FUNCTIONAL COMPONENTS FOR A DESIGN STRATEGY: HOT CELL SHIELDING IN THE HIGH RELIABILITY SAFEGUARDS METHODOLOGY

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ABSTRACT

The High Reliability Safeguards (HRS) methodology has been established for the safeguardability of advanced nuclear energy systems (NESs). HRS is being developed in order to integrate safety, security, and safeguards concerns, while also optimizing these with operational goals for facilities that handle special nuclear material (SNM). Currently, a commercial pyroprocessing facility is used as an example system. One of the goals in the HRS methodology is to apply intrinsic features of the system to a design strategy. This current study investigates the thickness of the hot cell walls that could adequately shield processed materials. This is an important design consideration that carries implications regarding the formation of material balance areas, the location of key measurement points, and material flow in the facility.

1. INTRODUCTION

Advanced nuclear energy systems (NESS) will be needed as more countries expand nuclear power capacity or establish new power grids, whether to address growing energy needs, grow national economies, enhance quality of life, or as a solution to climate change (USDOEGIF 2002; PRPPWG, 2011; IAEA, 2013). The growth of nuclear power is invariably intertwined with a potential increase in proliferation risk. Establishing the safeguardability of the advanced nuclear fuel cycle therefore is crucial to proliferation risk reduction. A distinguishing feature of the advanced fuel cycle is that special nuclear material (SNM) will be treated by pyroprocessing. The SNM will be in a different chemical and physical form than that of materials processed in the contemporary fuel cycle. Therefore, new approaches to address events related to safety, security, and safeguards and to develop design strategies for these facilities are needed.

To this end, the High Reliability Safeguards (HRS) methodology addresses the safeguardability of the advanced fuel cycle (Borrelli, 2014a,b). The HRS methodology proposes facility designs to integrate safety security, reduce proliferation risk, and enhance physical protection, while also maintaining operational goals. The HRS approach is currently studied for a hypothetical, commercial-scale pyroprocessing facility. An important part of HRS is the development of a set of adaptable and flexible functional components as part of a design strategy. This study is a continuation of research into this area. The overall intent HRS development is to establish how to design a pyroprocessing facility that can enhance the interrelated aspects of safety, safeguards, and security, rather than just designing a facility and then instituting costly retrofits post-construction, as was the case with the Rokkasho Nuclear Fuel Reprocessing Facility in Japan (Ehinger and Johnson, 2009; Johnson and Ehinger, 2010).

Previous work has modeled the curium flux (^{244}Cm) due to spontaneously fissioning neutrons (Borrelli, 2013; 2014c). ^{244}Cm is an overwhelming contributor to neutron emission rate in used fuel. Plutonium is not chemically separated from the transuranic elements (TRUs) in pyroprocessing. Therefore, the curium flux is potentially useful at all processing stages. Results for dose rate modeling in the full system from the prior works have shown that processing materials are not self-protecting under the current IAEA standard. That is, the dose rate is sufficiently low that the risk of theft or sabotage cannot be neglected. While the hot cells do

provide passive security, during the conceptual design phases for the facility, additional physical protection measures will be required. Additionally, results have shown that the neutron flux could affect the facility configuration, such as material balance area formation and operational goals in that detection of SNM in the hot cell could be affected by the neutron emission in an adjacent cell. Occupational safety could also be affected, if a maintenance cell is located near a processing cell. Of course, this can be addressed with shielding the hot cells adequately, and this is the motivation for the current study.

This study models the ^{244}Cm neutron flux with MCNPX consistent with the prior works and for different cell wall thicknesses. The intent is to find a nominal wall thickness for which occupational safety and a significant flux reduction could be satisfied and then compare the results to contemporary analogues. This is a scoping study to formulate preliminary design criteria based on expected neutron fluxes related to materials that will be processed in a previously established, hypothetical, commercial pyroprocessing facility. If the hot cells can be shielded adequately and the cells practically constructed, then a wider array of facility configurations can be developed for the commercial facility during the conceptual design phase.

2. BRIEF TECHNICAL NOTES FOR PYROPROCESSING

Pyroprocessing is integral to the sustainability and safeguardability of the advanced fuel cycle. Pyroprocessing is an electrochemical process in which nuclear materials are processed in hot cells with an inert atmosphere, typically argon, at high temperature. Used fuel, in UO_2 ceramic form, is treated in order to produce a metal alloy for a Generation IV reactor. The alloy contains uranium, TRU, including plutonium, some rare earth fission products (REFPs), and zirconium. Borrelli (2014a,b) contains a detailed technical discussion of pyroprocessing and includes an extensive review of the scientific progress in the field.

The main pyroprocessing subsystems studied in this paper are: (1) electroreduction, (2) electrorefining, (3) electrowinning, and (4) metal fuel fabrication. These are shown in Figure 1. Prior to processing, used fuel assemblies are chopped and decladded. Voloxidation converts the used fuel from ceramic to U_3O_8 powder. This increases the surface area of the material for more efficient electroreduction. Then, electroreduction transforms the powder to a metal by dissolution in $\text{LiCl-Li}_2\text{O}$ salt. Cesium and strontium are removed here, greatly reducing the heat output. Uranium and TRU metal are extracted, separately, during electrorefining and electrowinning, respectively, by dissolution in LiCl-KCl salt. Uranium is collected on the cathode, usually graphite, and TRU on a liquid cadmium cathode. Metal fuel slugs are fabricated by injection casting. These are used subsequently to assemble the fuel elements.

3. MODEL

3.1. Material composition

Radionuclide inventory for this study was obtained by ORIGEN2.2 simulation for a fresh fuel composition of 1 MTU 4.5% ^{235}U , 55 GWD/MTU burnup, cooled for 10 years with activation products neglected (Borrelli, 2013, 2014c). This results in 87 g of Cm in the used fuel, and 79 g of ^{244}Cm . The ratio of $^{244}\text{Cm}/\text{Pu}$ is 0.0071. A material flow for the pyroprocessing facility was then calculated using the process losses shown in Figure 1 and prescribed quantities for the commercial batch sizes (Borrelli 2013). The neutron rate from (α , n) reactions and neutron multiplication was neglected due to the extremely high neutron rate from ^{244}Cm for typical LWR used fuel (Rinard and Menlove, 1996; Ensslin et al., 1998).

3.2. Processing states

The state of TRU is paramount to safeguardability in order to identify, locate, and inventory plutonium. For pyroprocessing, the following ‘TRU processing states’ have been previously defined by Borrelli (2014c): (1a) electroreduced metal dissolved in LiCl-Li₂O salt, (1b) bare electroreduced metal, (2) uranium and TRU metal dissolved in LiCl-KCl salt, (3a) TRU metal dissolved in the same salt after U extraction, (3b) TRU metal and liquid cadmium, after extraction from the salt, and (4) the bare metal alloy for fuel fabrication, containing uranium, TRU, rare earth fission products, and zirconium. These processing states are numbered to correspond to the subsystems labeled in Section 2. Table I contains the commercial batch sizes for each processing state, the corresponding ^{244}Cm and Pu content, and the density. Note that while the Cm and Pu content is the same for states (1) - (3), the physical form is different.

3.3. Model geometry

The materials comprising each processing state were modeled as a solid cylinder with equal radius and height, determined by density. ^{244}Cm is assumed to be the sole neutron source, where emission is isotropic and due to spontaneous fission. The processing states are also assumed to comprise an ideal solution each with homogeneously distributed nuclides. Therefore, density can be obtained by using the principle of additive volumes (Mariani and Vaden, 2010).

3.4. Hot cell design model space

The model space is a hypothetical facility, with four cells exhibiting dimensions of 10 x

10 x 20 m, all containing an argon atmosphere. The process cell contains the source, housed in cylindrical equipment with 5 cm thickness, 2 m radius, and 3 m height, comprised of steel and filled with argon. The remaining cells are empty. The source is located in the center of the equipment, 1 m above the cell floor. This is shown in Figure 2. The cell walls consist of boron frits-baryte concrete. The material is commonly used for wall shielding of hot cells that contain radioactive materials (Borrelli, 2013).

3.5. Simulations

Intuitively, the shielding could be increased indefinitely until the flux decreases to zero in the empty cells. This is clearly not practical in terms of a realistic facility design. HRS seeks to establish practical guidelines for facility design. However, there are no current commercial scale pyroprocessing facilities under construction or in the conceptual design stages. To this end, the study of other nuclear fuel fabrication facilities can provide insight. Wall thickness for similar facilities can be up to 1 m concrete (Yoshimochi et al., 2004), and some pyroprocessing facilities have been proposed where the thickness is as much as 5 feet (Pope et al., 2009). For this study, the thickness of the walls starts at 30 cm and then increased to 45 cm, 60 cm, 75 cm, and 90 cm.

The intent of these simulations is to determine the extent of the reduction in the neutron flux for each processing state into the empty cells due to increasing cell wall thickness. Therefore, two metrics are used. The occupational dose limit of 20 mSv per year is used as a guideline for an acceptable level of reduction in the neutron flux in order to address occupational safety (ICRP, 2007). This corresponds approximately to 1 μ Sv/h for a standard year of 2000 working hours. Secondly, the volume-averaged flux (F4 tally) from each empty cell is divided by the F4 tally from the process cell for each wall thickness and for each processing state. This gives a fractional reduction in the flux due to wall thickness. These two metrics can provide a benchmark with regards to the effect of the wall shielding in the facility.

4. RESULTS

4.1. Overview

MCNPX v2.7.0 was used for the simulations with the default values for each card in the input decks (Pelowitz, 2008). Several tables and plots have been prepared to present all of the data. The plots are all semilog on the y axis. The F4 volume-averaged flux tally ($\text{n/cm}^2/\text{s}$) is given for the process (SE) cell in Table II. The mean dose rate ($\mu\text{Sv/h}$) is given for the SW, NW, and NE cells as a function of wall thickness in Figures 3, 4, and 5, respectively. Similarly, the F4 volume-averaged flux tally is given for the SW, NW, and NE cells as a function of wall thickness in Figures 6, 7, and 8. In these tables, the ‘simulation flux’ is given first; i.e., the flux obtained directly from MCNPX simulation. Then, the relative flux is given as a function of wall thickness, as defined in Section 3.4. Additionally, the plots for the dose rate show the occupational limit of $1 \mu\text{Sv/h}$ for reference. Similarly, the plots for the relative flux indicate 99%, 99.9%, and 99.99% reduction in flux for reference. The upper limit on the y axis for the dose rate plots are all the same, for comparison purposes, as is the case for the relative flux. Initially, the plots were created with error bars to represent the uncertainty in the MCNP tallies. However, because the magnitude of the error was so small, the error bars were barely perceptible on the plots. Therefore, they were not included. Further discussion regarding the error follows.

MCNPX recommends the relative error statistical test for each tally should be below 0.100. This is the case for all of the tallies except for three of them. In Figure 4, the results for the dose rate in the NW cell for processing states 1a, 1b, and 2 at 90 cm did not pass the statistical test for relative error. They were 0.154, 0.113, and 0.103. Typical variance reduction techniques were applied, such as the weight windows generator card and importance functions. Additional simulations then were run for an aggregate of nearly 75 billion histories per processing state, but a relative error below 0.100 could not be obtained. However, these results still are still reasonable, physically, as the tallies decreased with increasing wall thickness. Therefore, they were still reported here. When applying this modeling methodology as part of a realistic facility design strategy, then more precise tallies would be needed. There is a considerable amount of reliable data obtained otherwise, and meaningful discussions can still be made.

4.2. General trends

Table II shows the volume averaged flux for the process cell. The magnitude of the flux is sufficiently significant that shielding the process cell must be a design consideration. Clearly, the metal fuel alloy exhibits the highest flux because it contains the largest quantity of ^{244}Cm . This is also the trend for the dose rates shown in Figures 3, 4, and 5, and volume averaged fluxes in Figures 6, 7, and 8, over all the wall thicknesses. The volume averaged flux for the remaining processing states shown in Table II is approximately similar and within the same order of magnitude. The bare metal and TRU bearing forms (1b, 3a, 3b) exhibited slightly higher fluxes. This trend is also evident over the subsequent data for volume averaged fluxes in Figures 6, 7, and 8. The dose rates and the fluxes all predictably decrease essentially linearly on the semilog plots with increasing wall thickness. Slight deviations to linearity are due to the statistics of the simulations, but in all cases, flux and dose decrease with increasing wall thickness. Additionally, the dose rates and the fluxes in the SW cell are higher than that of the NE cell at each wall thickness due to the geometry of the model.

These observations are intuitively obvious. However, because there is a lot of data generated for this study, it is important to confirm that the defined model space and established conditions make physical sense prior to any analysis of the effects of shielding and related interpretations thereof, within the context of safeguardability.

4.3. Dose rate

The dose rate only exceeds the benchmark of the benchmark of $1\ \mu\text{Sv/h}$ for process state (4); i.e., the metal fuel alloy, at $1.4\ \mu\text{Sv/h}$ in the SW cell at 30 cm, shown in Figure 3. Otherwise, the dose rate is below the benchmark for all wall thicknesses in each cell, for each process state.

Excepting process state (4), the dose rate is on the order of $10^{-2}\ \mu\text{Sv/h}$ for the SW cell, shown in Figure 3—for 30 cm and 45 cm thicknesses. It falls within $10^{-2} - 10^{-3}\ \mu\text{Sv/h}$ in the NE cell, in Figure 5, also for 30 cm and 45 cm thicknesses, and on the order of $10^{-3}\ \mu\text{Sv/h}$ for 60 cm thickness in both the SW and NE cells. For 75 cm and 90 cm thicknesses, the dose rate is on the order of $10^{-4}\ \mu\text{Sv/h}$ in the SW cell and $10^{-4}\ \mu\text{Sv/h} - 10^{-5}\ \mu\text{Sv/h}$ in the NE cell. Process state (4) exhibits a dose about an order of magnitude higher in both cells. These cells are both located closest to the process cell.

In the NW cell, for Figure 6, the dose rate is lower than the other cells, clearly due to the further distance from the process cell. The dose rate is on the order of $10^{-4}\ \mu\text{Sv/h}$ for 30 cm

thickness. It decreases about an order of magnitude from 45 cm, to 60 cm, 75 cm, and 90 cm. Again, the dose rate for process state (4) is about an order of magnitude higher than the other processing states at all wall thicknesses.

4.4. Neutron flux

4.4.1. Simulation flux

For 30 cm wall thickness, the simulation flux is on the order 10^{-1} n/cm²/s in the SW and NE cells shown in Figure 6 and Figure 7. For process (4), the flux is 15 n/cm²/s in the SW cell and 6.3 n/cm²/s in the NE cell. The flux in the SW cell is also on the order of 10^{-1} n/cm²/s for 45 cm, decreasing by about an order of magnitude for 60 cm, and at about 10^{-3} n/cm²/s for 75 cm and 90 cm. In the NE cell, the trend is similar with the magnitude of the flux slightly less. It is on the order of 10^{-2} n/cm²/s for 45 cm and 60 cm thicknesses, then decreasing by an order of magnitude for 75 cm and 90 cm thicknesses. The flux in the NW cell is lower, at 10^{-2} n/cm²/s for 30 cm thickness, 10^{-4} n/cm²/s at 45 cm thickness, and decreasing by about an order of magnitude for 60 cm, 75 cm, and 90 cm thicknesses, shown in Figure 7 ~~Table VII~~. For all cells, process (4) exhibits a flux at about an order of magnitude higher than the other processing states at all wall thicknesses. The simulation fluxes described here are each divided by the flux shown in Table II, for the corresponding process state, in order to obtain the relative fluxes and discussed subsequently.

4.4.2. Relative flux

The relative flux for each wall thickness is approximately equal over all processing states for each cell. For the SW cell, in Figure 6, it is approximately 0.04 at 30 cm thickness for all processing states, including the metal fuel alloy. This is similar to the NE cell, where the relative flux is about 0.03 for 30 cm thickness over all the processing states. The relative flux decreases overall with increasing wall thickness, while still remaining fairly constant. It is about 10^{-3} for 45 cm and 60 cm wall thicknesses, and decreasing by an order of magnitude for 75 cm and 90 cm in the SW cell. It is also about 10^{-3} 45 cm in the NE cell, but then decreases to 10^{-4} for 60 cm and 75 cm thicknesses, and 10^{-5} for 90 cm. The relative flux is lowest in the NW cell, starting at 10^{-4} for 30 cm and decreasing to 10^{-5} for 45 cm, 10^{-6} for 60 cm, 10^{-8} for 75 cm, and about 10^{-9} for 90 cm wall thicknesses.

5. DISCUSSION

5.1. Functional components to facility design

A safeguardable pyroprocessing facility will incorporate design principles to reduce proliferation risk, while also not impacting significantly on operational goals. Past designs of nuclear handling facilities did not include these considerations at the outset, and as a result, costly safeguards retrofits were required. Building a methodology to include these concepts as part of the design strategy can avoid this. The results from this study offer potential strategies that can be used as part of the facility design.-The results for both the dose and relative flux offer evidence that this can be practicably achieved.

A wall thickness of 60 cm - 75 cm is proposed as a functional component to design for facilities similar to the configuration presented here. The dose falls well below the 1 $\mu\text{Sv/h}$ proposed benchmark, based on current standards for occupational safety. The relative flux at 60 cm is approximately 10^{-3} for the SW and NE cells, nearly a 99.9% reduction and nearly 10^{-6} for the NW cell. At 75 cm, the relative flux is on the order of 10^{-4} , indicating a reduction of 99.99% in the SW and NE cells, and it is approximately 10^{-7} for the NW cell. The hot cells overall are significantly shielded for wall thicknesses that are entirely reasonable based on the contemporary analogues and commonly used materials discussed in this paper.

There are undoubtedly numerous potential configurations that could be proposed for a potential facility design, and these will be based on cost, physical location, etc. However, this particular configuration, defined in Figure 2, can provide insight into the design of a safeguardable facility. In terms of electroreduction, this process may warrant its own cell because the salt is of different chemical composition than that of electrorefining and electrowinning. Similarly, the injection casting process may also occupy a single cell because the molds must be broken to obtain the solid alloy. This would result in a singular waste stream unique to the injection casting process, and for materials accounting, as much alloy as possible must be recovered from the broken molds. Similarly, there will be a random amount of material held up in the casting equipment left in the crucible. When conducting the mass balance of material for this process, any material unaccounted for would be known to be in the molds or the equipment the crucible if this process was in a single cell. These considerations are necessary for

safeguardability. The distance between these cells for this proposed configuration can be located in close proximity. Therefore, material transfer time can be reduced and operability can be enhanced.

These results show that the abstracted facility devised for this study offers potential benefits to a facility design within the context of safeguardability. This is useful if the physical location of the facility is limited. For example, a facility may be constructed underground or partially underground for security and physical protection enhancement.

An important functional components in the HRS methodology is to conduct maintenance in separate, dedicated cells. This is intended to reduce diversion pathways. Therefore, any complicated equipment required for maintenance would not be present in a process cell. Maintenance cells would potentially experience high human traffic. Even if the maintenance cells do not require personnel entry, there will still be a human presence to operate necessary equipment. Additionally, the transfer of equipment to a maintenance cell located far from any of the processes will increase operational downtime and degrade physical protection, as there is a greater opportunity for sabotage. Therefore, maintenance or storage cells may have to be located near a process cell. If the flux from the process cell into these adjacent cells are on par with background levels of radiation, then worker safety can be protected, and detection activities in the adjacent cells will not be masked by the processing cell. This will be needed when verifying equipment is clean and free of any SNM or verifying storage inventory. This would result in a facility with an overall smaller footprint than one that would require these cells to be located sufficiently far from the process cells. This suggests that construction and materials costs could also be reduced, but a life cycle assessment would be needed to confirm this. However, these results can aid in developing similar design concepts.

In addition to maintenance cells, there will need to be storage cells for processed materials. For example, noting Table I, process state (3b); i.e., electrowinning, takes a 1.1 kg batch with 231 g Pu, while the fuel fabrication process state (4) takes a 20 kg batch and 3400 g Pu. Approximately 18 batches must be processed from the electrowinner to prepare one batch for injection casting. Operationally, it is most efficient to have a continual flow of material from the electrowinner to the injection casting process. Therefore, there must be a storage buffer for this material. The electrowinning product is a bare metal, TRU ingot. This material must be carefully monitored. A potential storage cell of metal TRU may require personnel entry or a presence to

visually verify the batches. With sufficient wall thickness shown from these results, the flux from an adjacent processing cell should not affect monitoring and accounting for the TRU metal. Storing the TRU metal closer to the injection casting process is more efficient operationally and can also enhance physical protection and reduce proliferation risk because the amount of time available for potential diversion or sabotage is minimized.

Finally, the relative flux for each wall thickness is fairly constant over all the processing states. This indicates the effect of shielding is independent of the process or materials. This is important because, for the fuel fabrication process, the actual flux is the highest of the processing states, and contains the most SNM content, but the reduction in the flux is the same. In terms of facility design, then, no special materials would be needed for this processing state versus the others. Process cell design can be the same throughout the facility for the conditions established here. The dose rate is about an order of magnitude higher for the fuel fabrication process, but for 60 cm and 75 cm thicknesses, the dose rate still falls well below the 1 $\mu\text{Sv/h}$ benchmark.

5.2. Additional considerations and future work

Based on this study, future modeling work within the context of the HRS methodology is focused on discrete event simulation (DES). This can be used to analyze material throughput in the facility for different facility configurations. This will be important to safeguardability because the formation of material balance areas (MBAs) will affect and will be affected by operational goals. Materials accounting will be still be the main tool for safeguarding SNM. DES provides a way by which to optimize these considerations. The results here indicate a facility can be designed where non-process cells can be located adjacent to process cells. This may reduce overall difficulty in optimizing MBAs with material throughput. Therefore, models can be developed with more confidence that they can potentially reflect practical design concepts.

While the results here are promising in terms of safeguardability, these would need to be confirmed by experiment, in order to establish that shielding can reduce the flux from processing materials into adjacent cells consistent with the MCNPX results. Because there are currently no formal requirements or safeguardability goals for the design of a commercial pyroprocessing facility, presumably, the occupational dose limit would be applicable. It is possible that the relative flux developed for this study could serve as a possible design metric for safeguardability. This could be used to determine a ‘negligible flux’ benchmark.

With no site-specific data yet available for a potential facility, these design criteria are

reasonable for use as a starting point for preliminary conceptual designs, and then, as more site specific physical characteristics; e.g., different facility configurations, and other proprietary considerations; e.g., batch sizes, radionuclide content, or material flow are incorporated into the design, then additional modeling of that particular facility would require more sophisticated modeling, including the spatial distribution of the flux and identification of weakly shielded points in the design. The model and geometry developed in this study and used in the prior works can be readily advanced and adapted for more mature facility designs. Therefore, when needed, this modeling approach can be refined and adapted to model realistic physical conditions.

6. FINAL REMARKS

Safeguardability of the advanced fuel cycle will be essential to sustainability of nuclear power and the overall reduction of proliferation risk. The HRS methodology has been developed in terms of practical approaches to facility design that will optimize safety and security, reduce proliferation risk and enhance physical protection, while optimizing operational goals. This study focused on the hot cell shielding; i.e., wall thickness that would be needed to meet potential safeguardability goals. The ^{244}Cm content in the six processing states present in a commercial pyroprocessing facility were modeled using MCNPX. The goal was to investigate the neutron flux from a process cell into three, adjacent empty cells with wall thicknesses of 30 cm, 45 cm, 60 cm, 75 cm, and 90 cm. Two benchmarks were considered in order to describe the effect of the shielding: (1) a dose rate below 1 $\mu\text{Sv/h}$ and (2) a relative volume averaged flux in the empty cells to the process cell, in order to demonstrate the reduction in flux due to wall thickness.

The results are very promising for safeguardability. For wall thicknesses of 60 cm and 75 cm, the dose benchmark was satisfied. The relative flux was from 10^{-3} - 10^{-7} . The implication of these results is that cells needed for maintenance and storage can be located in proximity to process cells while meeting occupational safety goals. A closely located maintenance cell can reduce proliferation risk and enhance physical protection, while also reducing operational downtime. Storage cells located near relevant processes will also reduce transfer time. In terms of facility design, from a holistic perspective, this study would suggest that a facility may exhibit a smaller footprint and overall cost could be consequently reduced. When conceptual facility designs are eventually proposed for pyroprocessing systems on a commercial-scale, many different facility configurations will be generated based on different stakeholder interests and realistic constraints. However, achieving safeguardability must be the main goal. This study shows how facility design can be considered within the context of safeguardability in a straightforward way. Future work will build upon this concept, in order to develop a comprehensive approach to modeling and quantifying safeguardability.

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TABLE I. The processing states modeled in this study are: (1a) electroreduced metal dissolved in LiCl-Li₂O salt, (1b) electroreduced metal, (2) uranium and TRU metal dissolved in LiCl-KCl salt, (3a) TRU metal dissolved in the same salt after U extraction, and (3b) TRU metal and liquid cadmium, after extraction from the salt, and (4) the metal alloy for fuel fabrication, containing uranium, TRU, rare earth fission products, and zirconium. Commercial batch sizes are shown. The Cm and Pu content was determined by the ORIGEN simulation for a fresh fuel composition of 1 MTU 4.5% ²³⁵U, 55 GWD/MTU burnup, cooled for 10 years.

TABLE II. MCNPX results are shown for the F4 volume-averaged flux tally in the process cell (SE) for each processing state.

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Figure 1. Pyroprocessing material flowsheet. The main subsystems in a pyroprocessing facility are voloxidation, electroreduction, electrorefining, electrowinning/cadmium distillation, and metal fuel fabrication. These processes are highlighted with thick borders and primary material flow is shown by the red arrows. The flowsheet was calculated based on a prescribed metal fuel alloy composition by weight percent of 65U-20TRU-5REFP-10Zr. Material losses are shown at each processing stage.

Figure 2. The model space consists of four hot cells. A three-dimensional representation is shown in (a), and the plan view is shown in (b). The SE cell is the process cell. The source is located at the origin, 1 m above the floor. All of the cells are filled with an argon atmosphere. The cells are 10 m in width and height and 20 m in length. The cells are shielded on all sides as shown by thick boron frits-baryte concrete. This wall thickness is increased for this study.

Figure 3. MCNPX results are shown for the F4 tally for each processing state. The dose rate is given for the SW cell as a function of wall thickness. The occupational dose rate limit is shown for reference.

Figure 4. MCNPX results are shown for the F4 tally for each processing state. The dose rate is given for the NW cell as a function of wall thickness. The occupational dose rate limit is shown for reference.

Figure 5. MCNPX results are shown for the F4 tally for each processing state. The dose rate is given for the NE cell as a function of wall thickness. The occupational dose rate limit is shown for reference.

Figure 6. MCNPX results are shown for the F4 tally for each processing state. The top figure shows the simulation flux as a function of wall thickness. The relative flux is given next as a function of wall thickness, and 99%, 99.9%, and 99.99% flux reduction is indicated for reference. The fluxes reported are for the SW cell for each wall thickness.

Figure 7. MCNPX results are shown for the F4 tally for each processing state. The top figure shows the simulation flux as a function of wall thickness. The relative flux is given next as a function of wall thickness, and 99%, 99.9%, and 99.99% flux reduction is indicated for reference. The fluxes reported are for the NW cell for each wall thickness.

Figure 8. MCNPX results are shown for the F4 tally for each processing state. The top figure shows the simulation flux as a function of wall thickness. The relative flux is given next as a function of wall thickness, and 99%, 99.9%, and 99.99% flux reduction is indicated for reference. The fluxes reported are for the NE cell for each wall thickness.

TABLE I. The processing states modeled in this study are: (1a) electroreduced metal dissolved in LiCl-Li₂O salt, (1b) electroreduced metal, (2) uranium and TRU metal dissolved in LiCl-KCl salt, (3a) TRU metal dissolved in the same salt after U extraction, and (3b) TRU metal and liquid cadmium, after extraction from the salt, and (4) the metal alloy for fuel fabrication, containing uranium, TRU, rare earth fission products, and zirconium. Commercial batch sizes and density are shown. The Cm and Pu content was determined by the ORIGEN simulation for a fresh fuel composition of 1 MTU 4.5% ²³⁵U, 55 GWD/MTU burnup, cooled for 10 years.

STATE	BATCH SIZE (kg)	DENSITY (g/cc)	²⁴⁴Cm (g)	Pu (g)
1a: ERD metal + salt	70	2.03	1.6	231
1b: ERD metal	20	18.35	1.6	231
2: U + TRU + salt	70	2.33	1.6	231
3a: TRU + salt	38.1	1.71	1.6	231
3b: TRU + Cd	1.1	9.70	1.6	231
4: ALLOY	20	15.8	24	3400

TABLE II. MCNPX results are shown for the F4 volume-averaged flux tally in the process cell (SE) for each processing state. The F4 volume-averaged flux tally for the other rooms in the facility (SW, NW, NE) is normalized to the flux given here for each wall thickness.

STATE	FLUX (n/cm²/s)	$\pm 1\sigma$ (n/cm²/s)
1a: ERD metal + salt	1.9E+01	5.6E-03
1b: ERD metal	2.1E+01	6.2E-03
2: U + TRU + salt	1.7E+01	5.2E-03
3a: TRU + salt	1.9E+01	5.6E-03
3b: TRU + Cd	2.0E+01	2.0E-03
4: ALLOY	3.7E+02	7.4E-02

Figure 1. Pyroprocessing material flowsheet. The main subsystems in a pyroprocessing facility are voloxidation, electroreduction, electrorefining, electrowinning/cadmium distillation, and metal fuel fabrication. These processes are highlighted with thick borders and primary material flow is shown by the red arrows. The flowsheet was calculated based on a prescribed metal fuel alloy composition by weight percent of 65U-20TRU-5REFP-10Zr. Material losses are shown at each processing stage.

Figure 2. The model space consists of four hot cells. A three-dimensional representation is shown in (a), and the plan view is shown in (b). The SE cell is the process cell. The source is located at the origin, 1 m above the floor. All of the cells are filled with an argon atmosphere.

The cells are 10 m in width and height and 20 m in length. The cells are shielded on all sides as shown by thick boron frits-baryte concrete. This wall thickness is increased for this study.

Figure 3. MCNPX results are shown for the F4 tally for each processing state. The dose rate is given for the SW cell as a function of wall thickness. The occupational dose rate limit is shown for reference.

Figure 4. MCNPX results are shown for the F4 tally for each processing state. The dose rate is given for the NW cell as a function of wall thickness. The occupational dose rate limit is shown for reference.

Figure 5. MCNPX results are shown for the F4 tally for each processing state. The dose rate is given for the NE cell as a function of wall thickness. The occupational dose rate limit is shown for reference.

Figure 6. MCNPX results are shown for the F4 tally for each processing state. The top figure shows the simulation flux as a function of wall thickness. The relative flux is given next as a function of wall thickness, and 99%, 99.9%, and 99.99% flux reduction is indicated for reference. The fluxes reported are for the SW cell for each wall thickness.

Figure 7. MCNPX results are shown for the F4 tally for each processing state. The top figure shows the simulation flux as a function of wall thickness. The relative flux is given next as a function of wall thickness, and 99%, 99.9%, and 99.99% flux reduction is indicated for reference. The fluxes reported are for the NW cell for each wall thickness.

Figure 8. MCNPX results are shown for the F4 tally for each processing state. The top figure shows the simulation flux as a function of wall thickness. The relative flux is given next as a function of wall thickness, and 99%, 99.9%, and 99.99% flux reduction is indicated for reference. The fluxes reported are for the NE cell for each wall thickness.