Baseline Fuel Fabrication Facility

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Office of Defense Nuclear Nonproliferation
National Nuclear Security Administration
U.S. Department of Energy

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Contents

1. Introduction ............................................................................................................................. 4

2. Baseline Fabrication Facility Description ............................................................................. 5
   2.1 Fuel Assembly Description ................................................................................................. 5
   2.2 Fabrication Process Description ......................................................................................... 7
      2.2.1 Feed Receipt, Inspection, and Preparation ................................................................. 8
      2.2.2 Fuel Formation ........................................................................................................... 9
      2.2.3 Plate Production ......................................................................................................... 11
      2.2.4 Plate Finishing .......................................................................................................... 14
      2.2.5 Element Assembly ...................................................................................................... 15
   2.3 Fabrication model description ........................................................................................... 15
   2.4 Fabrication Floorplan ......................................................................................................... 16

3. Optimization strategy ........................................................................................................... 17

4. Future Work .......................................................................................................................... 18

List of Tables

Table 1. Fuel assembly design parameters ..................................................................................... 5
Table 2. Nominal fuel assembly dimensions .................................................................................. 6
Table 3. Fuel Fabrication Unit Operations – Holdup and Scrap ................................................... 11
Table 4. Failure Rates for Plate Production and Finishing Operations ........................................ 13
List of Figures

Figure 2.1. Fuel assembly. Image includes example fuel seat and fuel handling pin components. Fuel plates run parallel to the fuel pin shown and are supported by the side plates.......................6

Figure 2.2. Fuel assembly cross sections. On the left is a standard assembly, while the right is a control assembly showing space for control blade insertion and the replacement of the outer plates with aluminum blanks. The fuel meat is indicated by yellow coloration, while aluminum components of the plate and assembly are gray.................................................................7

Figure 2.3. Fabrication flow diagram for U₃Si₂-Al dispersion fuel. The orange and blue boxes with gray text are not assessed as part of the fabrication model developed to track the uranium utilization. ........................................................................................................................................8

Figure 2.4. Powder Production Process Flow .................................................................................................................................9

Figure 2.5. Fuel Plate Assembly .......................................................................................................................................................12

Figure 2.6. Fuel Plate ........................................................................................................................................................................14

Figure 2.7. General fuel fabrication facility floorplan. The alpha-numeric values in each box correspond to fuel fabrication steps outlined in Figure 2.4. The arrows in the diagram indicate the general material flow in the fabrication facility........................................16
1. Introduction

PRO-RR is the research reactor focused program element of the broader Proliferation Resistance Optimization program (PRO-X) under the National Nuclear Safety Administration (NNSA) in the U.S. Department of Energy (DOE). PRO-X provides a framework for integrating proliferation resistance in nuclear system designs to minimize weapons usable nuclear materials (WUNM) production and diversion pathways while optimizing systems performance for peaceful use missions. PRO-RR applies the PRO-X mission objectives to research reactor system design. This document serves as one of the foundational documents for the PRO-RR-Fuel System Design technical team by documenting a baseline fuel fabrication facility to be used for further optimization studies. The PRO-RR-Fuel System Design technical team consists of subject matter experts from Argonne National Laboratory (Argonne) and Savannah River National Laboratory (SRNL).

In order to develop specific strategies for fuel fabrication facilities to optimize proliferation resistance, performance, and safety, a baseline fuel fabrication facility design basis was developed. Having a baseline design basis allows for the qualitative and quantitative comparison of design choices in the optimization process. This report describes the baseline fuel fabrication facility and general optimization strategy. Chapter 2 describes the fuel system selected for examination, the fabrication process used as the baseline, a description of the model developed to track uranium utilization, and a generic floorplan of the fabrication facility. Chapter 3 describes the overarching optimization strategy that could be implemented for a fabrication facility.
2. Baseline Fabrication Facility Description

2.1 Fuel Assembly Description

The reference assembly chosen for initial analysis is a 20-plate materials test reactor (MTR)-type fuel assembly to be used in a 10 MW reactor. This fuel assembly was developed based on the conversion of the high-enriched uranium (HEU) fuel described in IAEA-TECDOC-233 [1]. The fuel system to be used for conversion was decided to be 4.8 g/cm³ U₃Si₂ fuel dispersed in an aluminum matrix (U₃Si₂-Al), as U₃Si₂ is the fuel system of choice for upcoming high-power research reactor conversions and 4.8 g/cm³ is the most common fuel loading for U₃Si₂-Al dispersion fuel [2]. It was decided, in order to minimize the impact on the fabricator, to maintain the fuel meat thickness (0.51 mm) and coolant channel gap (2.188 mm) of the HEU fuel design for the LEU design. The empirical correlation from the IAEA-TECDOC-233 [1], reproduced in equation (2.1), was developed to determine the fuel fabrication parameters for conversion of the HEU system described in the reference to an LEU fuel system with an enrichment of 19.75 % ²³⁵U.

\[
\rho = (35.65 + 2977e^{-0.1232Ndw}) \frac{1}{Nd_m}
\]  

(2.1)

where \( \rho \) is the uranium density in the fuel meat in g/cm³ (set to 4.8 gU/cm³), \( N \) is the number of plates, \( d_w \) is the coolant channel width in mm (set to 2.188 mm), and \( d_m \) is the fuel meat thickness in mm (set to 0.51 mm). The design parameters for the LEU fuel system are given in Table 1. It was assumed that the control assemblies would have six fewer fueled plates than the standard assemblies, as is the case with the HEU control assemblies.

<table>
<thead>
<tr>
<th>Fuel Design Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel material</td>
<td>U₃Si₂-Al dispersion</td>
</tr>
<tr>
<td>²³⁵U enrichment</td>
<td>19.75 wt.%</td>
</tr>
<tr>
<td>Uranium density in fuel meat</td>
<td>4.8 gU/cm³</td>
</tr>
<tr>
<td>Uranium loading</td>
<td>92.53 gU/plate</td>
</tr>
<tr>
<td></td>
<td>1850.60 g/assembly (standard assemblies)</td>
</tr>
<tr>
<td></td>
<td>1295.42 g/assembly (control assemblies)</td>
</tr>
<tr>
<td>Fueled plates per assembly</td>
<td>20 (standard assemblies)</td>
</tr>
<tr>
<td></td>
<td>14 (control plate assemblies)</td>
</tr>
<tr>
<td>Core size</td>
<td>23 standard assemblies</td>
</tr>
<tr>
<td></td>
<td>5 control assemblies</td>
</tr>
<tr>
<td>Refueling schedule</td>
<td>23 standard assemblies per year</td>
</tr>
<tr>
<td></td>
<td>4 control assemblies per year</td>
</tr>
<tr>
<td>Total required plates per year</td>
<td>516</td>
</tr>
</tbody>
</table>
The total amount of uranium supplied is sufficient for a reactor operating at 10 MW 85% of the time (approximately 6 days per week) and achieving at least 40% $^{235}$U burnup. The total $\text{U}_3\text{Si}_2$ required per plate to achieve 92.53 grams of uranium is 100 grams. This $\text{U}_3\text{Si}_2$ is dispersed in aluminum to form the fuel meat, with additional aluminum used for cladding surrounding the fuel meat. Nominal fuel meat and cladding dimensions are given in Table 2. The exact geometry of the fuel meat may vary within defined tolerances due to the manufacturing process, however the total uranium mass is conserved under these deformations.

Table 2. Nominal fuel assembly dimensions

<table>
<thead>
<tr>
<th>Fuel Assembly Dimension</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel meat thickness</td>
<td>0.51 mm</td>
</tr>
<tr>
<td>Fuel meat width</td>
<td>6.3 cm</td>
</tr>
<tr>
<td>Fuel meat length</td>
<td>60 cm</td>
</tr>
<tr>
<td>Cladding thickness</td>
<td>0.38 mm (plates 2-19)</td>
</tr>
<tr>
<td></td>
<td>0.495 mm (plates 1 and 20)</td>
</tr>
<tr>
<td>Water gap between plates</td>
<td>2.188 mm</td>
</tr>
<tr>
<td>Side plate thickness</td>
<td>0.48 cm</td>
</tr>
<tr>
<td>Assembly dimensions</td>
<td>7.6 cm by 6.96 cm</td>
</tr>
</tbody>
</table>

A standard assembly is shown in Figure 2.1.

Figure 2.1. Fuel assembly. Image includes example fuel seat and fuel handling pin components. Fuel plates run parallel to the fuel pin shown and are supported by the side plates.

A control assembly is similar in construction to the standard assembly but includes provisions for accepting the control blades and interfacing with the control blade drive mechanism. Cross sections through the fueled portion of the assembly are shown in Figure 2.2.
Fuel plates for both standard and control assemblies are identical except for the first and last plate in a standard assembly, which uses thicker 0.495 mm cladding rather than the standard 0.38 mm cladding. Relative to standard assemblies, control assemblies lack the outer three fueled plates on either side, two of which are replaced with aluminum blanks to form a guide for insertion of a control blade. The control blades themselves work with the control assembly during operation but are not part of the assembly for fuel fabrication purposes.

2.2 Fabrication Process Description

Higher uranium density required for the conversion of reactors operating on highly enriched uranium (HEU) to low-enriched uranium (LEU) in research reactors has led to the selection and development of a plate-type dispersion fuel consisting of U₃Si₂ metallic fuel particles dispersed in an aluminum matrix. The fuel meat is produced by a powder metallurgy process and then bonded to aluminum alloy cladding to ensure fission product confinement.

The composition of the uranium silicide fuel alloy selected for use in dispersion fuels is 92.5% U and 7.5% Si [3]. This is a greater amount of Si than required for stoichiometric U₃Si₂, as it was established that uranium-rich phases had poorer irradiation performance [4]. The final fuel compact has a U density of 4.8 gU/cm³, with an aluminum content of about 23%; each plate contains ≈100 grams of fuel with 92.5 grams of U. Annual operation of the baseline 10 MW reactor will require the fabrication of 23 fuel assemblies (20 plates/assembly) and 4 control assemblies (14 plates/assemblies), for a total of 516 plates containing approximately 47.7 kg U.

Fabrication of dispersion fuel requires processing of uranium metal as well as uranium and aluminum fines that can be pyrophoric. Inert or vacuum atmosphere confinement may be required for these workstations. Handling of the U₃Si₂ in an inert or vacuum atmosphere also prevents extensive oxidation of the fuel. Handling and storage of both fuel and cladding materials must be
rigorously controlled to prevent contamination or damage during fabrication. Care must be taken in all processing steps, e.g., selecting feedstocks and checking products, to ensure applicable specifications such as those found in IAEA-TECDOC-467 [5], IAEA-TECDOC-643 [6], ANL/RERTR/TM-11 [4], and NUREG-1313 [7] are met. Some key specifications and process step considerations are discussed in the following Sections. Based on [8, 9] and the author’s best knowledge, a flow diagram for the fabrication process of plate-type U₃Si₂-Al fuel was developed, and is shown in Figure 2.3.

![Fabrication flow diagram for U₃Si₂-Al dispersion fuel. The orange and blue boxes with gray text are not assessed as part of the fabrication model developed to track the uranium utilization.](image)

The fuel fabrication process consists of five major areas, which will be discussed in detail in the following sub-Sections: feed receipt, inspection, and preparation (Section 2.2.1), fuel formation (Section 2.2.2), plate production (Section 2.2.3), plate finishing (Section 2.2.4), and element assembly (Section 2.2.5).

### 2.2.1 Feed Receipt, Inspection, and Preparation

Feed receipt, inspection, and preparation includes activities for the receipt, storage, and handling of fuel materials (uranium, silicon), matrix material (aluminum powder) and plate materials (aluminum 6061 sheet, weld rods) to ensure that all specifications for quality have been met. These process steps are indicated by the blue boxes in Figure 2.3. Specifications for quality include features such as uranium isotopic content (19.75 ± 0.2% U-235), particle size distribution, and impurity measurement, as well as storage and handling requirements prior to process use. Preparation of aluminum for powder mixing and compact pressing (green process steps in Figure 2.3) should be closely coupled with these operations.
2.2.2 Fuel Formation

Fuel formation includes the preparation of the metallic uranium silicide alloy, production of fuel powder (yellow process steps in Figure 2.3), blending with the aluminum matrix material, and formation of the fuel compact to be incorporated in the fuel plate (green process steps in Figure 2.3). Key steps in the fuel powder production process are shown in Figure 2.4 and are discussed below.

Since the uranium silicide fuel has a high affinity for oxygen; storing, weighing, blending, and compacting require an oxygen-free (<4% O₂ maximum) environment, preferably in a high-purity argon atmosphere, as a nitrogen atmosphere could lead to uranium nitride formation [10]. Alloy preparation involves the mixing of uranium and silicon in the proper weight ratio (92.5% and 7.5%, respectively with adjustment for silicon lost in casting) and transfer of the mixture to an arc melting furnace in a helium/argon atmosphere to reach the melting point of 1665 °C. The resultant weight ratio must be as close to 7.5% as possible and not less than 7.4% in order to have some silicon in excess of the stoichiometric 7.31% value [5, 11]. Based on earlier development work [11], an ingot weight of 350 grams is assumed; this is sufficient for the production of three plates. The ingot undergoes a series (nominally 4 times) of melt-cool-remelt cycles to ensure homogeneous composition. Up to 2% of the mass may result in skull or other residue from the melting operations. This material is discarded to waste. The traditional furnace equipment approach is to use a water-cooled copper hearth, arc-melting furnace in contact with the alloy to minimize impurity pickup. The arc melting is conducted using a non-consumable tungsten electrode in a 80% He-20% Ar atmosphere. Although the other fabrication steps occur in a high-purity Ar environment, arc melting is done in a primarily He environment as Ar atmosphere can lead to degradation of the tungsten electrode.

The ingot may require annealing to ensure elimination of any uranium solid solution in the alloy microstructure. If required, the heat treatment is performed in an argon atmosphere at elevated temperature (~800 °C) for up to 72 hours. Minimal losses (≤0.1%) are expected during heat treatment. However, given demonstrated performance of the U₃Si₂ fuel without annealing [4], the heat treatment is not assumed to be necessary in the baseline.
The binary U/Si fuel alloy is first crushed in preparation for grinding using a jaw crusher and then processed through a ShatterBox® laboratory mill (e.g., SPEX® SamplePrep LLC) to produce the desired particle sizes. The ShatterBox® mill is tungsten carbide cobalt-lined to provide the needed hardness and minimize the introduction of impurities [11, 12].

Each ingot is divided into three batches (=110 grams each) for mechanical grinding to the proper particle size for the fuel compact. Each batch undergoes a series of grind and cool cycles, then is passed through +100 mesh and –325 mesh sieves. (grinder holdup, consisting of extremely fine particles for discard, is estimated to be less than 1%.) The –100/+325 mesh material (=23.5%) meets specifications for production of the fuel compacts. The large (+100 mesh) material (=59%) is recycled for regrinding. The –325-mesh material (“oa” =17.5%) may be blended with the acceptable powder to make fuel compacts, which may contain up to 40% fines material. While the fuel previously produced at Argonne allowed only 15% fines [5], the current demonstrated capability and specification for commercial vendors utilize up to 40% fines [4]. However, some vendors and reactor specifications have historically limited the fines content to lower levels, such as the 20% limit in Brazil [13, 14] and the 25% of the Oak Ridge Research Reactor [3]. The balance of the unused fines can be recycled to alloy casting or discarded to waste. (Fuel powder containing 40% of the fines utilizes 89% of the fines material; powder at 25% fines utilizes only 45%. The product powder is sampled and packaged for storage. Two ten-gram samples are required; one for analysis to demonstrate the specification is met and one held for future use [3]. Up to 5% of the powder may not meet specifications and will be recycled to alloy casting or discarded. Based on commercial experience 50% of the powder can be recycled.

The next step in the process is fabrication of the fuel compact. The fuel powder is combined with the required amount of aluminum powder, which has been degassed for oxygen removal. (The time between aluminum degassing and compact formation should be minimized, with interim storage in an inert or vacuum atmosphere.) The aluminum added ensures a final density of the compact of 4.8 gU/cm³. The compact powder is placed in dedicated (weighed and labelled) containers, which are sealed and then loaded into a V-blender for mixing. The bottles of mixed powder are stored pending compaction.

The blended powder is then transferred to the press. All surfaces must be meticulously cleaned prior to pressing. The powder is poured into the die, and the empty bottle is weighed to confirm the amount of powder transferred. The powder is pressed at a pressure calculated to produce the desired porosity of the fuel matrix. (The actual pressure depends on the composition of the charge and the size of the die.) The pressed compact is ejected from the die and stored in a vacuum environment. Estimates of material holdup and scrap generation from each of the unit operations discussed previously are shown in Table 3.
Table 3. Fuel Fabrication Unit Operations – Holdup and Scrap

<table>
<thead>
<tr>
<th>Operation</th>
<th>Holdup</th>
<th>Holdup Disposition</th>
<th>Scrap</th>
<th>Scrap Disposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed receipt, inspection,</td>
<td>—</td>
<td>—</td>
<td>10g sample</td>
<td>Discard</td>
</tr>
<tr>
<td>and preparation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Casting</td>
<td>2%</td>
<td>Discard</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Heat Treatment</td>
<td>—</td>
<td>—</td>
<td>0.1%</td>
<td>Discard</td>
</tr>
<tr>
<td>Ingot Crushing</td>
<td>1%</td>
<td>Discard</td>
<td>0.1%</td>
<td>Recycle to Crushing</td>
</tr>
<tr>
<td>Grinding of Fuel</td>
<td>1%</td>
<td>Discard</td>
<td>1%</td>
<td>Recycle to Grind</td>
</tr>
<tr>
<td>Sieving of Fuel</td>
<td>1%</td>
<td>Discard</td>
<td>76.5%</td>
<td>+100 mesh (59%): Recycle to Grind</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-325 mesh (17.5%): 89% to Product 9% Recycle to Casting</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2% to Discard</td>
</tr>
<tr>
<td>Samples (Ingot and Powder)</td>
<td>—</td>
<td>—</td>
<td>Two 10g samples</td>
<td>Discard</td>
</tr>
<tr>
<td>Product Powder</td>
<td>—</td>
<td>—</td>
<td>5%</td>
<td>2.5% Recycle to Casting 2.5% Discard</td>
</tr>
<tr>
<td>Fuel Compact Formation</td>
<td>—</td>
<td>—</td>
<td>0.05%</td>
<td>Discard</td>
</tr>
</tbody>
</table>

2.2.3 Plate Production

As a compact of U$_3$Si$_2$ fuel dispersed with aluminum powder, the fuel is stable in ambient conditions. This compact can then be brought out into the atmosphere and assembled with the frame and cover plates. The compact is placed in an aluminum frame and then cover plates are placed on the top and bottom of the frame (Figure 2.5).
Prior to assembly, the plate and covers are chemically cleaned to remove the aluminum oxide film. The assembly is then welded and hot rolled to approximate size. During the assembly operation, care in handling the compact is required to eliminate the generation of stray fuel on the frame/cover surfaces. Another good practice to avoid stray particles as demonstrated by NUKEM is to apply a thin coating of aluminum powder to the compact [4].

Hot rolling requires preheating of the plates in a furnace at 500 °C. According to experience reported by Babcock & Wilcox (B&W), care must be taken to prevent $U_3Si_2$ oxidation during this preheat cycle from oxygen entering through the exhaust port of the assembled billet during the preheating cycle [10]. The element is then processed through a series of runs in a rolling mill. Hot rolling results in bonding of the fuel and plate and reduces the resulting plate to at least 10% greater than the final plate thickness [15]. While the compact and preheating can be handled in air, some fabricators [13, 14] have elected to perform these operations in inert gloveboxes to avoid the potential of oxidation of the silicide fuel during heat up.

After hot rolling, the plate is subjected to blister threshold testing, where it is placed in a furnace and heated to $\approx 500$ °C for one hour, then removed and allowed to cool to room temperature. The plate is inspected; the evidence of blisters resulting from unbonded fuel may cause the plate to be rejected. The plate is stamped with a serial number and lot number. Radiography is performed to verify the dimensions and fuel location within the plate.

Fuel plates passing the blister test are cold rolled for reduction of the plate to its final desired thickness. At this point, the plates are roller-leveled prior to transfer to final finishing. The final reduction of the plate thickness shall be accomplished by cold rolling and shall not be less than 4% nor greater than 25% of the final hot-rolled thickness [3].

Scrap material generated during Plate Production and Finishing operations consists of partial or integral plates that fail to meet acceptance criteria. These are typically a result of equipment failure during individual operations. Since recovery and reuse of the fuel material from this scrap would
require chemical processing, this material is discarded to waste. Failure rates for the individual plate process steps are shown in Table 4.

Table 4. Failure Rates for Plate Production and Finishing Operations

<table>
<thead>
<tr>
<th></th>
<th>Failure Rate, %</th>
<th>Plates/year</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plate Production</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Random 1% destructive plate testing [3]</td>
<td>1.0</td>
<td>5</td>
</tr>
<tr>
<td>– Assembly (compacts + frame + upper/lower covers)</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>– Weld plate</td>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td>– Hot roll plate</td>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td>– Blister test</td>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td>– X-ray (fuel geometry)</td>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td>– Cold roll plate</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>– X-ray (fuel location &amp; density)</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>– Shearing to nominal size</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>– Machining to final dimensions</td>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Plate Finishing</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Etch plate</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>– Pickle/rinse plate</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>– Density measurement</td>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td>– Inspection</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>– Autoclave/pre-film</td>
<td>0.5</td>
<td>2.5</td>
</tr>
<tr>
<td><strong>Element Assembly</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Fuel Element</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>– Control Element</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Note: losses do not include pre-production demonstration plates- typically 24 plates for destructive analysis [3].
2.2.4 Plate Finishing

Radiography (fluoroscopic and/or radiographic examination) is performed on the levelled plate to establish fuel location and density and to verify hot spots are within limits [3, 10, 11]. The plate is then sheared and milled to its exact final dimensions (Figure 2.6). Samples are periodically taken for bend testing to determine metallurgical bonding quality of the assembled plates. Plates then undergo final cleaning to ensure residue removal, including sequential etching in a warm (80 °C) alkaline solution (e.g. Oakite® 160), rinsing in de-ionized water, then submersion in a pickling solution (55% nitric acid) for two minutes [11] followed by a final rinse.

![Figure 2.6. Fuel Plate](image)

Product plates can be selected for metallographic analysis to determine properties such as the microstructure of the fuel alloy, the distribution of the powdered fuel alloy in the aluminum matrix, the bonding of the fuel zone to the cover plates (cladding), the bending of the cover plates to the core frames, and the thicknesses of core and cover plates.

The finished plates undergo final inspection which includes measurement of plate height, length, thickness, and weight, verification of flatness and perpendicularity, and visual inspection for surface contamination or defects. The surface of the finished fuel plates shall be smooth and free of gouges (scratches, pits, or marks) in excess of 0.005 in. (0.127 mm) in depth. Dents in the fuel plate shall not exceed 0.012 in. (0.3 mm) in depth or 0.25 in. (6.4 mm) in diameter. In the dogboning zone, if there is evidence of dogboning in the plates, surface defects not deeper than 0.003 in. (0.076 mm) are acceptable [3].

Prior to assembly of fuel elements, exposure of the fuel plate cladding to ambient air forms a surface layer of aluminum hydroxide. Conditions during reactor operation (heat, radiation, water chemistry) may cause this layer to grow, causing excessive stressing or heating of the fuel plate. To improve performance, the low-density surface layer aluminum hydroxide is replaced by a thin film of a more durable mineral form of aluminum hydroxide (boehmite).
A process for application of an effective boehmite film (0.2 – 0.5 micron) utilizes an autoclave and deionized water to effectively seal the aluminum plate for enhance corrosion resistance [8, 16]. Conditions for film creation include:

- Temperature: 185 ± 8 °C
- pH: 5.6–6.0
- Time: 8.0 hours
- Pressure: 130 ± 30 psig
- Preheat time: ~ 4 hours

2.2.5 Element Assembly

The individual fuel plates are assembled into slotted side plates and are then secured by roll-swaging. For a fuel element, 20 fuel plates are secured in this fashion to form a rectangular-section fuel box. (A control element includes 14 fuel plates plus four aluminum blank plates.) End fittings are fixed to the box, by welding or riveting, to complete the fuel element assembly (Figure 2.1, Figure 2.2). After final inspection, the assembly is rinsed and dried to ensure residue removal pending storage and transport to the reactor.

2.3 Fabrication model description

The amount of holdup and scrap material produced during a fabrication process, as well as specific process decisions, were identified as “win-win” scenarios for proliferation resistance and performance. Reduction of scrap and holdup created during a fabrication step improve proliferation resistance by reducing the amount of material available for possible diversion. Reduction of scrap and holdup also improves performance by reducing the amount of raw material required for the fabrication process, reducing costs. Reducing the process time improves performance by increasing efficiency and improves proliferation resistance by decreasing the amount of time uranium is on the fabrication floor, rather than in a storage area where there is a lower opportunity for diversion.

To track the scrap, holdup, and process time for a particular fabrication process, as well as to quantify the impact of any modifications, a model initially developed for fuel cycle assessments was utilized. The Argonne Model for Pyrochemical Recycling (AMPYRE) was initially developed for quantification and assessment of an electrochemical processing facility [17]. The current baseline fabrication model is based on inputs from a spreadsheet specifying the process time (including setup and takedown and time needed for material control and accountability processes), but could be modified to incorporate output from thermochemical models of a specific fabrication process. For example, a model assessing the impact of temperature on the holdup potential for ingot heat treatment could be developed and used as an input.
2.4 Fabrication Floorplan

In developing the baseline fabrication facility, a general floorplan was developed, as shown in Figure 2.7, where the fabrication steps taking place in the workspace are included (per Figure 2.4). As the fabrication process is optimized, the fabrication floor plan will be further developed. Gray indicates multiple material forms are present, blue indicates material in its as-received state, orange indicates cladding material handling, yellow indicates the fuel form is alloyed, green indicates the fuel is mixed with the matrix material, and purple indicates that the materials are assembled as a fuel plate unit.

Figure 2.7. General fuel fabrication facility floorplan. The alpha-numeric values in each box correspond to fuel fabrication steps outlined in Figure 2.4. The arrows in the diagram indicate the general material flow in the fabrication facility.

This floor plan is intended to serve as a generic starting point for spaces that would be needed for fabrication. As the fabrication process is optimized, or specific equipment (and numbers of equipment) are identified through optimization, the relative space required for each location may change.
3. Optimization strategy

The optimization strategy for proliferation resistance, performance, and safety leverages the model described in Section 2.3, modified for the fabrication process to be optimized. The model enables identification of fabrication steps that produce a high level of scrap material or holdup, those that are over-producing, and the rate-limiting steps. After process changes are made, the model will enable quantitative assessment of the impact.

The largest impact from proliferation resistance, performance, and safety perspectives is the reduction of scrap material. Reducing the scrap by fabrication optimization reduces diversion potential, reduces cost (as less material will need to be purchased for the same number of plates), and reduces the amount of radiation workers are exposed to. After identification of fabrication steps that result in a high level of scrap material, optimization will work to identify the cause of the high scrap production, and propose methodologies to reduce the scrap produced, such as changing the fabrication process, or loosening of the specification. One possible scenario is a high level of scrap produced during the particle sieving step due to the use of a narrow range of particle sizes in the final product. Increasing the particle size distribution, which has historically been between 5 and 40% fines and particle sizes from 25 µm to 125 µm, (optimized with impacts to homogeneity and other plate parameters) would reduce the amount of fuel particles rejected during this stage.

In addition to identifying fabrication steps producing large amounts of scrap material, the fabrication process itself can be optimized by identifying steps that are either over- or under-producing for the amount of product needed. For fabrication steps that are under-utilized (over-producing), either smaller equipment and batch sizes could be implemented, or scheduling strategies could be investigated to optimize staff utilization. Reducing the equipment or batch size would improve proliferation resistance by decreasing the amount of fuel on the fabrication floor at one time and could be a cost-saving measure if maintenance and operation of the smaller unit is less expensive. For steps that are under-producing (rate limiting), the focus would be on ways to increase throughput for that particular fabrication step. That could include adding additional pieces of the same equipment or parallel processing lines, or recommending the replacement of the equipment with one that could handle a larger batch size, as long as criticality safety and other safety considerations are met. Replacement would particularly be recommended if the setup or takedown process is more extensive than the fabrication step.

Outside of the fabrication process itself, there is an opportunity to optimize the uranium utilization through collaboration with the PRO-RR Core team, for example through revision of the fuel assembly design or optimization of fuel management. The current fuel (and control) assembly design assumes the same fuel meat thickness and coolant channel gap for all plates in the assembly. It is possible that a more fuel-efficient design could be achieved though non-uniform fuel meat thicknesses (e.g., thinner fuel meat on the outer plates) while maintaining the desired performance.
4. Future Work

Future work with the baseline fabrication facility will focus on optimization of the fabrication process according to the strategy described in Section 3. This will include identification of specific fabrication processes and techniques, as well as numbers of pieces of equipment required for the most efficient fabrication route. Through this process, the generic floorplan will be updated to indicate the particular pieces of equipment.

The same model used to identify process steps for optimization, and quantification of the impact of any changes, could be modified to capture a collaborator’s fabrication process (either as-established, or planned). The same optimization scheme could then be applied to identify areas for possible improvement.

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