Uranium Dioxide Conversion

Chemical Science and Engineering Division
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Uranium Dioxide Conversion

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URANIUM DIOXIDE CONVERSION

1 INTRODUCTION

The Global Threat Reduction Initiative (GTRI) sponsored by the National Nuclear Security Agency is responsible for converting the five U.S. research reactors from high enriched uranium (HEU) to low enriched uranium (LEU) fuel. A description of the facility envisioned for manufacturing the LEU fuel from HEU feedstock is given by Wachs et al. (2008). In that document, they estimate that the proposed fuel manufacturing process would have an overall fuel manufacturing efficiency of 56% (net material to qualified fuel elements). The remaining 44% of the material accounts for more than 2000 kg of LEU to be recycled annually. The uranium recycle stream would be composed of a mixture of materials ranging from casting scrap from the downblending process, shearing losses from foil sizing, rejected fuel elements, and material from hold-up in crucibles and other contaminated equipment. In order to treat such a complex uranium recycle stream, an aqueous purification process was selected to remove the impurities via solvent extraction. Uranyl nitrate, the product from the solvent extraction process, is calcined to yield uranium dioxide, which is ultimately converted through nonaqueous processes to metallic uranium that is recycled to fuel fabrication. This report provides a flowsheet, process description, and material balance including waste streams for a baseline and alternative method to convert uranium dioxide from the aqueous purification process to uranium metal. In addition, a brief description of the process equipment, a facility layout, and cost estimate is provided for each conversion method.
2 BASELINE CONVERSION PROCESS

The baseline process consists of two well-established unit operations for converting uranium dioxide to uranium metal: hydrofluorination and calcothermic reduction. They are routinely used in the uranium enrichment and metal production processes. Over the years, the chemistry and engineering of these processes has been optimized to yield high quality product while minimizing waste production.

The hydrofluorination process converts uranium dioxide to uranium tetrafluoride by reaction with hydrogen fluoride gas. The chemical equation describing the process is

\[
\text{UO}_2(s) + 4 \text{HF}(g) = \text{UF}_4(s) + 2 \text{H}_2\text{O}(g).
\]  

(1)

This solid-gas reaction is typically completed in a fluidized-bed reactor at temperatures in the range 300°C to 500°C. Complete conversion of the UO$_2$ to UF$_4$ is routinely achieved on an industrial scale.

The calcothermic reduction process chemically reduces the UF$_4$ with calcium metal to produce uranium metal. The chemical equation describing the process is

\[
\text{UF}_4(s) + 2 \text{Ca} = \text{U}(s) + 2 \text{CaF}_2(s).
\]  

(2)

The reduction process is carried out in a batch reactor with a reaction initiation temperature of approximately 500°C. The enrichment level of the feed material and equipment design dictate batch size. As with the hydrofluorination process, complete conversion of the UF$_4$ to U is routinely achieved on an industrial scale. The product metal is separated from the CaF$_2$ and residual Ca in a billet-salt separation process. This mechanical operation removes the residual salt from the reduced metal to produce a clean ingot.

In addition to the major U conversion operations, there are auxiliary operations required to deliver the reagents and condition the waste streams. These supporting operations include the HF vaporizer for the hydrofluorination system, the off-gas treatment system, reduction vessel cleaning, and product and waste storage.

A simplified schematic of the conversion process and mass balance is presented in the next section of this report. A description of the proposed conversion equipment and facility follows the mass balance information.

2.1 MASS BALANCE

The GTRI has estimated that the proposed manufacturing process for fuel conversion will require 4759 kg of LEU annually (Wachs 2008). Using the overall efficiency factor of 56%, approximately 2094 kg of uranium scrap will be generated annually. The scrap uranium conversion facility is designed to treat 2500 kg annually, giving approximately 15% excess
capacity. The current facility would be required to operate for 250 days per year with an average daily processing amount of 10 kg of U. A detailed criticality safety analysis was not part of this study. Other assumptions used in developing the mass balance flowsheet are given below.

2.1.1 General Assumptions

1. Annual amount of uranium scrap is 2094 kg
2. Facility designed for 2500 kg/yr
3. Aqueous separations provide feed material in the form of UO₂

2.1.2 Hydrofluorination

1. Hydrofluorination process efficiency is 100%
2. 15 mol% excess HF gas is required to achieve conversion efficiency
3. Particle entrainment in gas phase is 0.01 wt% of total material
4. Entrained particle recycle efficiency is 90% by weight
5. UF₄ product particle size is adequate for reduction process

2.1.3 Calciothermic Reduction

1. Reduction efficiency of UF₄ to U is 100%
2. Batch size is limited to 10 kg U product
3. 15 mol% excess calcium required to achieve reduction efficiency
4. 5 mol% Li used to enhance reactivity and facilitate metal-salt separation
5. No salt is retained inside uranium billet
6. Ceramic crucibles have one-time use
7. Salt retention on uranium billet is 2 wt% or less
8. Product retention in crucible is 1 wt% or less
9. Unrecoverable product losses are 1 wt% or less

2.1.4 Waste Treatment

1. Excess HF can be recycled to aqueous separations
2. CaF₂, LiF, and excess Ca metal can be recycled to aqueous separations

A simplified schematic of the conversion process and mass balance is shown in Figure 1. The mass balance flowsheet reveals 98.8% efficiency for the production of U from UO₂. The residual uranium-bearing materials are sent to the aqueous separations process for recovery, purification, and recycle. Calcium fluoride (1590 kg/yr) and calcium (145 kg/yr) are sent to aqueous processing to recover the residual uranium and stabilize the waste. In addition, 145 kg of HF is delivered to aqueous separations as dilute hydrofluoric acid for treatment of process waste from fuel fabrication and uranium conversion (e.g., dissolution of refractory materials or
off-specification fuel). The largest waste stream from the baseline process is the one-time-use magnesia liner or crucible (1375 kg/yr). This material is sent to aqueous separations so that any residual uranium can be recovered prior to disposal.

### 2.2 HYDROFLUORINATION

Both dry and wet hydrofluorination processes are used in commercial applications to convert uranium dioxide to uranium tetrafluoride. Dry hydrofluorination uses anhydrous hydrogen fluoride gas at elevated temperatures within fluidized or moving bed reactors (IAEA 1999; Edwards and Oliver 2000). For the conversion process, 10 to 25 mol% excess
HF gas is required to ensure the complete conversion to UF₄ (Perkins 1982; Patisson and Ablitzer 2002; Roddy et al. 1977). The excess HF gas is collected using a scrubber system and recovered in the form of dilute hydrofluoric acid, which can be recycled to the aqueous process (IAEA 1999). In contrast, wet hydrofluorination uses aqueous hydrofluoric acid and precipitates the UF₄ from solution (Edwards and Oliver 2000). This approach minimizes the cost of the HF scrubber systems but requires drying the UF₄ product (Edwards and Oliver 2000). It is more commonly used in uranium enrichment where the next step is conversion to UF₆ rather than the metal production process.

2.2.1 Fluidized Beds

Two vertical fluidized-bed reactors in series with countercurrent flow of solid and gas would be used for the hydrofluorination process (Perkins 1982; Roddy et al. 1977; Goorevich 1998). A schematic of the hydrofluorination step with fluidized beds is shown in Figure 2. The first bed is operated at 300°C, where the UO₂ feed, which is charged by a steel hopper, is partially converted to UF₄. An approximately 70% conversion rate can be expected for this first bed. The effluent stream from this process consists of steam and approximately 15% HF gas.

The second bed has anhydrous HF added directly to the partially converted UO₂ at 500°C to finish the conversion process. A screw feeder powered by an electric motor will charge the second reactor with the partially converted UO₂ from the first reactor. Conversion efficiencies of approximately 100% are quite common with the hydrofluorination process.

The UF₄ product is discharged from the second bed into a storage hopper for transfer to the reduction operation. Nitrogen gas is used to prevent caking in the fluidized bed (approximate flow rate of 100 scfm). Stirring can also be employed to prevent caking but may not be required. The typical footprint for a 50-kg batch fluidized-bed system is approximately 32 ft² with bed dimensions of 3 ft high by 0.5 ft in diameter. A pair of horizontal counter-current fluidized beds with ribbon stirrers could also be used for the hydrofluorination operation, but this approach may
lead to a larger facility footprint. The materials of construction for the equipment and subsequent piping in contact with HF (wet or dry) is Hastelloy, Inconel, or Monel (Goorevich 1998; Bonini et al. 1998).

2.2.2 Moving Bed Furnace

An alternative to the fluidized-bed reactor is a moving-bed furnace (Dussoubsa et al. 2002, 2003a,b). A diagram of the furnace is shown in Figure 3. The system consists of two distinct zones that behave similarly to the two independent fluidized beds. The UO$_2$ is gravity fed through the top of the moving-bed furnace and is preheated to 200°C prior to entering the furnace. The average particle size of the UO$_2$ entering the vertical zone is 6 mm or less to ensure high efficiency conversion to UF$_4$. The vertical zone temperature is carefully controlled with heat exchangers capable of cooling the vessel, if the exothermic reaction drives the temperature above the desired range of 300°C to 700°C. The partially reacted UO$_2$ automatically enters the horizontal zone of the moving-bed furnace.

An Archimedes screw is used to transport the material through the horizontal zone. The screw also prevents the material from caking. Counter-flow anhydrous HF is introduced at 340°C into the horizontal zone of the furnace and proceeds up through the vertical zone. The gas velocity through the vertical zone is approximately 2 ft/s while the solid flow is about $2 \times 10^{-2}$ ft/s in the opposite direction. The process time from entrance into the vertical zone to exit of the furnace is approximately six hours.

The approximate footprint of the furnace system is 32 ft$^2$ and 16 ft in height. The moving-bed furnace is several meters high with a diameter up to 1.6 ft.

2.3 CALCIOTHERMIC REDUCTION

Uranium metal is produced by reacting the uranium tetrafluoride from the hydrofluorination operation with calcium metal. The major by-product of the process is calcium fluoride. Excess calcium metal, 10 to 25 mol%, is required to completely convert the UF$_4$ into U. Magnesium, which is more economical than calcium, may also be substituted as the reducing agent; however, calcium produces a higher quality uranium billet (Goorevich 1998).
Calcium reduction often uses iodine and/or lithium metal as a booster to lower the salt slag melting point from approximately 1360°C to the uranium melting point of approximately 1150°C (Sheller 1961). Without the addition of iodine or lithium, the salt will solidify before the uranium and become entrapped within the uranium billet. The addition of iodine and lithium also reduces the initial starting temperature of the reaction from 515°C to approximately 410°C (Sheller 1961; Baker et al. 1945).

Process equipment used for the calciothermic reduction is an inert glovebox, an induction furnace, a ceramic crucible or liner, and a steel containment or bomb assembly (Baker et al. 1945). A dolomitic lime (fused CaO-MgO) or MgO liner is one of the key components of the reduction process because of its inertness with liquid uranium (Goorevich 1998; Bonini et al. 1998). The liner, with a mass of about 5.5 kg, would be used once and discarded.

The inert argon atmosphere glovebox is 12 ft long × 4 ft wide × 8 ft high and contains three separate stations: (1) reduction vessel loading, (2) reduction and subsequent vessel cleaning, and (3) billet-salt separation and storage. Figure 4 is a diagram of the glovebox proposed for reduction and billet-salt separation. The glovebox should be maintained at negative pressure to the facility to protect workers from possible uranium dust releases in the event of a glove failure. The argon atmosphere in the glovebox would be maintained at low (ppm) O₂, H₂O, and N₂ levels using a dedicated purification system.

2.4 BILLET-SALT SEPARATIONS

The uranium billet produced in the calciothermic reduction operation is readily separated from the ceramic liner and salt slag. The molten uranium forms a puck at the bottom of the liner while the lower density CaF₂ salt solidifies above. The separation process involves cracking the ceramic liner and segregating the CaF₂ from the billet. Mechanical cleaning and polishing of the billet requires a small (~10 ft²) section of the glovebox to separate the uranium product from the

![FIGURE 4 Reduction Glovebox Diagram](image-url)
salt. The uranium billet that is collected would be stored in a well prior to transfer out of the
glovebox for use in fuel fabrication or long-term storage. The salt slag and the broken ceramic
liner are also stored within their respective locations in the glovebox prior to discharge to the
aqueous recovery process. The reduction vessels will undergo mechanical cleaning to remove
residual salt and calcium metal prior to being reused.

If mechanical polishing does not effectively remove the salt from the billet, a chemical
wash can be performed in an adjacent area outside the reduction glovebox. Two chemical wash
schemes are reported to work effectively. In one scheme, the billet is placed in a dilute acetic
acid solution, followed by a water rinse, and, lastly, acetone for through drying (Baker et al.
1945). The other scheme involves a four step process: (1) immersion of the billet in an alkali
metal salt bath, (2) a water quenching step, (3) a warm nitric acid bath, and (4) a water rinse
(Banker et al. 1981).

2.5 OFF-GAS TREATMENT

The gaseous HF and N\textsubscript{2} that flow through the hydrofluorination equipment will capture
fine UO\textsubscript{2} and UF\textsubscript{4} particles. The entrained particles are captured using carbon-metal filters that in
combination trap 99.999\% of the dust particles (Perkins 1982; Roddy et al. 1977). The captured
material is collected from the filters and returned to the hydrofluorination process.

The remaining gases are treated through venturi water scrubbers that condense the HF
into dilute hydrofluoric acid (DHF). The DHF can be recycled for use within the aqueous
separations operation that converts scrap uranium to UO\textsubscript{2}. Excess DHF is neutralized with lime
producing CaF\textsubscript{2} and disposed according to environmental regulations. The nitrogen gas
containing residual HF gas is passed through a potassium hydroxide (KOH) venturi scrubber as
well as a KOH solution in a packed tower before being released from the facility. A flowsheet of
the off-gas system is given in Figure 5.

2.6 FACILITY DESCRIPTION

The facility required for the baseline conversion process consists of two areas, the
laboratory area and the basement. A schematic of the laboratory area is shown in Figure 6. The
approximate size of the nonaqueous process area shown in Figure 6 is 2000 ft\textsuperscript{2}, or 40 ft × 50 ft
(i.e., omitting the aqueous uranium recovery, waste packaging, and offices). A brief description
of the process areas follows.

2.6.1 Laboratory Area

Four separate laboratory areas are required in the facility. The first laboratory contains
the aqueous separations area, which accepts the uranium scrap from the carrier bay and converts
the material into UO\textsubscript{2}. The second area, the hydrofluorination laboratory, contains the bed
reactors and serves as a housing unit for both the UO\textsubscript{2} and UF\textsubscript{4} material hoppers. Adjacent to this
laboratory is the reduction lab that contains a glovebox, an inert atmosphere purification system, an induction furnace controller, and intermediate storage for the raw and final products. The fourth and final laboratory serves as the uranium and solid waste packaging area. This laboratory would organize the waste streams and direct the materials to the final storage or recycle locations within the facility. All four of these areas would be fitted with overhead bridge cranes equipped to handle both equipment installations and product transfers.
2.6.2 Basement Area

In order to limit the footprint of the controlled area around the radioactive operations, the basement would be used whenever possible to house supporting equipment. The types of equipment found include air compressors, water chillers, pumping stations, gas cylinder racks for the reduction glovebox, the HF vaporizer, and the off-gas treatment equipment.

Hydrogen fluoride gas is generated by vaporizing the anhydrous HF feed. The vaporization equipment includes electrical heat exchangers to raise the temperature of the gas stream to 425°C.
The material hoppers can be constructed of steel but would maintain a nitrogen atmosphere in order to prevent side reactions with moisture to reduce corrosion. The UO₂ feed hopper would be fitted with heaters to preheat the feed material prior to entering the hydrofluorination furnace. The UF₄ hopper is the primary storage station for the fluorinated product. The UF₄ would be stored until the material was transferred into the reduction glovebox and prepared for use in the reduction vessel. Both hoppers would be sized to hold up to 50 kg.

2.7 COST ESTIMATE

An estimated equipment cost for the baseline process is shown in Table 1. The hydrofluorination beds, the HF vaporizer, the glovebox purification system, and the induction furnace are all commercially available pieces of equipment and require few modifications for this implementation. The total baseline facility cost (process equipment + glovebox) is estimated to be $1655k. No cost estimate is provided for the aqueous separations required for treating ~1800 kg of calcium fluoride salt and the 1375 kg of ceramic crucibles.

<table>
<thead>
<tr>
<th>Reduction Glovebox</th>
<th>Cost ($k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glovebox 12' × 4' × 8' with Small Crane</td>
<td>1155</td>
</tr>
<tr>
<td>Purification System</td>
<td>155</td>
</tr>
<tr>
<td><strong>Total Glovebox Cost</strong></td>
<td>1310</td>
</tr>
<tr>
<td>Experimental Equipment</td>
<td></td>
</tr>
<tr>
<td>Fluidized Beds</td>
<td>150</td>
</tr>
<tr>
<td>HF Vaporizer</td>
<td>25</td>
</tr>
<tr>
<td>Uranium Storage System</td>
<td>20</td>
</tr>
<tr>
<td>Induction Furnace</td>
<td>50</td>
</tr>
<tr>
<td>Off-gas Treatment</td>
<td>100</td>
</tr>
<tr>
<td><strong>Total Equipment Cost</strong></td>
<td>345</td>
</tr>
<tr>
<td><strong>Total Facility Cost</strong></td>
<td>1655</td>
</tr>
</tbody>
</table>
3 ALTERNATIVE PROCESS

An alternative conversion method is available for the conversion of UO₂ to uranium. The method consists of the electrochemical reduction of uranium dioxide to yield uranium followed by a salt-metal separation process (Gourishankar et al. 2002; Westphal et al. 2002). The electrochemical (or electrolytic) reduction process comprises loading the UO₂ from the aqueous purification process into a basket that functions as the cathode in the electrochemical cell. The basket with the dioxide is then immersed in molten LiCl that contains 1 wt% Li₂O. As current is passed between the cathode and anode of the cell, uranium ions in the UO₂ are reduced to uranium metal and oxide ions are liberated to the salt phase. Simultaneously, oxide ions are oxidized at an inert anode to produce oxygen gas that is swept from the cell. The resulting metallic product is removed from the cathode and treated in a furnace to remove the salt adhering to the metal and, ultimately, melt the uranium into a billet.

The advantages of the electrolytic reduction process as compared to hydrofluorination and calciothermic reduction include limited need for chemical reagents because the process uses electrons for the oxide-to-metal conversion; reduced process waste since no HF, no reductant metal, or one-time-use liners are needed; enhanced process safety due to no HF or steam handling requirements; and reduced process footprint.

A flowsheet for the conversion process and mass balance is presented in the next section of this report. A brief description of the proposed conversion equipment and facility follows the mass balance information.

3.1 MASS BALANCE

As described for the baseline process, the GTRI has estimated that the proposed manufacturing process for fuel conversion will require 4759 kg of LEU annually (Wachs 2008). Using the overall efficiency factor of 56%, approximately 2094 kg of uranium scrap will be generated annually. The scrap uranium conversion facility is designed to treat 2500 kg annually, giving approximately 15% excess capacity. The current facility would be required to operate for 250 days per year with an average daily processing amount of 10 kg of U. A detailed criticality safety analysis was not part of this study. The other assumptions used in developing the mass balance flowsheet are given below.

3.1.1 General Assumptions

1. Annual amount of uranium scrap is 2094 kg
2. Facility designed for 2500 kg/yr
3. Aqueous separations provide feed material in the form of UO₂
3.1.2 Electrolytic Reduction

1. Reduction process efficiency is 100%
2. Complete recovery of uranium metal from cathode basket
3. 15 wt% carryover of molten salt with product metal to cathode processor
4. Cathode baskets reused 25 times before disposal as waste

3.1.3 Cathode Processing

1. Salt/metal separation efficiency is 100%
2. Crucibles reused 25 times before recycle
3. Salt collected in distillation process recycled to electrolytic reduction system

3.1.4 Waste Treatment

1. Cathode baskets treated by aqueous separations to remove adhering salt and discharged as waste
2. Crucibles from cathode processing treated by aqueous separations to remove adhering salt and material is recycled

A simplified schematic of the conversion process and mass balance is shown in Figure 7. The mass balance flowsheet assumes 100% efficiency for conversion of UO$_2$ to uranium metal.

FIGURE 7 Alternative Facility Mass Balance Flowsheet
The waste from the process is composed of cathode baskets from the electrolytic reduction system and crucibles from cathode processing. However, the amount of waste is small—106.4 kg of steel from the reduction system and 182 kg of niobium from the cathode processor, which may be recycled to the crucible manufacturer. Other process waste from the system is very small. The LiCl-Li_2O molten salt is recycled from the cathode processor to the electrolytic reduction process. Small additions of LiCl or Li_2O will be required to offset the small amount of material sent to aqueous separations.

3.2 ELECTROLYTIC REDUCTION

Electrolytic reduction was originally conceived for the treatment of spent oxide nuclear fuel from light water and fast neutron spectrum reactors. Gourishankar et al. (2002) demonstrated the electrolytic reduction of uranium dioxide as part of the technology development activities for the treatment of spent nuclear fuel. Since that study, other researchers have confirmed the viability of using the process for converting uranium and spent fuel oxides to metal (Barnes and Willit 2007; Barnes 2008; Li et al. 2006; Sakamura et al. 2006). Barnes has demonstrated the complete conversion of UO_2 and U_3O_8 to uranium by electrolytic reduction. Current development activities focus on scale-up and optimization of the technology. Implementation of this technology for uranium oxide conversion is straightforward.

In the process, the uranium dioxide functions as the cathode of the electrolytic cell. The half-reaction describing the reduction process is

\[ \text{UO}_2(s) + 4e^- = \text{U}(s) + 2\text{O}^{2-}. \]  

The anode process consists of the oxidation of the oxide ions and evolution of oxygen gas. The half-reaction describing this process is

\[ 2\text{O}^{2-} = \text{O}_2(g) + 4e^- . \]  

Platinum or another similar inert conductive material functions as the cell anode. Lithium chloride molten salt that contains 1 wt% lithium oxide is used as the electrolyte in the cell. The normal operating temperature for the cell is 650°C. The cell is operated at approximately 3 volts to reduce the uranium ions but not degrade the LiCl electrolyte. Cell currents depend on the size of the cathode system, but can range from tens to thousands of amps.

The electrolytic reduction process is completed in a furnace well attached to an inert atmosphere glovebox. The reduction process is sized to be filled with 56.7 kg of UO_2 (50 kg U) per loading. A process schedule that would meet the throughput requirements of 10 kg per day is one day for UO_2 basket loading, two days for reduction of the dioxide, one day for U product removal, and one day for cell clean-up. The uranium that is recovered from the basket is expected to contain approximately 15 wt% salt.

The cathode baskets would be constructed of stainless steel and are sized to contain approximately 23 L of material, assuming a conservative bulk density of 2.5 kg/L. A set of
six baskets that are 24 in. wide × 1 in. thick × 10 in. tall would appropriately accommodate this material. The basket dimensions are limited to 10 in. tall to simplify the product loading and harvesting process. The six-basket set has an estimated empty mass of 53.2 kg and 109.9 kg when fully loaded with UO\textsubscript{2}. It is estimated that the baskets can be reused 25 times before replacement. The overall basket assembly footprint would be approximately 2 ft × 2 ft and fit within the reduction vessel opening sized to be 3 ft × 3 ft.

### 3.3 URANIUM CATHODE PROCESSING

Uranium cathode processing is required to remove residual salt that adheres to the metal and to consolidate the uranium into an ingot (Westphal et al. 2002; Brunsvold et al. 2000). In practice, the uranium metal covered with residual salt is recovered from the cathode of the reduction cell and placed into a crucible that is installed in an induction furnace. The furnace is evacuated to a slight vacuum (e.g., 50 torr) and the crucible is heated to 850°C to allow the salt to distill from the uranium and then heated to 1200°C to melt the uranium to allow formation of an ingot. Salt is collected in a condenser and eventually recycled to the reduction system. After cool-down, the uranium ingot is removed from the crucible and recycled to fuel fabrication or prepared for storage.

The principal components of the cathode processor are the stainless steel vessel, the loading/unloading trolley, the induction furnace, vacuum pumps, and the condenser assembly. The equipment is sized to process 50 kg of U per loading. The main crucible is constructed of a hafnium nitride-coated niobium that is estimated to be reused 25 times. The crucible has an empty mass of 91 kg. Many of these components are commercially available and require few modifications before installation. The overall footprint of the cathode processor is approximately 8 ft by 16 ft. Due to the large footprint and the desire to reduce the glovebox manufacturing costs, only the loading and unloading of the cathode processor would be performed in the inert glovebox. The trolley rail system would be designed to deliver the crucible to the consolidation vessel while maintaining an inert atmosphere. The consolidation vessel is located next to the glovebox to minimize the distance that the crucible must travel.

### 3.4 FACILITY DESCRIPTION

Both processes are performed within an inert argon glovebox that is maintained with oxygen, water, and nitrogen purification systems. Additional equipment requirements include: UO\textsubscript{2} and U hoppers, power supplies, a heated reduction furnace well, an oxygen gas collector system, an induction furnace, and an overhead glovebox crane.

#### 3.4.1 Electrolytic Reduction Glovebox

The inert atmosphere glovebox shown in Figure 8 is 16 ft long by 8 ft wide and contains two distinct areas: (1) electrolytic reduction, and (2) consolidation. The electrolytic reduction area requires five separate window stations each 4 ft by 4 ft wide. These stations are the heated salt well, salt and basket storage, basket loading, basket cleaning, and uranium harvesting. The
consolidation area is made up of the remaining three stations. These stations are used for the crucible loading, uranium removal from the crucible, and salt recovery. The crucible loading and uranium harvesting stations are located next to each other and share a storage location. The uranium billets formed in the cathode processor are stored in a well within the station for uranium recovery from the crucible.

### 3.4.2 Cathode Processor

The cathode processor trolley would take the loaded crucible to the induction heater equipment located next to the glovebox and return the uranium ingot and salt after the cycle is completed. Figure 9 shows the overall layout with the cathode processor next to the glovebox. The glovebox pressure should be maintained negative to the facility to protect workers from possible uranium dust releases. The glovebox argon atmosphere would be maintained at low (ppm) O₂, H₂O, and N₂ levels using a dedicated purification system.
3.4.3 Laboratory Area

Three separate laboratory areas are required to make up the facility. The first laboratory contains the aqueous separations area, which accepts the uranium scrap from the carrier bay and converts the material into purified UO₂. The second area, the glovebox laboratory, contains the electrolytic reduction glovebox and the uranium consolidation equipment. This area also contains the inert atmosphere purification system, an induction furnace controller, and intermediate storage for the feed and final product. The third and final laboratory serves as the uranium and solid waste packaging area. Each of these areas would be fitted with overhead bridge cranes equipped to handle both equipment installation and product transfer. The approximate size of the nonaqueous process area (Figure 10) is 1350 ft², or 30 ft by 45 ft (i.e., excluding aqueous uranium recovery, waste packaging, and offices).

FIGURE 10 Alternative Facility Layout
3.5 COST ESTIMATE

An estimated equipment cost for the alternative process is shown in Table 2. The electrolytic reduction furnace well, the glovebox purification system, and the induction furnace are all commercially available pieces of equipment and require few modifications. The electrolytic reduction system would be designed based on current knowledge. Design improvements would be implemented as the technology is matured. The overall equipment cost for the alternative process is estimated to be $2220k.

<table>
<thead>
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<th>TABLE 2 Alternative Equipment Costs</th>
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<tr>
<td>Reduction Glovebox</td>
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<td>Glovebox 16’ × 8’ × 8’ with Crane</td>
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<td>Purification System</td>
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<td><strong>Total Glovebox Cost</strong></td>
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<td>Electrolytic Reduction</td>
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<td><strong>Total Equipment Cost</strong></td>
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The facility envisioned for manufacturing the LEU fuel from HEU feedstock would create more than 2000 kg of LEU to be recycled annually. Two processes were proposed to treat the uranium dioxide produced by the aqueous purification process, which would remove the impurities from the recycle uranium. The baseline process consisting of hydrofluorination and calciothermic reduction is well established and yields high quality metallic product. The alternative process comprised of electrolytic reduction and cathode processing has been developed on the engineering scale, but requires demonstration at the scale proposed by this study. Although this alternative process has been shown to yield high purity uranium metal, it needs to be demonstrated a statistically significant number of times before comparison with the baseline process is meaningful.

The waste created in both processes is sent to the aqueous purification step to recover the uranium and stabilize the waste material into a suitable disposal form. The baseline process produces approximately 1800 kg of salt and 1400 kg of ceramic waste per year. In contrast, the alternative process is expected to produce an insignificant amount of salt waste (<1 kg), 106 kg of steel waste, and 186 kg of niobium for recycle. Significant annual savings in waste disposal and associated waste processing cost are anticipated for the alternative process.

Implementation of the baseline process is the lowest technical risk option for conversion of uranium dioxide to metal. However, this process produces substantially more waste than the alternative, which could lead to higher operational costs. Investment in a modest program to verify product quality for the alternative process would lower the technical risk associated with that approach and also provide additional confidence in the waste estimates for the large conversion facility.

A conceptual facility layout was developed for the baseline and alternative conversion processes. The nonaqueous processing area was 2000 ft$^2$ for the baseline process, while the alternative process would only require 1350 ft$^2$. Refinement of equipment design and layout would lead to optimization of laboratory space and perhaps yield a reduced space requirement for the baseline process. Nonetheless, the alternative requires a significantly less facility footprint.

The capital costs for baseline process equipment to convert uranium dioxide to uranium metal were estimated to be $1655k, while those for the alternative process were estimated to be $2220k. Although the capital cost for the alternative process is higher, savings are anticipated in operating and waste disposal cost for the alternative process. In a few years of operation, these savings could off-set the slightly higher capital cost for the alternative.

A follow-on design study to optimize the facility layout and yield more detailed equipment design information including a criticality safety analysis would provide additional confidence in the estimated facility requirements for each system. This design information would also allow for an improved bottoms-up cost estimate based on the newly generated data. Estimates of operating and waste management costs could also be derived as part of the design study and would provide additional insight into the selection of a preferred approach.
5 REFERENCES


Barnes, L., 2008, private communication.


