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# Candidate Processes for Diluting the $^{235}\text{U}$ Isotope in Weapons-Capable Highly Enriched Uranium

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Prepared for Presentation at the  
American Institute of Chemical Engineers  
1996 Spring National Meeting  
Wednesday, February 28, 1996  
Session #97: Processing Excess Weapons Usable  
Uranium and Plutonium

MANAGED BY  
LOCKHEED MARTIN ENERGY SYSTEMS, INC.  
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Lockheed Martin Energy Systems, Inc.  
Oak Ridge, Tennessee

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Oak Ridge Y-12 Plant  
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## CANDIDATE PROCESSES FOR DILUTING THE $^{235}\text{U}$ ISOTOPE IN WEAPONS-CAPABLE HIGHLY ENRICHED URANIUM

### ABSTRACT

The United States Department of Energy (DOE) is evaluating options for rendering its surplus inventories of highly enriched uranium (HEU) incapable of being used to produce nuclear weapons. Weapons-capable HEU was earlier produced by enriching uranium in the fissile  $^{235}\text{U}$  isotope from its natural occurring 0.71 percent isotopic concentration to at least 20 percent isotopic concentration. Now, by diluting its concentration of the fissile  $^{235}\text{U}$  isotope in a uranium blending process, the weapons capability of HEU can be eliminated in a manner that is reversible only through isotope enrichment, and therefore, highly resistant to proliferation. To the extent that can be economically and technically justified, the down-blended uranium product will be made suitable for use as commercial reactor fuel. Such down-blended uranium product can also be disposed of as waste if chemical or isotopic impurities preclude its use as reactor fuel.

The DOE has evaluated three candidate processes for down blending surplus HEU.

These candidate processes are:

- (1) uranium hexafluoride blending.
- (2) molten uranium metal blending.
- (3) uranyl nitrate solution blending.

This paper describes each of these candidate processes. It also compares the relative advantages and disadvantages of each process with respect to: (1) the various forms and compounds of HEU comprising the surplus inventory, and (2) the use of down-blended product as either commercial reactor fuel or waste for disposal.

## INTRODUCTION

In order to demonstrate the United States' commitment to reducing the threat of nuclear weapon proliferation, President Clinton announced on March 1, 1995, that approximately 200 metric tons (t) of United States-origin fissile material had been designated as surplus to national defense-related activities. Approximately 165 t of this surplus quantity is HEU (DOE, EIS-0240-D, 1995).

Natural uranium comprises three isotopes:

- (1)  $^{234}\text{U}$ , which makes up less than 0.01 percent by weight.
- (2)  $^{235}\text{U}$ , which makes up about 0.71 percent by weight.
- (3)  $^{238}\text{U}$ , which makes up about 99.28 percent by weight.

Of these naturally occurring isotopes, only  $^{235}\text{U}$  is fissile. By enriching its concentration of  $^{235}\text{U}$ , uranium can be made into a useful energy source. With sufficiently high concentrations of  $^{235}\text{U}$  and under appropriate physical conditions, enriched uranium can be forced to undergo a self-sustaining, nuclear chain reaction, thereby releasing large amounts of energy.

In this paper, the term "assay" refers to the concentration of the  $^{235}\text{U}$  isotope in uranium expressed by weight percent of total uranium. Typical assays of enriched uranium used as commercial reactor fuel are 3-to-5 percent. Such uranium falls within the larger category of low enriched uranium (LEU), which includes all enriched uranium with an assay under 20 percent. Any enriched uranium with an assay above 20 percent is considered to be HEU, and can theoretically be used in nuclear weapons. Individual batches within the surplus HEU inventory have assays ranging from 20 percent to over 90 percent. Depleted uranium (DU), a by-product of the uranium enrichment process, has an assay below that of natural uranium (typically 0.2-to-0.3 percent).

The DOE is the federal agency responsible for the management and storage of weapons-capable fissile materials, including the 165 t of U.S.-owned, surplus HEU. The DOE plans to destroy the weapons capability of this surplus HEU by blending it with low assay uranium (natural assay, DU, or LEU), thereby irreversibly diluting the concentration of  $^{235}\text{U}$  to below 20 percent. The weapons capability of such down-blended uranium could only be restored through an isotope enrichment process.

The DOE intends to down blend surplus HEU to an LEU product that will be suitable for use as reactor fuel. Such down-blended LEU product will be marketed to commercial utilities that operate reactors. Some surplus HEU contains concentrations of other elements or uranium isotopes that will make its

down-blended LEU product unsuitable for reactor fuel use. Such surplus HEU will be down blended to low-level radioactive waste (LLW) for disposal.

## BACKGROUND

The DOE initially screened nine options for dispositioning surplus HEU (DOE, MD-0002, 1995). Three options were eventually identified as reasonable for further analysis:

- (1) No disposition action (i.e., continued storage).
- (2) Blend HEU to 5 percent assay LEU for use as reactor fuel.
- (3) Blend HEU to 0.9 percent assay LEU waste for disposal.

The DOE followed the requirements set forth by the *National Environmental Policy Act* of 1969 by evaluating these HEU disposition options in an Environmental Impact Statement (EIS). The results of this evaluation are published in the *Disposition of Surplus Highly Enriched Uranium Draft Environmental Impact Statement* (HEU EIS), (DOE, EIS-0240-D, 1995).

Two of the three disposition options evaluated in the HEU EIS can destroy the weapons capability of surplus HEU through blending operations that would dilute its high concentration of the fissile  $^{235}\text{U}$  isotope. Independent of the assay of either the surplus HEU or the diluent uranium, the various uranium isotopes in the down-blended LEU product must be thoroughly mixed, making isotope separation possible only by use of uranium enrichment technologies. Therefore, only those

blending process technologies that mix uranium isotopes at the molecular level were considered by DOE for evaluation in the HEU EIS.

It may be possible to down blend surplus HEU and fabricate its LEU product into reactor fuel at the same facility. However, only two domestic fuel fabricators licensed to process HEU are capable of producing reactor fuel. Two DOE sites have existing capability to down blend surplus HEU, but neither produces reactor fuel. Therefore, DOE did not evaluate the option of down blending HEU and producing reactor fuel at the same site because this would exclude most domestic fuel fabricators and both of the applicable DOE sites from the disposition process.

#### **DOWN-BLENDED LEU COMPOUNDS**

The disposition option to down blend HEU to 5 percent assay LEU for sale as reactor fuel feed material requires that the down-blended product be in a form acceptable to the reactor fuel fabrication industry. Because it has long been the enriched uranium product from domestic enrichment facilities, uranium hexafluoride ( $UF_6$ ) is the standard form of LEU feed material used by reactor fuel fabricators. The ammonium diuranate (ADU) conversion process is utilized at fuel fabrication facilities to convert LEU  $UF_6$  feed into qualified uranium dioxide ( $UO_2$ ). This qualified  $UO_2$  is formed into fuel pellets that are eventually fabricated into fuel assemblies. Because it remains the standard feed material used by the fuel fabrication industry,  $UF_6$  is the preferred LEU compound down blended for use as reactor fuel.

There may be alternate forms of LEU, other than  $UF_6$ , that could be used as feed material by the fuel fabrication industry. Various methods have been proposed for introducing alternate LEU compounds into the ADU conversion process. Although outside the scope of this paper, one proposed method would have the ADU conversion process bring in down-blended LEU in the way that it recovers and recycles scrap  $UO_2$ . Alternate LEU compounds that could potentially be supplied to fuel fabrications include uranyl nitrate hexahydrate [ $UO_2(NO_3)_2 \cdot 6H_2O$ ] crystals and uranium trioxide ( $UO_3$ ). Use of either of these LEU compounds as feed might affect a fuel fabricator's ability to produce qualified  $UO_2$  product. Even if the fuel fabrication industry accepts an alternate form of feed material, the industry's current capacity to receive these LEU compounds as feed is limited.

The disposition option to down blend HEU to 0.9 percent assay LEU for disposal requires that the down-blended product be in a form acceptable for disposal as LLW. Being an environmentally stable uranium oxide compound, triuranium octoxide ( $U_3O_8$ ) is a preferred LEU compound down blended for disposal as waste. The HEU EIS evaluated LLW disposal of down-blended LEU in the form of  $U_3O_8$ .

#### DILUTION OF MINOR URANIUM ISOTOPES

In this paper the term "minor uranium isotope" refers to any uranium isotope that is neither  $^{235}U$  nor  $^{238}U$ . The naturally occurring  $^{234}U$  is an example of a minor uranium isotope. Concentrations of minor uranium isotopes are often expressed as

the ratio of their abundance in micrograms ( $\mu\text{g}$ ) relative to the abundance of  $^{235}\text{U}$  in grams (g). The concentration of  $^{234}\text{U}$  in natural uranium is about  $7,606 \mu\text{g/g } ^{235}\text{U}$ .

As the gaseous diffusion enrichment process increases the concentration of  $^{235}\text{U}$  it lowers the concentration of  $^{238}\text{U}$ . It also increases the concentration of the other naturally occurring isotope,  $^{234}\text{U}$ . This enrichment of  $^{234}\text{U}$  occurs at a rate that is slightly greater than the rate at which  $^{235}\text{U}$  is enriched. Enriching uranium to 93 percent assay will significantly increase its concentration of  $^{234}\text{U}$ . As a result of this and other factors (e.g., types of uranium fed to the gaseous diffusion plants), most weapons-grade HEU with 93 percent assay has a  $^{234}\text{U}$  concentration around  $10,900 \mu\text{g/g } ^{235}\text{U}$ .

The American Society of Testing and Materials (ASTM) created a specification (ASTM, C 996-90, 1990) which limits the concentration of minor uranium isotopes in LEU  $\text{UF}_6$  (below 5 percent assay) used in the fabrication of reactor fuel. Its limit for the maximum concentration of  $^{234}\text{U}$  is  $10,000 \mu\text{g/g } ^{235}\text{U}$ . Blending 93 percent assay HEU with natural uranium to produce LEU may not adequately dilute the  $^{234}\text{U}$  concentration to meet specification. To compensate for elevated  $^{234}\text{U}$  concentrations in some surplus HEU, a slightly enriched uranium diluent may be required to adequately dilute the  $^{234}\text{U}$  in down-blended LEU product that meets the reactor fuel specifications for  $^{234}\text{U}$ . However, most surplus HEU at lower assays

(e.g., 25-to-75 percent) has sufficiently low concentrations of  $^{234}\text{U}$  present that it can be blended with natural uranium, or even slightly depleted uranium.

Much of the surplus HEU also contains  $^{236}\text{U}$ , another minor uranium isotope. The concentration of  $^{236}\text{U}$  is also limited by specification (ASTM, C 996-90, 1990). Not present in natural uranium,  $^{236}\text{U}$  is produced when uranium is exposed to a neutron flux (e.g., in a reactor). There are two sources of  $^{236}\text{U}$  in surplus HEU:

- (1) some surplus HEU has been slightly exposed to a neutron flux.
- (2) reprocessed fuel from plutonium production reactors was used as feed to the gaseous diffusion plants that produced HEU.

Some surplus HEU has concentrations of  $^{236}\text{U}$  near the limit specified by ASTM. Since diluent uranium will not typically contain  $^{236}\text{U}$ , this surplus HEU can be down blended to an LEU product that meets reactor fuel specifications for  $^{236}\text{U}$ .

The ASTM (ASTM, C 996-90, 1990) allows its limits on minor uranium isotope concentrations to be exceeded, contingent upon acceptance by the utility using the reactor fuel. Some utilities may accept elevated concentrations of uranium minor isotopes in reactors if the use of down-blended LEU as fuel is economically favorable. This paper's evaluation of HEU down-blending processes is based upon compliance with current reactor fuel specifications.

## DILUENT URANIUM SELECTION

The selection of the diluent uranium to be blended with surplus HEU will primarily depend upon economics. Because the uranium's value generally increases as a function of assay, the diluent uranium selected for a specific batch of surplus HEU will usually have the cheapest available uranium (i.e., lowest assay) that yields an acceptable, down-blended LEU product. In addition, the use of lower assay diluent is more efficient at diluting  $^{235}\text{U}$  in HEU, further reducing blending costs. However, the selection of diluent uranium will also be affected by other criteria such as material form, chemical composition, and physical location of the diluent material.

Down blending operations used to produce LLW for disposal will use the lowest assay DU available in usable form as diluent feed. Chemical and minor isotopic concentrations in the diluent uranium will rarely be problematic in the down-blended LEU product disposed as LLW. The United States has large, surplus inventories of low-assay DU that could be made available as diluent feed for down-blending operations.

As described previously, down-blending operations that produce LEU suitable for reactor fuel feed material will require a variety of diluent assays, including DU, natural uranium, and even LEU. Since impurities and minor uranium isotopes can cause LEU to exceed reactor fuel specifications, diluent uranium used to down blend surplus HEU for reactor fuel must be selected carefully.

## **BLENDING RATIOS**

The HEU EIS assumes that surplus HEU being dispositioned as LLW for disposal will be down blended to 0.9 percent assay. DU having 0.2 percent assay will frequently be selected as diluent uranium for such down blending operations. The ratio of diluent uranium to surplus HEU required to produce a 0.9 percent assay LEU product for disposal can be expected to range between 27:1 and 130:1.

The HEU EIS assumes that surplus HEU being dispositioned as reactor fuel will be down blended to 4 percent assay. As stated previously, the assay of diluent uranium used for such down blending operations will vary depending upon factors such as HEU assay. Based upon assumptions about available diluent assay, the ratio of diluent uranium to surplus HEU required to produce 4 percent assay LEU for reactor fuel feed material can be expected to range between 8:1 and 50:1.

## **CANDIDATE DOWN-BLENDING PROCESSES**

Two of the disposition options evaluated in the HEU EIS require down blending surplus HEU with diluent uranium to create an LEU product. As part of its evaluation, the DOE considered three blending processes that can adequately dilute the <sup>235</sup>U isotope in surplus HEU and create usable LEU product:

- (1) Blending as UF<sub>6</sub>--considered appropriate only for the disposition option that would produce an LEU material suitable for reactor fuel feed material.

- (2) Blending as molten uranium metal--considered appropriate only for the disposition option that would produce an LEU material suitable for disposal as LLW.
- (3) Blending as uranyl nitrate (UN) solution--considered appropriate for both of the disposition options that produce LEU material.

### **BLENDING AS URANYL NITRATE SOLUTION**

A process commonly used in the United States to purify uranium is UN solution processing. The UN solution process described here is attractive for diluting the  $^{235}\text{U}$  isotope in surplus HEU. It can down blend HEU to produce LEU in forms usable under two disposition options: (1) for use as reactor fuel feed material (Lockheed Martin Energy Systems, Inc. [LMES], Y/ES-064, 1995), and (2) for disposal as LLW (LMES, Y/ES-097, 1995).

Steps involved in down blending surplus HEU using the UN solution process include:

- Both feed streams (surplus HEU and diluent) are converted to UN solution for subsequent blending.
- One or both of the UN solution streams are purified as needed.
- The two UN solution streams (surplus HEU and diluent) are mixed together.

- The down-blended LEU UN solution is converted to the final compound required as product.

The UN solution is produced by dissolving uranium in nitric acid, forming an aqueous solution of uranyl nitrate  $[\text{UO}_2(\text{NO}_3)_2 \cdot x\text{H}_2\text{O}]$ . The compound  $\text{U}_3\text{O}_8$  is a preferred form of uranium fed into the UN solution process. Typically a powder, its high surface-area-to-volume ratio enhances dissolution. Its feed rate can be metered, providing for precise process control. Although uranium metal and most other solid uranium compounds can be dissolved in nitric acid, their size and configuration need to be optimized for efficient dissolution and controlled feed. Metal is not a preferred form of uranium fed into the dissolution process. Metal that is sufficiently reduced in size for adequate process control and efficient dissolution is pyrophoric, making handling operations difficult.

In addition to uranium, nitric acid dissolves other constituent elements that may be present in the uranium feed materials. These impurities will generally be of little concern in LEU down blended for disposal. These impurities will usually require removal from LEU down blended for use as reactor fuel. If only one feed stream (surplus HEU or diluent uranium) has high impurity levels, then purification will occur before the two UN solution streams are mixed. If both feed streams require purification, then the specific process design will dictate whether purification should occur before or after mixing.

Independent of the need for purification, mixing the HEU and diluent UN solution streams can be accomplished in a variety of ways, including agitation, stirring, or multiple transfers between two tanks.

The UN solution process removes chemical impurities in a two-step purification process. A primary extraction process is first used to remove the bulk of these chemical impurities. The impure UN solution is fed into a primary extraction column where it is contacted with a counterflow of immiscible organic solvent, typically dibutyl carbitol or tributyl phosphate (TBP). The uranyl nitrate is extracted into the organic stream, leaving most chemical impurities in the aqueous raffinate. The organic stream is contacted with a counterflow of dilute nitrate acid in a primary strip column to strip the uranyl nitrate from the organic solvent. After the dilute UN solution produced is concentrated in evaporators, nitric acid is added to form a UN/nitric acid solution. The aqueous raffinate is tested to determine whether it requires processing for uranium recovery before being sent to a waste treatment and disposal facility.

Next, a secondary extraction process is used to provide a high purity UN solution. The concentrated UN/nitric acid solution from the primary extraction process is fed into a secondary extraction column, where it is contacted with a counterflow of solvent consisting of TBP and a N-dodecane (or high-grade kerosene) diluent. The uranyl nitrate is extracted into the solvent stream to produce a UN-TBP complex, leaving the remaining chemical impurities in the aqueous raffinate. The

UN-TBP complex is contacted with a counterflow of dilute nitrate acid in a secondary strip column to strip the uranyl nitrate from the solvent. The purified, dilute UN/nitric acid solution is concentrated in evaporators.

The UN solution process is capable of producing a variety of purified uranium compounds. When the down-blending operations are used to produce LEU for waste disposal, the mixed LEU UN solution will be converted to  $U_3O_8$ . This will be accomplished by thermally decomposing the concentrated LEU UN solution to produce  $UO_3$ . This  $UO_3$  will be oxidized to produce impure LEU  $U_3O_8$  powder.

When down-blending surplus HEU for use as reactor fuel, the mixed LEU UN solution will be converted to uranyl nitrate hexahydrate (UNH) crystals. This will be accomplished by heating the UN solution and evaporating water until it becomes molten UNH. Cooling produces solid, purified LEU UNH crystals.

Because of concerns that enriched uranium may gather in configurations that could go critical, down-blended LEU must be treated as high-assay uranium until its lowered assay is verified. Therefore, the down-blended LEU (UN solution, UNH crystals, or  $U_3O_8$ ) cannot be processed, stored, or transported in equipment not designed for high-assay criticality safety before assay verification. Specific facility designs may require that diluent uranium material be considered as high-assay uranium before it is mixed with HEU.

The down-blended LEU product (UNH crystal or  $U_3O_8$ ) will be packaged for delivery to either a reactor fuel fabrication facility or a LLW disposal site. Both of these LEU compounds are currently shipped overland in packaging containers approved for such use by the U.S. Department of Transportation (DOT).

### **BLENDING AS URANIUM HEXAFLUORIDE**

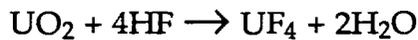
The compound  $UF_6$  has long been the enriched product from uranium enrichment facilities. It is therefore readily available and commonly handled. The  $UF_6$  blending process described here is an attractive candidate for diluting the  $^{235}U$  isotope in surplus HEU being down blended for use as reactor fuel (LMES, Y/ES-063, 1995). Its down-blended product is in the form used as feed by fuel fabrication facilities.

Steps involved in down blending surplus HEU using the  $UF_6$  blending process include:

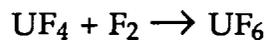
- The surplus HEU feed material is converted to  $UF_6$  for subsequent blending operations. Such conversion will be required because most surplus HEU being down blended to reactor fuel is either metal or in oxide compounds. Because low-assay  $UF_6$  can be made available from either existing inventories or by other domestic facilities, no fluorination process will be required for the diluent stream.
- The surplus HEU and diluent feed streams are mixed together.

Various methods can be used to convert uranium metal and oxide compounds to UF<sub>6</sub>. One method would convert UO<sub>2</sub> to UF<sub>6</sub> using two separate hydrofluorination and fluorination reactions. This method can also accommodate uranium metal and UO<sub>3</sub> if they are first processed for conversion to UO<sub>2</sub>.

The first step, hydrofluorination, occurs in a fluid bed reactor where the UO<sub>2</sub> is reacted with hydrogen fluoride (HF), producing uranium tetrafluoride (UF<sub>4</sub>):



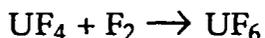
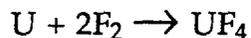
The second step, fluorination, occurs in a vertical tower reactor where the UF<sub>4</sub> is reacted with fluorine (F<sub>2</sub>), producing UF<sub>6</sub>:



The UF<sub>6</sub> gas is captured in a series of cold traps where it is desublimed to a solid. A sodium fluoride (NaF) trap catches any gaseous UF<sub>6</sub> that gets past the cold traps. Exhaust from both reactors (hydrofluorination and fluorination) is routed through a series of filters that trap any entrained HEU material. The exhaust from these filters is monitored to verify the absence of uranium and scrubbed with potassium hydroxide (KOH) to prevent any HF or F<sub>2</sub> from being released.

Uranium metal can also be converted to UF<sub>6</sub> in a single, direct fluorination method. The uranium metal is sealed in a tube furnace with a gaseous mixture of F<sub>2</sub> and a

diluent (e.g., nitrogen). The furnace heat initiates and sustains the fluorination reaction, but excess  $F_2$  is required to maintain reaction temperature:



Collection of the  $UF_6$  gas and the filtering of exhaust gases can be performed as in the two-step hydrofluorination/fluorination method previously described.

Each of the previously described HEU  $UF_6$  production processes has distinct advantages:

- The two-step hydrofluorination/fluorination method is easier to control than the direct fluorination method. If the  $F_2$  is fed into the furnace too quickly in the direct fluorination method, then the uranium metal will ignite at local hot spots, producing molten metal and molten  $UF_4$ .
- The two-step hydrofluorination/fluorination method will accept most surplus HEU as feed, including uranium metal and uranium oxide compounds. The direct fluorination method will be limited to accepting surplus HEU metal as feed.

- The two-step hydrofluorination/fluorination method will likely cost less than will the direct fluorination method because  $F_2$  costs significantly more than HF. Although both of these processes will require that  $F_2$  be produced from HF in electrolytic cells, the direct fluorination method will use three times as much  $F_2$  as the two-step hydrofluorination/fluorination method.

At atmospheric pressure  $UF_6$  has a sublimation point of  $56.2^\circ C$ . At elevated pressures,  $UF_6$  can be liquified. The two  $UF_6$  feed streams can be mixed in either the liquid or gaseous phase, each with distinct advantages:

- Design and operation of a down-blending facility based on gaseous phase mixing may require less process and equipment development than for a facility based on liquid phase mixing. Processes that involve gaseous  $UF_6$  (e.g., gaseous diffusion enrichment and ADU conversion) are mature.
- The capital investment required to construct a  $UF_6$  blending facility may be significantly less if blending occurs in the liquid phase. The volume required for mixing  $UF_6$  as liquid would allow for smaller process equipment than would be required for mixing as gas.

Because of concerns that enriched uranium may gather in configurations that could go critical, down-blended LEU must be treated as high-assay uranium until its new, lowered assay is verified. Therefore, the down-blended LEU  $UF_6$  cannot be processed, stored, or transported in equipment not designed for high-assay criticality safety before assay verification. Specific facility designs may require that diluent uranium material be considered as high-assay uranium before it is mixed with HEU.

After mixing, the down-blended LEU  $UF_6$  product will be packaged for delivery to a reactor fuel fabrication facility. Packaging containers approved for such use by the DOT are currently used to ship LEU  $UF_6$  overland.

#### **BLENDING AS MOLTEN URANIUM METAL**

Uranium metal, whether pure or alloyed, can be melted and recast using vacuum induction furnaces. Two DOE sites have a high-assay uranium casting capability. The molten metal blending process described here is an attractive candidate for diluting the  $^{235}U$  isotope in surplus HEU being down blended for disposal as waste (LMES, Y/ES-062, 1995). The DOE considers that the final down-blended LEU  $U_3O_8$  product from this process can be disposed as LLW.

Steps involved in blending down surplus HEU using the molten metal blending process include:

- Both the HEU and diluent uranium metal are reduced in size.
- The surplus HEU and diluent uranium metal are melted together in the furnace, where circulation provides mixing.
- The mixed molten metal is solidified in a casting mold.
- The down-blended LEU metal casting is converted to  $U_3O_8$ .

The molten metal blending process can accept only pure uranium metal and uranium alloys from either feed stream (surplus HEU and diluent uranium). The ability to accurately portion batches from each feed stream will be required in order to achieve the desired down-blended assay. Size reduction capability will be required for large pieces of uranium metal or alloy. Methods that produce moderate sized pieces such as pressing, shearing, or sawing can be used. Fines or machined chips of uranium metal may not be safe to feed because they are pyrophoric. Even when moderate sized pieces of uranium metal are fed, machine coolants and inert cover gases will be required to prevent metal fires.

Properly weighed batches from each feed stream are loaded together into a graphite crucible at the furnace. Melting occurs after the air inside the furnace has been replaced with an argon blanket gas. The molten metal circulates and mixes in the furnace crucible. Sufficient time is allowed to assure a homogeneous blend before the molten metal is poured into a graphite casting crucible. After cooling allows

solidification, the cast LEU ingot is placed in a stainless steel container for interim storage or transportation to subsequent process areas.

This type of molten metal processing results in appreciable diversion of uranium from the primary LEU product stream. Uranium oxide compounds and casting slag produced in conjunction with the cast ingot must be chemically processed (e.g., UN solution process) for recovery of down-blended LEU.

Before shipment to an LLW disposal site, the down-blended LEU metal casting must undergo size reduction and conversion to  $U_3O_8$ . Since pieces of uranium metal fed into the  $U_3O_8$  conversion process should be smaller than those needed for the casting process, machining to chips may be an appropriate size reduction method. Machine coolants and inert cover gases are utilized to prevent spontaneous ignition of small metallic pieces and fines during handling. Size reduced metal is fed into an oxidizing furnace and allowed to burn in air, producing LEU  $U_3O_8$ . Atmosphere in the furnace is confined and filtered to prevent uranium emissions.

Because of concerns that enriched uranium may gather in configurations that could go critical, down-blended LEU must be treated as high-assay uranium until its new, lowered assay is verified. Therefore, the down-blended LEU product (metal or  $U_3O_8$ ) cannot be processed, stored, or transported in equipment not designed for high-assay criticality safety before such assay verification. Specific facility designs may require that diluent uranium metal be considered as high-assay uranium

before it is mixed with HEU. For example, the mass of a DU metal batch entering a molten metal casting facility may be limited as if it were HEU.

Down-blended LEU  $U_3O_8$  will be packaged for delivery to a LLW disposal site. Packaging containers approved for such use by the DOT are currently used to ship LEU  $U_3O_8$  overland.

#### **OTHER POTENTIAL METHODS OF BLENDING URANIUM**

Although not evaluated in the HEU EIS, the  $UF_6$  blending process could also be used to down blend surplus HEU to a  $U_3O_8$  LEU product suitable for disposal. The processes involved in supplying and mixing the  $UF_6$  streams would be identical to those described previously. Additional processing would be required to convert the down-blended LEU  $UF_6$  to  $U_3O_8$  product. The LEU  $U_3O_8$  product will be packaged for delivery to a LLW disposal site as was described for the UN solution process.

Most mechanical blending processes that mix uranium compounds are considered to be inadequate at destroying the weapons capability of HEU. When HEU and diluent powders are mixed together each individual particle can retain physical attributes that could allow separation of the different powders. For example, the specific gravity of high-assay  $U_3O_8$  is about 1 percent greater than that of DU  $U_3O_8$ . Also, particle size and morphology will likely vary between two uranium feed streams if produced in separate processes, even if these processes replicate one

another. The possibility that weapons-capable HEU can be separated from mechanically down-blended LEU is an unacceptable proliferation risk.

However, some high energy mills may actually mash or fuse different particles, creating new particles of mixed assay. If fusing is thorough enough, then it may be impossible to mechanically separate the HEU material from diluent uranium. Applicability of such technology for down blending weapons-capable HEU is unproven. It was therefore not evaluated in the HEU EIS.

#### COMPARISONS OF CANDIDATE BLENDING PROCESSES

Each of the candidate blending processes has distinct advantages for specific disposition options.

Use of the UN solution process to down blend surplus HEU to LEU has several advantages:

- It can be utilized to down blend surplus HEU to LEU product under both disposition options (fuel and waste).
- It can produce stable uranium compounds required for each disposition option (fuel and waste), including  $U_3O_8$  (the preferred compound for disposal as LLW) and UNH crystals (a potentially acceptable feed material for reactor fuel fabricators).
- It can accept most surplus HEU material as feed (metal and various compounds).

- It can utilize large quantities of surplus uranium material that the U.S. Government plans to disposition as diluent feed.
- It can purify one or both of the uranium feed streams (HEU and diluent).
- The technologies for safely handling, processing, and transporting UN solution and its resulting products (UNH crystals and  $U_3O_8$ ) are mature.
- There are several existing domestic facilities, each designed for criticality safe processing of HEU, that can perform UN solution blending with little or no upgrade and expansion.

Possibly to its disadvantage, the UN solution process may cost more to down blend surplus HEU than the other two competing processes ( $UF_6$  blending and molten metal blending) because both feed streams undergo extensive processing.

Use of the  $UF_6$  blending process to down blend surplus HEU to LEU for reactor feed has several advantages:

- It can accept most surplus HEU material as feed (metal and oxide compounds).
- It can utilize large quantities of surplus DU  $UF_6$  that the U.S. Government plans to disposition as diluent feed. If additional diluent is required, then several domestic facilities exist that can produce additional  $UF_6$ .

- It can purify the surplus HEU feed stream either during the conversion to  $UF_6$  or by first utilizing an up-front UN solution process.
- Its diluent  $UF_6$  feed doesn't require purification or processing prior to blending.
- Its  $UF_6$  product is the standard form of LEU supplied to domestic fuel fabrication facilities.
- The technologies for safely handling, processing, and transporting  $UF_6$  are mature.
- It may be a cheaper process than UN solution process for producing reactor fuel feed material because it requires much less processing of the diluent feed.

To its disadvantage,  $UF_6$  blending will not be a viable process to disposition surplus HEU until a facility has been built that can convert surplus HEU to  $UF_6$ . The capital costs to provide a  $UF_6$  blending process capability will probably exceed those required for the other candidate processes which can utilize existing process facilities.

Use of the molten metal blending process to down blend surplus HEU to LEU for LLW disposal has several advantages:

- It can accept uranium metal and most uranium alloys as feed.
- It is the only candidate process that does not chemically convert either feed stream (surplus HEU or diluent) for blending.
- It can be utilized to declassify surplus HEU metal for delivery to down blending process facilities. It may prove beneficial to use the molten metal process solely to provide unclassified HEU metal to other facilities where down blending will be accomplished by one of the other candidate processes.
- The technologies for handling, processing, and transporting uranium metal and the final LEU  $U_3O_8$  product are mature.
- There are at least two existing domestic facilities, each designed for criticality safe processing of HEU, that can perform molten metal blending.
- It may be a cheaper process than the UN solution process for producing LLW for disposal because it requires much less processing of the feed streams (surplus HEU and diluent).

To its disadvantage, molten metal blending may only be applicable for dispositioning a small portion of the surplus HEU inventory. Much of the surplus HEU inventory cannot be fed to this process because it is not in the form of metal. Most surplus HEU that is metal will likely be dispositioned as reactor fuel

using a different process (UN solution process or  $UF_6$  blending process). In addition, a significant portion of the uranium fed to the furnace (including the valuable HEU feed) will be diverted from the product casting. Recovery of this diverted uranium would be expensive because it would require UN solution processing.

## CONCLUSIONS

The UN solution process will probably be required to disposition surplus HEU compounds destined for disposal as waste. If any of the down-blended products from the UN solution process gain acceptance by fabricators, then UN solution processing could be used to disposition surplus HEU as reactor fuel. Although not always economically justifiable, the UN solution process could be utilized to disposition the entire 165 t of surplus HEU.

Contingent upon construction and licensing of an operating facility, the  $UF_6$  blending process will be preferred for dispositioning surplus HEU as reactor fuel. If the  $UF_6$  blending process proves to be cheaper than the UN solution process for dispositioning surplus HEU destined for disposal as waste, then it could also be used to disposition surplus HEU as waste for disposal.

With relatively low blending costs, molten metal blending will probably be used to disposition surplus HEU metal destined for disposal as waste. However, the down-blended LEU product trapped in casting residues will require recovery

through UN solution processing. Molten metal blending will probably be applicable for only a small portion of the 165 t of surplus HEU.

It is likely that all three candidate blending processes will be used to disposition the 165 t of surplus HEU. The selection of the best process for each specific batch of surplus HEU will be made predominately on the basis of economics.

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