm	[2, Sec. 3.2.2]
Active fuel height	70 cm (in 80 cm plate)	[5, Fig. 7]
Cd wire diameter	0.05 cm, along 41 cm	[2, Sec. 3.2.2; 3, Fig. 8]
Coolant channel geometry	Per [2, Table 5-2]	[2, Table 5-2]

A.3. Candidate Fuel Management Strategies

Baseline Fuel Management

The current design employs a three-batch, in-out scheme, described by the following:

- **Cycle 1 (fresh):** A-a2, B-b2, C-c2 loaded into center column.
- **Cycle 2 (once-burned):** A-a2→A'-c1, B-b2→B'-b3, C-c2→C'-a1(peripheral positions).
- **Cycle 3 (twice-burned):** A'-c1→A''-a3, B'-b3→B''-b1, C'-a1→C''-c3 (discharge positions).

Three fresh assemblies are loaded per cycle; each resides for three cycles. The scheme achieves 40-day cycles with 8-day outages (83% capacity factor) [2]. The equilibrium core at SU contains ~32.2 kg U and ~92 g Pu [5]. Figure A-1 depicts the baseline scheme:

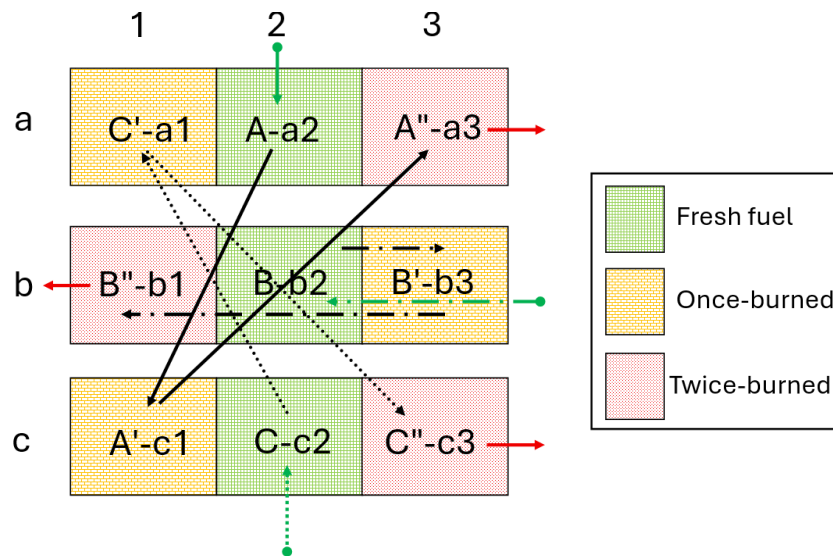


Figure A-1. Baseline Box9 fuel shuffling scheme.

Potential Areas for Further Investigation

1. **Elevated peaking in second-cycle assemblies at SU/BOC.** Once-burned assemblies with depleted Cd wires occupy peripheral positions exposed to D₂O reflector return, producing the highest stripe peaking (1.75 at SU in C'-a1) and axial peaking (1.89 at BOC) [5, Figs. 16–19]. This may contribute to localized power peaking and reduced thermal-hydraulic margins relative to other fuel-management approaches [2, Table 5-5].
2. **Asymmetric power distribution.** The two western-corner second-cycle assemblies (C'-a1, A'-c1) contain more U-235 than the east-central B'-b3, potentially contributing to azimuthal power asymmetries that may be influenced by CNS cavity orientation [5, Sec. 3.2, Fig. 17].
3. **Non-uniform discharge burnup.** Corner discharge positions see enhanced reflector return while edge-center B''-b1 is adjacent to control blade guides, producing unequal discharge burnup. The maximum fission density reaches $\sim 4.5 \times 10^{21}$ fissions/cm³ [5, Fig. 20]; alternative fuel-management approaches may provide more uniform discharge-burnup distributions and a more consistent approach to this limit.
4. **Proliferation resistance considerations.** The in-out pattern places the most attractive (fresh) fuel in the highest-importance center positions. Excess reactivity at SU is $< 6\%$ $\Delta k/k$ [2, Table 4-1]. Fuel-management approaches that reduce this value while maintaining mission-performance objectives may provide benefits with respect to selected proliferation resistance metrics.

Alternative Fuel Management

Proposed alternative fuel management schemes will seek to optimize the symmetry, uniformity and level of burnup for proliferation resistance benefits with a focus on mission performance while maintaining reactor safety.

Alternative A: Out-In Loading. Fresh assemblies load into peripheral columns (1 and 3); once-burned fuel moves inward; twice-burned fuel occupies center positions before discharge.

Shuffling Pathway:

A-a1 (fresh, col 1) → A'-b2 (2nd, center) → A''-c2 (3rd, center)

B-b3 (fresh, col 3) → B'-c1 (2nd, col 1) → B''-a3 (3rd, col 3)

C-c3 (fresh, col 3) → C'-a2 (2nd, center) → C''-b1 (3rd, col 1)

Figure A-2 shows the alternative scheme A:

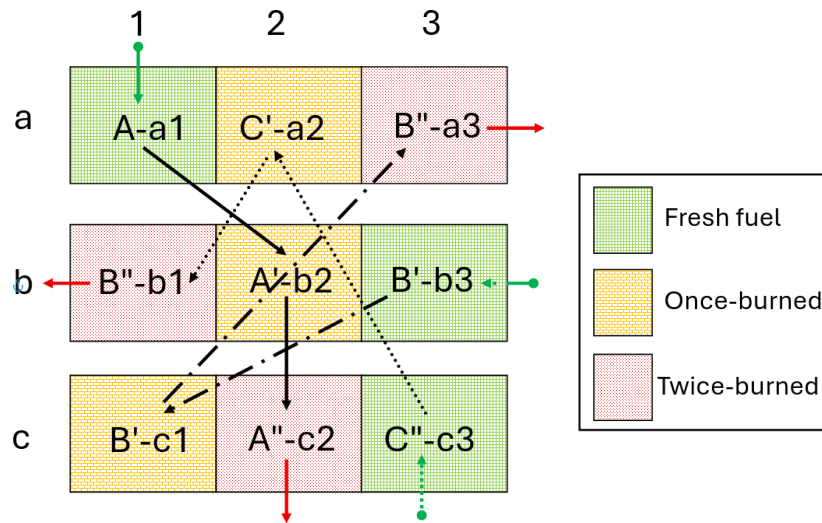


Figure A-2. Alternative fuel management Scheme A.

Key features of Scheme A:

- Fresh assemblies (green) are placed at the periphery (columns 1 and 3), where the Cd burnable absorber wires suppress their reactivity while the D₂O reflector provides moderation
- Once-burned assemblies (yellow) move inward toward the center column, where the highest thermal flux extracts additional burnup
- Twice-burned assemblies (red) occupy the remaining positions before discharge
- No fresh assembly has two fresh neighbors
- The control blades (between rows A–B and B–C) are adjacent to a mix of fresh and burned fuel, potentially providing more uniform reactivity control

Pros and Cons of Scheme A:

- *Proliferation resistance and performance advantages:* Moving depleted fuel inward extracts additional burnup from the highest-flux center positions, which may improve discharge uniformity and reduce residual fissile content—a direct proliferation resistance benefit. May reduce excess reactivity at SU if peripheral fresh-fuel positions contribute less reactivity than center-column positions.
- *Potential disadvantages:* Peripheral fresh fuel may not sustain 40-day criticality; control blades would be adjacent to fresh rather than burned fuel, potentially altering their effectiveness and the reactivity swing [5, Fig. 24].

Alternative B: Scatter Loading. Fresh assemblies are distributed across non-adjacent positions (e.g., diagonal: 11, 22, 33) rather than concentrated in a single column.

Shuffling Pathway:

A-a1 (fresh, col 1) → A'-a3 (2nd, col 3) → A''-a2 (3rd, center)

B-b2 (fresh, col 2) → B'-b1 (2nd, col 1) → B''-b3 (3rd, col 3)

C-c3 (fresh, col 3) → C'-c2 (2nd, center) → C''-c1 (3rd, col 1)

Figure A-3 shows the alternative scheme B:

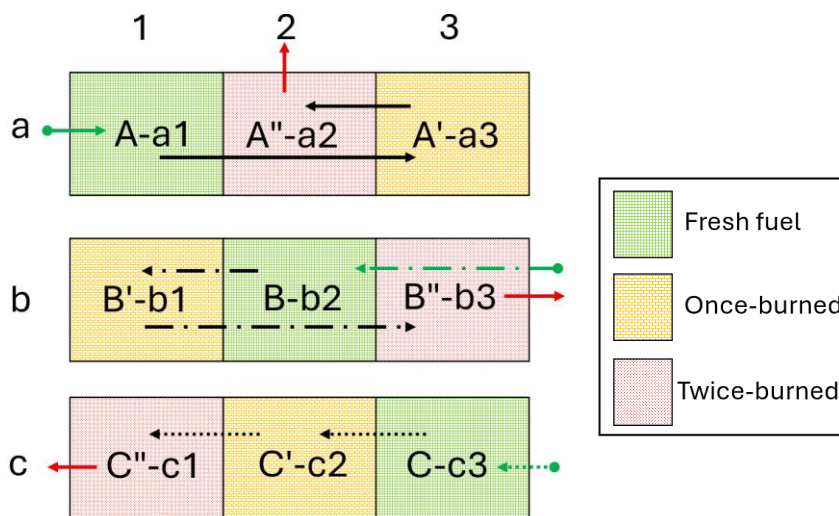


Figure A-3. Alternative fuel management Scheme B.

Key features of Scheme B:

- No adjacent fresh assemblies. Fresh fuel is placed on the main diagonal (positions a1, b2, c3), ensuring no two fresh assemblies share a row, column, or face.

- Every row and every column contains exactly one assembly from each burnup batch, producing inherently balanced power and reactivity distributions.
- Eliminates same-burnup clustering. Unlike the baseline (all fresh in center column), no group of same-resident time assemblies occupies adjacent positions, eliminating the ring of high-power second-cycle assemblies at SU/BOC.
- Balanced control blade exposure. Each control blade (between Rows a–b and b–c) is surrounded by one assembly from each burnup batch at all times, providing more uniform and predictable reactivity control.
- The diagonal distribution of fresh assemblies combined with burnup distribution produces a more symmetric power distribution, reducing the azimuthal tilt observed in the baseline scheme.
- Each assembly visits all three columns during its three-cycle residence, promoting more uniform discharge burnup across the core.
- Despite the distributed loading, the pattern is deterministic and repeats identically every cycle once equilibrium is reached.

Pros and Cons of Scheme B:

- *Proliferation resistance and performance advantages:* The scheme ensures balanced control blade exposure and eliminates same-burnup clustering, breaking the ring of high-power second-cycle assemblies at SU/BOC. Each assembly visits all three columns during its residence, promoting more uniform discharge burnup and reducing residual fissile content in spent fuel. Fresh fuel distributed along the diagonal rather than concentrated in a single column may reduce the spatial concentration of attractive fissile material, and potentially improve proliferation resistance metrics.
- *Potential disadvantages:* Requires tracking three distinct row-specific shuffling pathways rather than a single column-based pattern, adding operational complexity. The diagonal reactivity distribution differs from center-column or peripheral loading, requiring verification that the target cycle length (≥ 40 days) is achievable. Control blade reactivity worth may differ from the baseline and must be evaluated.

Optimization Metrics

Metric	Objective	Category
Equilibrium fissile inventory ($^{235}\text{U} + \text{Pu}$)	Minimize	Proliferation resistance
Annual Pu production	Minimize	Proliferation resistance

Metric	Objective	Category
Annual fresh fuel throughput	Minimize	Proliferation resistance
Excess reactivity at SU	Minimize	Proliferation resistance / Safety
Fuel handling operations per cycle	Minimize	Proliferation resistance / Operational
Cycle length	≥ 40 days	Performance
Peak-to-average power (assembly, plate, stripe)	Minimize	Safety
Peak local power density	Minimize	Safety
Discharge burnup uniformity	Maximize	Proliferation resistance / Performance

When multiple options satisfy performance thresholds, those with superior proliferation resistance metrics are preferred.

A.4. Fuel Assembly Features to Limit Power Peaking

Two peaking issues are identified in NIST TN 2316 [5]:

1. **Radial peaking in peripheral plates:** Plates 1 and 21 experience enhanced thermal flux from the chimney water gap and D₂O reflector return. Maximum stripe peaking reaches 1.75 at SU; maximum local peaking reaches 1.98 at BOC [5, Figs. 17–18].
2. **Corner assembly power:** Corner positions see reflector return from two sides. At EOC, maximum assembly peaking is 1.12 in B-b2 [2, Sec. 4.4; 3, Fig. 16], but plate-level peaking within corners is more severe at SU/BOC.

Mitigation Options

1. **Discrete Burnable Absorbers (Baseline: Cd Wires).** The 0.05 cm Cd wires in side plates suppress fresh-fuel reactivity effectively at SU/BOC but deplete rapidly (Cd-113 dominant absorber), causing the mid-cycle power shift [5, Figs. 16–17]. Optimization variables include wire diameter, axial extent/placement, number per side plate, and alternative

materials (Gd, Eu). The Cd wires contribute to keeping SU excess reactivity below 6% [2, Table 4-1]—a proliferation resistance benefit.

2. **Integral Burnable Absorbers (for dispersion fuel).** If a dispersion fuel U_3Si_2 -Al or U-7Mo/Al is selected, Gd_2O_3 or B_4C particles can be dispersed in the Al matrix, providing spatially distributed flux suppression more uniform than edge-located wires. This may reduce the radial peaking gradient across the three transverse stripes [5, Fig. 17]. Adds fabrication/qualification complexity.
3. **Alternative Poison Wires.** Hafnium wires enable gradual, sustained suppression through multiple absorbing isotopes and avoid the sharp depletion behavior associated with a single isotope, potentially reducing the mid-cycle power shift [5, Figs. 16–17]. Europium wires offer intermediate characteristics. Gadolinium wires provide strong initial suppression with very rapid depletion.
4. **Water Displacers.** Aluminum inserts replacing coolant in the outermost channels (between end plates and chimney wall) would reduce the enhanced moderation that drives peripheral plate peaking.

Evaluation Criteria

Criterion	Target	Category
Reactivity swing ($SU_{\text{excess}} - EOC_{\text{excess}}$)	Minimize	Proliferation resistance / Safety
Peak-to-average power ratio	Minimize	Safety
CHF and OFI margin	Satisfy regulatory requirements	Safety
Cladding temperature margin (vs. 645 K blister limit [2, Sec. 5.1])	Maximize	Safety
Cycle length	Preserve ≥ 40 days	Performance

A.5. Cold Neutron Sources

The compact core produces a peak unperturbed thermal flux of $\sim 5 \times 10^{14} \text{ cm}^{-2}\text{s}^{-1}$ in the reflector— $2.5\times$ higher than the NBSR at the same power [2, Requirement R1.2; 2, Fig. 3]—because the flux peaks outside the fuel where CNS thimbles can access it. Core enlargements (e.g., for U_3Si_2) may reduce this advantage.

Key optimization variables:

Variable	Baseline	Tradeoff	Reference
Number of CNSs	2 identical LD ₂	Dissimilar CNSs possible	[2, Sec. 3.2.4; 2, Sec. 2]
Location	(± 45 , 0) cm from core center	Closer $\rightarrow$ higher brightness but higher heat load and lower SNR	[4, Sec. 2.1.1; Appendix B, Tables B-1, B-2]
LD ₂ vessel diameter	30 cm	Larger $\rightarrow$ higher brightness (diminishing returns > 40 cm) but $\sim$ quadratic heat load increase	[4, Figs. 4–6, Table 6, Fig. 11]
Height	30.5 cm	Minimize consistent with full guide illumination (full to $\sim \lambda = 0.8$ nm)	[2, Sec. 2.2, Fig. 10]
Re-entrant cavity	Single He-filled cavity	10–30% brightness gain on cavity side; dual cavity complicates structure	[4, Fig. 8; 1, Fig. 8-8; 2, Appendix A]

Performance metrics [2, Table 1; 1, Tables 8-1 through 8-5]:

- **Cold brightness** ($\lambda > 4 \text{ \AA}$): $5.01 \times 10^{12} \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ — $3.48\times$ NBSR Unit 2 (LH₂), $2.64\times$ NBSR Unit 3 (LD₂).

- **Cold neutron current** at 16 guide entrances: $9.2\times$ gain (6×15 cm) to $11.1\times$ gain (6×20 cm) vs. NBSR Unit 2.
- **Nuclear heat load:** ~ 4.5 kW at 30 cm diameter; ~ 6.5 kW at 36 cm; requires ≥ 15 kW total cooling for two 36 cm sources [4, Table 6].

A.6. Thermal Neutron Beam Tubes and Waveguides

Baseline Design

The eight baseline thermal beam tubes are tangential to the core (5° cant), viewing the thermal flux peak while avoiding direct fuel sight lines [4, Sec. 4, Fig. 13; 3, Fig. 11]. Thermal brightness is $\geq 2\times$ NBSR BT-6 at equivalent power, with effective Maxwellian temperature 317 K [4, Fig. 14; 2, Fig. 8-14]. Positions are near-optimum: displacing toward fuel increases only fast flux; displacing away reduces thermal flux [4, Sec. 4].

Optimization variables: Cant angle (fine-tuning); beam tube cross-section (baseline: accommodates 6×20 cm guide [4, Fig. 15]); thermal guide m-value and geometry (useful for instruments > 8 m from shield exit at $\lambda > 1.5$ Å [4, Fig. 16; 2, Fig. 8-15]).

Tradeoff considerations:

- *Reflector displacement:* Eight thermal tubes plus four cold conduits plus two CNS thimbles represent significant D₂O displacement; cumulative perturbation must respect the 5% CNS flux constraint [2, Requirement R1.4].
- *Streaming and leakage:* Tangential arrangement mitigates fast neutron/gamma streaming, but intersections with cold conduits require shielding evaluation.
- *Proliferation resistance implications:* Beam penetrations are physical protection considerations; number and security provisions should be evaluated within the facility protection assessment.
- *Power peaking near penetrations:* Tangential offset minimizes fuel perturbation [4, Sec. 4], but should be quantified for tubes passing between core and CNS, where thermal flux is maximized [5, Fig. 13].

A.7. Pneumatic/Hydraulic Rabbit Tubes

The NAA community has articulated specific requirements [6, Table 1; 7] summarized in Table A-1.

Table A-1. NAA irradiation requirements for the NNS.

Requirement	Specification	Source
Thermal flux	$\geq 10^{14} \text{ cm}^{-2}\text{s}^{-1}$ preferred; $\geq 10^{13}$ minimum	[6, Table 1; 7]
Flux uniformity	Minimize gradients; NBSR RT-2 has ~50% axial drop	[7; 8, Fig. 1]
Thermal/fast ratio	Maximize; NBSR RT-2: th/epi ~300, th/fast >15,000	[7]
Spectral positions	≥ 1 thermal-optimized, ≥ 1 fast/epithermal-optimized	[7]
Gamma heating	Minimize for plastic rabbit irradiation; NBSR RT-2 ~100 Gy/s	[7; 8]
Active cooling	Desirable for high-Li, high-B, or heat-generating samples	[7]
Reactivity impact	Minimize to simplify approval for new irradiation materials	[6; 7]
Number of tubes	Minimum 6 quick-transfer rabbits + 1 PGNAA port/beamline	[6, Table 1]
Bulk irradiation	≥ 1 position for paint-can-sized samples; multi-day; passive cooling	[7]

Flux stability	$\leq 2\%$ variation over fuel cycle, per NBSR RT-2/RT-4 experience	[8, Fig. 2]
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Lessons from NBSR Experience

The Lindstrom et al. (2008) characterization of NBSR RT-2 [8] provides key benchmarks:

1. **Flux gradients.** RT-2 has a nearly twofold axial gradient along its 7.6 cm length [8, Fig. 1], “nearly compensated by flipping the rabbit midway through the irradiation” but imperfect due to asymmetric moderator environment [8]. The NNS design should reduce this gradient through optimized radial positioning and moderator geometry.
2. **Spectral characterization.** RT-2 achieves consensus thermal flux of $3.1 \times 10^{13} \text{ cm}^{-2}\text{s}^{-1}$ with $f \approx 350$ and $\alpha \approx 0.2$ [8, Table 1]. The NNS compact core with D₂O reflector is expected to provide substantially higher thermal flux and better thermalization at equivalent positions [2, Sec. 9.4].
3. **Temporal stability.** RT-2 and RT-4 fluence rates are constant to better than 2% over the fuel cycle once equilibrium is reached [8, Fig. 2]. RT-1, being closer to fuel, shows greater sensitivity to control element position—directly relevant to NNS rabbit placement.
4. **Gamma heating.** The $\sim 100 \text{ Gy/s}$ dose rate limits plastic rabbit irradiation time and makes Cd-covered irradiations impractical (Cd reaches $>115^\circ\text{C}$ within two minutes) [8]. NNS positions should consider active cooling provisions where gamma heating is elevated.

Preliminary NNS MCNP Results

Cook (2025) [6] assessed a high-flux rabbit position at (0, -45, 0) cm from core center—similar radius to the CNSs but on the south side, not interfering significantly with thermal beam tubes [6, Fig. 1]. Key findings:

- **Flux levels.** Total flux is $(1.0 \pm 0.1) \times 10^{14} \text{ cm}^{-2}\text{s}^{-1}$ with $\sim 89\%$ thermal ($<414 \text{ meV}$), $\sim 10\%$ epithermal, $\sim 1\%$ fast [6, Table 2]. Thermal/fast ratio ranges from 77 to 89. These levels meet the $\geq 10^{13}$ minimum and approach the $\geq 10^{14}$ preferred threshold [7].
- **Gradients.** Axial gradient is $2 \times 10^{12} \text{ cm}^{-2}\text{s}^{-1}/\text{cm}$ (2%/cm); radial gradient across the $\sim 1 \text{ cm}$ sample diameter is $\sim 5\%$ [6, Sec. 4]—significantly improved over the NBSR RT-2 $\sim 50\%$ axial gradient [7; 8, Fig. 1].

- **Spectral quality.** The ~89% thermal fraction confirms excellent D₂O reflector thermalization at 45 cm radius [6, Table 2], substantially better than NBSR RT-2 at 95 cm [8].
- **Reactivity impact.** One rabbit tube with nine silica samples reduces core reactivity by ~32 cents ($\Delta k \approx -0.00208$) [6, Table 3]—non-negligible against the <6% SU excess reactivity budget [2, Table 4-1; 5, Table 4].

Candidate Configuration for Further Evaluation

Based on the NAA requirements [6, 7], NBSR experience [8], preliminary MCNP results [6], and the Seo conceptual layout [7, Fig. 1]:

RT-1 — High fast flux. Below the hot leg; highest fast flux but also highest gamma heating and reactivity impact. Facilitates transport of irradiated targets to the measuring room [7].

RT-2 — High thermal flux. In D₂O reflector at ~45 cm from core center, per Cook trial [6]. Target: $\geq 10^{14} \text{ cm}^{-2}\text{s}^{-1}$ with ~89% thermal fraction [6, Table 2].

RT-3, RT-4 — Maximum thermal/fast ratio. At ~100 cm from core center, analogous to NBSR RT-2 [7; 8]. Lower absolute flux but superior spectral purity for high-precision comparator NAA. Expected to exceed NBSR RT-2 thermal flux due to compact core design [7].

RT-5 — Bulk irradiation. Opposite side of hot leg from RT-2; paint-can-sized samples for multi-day irradiations with passive water cooling [7]. Positions of RT-3 and RT-5 may be interchanged if target transport is difficult [7].

Additional positions. Space between RT-1 and RT-3/RT-4 reserved for NDP and radioisotope production [7]. East/west sides (CNS sides) are kept free for additional cold neutron beams or thermal column [7].

Figure A-4 shows the locations of the conceptual layout of the rabbit tubes and neutron detectors.

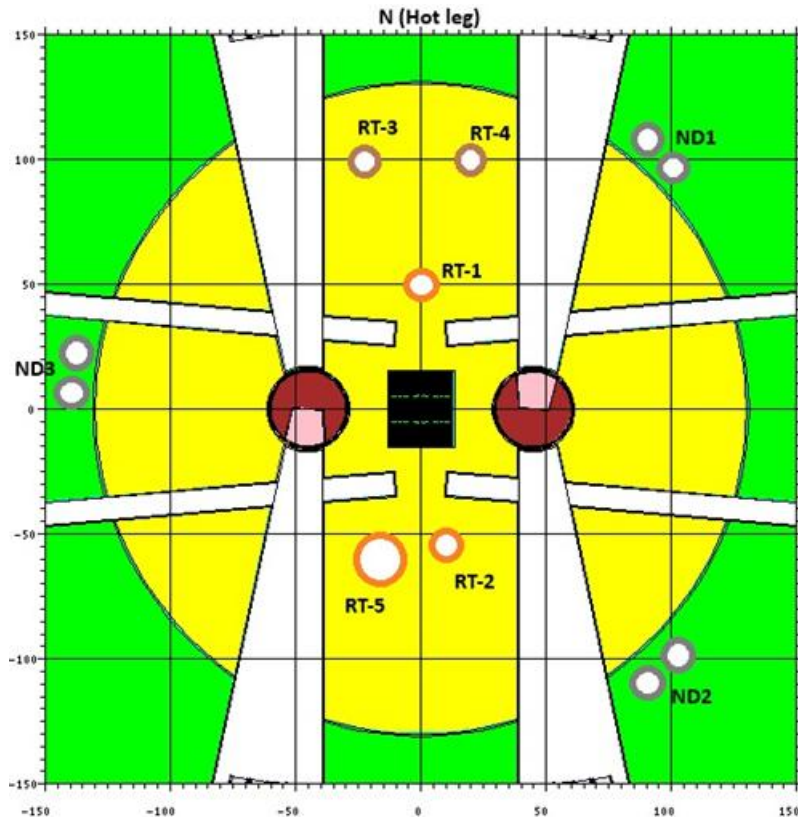


Figure A-4. Notional layout for the rabbit systems and neutron detectors.

Neutron Detector Coupling

Neutron flux detectors must be positioned near the outside of the D₂O tank where flux drops rapidly, but their response must be immune to rabbit loading/unloading perturbations [7, Fig. 1]. Detector positions should be determined concurrently with the rabbit layout, reinforcing the treatment of rabbit tubes as coupled optimization variables [7].

Optimization Considerations

- **Limited Reflector space.** Rabbit tubes at 45 cm radius compete with CNSs and thermal beam tubes. Consistent with [2, R1.5] irradiation facilities are considered secondary to beam-based experimental capabilities when reflector-space conflicts arise. The Seo layout [7, Fig. 1] addresses this by placing rabbits on the north/south sides while keeping east/west sides (CNS sides) free.
- **Reactivity budget.** The ~32 cents per tube [6, Table 3] is significant against <6% SU excess reactivity [2, Table 4-1]. Multiple tubes will consume substantial excess reactivity, potentially affecting cycle length. Cumulative impact must be quantified for the full complement.

- **Flux uniformity vs. proximity.** Closer positions provide higher flux but steeper gradients and greater reactivity impact. At 45 cm, gradients ($\sim 2\%/cm$ axial, $\sim 5\%$ radial) are acceptable [6, Sec. 4]; positions at ~ 100 cm (RT-3/RT-4) trade flux for spectral purity.
- **Proliferation resistance implications.** Rabbit tubes provide material insertion/retrieval pathways in high-flux regions. Tube diameter (1.65 cm internal radius [6]) and sample capacity should be evaluated against NAA requirements and facility protection considerations. The minimum six tubes [6, Table 1] represent significant reflector penetrations for the physical protection assessment.

A.8. Ultracold Neutron Source

Proposed location: In the D₂O reflector tank, on the north or south side (thermal beam tube sides), at ~ 45 to ~ 60 cm from core center. Not coupled to either CNS; currently identified as having limited geometric interaction with CNS placement. Thermal flux at this location: 2×10^{14} to 4×10^{14} $\text{cm}^{-2}\text{s}^{-1}$ [5, Fig. 12].

Typical performance parameters

Parameter	Typical Range	Notes
UCN density in storage	10 to 1000 cm^{-3}	Source/extraction dependent
UCN production rate	10^4 to 10^7 s^{-1}	Cold flux and converter volume dependent
Converter material	Superfluid ^4He or solid D_2	Superfluid He: longer storage; resonant at $\lambda \approx 8.9$ Å
Converter temperature	0.5 to 1.2 K (He); ~ 5 K (D_2)	Dedicated sub-K cryogenics required

Coupled design considerations:

- *Reflector perturbation:* Converter vessel (5 to 30 L) displaces D₂O and introduces materials with distinct neutronic properties; perturbation should be assessed using the established MCNP framework [5, Sec. 2].

- *Cryogenic infrastructure:* Dilution refrigerator plumbing must not interfere with CNS cryogenics or the reflector dump mechanism [2, Sec. 3.2.4; 5, Sec. 3.4.5].
- *Reflector dump compatibility:* Draining ~50 cm of the 130 cm D₂O column compensates total SU excess reactivity [5, Fig. 30]. UCNS structures must not impede drainage.
- *Proliferation resistance implications:* No fissile materials involved; additional shield penetrations for UCN guides are physical protection considerations.