# *Advanced Fuel Cycle – Cost Basis Report: Module C3 High-Assay Low-Enriched Uranium (HALEU) Enrichment and Deconversion/ Metallization*

## Nuclear Fuel Cycle and Supply Chain

***Prepared for***

***U.S. Department of Energy***

***Systems Analysis and Integration***

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***Revision 2***

# REVISION LOG

| Rev. | Date | Affected Pages | Revision Description |
|---|---|---|---|
| | 9/5/23 | All | This is a new module as part of the Module C family of modules. |
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# ACKNOWLEDGEMENT

This latest version of the Module C3: High Assay Low Enriched Uranium (HALEU) Enrichment and Deconversion/Metallization is the result of the cumulative effort of many authors that have contributed to the Advanced Fuel Cycle Cost Basis Report (AFC-CBR). It is not possible to identify and acknowledge all those contributions to the AFC-CBR and this module. All the authors, including the four primary authors, fifteen contributing authors, the twelve contributors acknowledged, and the many other unacknowledged contributors in the 2017 version of the report may have contributed various amounts to the development and writing of this module prior to this current revision. Unfortunately, there is not a consolidated history that allows us to properly acknowledge those that built the foundation that was updated and revised in this latest revision.

This update reformats previous work to the current format for rerelease of the entire report as individual modules so there is no primary technical developer or lead author. J. Hansen (INL) and E. Hoffman (ANL) can be contacted with any questions regarding this document.



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# ACRONYMS

| | |
|---|---|
| ADU | Ammonium Diuranate |
| AEC | US Atomic Energy Commission |
| AFC-CBR | Advanced Fuel Cycle Cost Basis Report |
| AFCI | Advanced Fuel Cycle Initiative |
| ANEEL | Advanced Nuclear Energy for Enriched Life (proposed thorium and HALEU fuel) |
| ANL | Argonne National Laboratory |
| BWXT | BWX Technologies |
| CENTRUS | Centrifuge USA (formerly USEC) |
| COCO | Contractor-owned, contractor-operated |
| DOE-EM | Department of Energy-Environmental Management |
| DOE-NE | Department of Energy-Nuclear Energy |
| DP | Defense Programs |
| DU | depleted uranium |
| DU3O8 | depleted triuranium octoxide |
| DUF6 | depleted uranium hexafluoride |
| EBR | Experimental Breeder Reactor (ANL and INL) |
| ES&H | environmental, health and safety |
| EU | enriched uranium |
| EUF6 | enriched uranium hexafluoride |
| EUO2 | enriched uranium dioxide (i.e., EUOX) |
| FC | fuel cycle |
| FCM | Fully Ceramic Microencapsulated fuel |
| FCRD | Fuel Cycle Research and Development |
| FHR | fluoride-salt high-temperature reactor |
| FMPC | Feed Materials Production Center (former Fernald Plant) |
| FOAK | first-of-a-kind |
| FSR | fluoride salt reactor |
| GDP | Gaseous Diffusion Plant |
| GOCO | Government-owned, contractor-operated |
| HALEU | high-assay, low-enriched uranium |
| HALEUF6 | high assay, low-enriched uranium hexafluoride |
| HALEUOX | high-assay low-enriched uranium oxide |
| HEU | highly enriched uranium |

| | |
|---|---|
| HM | heavy metal |
| HOLOS-GEN | HOLOS Generators Company |
| HTGR | high-temperature gas-cooled reactor |
| HTR | high-temperature reactor |
| IAEA | International Atomic Energy Agency |
| INL | Idaho National Laboratory |
| Kg | kilograms |
| KP | Kairos Power |
| LCC | life cycle cost |
| LCOE | levelized cost of electricity |
| LEU | Low-enriched uranium |
| LEUF6 | low-enriched uranium hexafluoride |
| LEUO2 | low-enriched uranium dioxide (i.e., LEUOX) |
| LIS | laser isotope separation |
| LUEC | levelized unit electricity cost |
| LWR | light-water reactor |
| MEU | medium enriched |
| MMR | micro-modular reactor |
| MPC&A | materials protection, control, and accountability |
| MSR | molten-salt reactor |
| MTHM | metric tons of heavy metal |
| MTU | metric tons of uranium |
| MW(e) | megawatts electric |
| MW(th) | megawatts thermal |
| N/A | not applicable or not available |
| NARUC | National Association of Regulatory Utility Commissioners |
| NATU | natural uranium (0.71% U-235) |
| NEA | Nuclear Energy Agency (part of OECD) |
| NEI | Nuclear Energy Institute (USA) |
| NFS | Nuclear Fuel Services (Erwin, TN) |
| NIA | Nuclear Innovation Alliance |
| NNSA | National Nuclear Security Administration (defense part of USDOE) |
| NOAK | Nth-of-a-kind |
| NPP | nuclear power plant |
| NPR | new production reactor |

| | |
|---|---|
| NRC | Nuclear Regulatory Commission (USA) |
| ORGDP | Oak Ridge Gaseous Diffusion Plant (i.e., K-25 Plant) |
| ORNL | Oak Ridge National Laboratory |
| PIDAS | Perimeter intrusion detection and assessment system |
| PORTS | Portsmouth Gaseous Diffusion Plant (Piketon, OH) |
| PWR | pressurized-water reactor |
| RF | Russian Federation |
| SA&I | Systems Analysis and Integration (part of DOE-NE-FCRD) |
| SEU | slightly-enriched uranium |
| SNF | spent nuclear fuel (i.e., UNF for used nuclear fuel) |
| SNM | special nuclear material |
| SQ | significant quantity |
| SRS | Savannah River Site |
| SST | safe and secure transport |
| SWU | separative work unit |
| TENEX | Techsnabexport (Russian SWU and feed marketing company for ROSATOM) |
| TF3 | TRISO Fuel Fabrication Facility (X-energy) |
| TRISO | tristructural isotropic (particle fuel) |
| TVA | Tennessee Valley Authority |
| UK | United Kingdom |
| UOC | uranium oxycarbide |
| UOX | uranium dioxide (i.e., UO2) |
| URENCO | uranium enrichment consortium (UK, Netherlands, Germany) |
| USAEC | United States Atomic Energy Commission (predecessor to USDOE) |
| USEC | United States Enrichment Corporation |
| USNC | Ultra Safe Nuclear Corporation |
| USNRC | U.S. Nuclear Regulatory Commission |
| WEC | Westinghouse Electric Company |
| WIT | what-it-takes |
| WNA | World Nuclear Association |
| ZIRCEX | zirconium extraction |
| ZPPR | Zero-power Physics Reactor (INL) |

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# Module C3
# High-Assay Low-Enriched Uranium (HALEU) Enrichment and Deconversion/Metallization

This Advanced Fuel Cycle Cost Basis Report (AFC-CBR) C3 Module is entirely new and is meant to cover an evolving fuel cycle step, HALEU production, not covered under the present Module C1 which covers only primary enrichment up to 4.95% U-235 for LWRs. Module C3 has been given priority development over the last two years because many advanced reactor concepts now under development require HALEU fuel, and its unit cost ($/kgU) will be an important input for analysis of new open and closed fuel cycles requiring its use. The format of this module follows that of the other AFC-CBR cost modules. This module also covers the deconversion of HALEUF6 to metal or other uranium compounds required as feed to the advanced reactor fuel fabrication process.

This module has been authored by a nuclear chemical engineer (Dr. Kent A. Williams) with 15 years of analysis experience at the former Oak Ridge uranium enrichment facility (K-25 or Oak Ridge Gaseous Diffusion Plant) and 35 years of nuclear fuel cycle economic analysis experience at Oak Ridge National Laboratory. Since no detailed design or cost data are available on HALEU production facilities, the author had to depend on trade press articles, viewgraphs from public meetings, news releases from commercial enrichers, DOE, GAO, NEI, and NNSA reports, and cost estimating analogies based on his having authored many of the other AFC-CBR Cost Modules. No discussions were held with commercial enrichers, regulators (such as USNRC), or NNSA defense production organizations. Many design and cost assumptions were made to establish base cases for economic analysis, and they should be considered educated guesses in some cases.

Hopefully this Module will be of use to those people interested in the HALEU fuels. The reader will find over 50 references, most of which have URLs for rapid web access. As a final note the front-end unit fuel cycle costs for U3O8 feed and U3O8 to UF6 conversion are based on escalation of those in the 2017 AFC-CBR. It is likely that new US Congressional legislation mandating the use of domestically mined U-ore and domestic conversion may result in significant increases in future unit costs for these components of the overall HALEU unit cost.

## SHORT DESCRIPTION OF METHODOLOGY USED FOR ESTABLISHMENT OF MOST RECENT COST BASIS AND UNDERLYING RATIONALE

- **Constant $ base year for the 2021 update:** fiscal year (FY) 2021.
- **Nature of this 2021 module update from previous AFC-CBRs:** New sub-module supporting Module C (Uranium Enrichment).
- **Estimating methodology for latest (2017 AFC-CBR) technical update from which this 2021 update was escalated:**
  - Literature survey and some rough unit cost calculations for known “primary” uranium enrichment, UF6 deconversion, and uranium metal production (i.e., metallization) projects. Information from DOE planning documents, NNSA Category-I facilities, and top-down estimating “rules-of-thumb” (Williams 2009) are used for lack of any publicly-available, detailed “bottom-up” life cycle cost estimates for this evolving step of the front-end uranium-based nuclear fuel cycle.
  - For metallization (reduction of UF6 to uranium metal), consideration of projected unit costs for fabrication of high-assay low-enriched uranium (HALEU) metal-alloy fuels from updated AFC-CBR Module D1-6A.

- Blending of highly enriched uranium (HEU) from sodium-fast reactor (SFR) spent-nuclear fuel (SNF) or blending of HEU-SNF from military or research reactor stocks is not a HALEU production technology covered in this document due to limited future availability of such HEU. It is realized that early production of limited quantities of HALEU may come from such sources (Patterson et al. 2019); however, such SNF-derived material may require shielded glovebox handling due to trace fission products and U-232 daughter radionuclides in the recovered uranium. Two such purification/blend processes described in (Nuclear News 2022c) are: (1) electrochemical processing at Idaho National Laboratory (INL) and (2) a hybrid zirconium extraction process (ZIRCEX).
- Producing HALEU by a blend down of existing surplus unirradiated weapons-grade HEU is also not considered since quantities of this material are very limited compared to the eventual HALEU needs of a mature advanced reactor industry.
- A future update to Module C2 ("Secondary U-enrichment including Blend-down") could possibly cover such methodologies as the two mentioned in the bullets above.

# REVISION HISTORY

- **Version of AFC-CBR in which Module C3 first appeared:** This module is new this year.
- **Latest version of module in which new technical data was used to establish unit cost ranges:** not applicable.
- **New technical/cost data which has recently become available and may benefit next revision:**

  New data may become available from industry and institutional responses to the *Request for Information (RFI) Regarding Planning for Establishment of a Program to Support the Availability of HALEU for Civilian Domestic Research, Development, Demonstration, and Commercial Use* (Federal Register 2021) issued by U.S. Department of Energy (DOE), Office of Nuclear Energy (NE) on December 14, 2021. A multi-lab team in DOE-NE's Systems Analysis and Integration (SA&I) organization conducted a HALEU utilization systems analysis effort somewhat parallel to this report (Kim et al. 2022). In the future, publicly available technical reports should also result from this effort.

# C3-1. BASIC INFORMATION

## C3-1.1. Generic Information on HALEU Fuel and Its Possible Use in Various Types of Advanced Reactor Fuel Assemblies

**Definitions**. Enriched Uranium: The enrichment level of enriched uranium (EU) is measured by the uranium-235 isotopic content and is divided into two internationally recognized ranges: LEU (low-enriched uranium) for U-235 content from 0.71% (mass%) U-235 (natural-U) up to nominally 20% U-235. (The actual recognized maximum is 19.75% U-235.) Any U-235 concentration above the 20% level is considered HEU (highly enriched U). This isotopic breakpoint is considered the U-235 level for which it would be possible to produce a supercritical nuclear explosive. The International Atomic Energy Agency (IAEA) bases its Safeguards and Security Protocols on this definition, as well as DOE and the U.S. Nuclear Regulatory Commission (USNRC).

Depleted U: Uranium with U-235 assay less than 0.71% is called "depleted" U and is the "tails" product from uranium enrichment operations. Hundreds of thousands of metric tons of this material exist worldwide in the forms of DUF6 or DU3O8, most in the assay range of 0.15 to 0.35% U-235.

Natural U: Nearly all natural-U (NATU) is 0.711% U-235 except for a tiny amount of U-ore in Africa which is slightly below this by a few hundredth of a percent due to fissile depletion in natural nuclear reactions in the earth's crust which occurred two-billion years ago when the U-235 content of NATU was higher and capable of a critical mass in a wet "moderated" environment.

Within the LEU range, further regulatory divisions by U-235 content are recognized. Table C3.1 and Figure C3.1 show these LEU sublevels along with those defined above. Uses for these uranium materials are also listed.

The more definitive EU sublevels depend on regulations promulgated to recognize the "strategic nuclear materials attractiveness level" to a proliferator or terrorist attempting to divert or steal uranium which could be more easily fabricated into a crude nuclear weapon or re-enriched with fewer separative work units (SWUs) into a more sophisticated HEU weapon. The designations Safeguards and Security (S&S) Categories I–III are defined by the USNRC for U.S. commercial nuclear facilities and are also recognized by DOE National Nuclear Security Administration (NNSA) regulators. (See Appendix C3-1 to this document for the USNRC definitions.) The table below uses the abbreviations CAT-I, CAT-II, and CAT-III for these levels. It should be noted that HALEU can exist as a CAT-II or CAT-III uranium material depending on its enrichment level. It will be seen later that these S&S categories could possibly have a very significant impact on the design and life cycle costs of related fuel cycle facilities, including enrichment, deconversion, and metallization facilities.

Table C3.1. Acronyms and uses for uranium at various U-235 assay levels.

| Acronym | U-235 Assay (mass%) | Safeguards & Security Category | Uses |
|---|---|---|---|
| DU (depleted U) | < 0.71% (typically 0.15 to 0.65%) | Not applicable | U-metal alloy munitions, radiation shielding, counterweights, feed for future re-enrichment, diluent for U, Pu fuels, fertile blanket fuel for sodium-fast reactors (SFRs) |
| NATU (natural U) | 0.71% | CAT-III | Feed to enrichment plants, fuel for pressurized heavy-water reactors (PHWRs) (i.e., Canada Deuterium Uranium [CANDU] reactors) |
| Commercial LEU | .72 to 4.95% (material up to 2% U-235 sometimes called SEU or "slightly enriched U") | CAT-III | Water reactor fuel (some PHWRs can use 1.5% SEU, LWRs typically use 2.5 to 4.95% for conventional fuel) |
| CAT-III HALEU | 5 to 9.95% (this range sometimes called "LEU-plus") | CAT-III | LWR using higher-burnup advanced fuels (DOE-NE 2022), some pebble-bed high-temperature reactors |
| CAT-II HALEU | 10 to 19.75% | CAT-II | Many advanced reactor fuels: (SFRs, seed/blanket-type metal-fueled LWRs, tristructural isotropic [TRISO]-fueled designs, research reactors, PHWRs using advanced nuclear energy for enriched life [ANEEL] fuel) (Conca 2021) |
| HEU | 20% and above (range 30 to 50% sometimes called | CAT-I | Nuclear weapons, some research reactors, maritime |

| Acronym | U-235 Assay (mass%) | Safeguards & Security Category | Uses |
|---|---|---|---|
| | MEU [medium enriched U]). This category is applied to “direct military use” fissile material such as HEU, plutonium, and U-233 | | reactors, military production reactors, targets for medical isotope production, very small outer space, or terrestrial power reactors |

The following historical information may be useful in this regard:

- All currently operating U.S. fuel cycle facilities handling LEU and supporting the LWR-LEU fleet are Category III facilities. These include the URENCO-USA enrichment plant in New Mexico and the three LEUOX fuel fabricators: the Westinghouse Columbia (SC) Fuels Facility, the Global Nuclear Fuels (GE/Hitachi) facility in Wilmington, NC, and the AREVA Fuels Facility in Hanford, WA. Uranium throughputs for these latter fuel fabrication facilities vary from several 100 metric tons of uranium (MTU) to over 1,000 MTU per year. (AFC-CBR Fuel Cycle Modules C1 and D1-1 have considerable cost data on such CAT-III facilities.)
- No Category II facilities exist in the commercial or government (DOE-NNSA) complex. This is mainly due to the fact that few regulations concerning the use of CAT-II material have been developed. The initial USNRC effort in this area was never completed. Recently, X-Energy’s fuel fabrication subsidiary TRISO-X has announced plans for a USNRC 10CFR70 Category II TRISO fuel fabrication facility (TF3) to be sited in Oak Ridge, TN. A license application was recently submitted for this 8 to 14 MT HALEU/yr project (WNN 2022; X-energy 2022). DOE-NNSA is also evaluating the need for regulations for HALEU materials.
- There have been and still exist multiple CAT-I nuclear facilities in the United States. These HEU processors are related to defense requirements and specialty fuels. Throughputs for these facilities are small, typically a few to tens of MTU per year. The three major HEU-handling production facilities in the United States are the Y-12 Plant (Oak Ridge, TN) and the two BWXT nuclear fuel facilities at Lynchburg, VA and Erwin, TN. Other now decommissioned facilities include a SFR fuels plant at Apollo, PA and the General Atomics HEU-TRISO pilot plant at Sorrento Valley, CA. Very little cost data is available on such facilities due to proprietary and classification requirements, plus the fact that financial records for these decades-old facilities are likely to have been discarded.

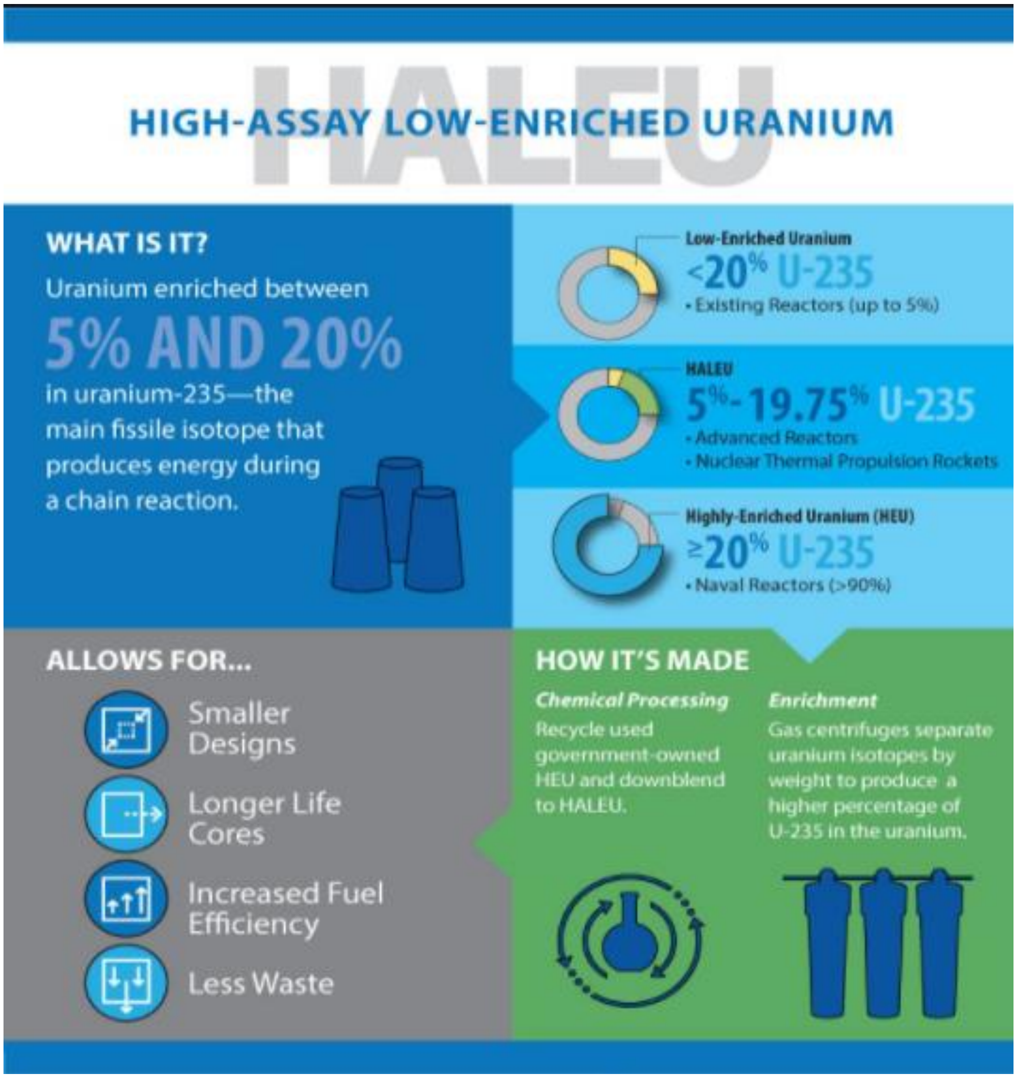
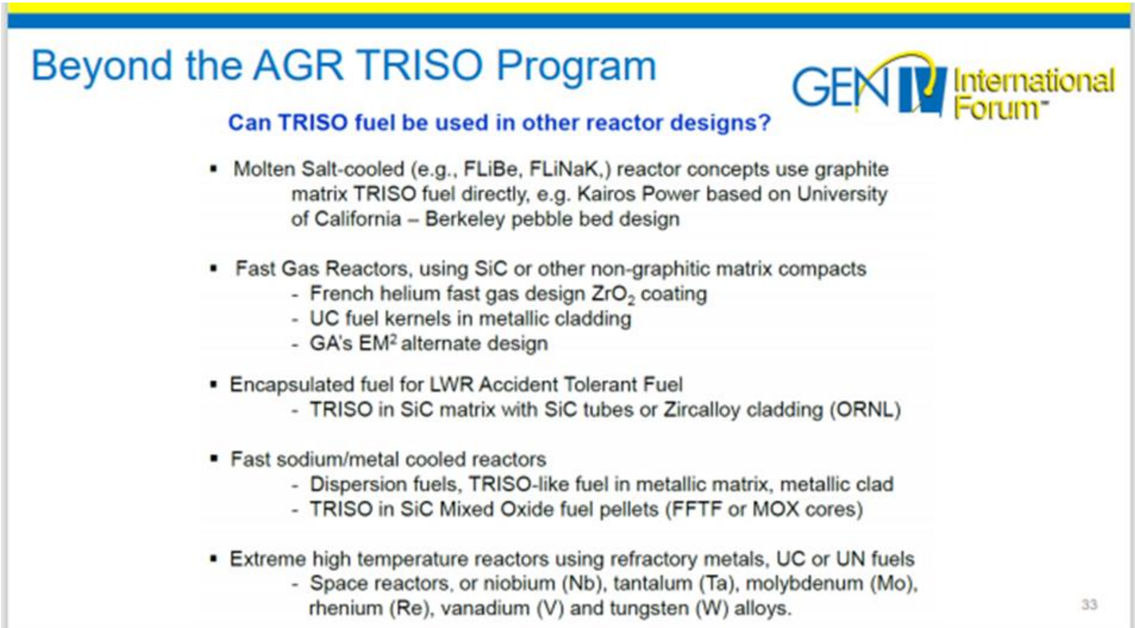



Figure C3.1. HALEU definitions from DOE-NE website.

Most of the anticipated HALEU incremental costs, i.e. those costs above those for handling conventional < 5% U-235 material, will be related to meeting the additional regulatory constraints imposed by the lower critical mass for HALEU (and its chemical compounds) and the more stringent requirements for material accountability, security, worker safety, and physical protection. As will be discussed later, CAT-II regulatory requirements, which are not yet well-defined, are likely to be more stringent than those for CAT-III and in some cases could approach those for CAT-I facilities. Appendix C3-1 lists some of the formal definitions of CAT-I through CAT-III materials as designated by the USNRC for commercial fuel cycle facilities licensed under 10CFR70.

**Possible HALEU Fuel Users.** The lower left side of Figure C3-1 above lists the attributes requiring the use of HALEU fuel in advanced reactors. Figure C3.2 below lists several of the known advanced reactor projects which are anticipated to require HALEU in the form of TRISO particles. (Through the AGR-TRISO program, DOE has funded the development of an improved TRISO fuel fabrication process.) The left side of Figure C3.3 below shows an advanced SFR concept (NATRIUM) requiring HALEU metal as the starting point for fabrication of its metal alloy fuel. Figure C3.3 also illustrates the two major Generation IV advanced reactor demonstration projects funded by DOE-NE: a NATRIUM-SFR demo and the Xe-100 high-temperature reactor (HTR) demo which will use TRISO fuel.





| Company or Research Group | TRISO Fuel Form, Reactor Type, Design Concept | Deployment (target date) |
|---|---|---|
| **Near-term Fuel and Reactor Concepts** | | |
| **X-Energy** | TRISO pebble bed HTGR **Xe-100 Reactor, TRISO-X fabrication facility** (Current funding: ART-15, 2 Industry FOAs, ORNL CRADA at $11.5M); Collaboration with Global Nuclear Fuel for DOD Micro-reactor and NASA nuclear thermal propulsion for space exploration. Collaboration with Centrus for X-energy TRISO fabrication facility | 2024-2030 |
| NGNP Alliance/**AREVA** | TRISO compacts, prismatic TRISO fueled HTGR **SC-HTGR** (steam cycle) | 2027-2030 |
| NC-II **AREVA** (Poland) | TRISO compacts, prismatic HTGR **SC-HTGR** (steam cycle) for Europe, Poland | 2027-2030 |
| **Dept. of Defense** | TRISO fueled mobile micro-reactors for strategic combat locations. Possible designs: HALOS, GA-vSMR, BWXT Nuclear, etc. | 2025 demo 2028 FOAK |
| **BWXT** | TRISO fuel fabrication for DOD microreactors, Potential DOD microreactor | 2022 (DOD) |
| **Kairos Power** | TRISO pebble bed, fluoride salt ($Li_2BeF_4$) cooled FHR, 3 cm dia. Pebbles, **Mark 1 Pebble-Bed FHR** (DOE Funding: 2 Industry FOAs announced) | 2030 Demo, 2035 FOAK |
| **Urenco**, Amec Foster-Wheeler | TRISO compacts, prismatic HTGR, UCO or Th/U/O TRISO kernels for **U-Battery** 10 MW and 20 MW. Canadian review underway | 2025 Demo 2030 FOAK |
| **StarCore** Power (USA) | TRISO in graphite matrix pebbles, helium-cooled HTGR, 20 or 80 MW, **STARCORE 20, STARCORE 80,** StarCore Nuclear (Canada) Canadian review underway. | 2025-2030 |
| **General Atomics** | UC bare kernels in SiC tubes. May use TRISO-like coating(s) as an optional design for fast-gas reactor **Energy Multiplier Module ($EM^2$)** | 2030-2035 |
| **ORNL** Accident Tolerant Fuel | FCM TRISO particles in SiC matrix pellets inside Zr, SiC or Stainless Steel cladding, as future LWR **ATF replacement** fuel | 2030-2035 |
| **Longer-term Fuel and Reactor Concepts** | | |
| **NASA** | TRISO fueled compact reactor for future long-range missions for Mars for Space Nuclear Thermal Propulsion (UC or UN) | |
| **MIT** (Forsberg) | TRISO compacts, prismatic HTGR Fluoride salt ($Li_2BeF_4$) cooled FHR | |
| **UltraSafe Nuclear** | Various TRISO fuel forms: FCM TRISO in SiC matrix pellets in SiC tubes to replace LWR fuel pins, CANDU bundle rods, TRISO with refractory coatings for Space Applications, Canadian review underway. | |

Figure C3.2. TRISO-fueled advanced reactor concepts requiring HALEU.


Figure C3.3. Schematic of NATRIUM metal-fueled SFR concept and Xe-100 HTR TRISO-fueled concept funded by DOE-NE.

**Feed and SWU requirements for HALEU and other enrichment levels.** As the U-235 content of EU increases, more natural feed (0.71%) UF6 and SWUs (separative work units) are required to produce a kilogram of EU product. To illustrate this. the critical masses of both a sphere of bare unmoderated U-metal and U-metal sphere jacketed in beryllium are shown on the two rightmost columns of Table C3.2 below. Both critical masses decrease with increasing U-235 enrichment. The left side of Table C3.2 below also shows the quantities of natural feed and separative work required to produce 1 kilogram of EU. (The concept of separative work units, abbreviated as "SWU," is discussed in paragraphs below.) As the enrichment plant product assay increases, criticality and MPC&A (material protection, control, and accountability) issues become more important and also more costly to implement.

Table C3.2. Important U-235 enrichment-related parameters.

| Mass % U-235 of EU product | Kg U of natural feed required to produce 1 kgU of EU product[a] | SWUs required to produce 1 kgU of EU product[a] | Critical mass (kgU) for an unmoderated bare metal EU sphere at given product enrichment (Los Alamos 1986) | Critical mass (kgU) for a beryllium moderated bare metal EU sphere at given product enrichment (Glaser 2005) |
|---|---|---|---|---|
| 4.5 (typical pressurized-water reactor [PWR]) | 9.24 | 6.88 | NA[b] | NA[b] |
| 5 (max for today's LWRs) | 10.33 | 7.93 | NA[b] | NA[b] |
| 10 (transition from CAT-III to CAT-II HALEU) | 21.2 | 18.87 | 390 | Not available |
| 19.95 (Maximum for CAT-II HALEU) | 42.39 | 41.04 | 150 | 142 |
| 50 | 108.2 | 111.8 | 73 | 60 |
| 90 (weapons and maritime propulsion grade) | 195.1 | 208.2 | 50 | 21 |

a. Enrichment plant tails assay of 0.25% U-235 assumed for depleted UF6 waste stream.
b. NA – Does not apply at this assay level.

## C3-1.2. Basic Uranium Enrichment Information from Module C1 and Special Considerations for HALEU Enrichment

**Separative Work.** The production capacity of a uranium enrichment facility is expressed as separative work or separative capacity expressed as SWUs/yr. SWU gives a quantitative measure of the amount of effort required to separate a given feed material, such as natural uranium, into a product of a stated assay (such as 3.5% U-235 LEU fuel) and a “tails” waste stream of depleted U at an assay less than 0.71% U-235 (typically 0.2 to 0.3% U-235). Separative work is somewhat analogous to the “free energy” concept discussed in chemical thermodynamics textbooks and chemical engineering texts such as (Benedict, Pigford, and Levi 1980). The separative work associated with an enrichment facility is calculated from the overall material balance (feed, product, and waste) along with the “value function” associated with each of these streams. The value function equations and other enrichment-related separations theory are covered in nuclear chemical engineering textbooks such as (Benedict, Pigford, and Levi 1980). A piece of isotopic separation equipment, such as a single gas centrifuge, also has its own “separative capacity” also expressed in SWUs/yr.

**Cascades.** An enrichment plant consists of individual separation units, such as gas centrifuges, connected in series/parallel configurations called separation cascades. A large centrifuge plant may consist of multiple cascades operated in parallel and serviced by common pipe headers and feed and product/tails withdrawal stations. At a feed station, solid UF6 in a steel cylinder is heated using an autoclave and sublimed directly to UF6 at a pressure well below atmospheric. At the two withdrawal stations of a simple cascade, enriched product UF6 (EUF6) and depleted tails UF6 (DUF6) are de-sublimed back to a solid UF6 form in steel cylinders. The natural feed and depleted tails cylinders can also be large (>10 MTU in capacity); however, for criticality consideration, the EUF6 product cylinder must be smaller. UF6 handling and cylinder management are discussed in industry document USEC-651 (USEC 1995) prepared by the United States Enrichment Corporation (USEC), the predecessor to CENTRUS Corporation today. On most fuel cycle diagrams, enrichment cascades are often shown as diamonds with feed introduced at a horizontal vertex, product at the top vertex, and tails at the bottom vertex. The diamond shape represents the fact that cascade interstage UF6 flows must be “tapered” below and above the mail feed point for material balance efficiency (i.e., avoiding the remixing of already separated upflow and downflow streams). Staging for enrichment cascades is discussed fully in (Benedict, Pigford, and Levi 1980) and specifically for centrifuges in (VonHalle 1978).

**Centrifuge Characteristics.** The following characteristics of gas centrifuges and centrifuge cascades will be important to the discussions below:

- Modern centrifuges can have separative capacities of 10 to 320 SWU/yr. The higher the SWU capacity of the machine, the fewer the number of machines required for a given size enrichment plant. A plant size of a few million SWU (MSWU) per year is typical of an enrichment plant producing LEU for multiple commercial 700 to 1,500 Mwe LWR utility customers. The URENCO-USA facility in New Mexico, the only enrichment plant operating in the United States, has a separative capacity of 4.9 MSWU/yr.
- Centrifuges are very low UF6 inventory machines with gas pressure at the rotor wall substantially below atmospheric. Nearly all of the UF6 inventory of an enrichment plant will be at the feed and product/tails withdrawal stations and in the feed, product, and waste (tails) UF6 cylinders stored onsite. During storage at typical room and outdoor temperatures, the cylinder-enclosed UF6 is in the form of a waxy white solid.

- A very small amount of UF6 escapes from the rotating centrifuge rotor/stationary "axis" feed post gap, which is an opening to the vacuum inside the floor-mounted tall cylindrical machine casing. This slowly escaping UF6 material eventually can react with non-UF6 process fluids and accumulate in cold traps or other vacuum pumping materials such as lubricants. Any uranium compound accumulation must be monitored to prevent criticality under conditions where hydrogenous (moderating) materials such as cooling water or polymers are nearby.
- Any "plate out" of uranium compounds on equipment such as piping and discarded centrifuges may be an issue for safe low-level waste (LLW) treatment, packaging, and disposal of failed or obsolete equipment.
- For MPC&A, international safeguards, criticality safety monitoring, and process control, it is necessary to measure the U-235 content (i.e., assays) at various locations in the overall plant and cascade piping. Tap points for manual sampling or direct piping to a centralized mass spectrometry laboratory will be required.

# C3-2. FUNCTIONAL AND OPERATIONAL DESCRIPTION

## C3-2.1. Enrichment Plant Technologies and Production Concepts Applicable to HALEU

HALEU can be produced by any enrichment technology including gaseous diffusion, gas centrifuge, and proposed advanced methods such as separation of isotopes by laser excitation (SILEX). Since gas centrifuge is the mature, proven, and most efficient enrichment technology used by most nations, it is likely that HALEU production would be accomplished by this method, hence this technology choice assumption is made for this report.

For those countries already producing HEU for weapons via centrifuge technology, HALEU would be a possible intermediate product or might be withdrawn as a side stream from an enrichment cascade. China, Pakistan, North Korea, and Iran are known to have or be developing such HEU facilities. The major nuclear powers of Russia, the United States, the United Kingdom, and France are known to have been operating HEU facilities in the past; however, most of these would have initially been gaseous diffusion rather than centrifuge plants. The United States stopped enriching uranium for HEU for weapons in the mid-1960s, the Portsmouth Gaseous Diffusion Plant (PORTS) higher-assay "topping stages" were shut down.

## C3-2.2. Historical HALEU Production and Present Status of Industry

The United States was the first nation to enrich uranium for weapons purposes in 1944–1945, and eventually product assays of 90%+ were available from the original Manhattan Project K-25 Plant (i.e., Oak Ridge GDP [ORGDP] in Oak Ridge TN). If any intermediate assays, such as HALEU, were required, they could be withdrawn as side streams from this original plant. During the 1950s, the U.S. Atomic Energy Commission (predecessor to DOE) built two more GDPs at Paducah, KY and Portsmouth, OH. They also replaced the original K-25 and K-27 stages with improved GDP technology in the K-29, K-31, and K-33 buildings at Oak Ridge. In the mid-1950s, LEU was first made available for nuclear power plants on a uranium lease basis, and in the late 1960s, under a "toll enrichment" program, a private utility could own the uranium. To supply this significantly larger demand for LEU, the GDP complex was operated as one gigantic enricher with three cascades, each at a different site. Figure C3.4 from the U.S. Atomic Energy Commission's (AEC's) "Gaseous Diffusion Operations" (USAEC 1972) brochure shows how various feed and product assays were utilized. UF6 containing cylinders were routinely shipped by truck or rail between plants to enable this fully optimized operation. Note that what is now called "HALEU" is labeled "Shipments to Government and Industry" on the rightmost "diamond" of the Figure C3.4 diagram and were products from the PORTS facility. Because of (1) high energy per SWU costs (high electric power usage endemic to gaseous diffusion), (2) foreign competition, and (3) smaller than predicted growth of nuclear power in the United States, all three of the U.S. GDPs have been shut down or have been totally decommissioned. Any new U.S. enrichment capacity will be either centrifuge or SILEX-based laser isotope separation (LIS). Table C3.3 lists centrifuge enrichment developers in the United States who are currently active. It should be noted that at the time of GDP operations the terms CAT I and CAT II were not in common use. Because of the proliferation and military sensitivity of enrichment technology, all of the GDP government-owned sites were remote, fenced and highly protected by "guns, gates, and guards." All personnel were required to hold the highest level of a U.S. AEC security clearance. The Oak Ridge K-25 site also hosted pilot scale centrifuge facilities which were successfully operated for product assays less than 5%. The U.S. Enrichment Corporation (now CENTRUS) had proposed and started to build a multi-million SWU per year centrifuge plant on the Portsmouth site for product assays less than 5% U-235. The project was abandoned due to a poor SWU market and financing difficulties. Producing HALEU was at no time planned at an NRC-licensed CAT-III enrichment facility. Today Russia, via their fuel export company TENEX, is the only possible provider of significant amounts of HALEU, which it can produce by blend-down of HEU from its vast stockpiles.

The DOE-NNSA (defense part of DOE) has been concerned that under non-proliferation agreements the only tritium-producing commercial reactor, the Tennessee Valley Authority (TVA) Watts Bar PWR Plant at Spring City, TN, cannot utilize as fuel LEU-enriched by a mostly foreign-owned company such as URENCO USA. (Tritium [i.e., hydrogen-3], a special nuclear material for thermonuclear weapons, is produced by inserting lithium-6 containing ceramic rods called TPBARs (tritium producing burnable absorbers) in the reactor along with the normal LEUOX fuel rods and control rods. After discharge these irradiated, TPBARs are transported to the Savannah River Site (SRS) for removal of the embedded tritium.) There is therefore a projected need for "unencumbered" enriched LEU which is produced by a domestic U.S. owner or an NNSA-owned facility. It is likely that if such a new U.S. government-owned facility were built, it would have the capability to enrich above 5% U-235, especially if the LWR reactors started using higher-burnup accident-tolerant ceramic fuels (Conca 2021) in the CAT-II HALEU or "LEU-plus" enrichment range of 5 to 10%. Such a new enrichment plant is not yet funded; however, cost and schedule studies have been made (USDOE 2015) but with no life cycle cost details published. Von Hippel and Weiner discuss and criticize these NNSA tritium co-production studies and their non-proliferation implications in an article for *Arms Control Today* (Von Hippel and Weiner 2021).

HALEU is of course available from the blending of unirradiated surplus HEU or the blending of recovered HEU from the reprocessing of government-owned spent. **This latter blending option is not considered in this document since the amount of material available from these sources is limited to tens of metric tons annually for less than 10 years. It is possible, however, that some of the earliest HALEU used for reactor development projects may come from these DOE sources, especially treated and blended EBR-II SNF from INL (Patterson et al 2019). Another source of unirradiated HEU blendstock might be never-irradiated HEU declared surplus by NNSA. This latter material would be easier for fuel fabricators to handle, since trace amounts of fission products, U-232 decay daughters, or higher actinides arising from irradiation would be absent. As noted above, Russia also has very large stocks of unirradiated former-weapons HEU which could be purchased and blended down in Russian facilities. This was done for U.S. commercial LEU (<5% u-235) for over a decade from the late 1990s onward under a "Megatons to Megawatts" program. For several years (1995-2013), half the nuclear power in the United States came from such blended Russian Federation (RF) material, and the program produced significant economic benefits for both Russia and the United States. It is highly unlikely for national security reasons that such a program would be initiated for HALEU. Freedom from dependency on Russian energy sources has become a major political issue following the Russian invasion of Ukraine (Third Way 2022).**

Table C3.3. Current 2021 HALEU centrifuge enrichment developers in the United States with possible plans for significant capacity.

| Company | Development or Production Locations | Enrichment Development Projects Presently Supported | Comments |
|---|---|---|---|
| URENCO USA (National Enrichment Facility) | Eunice, New Mexico | Interested in producing CAT-III HALEU | Present capacity is 4.9 million SWU/yr for 4.95% U-235 or less. Licensed for up to 8% U-235 with some modifications. USNRC licensed under 10CFR-70. Presently 230 employees are onsite. At tails assay of 0.25, this plant could produce 627 MTU/yr of 4.95% U-235 EU product, enough for ~30 to 40 typical LWR reloads. |
| CENTRUS Inc | Piketon, OH (on site of now shuttered PORTS GDP) | DOE-funded lead cascade for HALEU production | Will consist of 16 centrifuges of 320 SWU each (small pilot cascade of 3 to 4 thousand SWU capacity). Under construction with operation in FY 2022 anticipated (CENTRUS 2021a; and (CENTRUS 2021b). |
| Oak Ridge National Laboratory | Oak Ridge, TN | Centrifuge development funded by DOE | No plans for HALEU announced. |
| AREVA USA | Eagle Rock, ID (proposed) | | Project on hold. |

## C3-2.3. Historical Deconversion and UF6 to U Metallization Efforts

In the United States, HEU metal for government uses has been stockpiled to the extent that no deconversion or metallization services are presently needed, and these facilities, many going back to the Manhattan Project, are now shuttered or being decommissioned. Some of this history is described under "metallization considerations" below. The only large-scale UF6 deconversion presently underway is by commercial fuel fabricators for LEUF6 to LEUO2 for LWR fuel assemblies and the very large-scale (10000+ MTU/yr) deconversion of DUF6 legacy tails from the US GDPs to more stable DU3O8 for storage and ultimate shallow geologic disposal. (See AFC-CBR Modules K1 & K2). DOE/NNSA has indicated that a deconversion/metallization facility for the production of new depleted uranium (DU) metal weapons components may eventually be needed (GAO 2020).

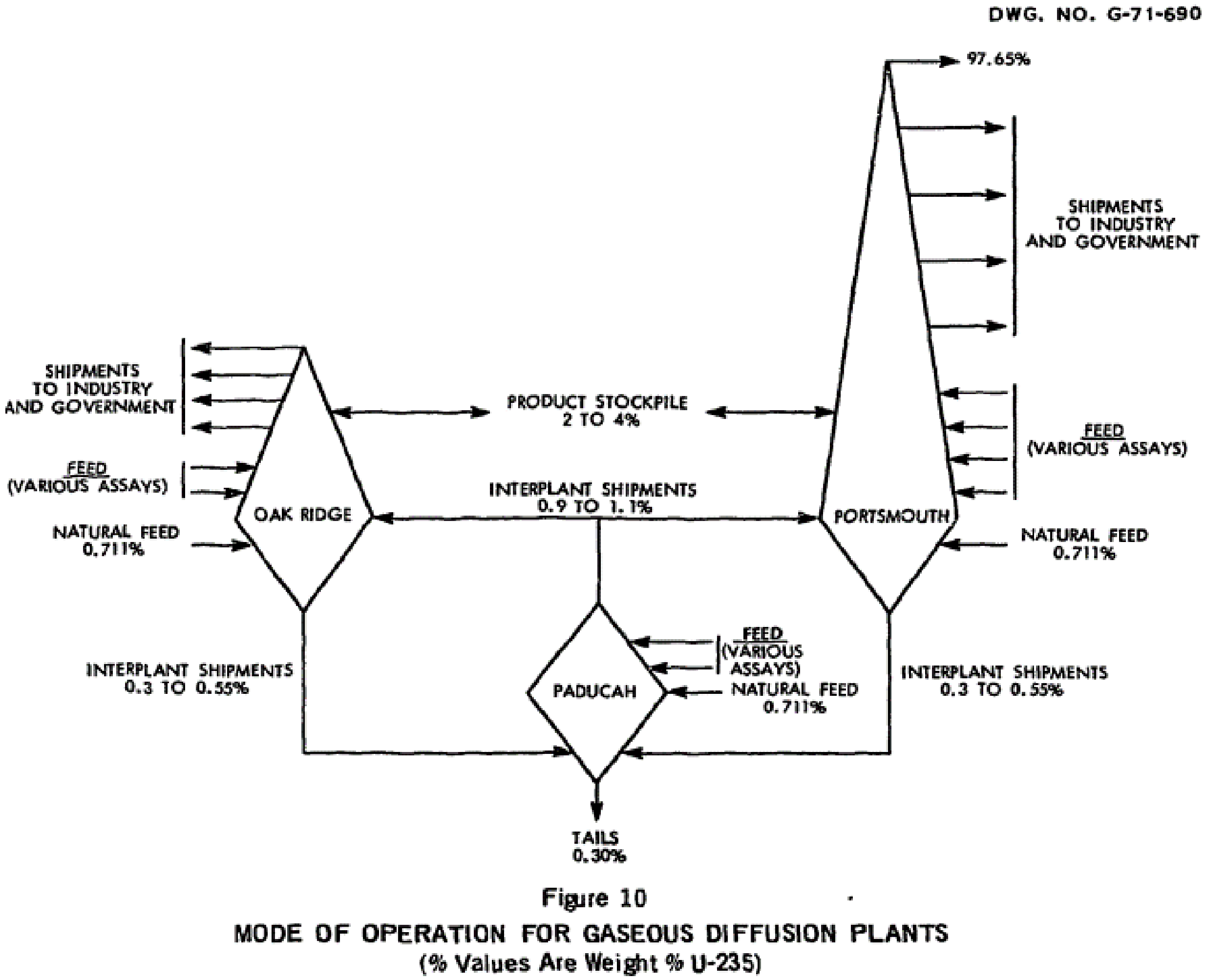



Figure C3.4. Former integrated operations of U.S. gaseous diffusion plants (USAEC 1972). (Capacity of three-plant complex was 17.2 MSWU/yr; in 1972, ~9 MSWU were produced during that year.)

**Market for HALEU**. NEI (NEI 2019), NIA (NIA 2022), EURATOM (Euratom 2019), and the U.S. national laboratories (Dixon et al 2021) have conducted studies on the potential long-term requirements for HALEU. The results depend on the projected market penetration of advanced higher-burnup reactors such as SFRs, HTRs, and metal-fueled LWRs into the U.S. commercial reactor fleet. The most recent multi-lab study (Dixon et al 2021) indicates that 500 MTU/yr of HALEU might be required by 2050. This 500 MTU annual production level will therefore form the basis for most of the cost studies discussed later in this report for a large, Nth-of-a-kind (NOAK) HALEU enrichment and HALEU deconversion or metallization facilities as well, at a target product assay of 19.95% U-235. Most reactor concepts of interest require CAT II HALEU in the 15 to 19.95% range. CAT-II HALEU assays less than 19.95% can be produced by blending with LEU, NATU, or DU in the forms of metal, UF6, or aqueous solutions. More complex cascades could be designed where withdrawal of side streams < 19.95% U-235 is possible; however due to lack of design data, this option is not considered in this report. Future HALEU program industrial participants may want to consider this multi-assay products option.

**Metallization Considerations**. For SFR fuel, such as NATRIUM, and for advanced LWR fuels, such as the Lightbridge "seed/blanket" metal driver rods, HALEU is required as a metal rather than as UF6 to begin the fuel fabrication process. (In forthcoming AFC-CBR Fuel Fabrication Module D1-6A "Uranium-metal alloy fuel," the starting material for the fuel fabrication process is assumed to be U-metal billets or shards ready for blending with other metals, such as molybdenum and zirconium, and ultimately for casting or for extrusion of metal alloy fuel pins). Deconversion of EUF6 to EU-metal would be new step for which no commercial facility is presently available in the United States. This does not mean, however, that there is no technology available for metallization, or that this "deconversion by chemical reduction" step has never been successfully accomplished domestically.

In the later years of the Manhattan Project (1945–1946), HEUF6 from the ORGDP (K-25) was sent to other government sites, including initially Los Alamos, for reduction to HEU-metal. For later weapons designs, both HEU metal and DU metal were required. The basic metallization process which was ultimately deployed on a large scale included two steps: defluorination followed by bomb reduction of UF4 "green salt" via an alkali metal:

- Partial UF6 defluorination by vapor phase reduction by hydrogen $UF6 + H2 \rightarrow UF4 + 2HF$
- Exothermic batch bomb reduction of green salt $UF4 + 2Mg \rightarrow U + 2MgF2$.

This latter chemical reaction is sometimes called the "Ames Process," developed under the Manhattan Project at Iowa State University in Ames, IA.

Among the "Cold War" nuclear facilities which performed these steps were the Mallinckrodt Chemical Plant (St. Louis, MO), the Fernald Feed Materials Processing Center (FMPC in southwest Ohio), the Paducah GDP (for UF4) in Kentucky, and ultimately the Oak Ridge Y-12 plant (Oak Ridge, TN) which conducted such operations until the late 1980s. Aerojet Ordnance Tennessee (Jonesborough, TN) also produced DU-tungsten projectiles from DUF4 "green salt" for use as anti-tank munitions. All of these facilities or processes are now at least partially shuttered, and some continue to be environmental remediation projects under DOE-EM (Environmental Management) funding. For most of the Cold War the Y-12 Plant fabricated the HEU and DU metal into weapons parts, and the FMPC fabricated U metal into metal driver fuel and targets for the Hanford and SRS nuclear materials (Pu and tritium) production reactors.

The first defluorination step is a relatively simple continuous process step and is the reverse of a fluorination step utilized in the natural U3O8 to UF6 conversion process at the U.S. CAT-III Honeywell Plant in Metropolis Illinois. For 19.95% U-235 HALEUF6, the process would have to be redesigned for criticality limited equipment sizes and a CAT-II operating environment. NNSA is considering building an addition to the DUF6 to DUOX deconversion facility at Portsmouth, OH to deconvert DUF6 to DUF4, a precursor salt needed for the production of high-purity metal alloys for the non-HEU parts for nuclear weapons (GAO 2020). A commercial vendor would be contracted for the second step of DUF4 to DU metal reduction.

The second reduction step is a more difficult batch process involving a highly exothermic “thermite” type reaction in a hemispheric refractory crucible with external cooling. The batch size for each “bomb-reduction” reactor would be limited by criticality concerns. The resulting U-metal “derby” (so named because of its hat shape) could then be cast or extruded into smaller pieces such as billets or shards for shipment to a fuel fabricator. It is possible that a one-step (Scott 1961) or continuous reduction process might be developed; however, some economic incentive would have to be present. The Oak Ridge Y-12 Plant (Hassler and Parker 2005) has investigated process improvements for similar type uranium metallurgy applications. Of the facilities still operating, the Oak Ridge Y-12 Plant, operated by Consolidated National Security (CNS LLC), has had the most experience on this type of process; however, their reduction facilities have been dormant for over 30-years (Hassler 2021). Y-12 is already a CAT-I nuclear facility, hence CAT-II HALEU process development or operations could be readily accommodated if space were available. For economic reasons development of a continuous HALEUF6 to HALEU-metal reduction process might be timely. This is especially true if a metallization plant size of 500 MTU/yr (to accommodate the CAT-II HALEU enrichment plant product) is anticipated.

**Opportunity for Consortium-based Operations on a Common Site**. Because of the costs and regulatory issues associated with transporting CAT-II HALEU over public roads or railways, it may be advisable to co-locate a CAT-II enrichment plant, the deconversion or metallization plant for the E-plant product, and perhaps even the advanced reactor fuel fabrication facilities utilizing the HALEUF6 or HALEU metal products on a common site with a shared security perimeter. Since centrifuge enrichment plant operations are vastly different than metallurgical “foundry”-type operations, different types of GOCO (government-owned, contractor-operated) or privately owned industrial entities may show interest. A multi-company HALEU Consortium might be established to manage the HALEU Front-End Fuel Cycle Complex. This complex might produce more than one type of fuel (e.g., TRISO particle fuel for HTRs and metal alloy fuel for SFRs and seed/blanket LWRs).

The OKLO Reactor Project (Patel 2020) and Terrapower “Natrium” Project (Nuclear News 2020) are both advanced SFR projects which are examining a consortium-type arrangement for the front end of their respective reactor’s fuel cycles.

## C3-3. PICTURES AND DIAGRAMS

Figure C3.5 below shows a conceptual front-end fuel cycle for 19.95% HALEU-using high-burnup advanced reactors. A consortium might be formed to operate the “fenced” CAT-II facilities on the right side of the schematic. The enrichment step for the CAT-III 9.95% U-235 product, required as feed to the consortium, might be undertaken by an existing enricher, such as URENCO-USA, who could add more centrifuge stages to their present licensed CAT-III facility or construct a dedicated new CAT-III cascade for enrichment to 9.95% U-235. The diagram below shows the latter option.

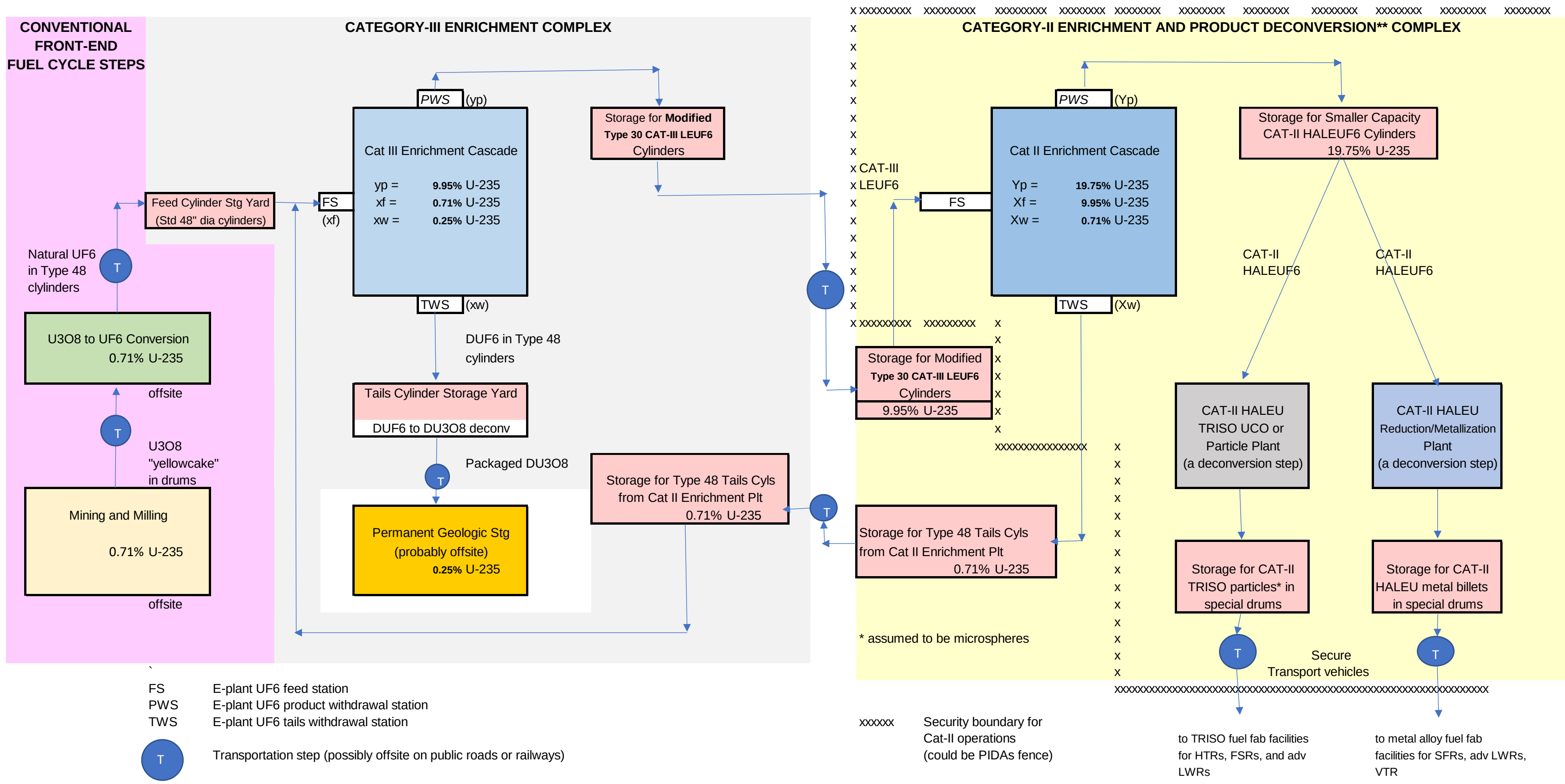



Figure C3.5. Possible configuration for a HALEU front-end fuel cycle complex supporting advanced reactors.

Other cascade configurations and tails assay options are certainly possible. It will be up to HALEU program industrial participants to develop and optimize other material balance options. At some point, bottom-up cost estimating will be needed as part of the optimization process. The author of this report chose a single option for analysis for the purpose of brevity.

## C3-4. MODULE INTERFACES

**Front-end interfaces.** The CAT-III enrichment plant or cascade producing LEUF6 products < 10% U-235 requires natural UF6 feed from a commercial U3O8 (i.e., "yellowcake") to UF6 converter such Honeywell-Metropolis or as recycled tails 0.71% U-235 UF6 from the CAT-II HALEU enrichment cascade. These two NATU streams can be simultaneously introduced into the CAT-III cascade. Type 48 (48-inch diameter) UF6 cylinders (Figure C3.6) are required to move UF6 between facilities. Outdoor storage areas for both full and empty UF6 cylinders are needed on both the Cat-III and CAT-II sites. U-capacities and U-235 enrichment limits for the various types of internationally recognized UF6 cylinders are shown on Table C3.4 below from (Eccelsion and Wonder 2010). Figure C3.6 and Figure C3.7 show photos or diagrams of the most commonly used UF6 cylinders in use today. (UF6 is commonly referred to as "hex" in the front-end fuel cycle industry.)

**Intermediate interfaces.** The CAT-III enrichment product shown on the diagram is assumed to be 9.95% U-235 HALEUF6 produced in a dedicated CAT-III cascade and introduced into the CAT-II cascade. Lower assay feed, such as 3 to 4.95% feed could also be introduced to the CAT-II cascade. This conventional LEUF6 could arise from existing ore, conversion, and enrichment operations and could be purchased from a uranium broker, a utility with excess EU feed contracts, or individual front-end fuel cycle providers. AFC-CBR Modules A (uranium mining and milling), B (U3O8 to UF6 conversion), and C1 (conventional primary enrichment up to 5% U-235) cover the unit costs associated with these fuel cycle steps. As conventional enrichers become licensed to produce product above 5% but less than 10% U-235, it becomes economically advantageous to send this somewhat higher-assay CAT-III HALEUF6 product to the CAT-II enricher.

**Back-end interfaces.** The CAT-III enricher will have DUF6 tails at ~0.25% U-235 as a waste that must be stored and eventually disposed or utilized for another purpose. In the diagram above, it is assumed that it is converted to more stable DU3O8, repacked into modified empty hex cylinders, and stored on site. At some point, these DU3O8 powder-containing cylinders are buried in shallow, retrievable geologic repositories similar to those for low-level waste. AFC-CBR Module K1 deals with this waste handling and disposal step.

CAT-II HALEUF6 is withdrawn from the CAT-II cascade in small cylinders which are yet to be designed and certified. Hopefully, they will hold more material than the Type-5 cylinder (Figure C3.7) but less than the Type-8 cylinders shown in the Table C3.4 below. Presently, CAT-III E-plant product less than 5% U-235 is withdrawn in Type-30B cylinders which are overpacked for transportation. For CAT-III product in the 5 to 10% range, a modified 30B or entirely new cylinder design may be required.

The small cylinders with CAT-II 19.95% product will perhaps require safe, highly secure indoor storage on the consortium site. The next step beyond storage will depend on the type of fuel required by an advanced reactor. A TRISO fuel fabrication facility should be able to take the HALEUF6 cylinders and sublime the UF6 gas directly into a dissolution/hydrolysis step for UCO fuel kernel fabrication. (The manufacture of TRISO particles starts with a sol-gel prepared from aqueous solution.) For this reason, a generic TRISO-particle manufacturer might want to locate on site and sell small drums of TRISO particles for further fabrication into various reactor design-specific geometric configurations or shapes (e.g., graphite compacts or spheres). For metal fuels such as those for SFRs (e.g., OKLO or NATRIUM, or Lightbridge extruded alloy LWR drivers), the fabricator will need U-metal feed in the form of billets or shards. A CAT-II metallization facility on site with the CAT-II enrichment plant would be the best option for sharing of security and other overheads. Figure C3.5 shows collocated facilities sharing a site with a common security perimeter, possibly surrounded by a perimeter intrusion detection and assessment system (PIDAS) fence. These PIDAS security systems are now in use at NNSA CAT-I nuclear facilities, and depending on future regulations could become a requirement for CAT-II facilities.

**Waste interfaces.** Operations such as those above associated with uranium typically produce low-level waste. A metallization facility would produce slightly contaminated hydrogen fluoride which must be sold or converted to stable alkali metal fluoride solid product for disposal.

**Transportation.** A transportation network of certified suppliers for rail and highway transport of UF6 cylinders containing less than 5% U-235 already exists for the front end of the LWR fuel cycle. For the HALEU complex envisioned in Figure C3.5 , an on-site cylinder transportation network for UF6 cylinders would be required. Most problematic is transportation of the small HALEUF6 cylinders to onsite fuel fabrication or metallization facilities. Special safe and secure transport overpacks and vehicles may be required. Regulatory guidance in these areas is needed. Design and certification issues for HALEUO2 transport casks are discussed in a recent report by (Eidelpes et al. 2019). This step would be needed for blended-down UO2 product from the INL reprocessing of EBR-II spent fuel. The specific activity for such blended product would be considerably higher than for unirradiated HALEUF6 from an enrichment plant.

Table C3.4. Capacity and U-235 enrichment limits for UF6 cylinders.[a]

| Cylinder Model | Nominal Diameter inches | Maximum $UF_6$ kgs | Maximum U kgs | Maximum Enrichment % $^{235}U$ | Maximum $^{235}U$ kgs |
|---|---|---|---|---|---|
| 1S | 1.5 | 0.45 | 0.30 | 100 | 0.30 |
| 2S | 3.5 | 2.22 | 1.50 | 100 | 1.50 |
| 5A/5B | 5 | 24.95 | 16.9 | 100 | 16.9 |
| 8A | 8 | 115.7 | 78.2 | 12.5 | 9.8 |
| 12A/12B | 12 | 208.7 | 141.1 | 5.0 | 7.1 |
| **30B** | **30** | **2,277** | **1,540** | **5.0** | **77** |
| 48A/X | 48 | 21,030 | 14,219 | 4.5 | 640 |
| 48F | 48 | 27,030 | 18,276 | 4.5 | 822 |
| 48G | 48 | 26,840 | 18,148 | 1.0 | 181 |
| **48Y** | **48** | **27,560** | **18,634** | **4.5** | **839** |
| 48H/HX/OM | 48 | 27,030 | 18,276 | 1.0 | 183 |

For criticality safety, the cylinder diameter is decreased as the uranium enrichment increases.

a. The UF6 Manual, USEC-651, Rev. 8, January 1999, page 6.

Within DOE-NNSA, regulations exist for transportation of CAT-I nuclear materials. The safety and security overhead cost associated with their handling are considerable. For transport over public roads, most CAT-I special nuclear materials (SNMs) require transport within a DOE-NNSA-owned and -operated fleet of safe and secure transport (SSTs) vehicles with specially trained and armed drivers. Similar transport arrangements might be needed, at least initially, for CAT-II HALEU products.

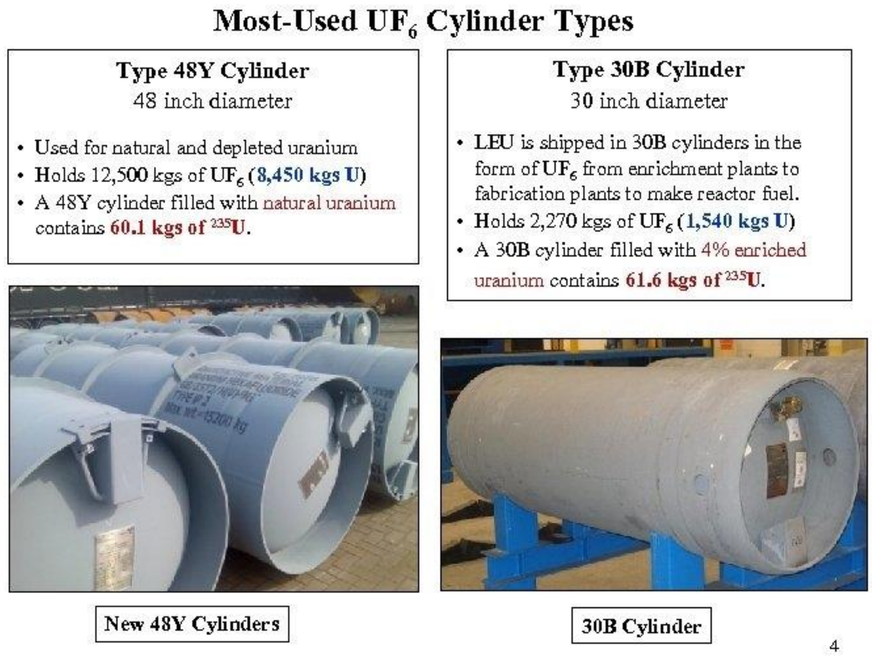



Figure C3.6. UF6 cylinders used for today’s front-end LWR fuel cycle.

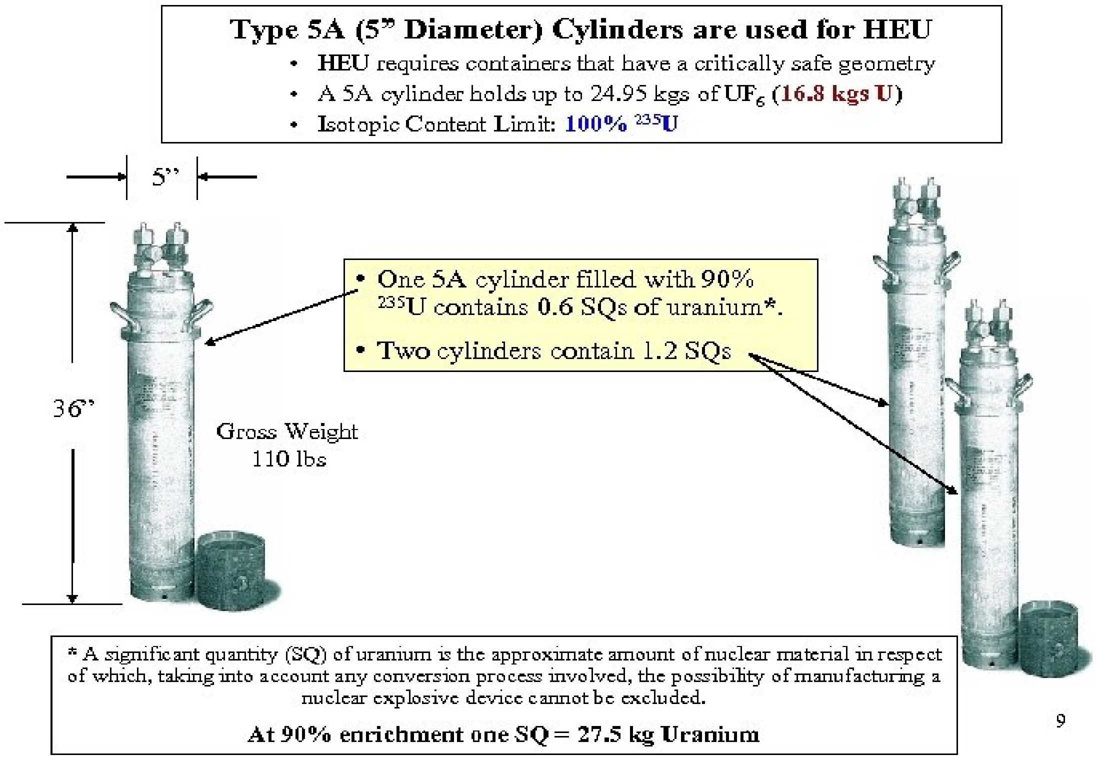



Figure C3.7. UF6 cylinders used for HEUF6.

## C3-5. SCALING CONSIDERATIONS

Because centrifuge facilities generally consist of multiple identical separation units (of the same SWU/machine and cost per machine) connected by pipes, the overall cost capital cost of the separation equipment tends to scale nearly linearly with separative capacity. The building area (i.e., footprint) also scales nearly linearly if the centrifuges are laid out in a single-story building in repetitive rectangular arrays. A CAT-II centrifuge building, including its feed and withdrawal areas, is likely to require a more robust structure than a CAT-III facility to meet what are anticipated to be more stringent physical protection regulations.

Operations costs, including personnel, machine replacements, and utilities, should also scale somewhat linearly, since adding more separative capacity means operating, maintaining, and ultimately replacing more centrifuge machines of a given capacity. Each machine is likely to require a fixed number of operations and maintenance (O&M) hours annually to keep it spinning. Personnel requirements and associated costs for a CAT-II facility as compared to a CAT-III facility) may have a larger fixed staffing component due to need for a significant security force and material control, protection, and accountability (MCP&A) staff regardless of plant capacity.

In the following section, these operational and construction compliance cost issues will be addressed without the benefit of actual "bottom-up" cost or operational data for a real HALEU facility. There is not even a preconceptual design or cost estimate for a hypothetical HALEU facility that is publicly available. Until regulations for CAT-II HALEU are fully developed and reviewed, it is unlikely that a prospective enricher will prepare such detailed documentation until it has some idea as to what regulations will apply and will appear in the design requirements documentation. For now, the authors of this report must rely upon what knowledge they have on the design of CAT-III commercial fuel cycle facilities and the design of CAT-I NNSA GOCO or CAT-I private contractor-owned, contractor-operated (COCO) nuclear facilities handling HEU.

# C3-6. COST BASES, ASSUMPTIONS, AND DATA SOURCES

**Cost Figures-of-Merit for HALEU Enrichment and Deconversion/Metallization.** In this section, an attempt is made to establish ranges for the following cost figures-of-merit:

1. **The percent "CAT-III HALEU premium" above the conventional mean-value unit SWU cost (price) appearing in Module C1 of the AFC-CBR, for any SWUs required to enrich above 4.95% U-235 and up to 9.95% U-235.** These would be CAT-III HALEU SWUs. The unit cost range for conventional LEU LWR SWUs, in the 2020 AFC-CBR Summary Table, is as follows: low 126 $/kg-SWU, mode 145 $/kg-SWU, and high 164 $/kg-SWU, with a mean value of $145/kg-SWU. These long-term price projections are based on a market and technology analysis performed in 2015 and subjected to normal escalation from that year. They are for the production of LEUF6 up to 4.95% U-235. **The "CAT-III SWU premium" would be expressed as the projected percent increase in the unit cost above the "conventional mean SWU" price depicted in Module C1.** Since there is no present market for this HALEU material, the projection discussed in this section is based on the authors' rough estimation of the cost penalties imposed for likely increased regulatory and security-related cost factors. As an example, a 10% CAT-III HALEU premium would increase the "mean" $145 unit cost of SWU from Module C1 by a multiplier of 1.1 to $159.5 $/SWU and would apply only to the portion of an enrichment plant operating at > 5% U-235 and < 10% U-235.
2. **The percent "CAT-II HALEU premium" above the conventional unit SWU costs appearing in Module C1 of the AFC-CBR, for any SWUs required to enrich above 9.95% U-235 and up to 19.95% U-235.** These would be CAT-II HALEU SWUs. Again, the unit cost range for conventional SWUs in the 2020 AFC-CBR Summary Table is: low 126 $/kg-SWU, mode 145 $/kg-SWU, high 164 $/kg-SWU, and **a mean of $145/kg-SWU**. These long-term price projections are based on a market and technology analysis performed in 2015 and subjected to normal escalation from that year. They are the production of LEU up to 4.95% U-235. **The "CAT-II SWU premium" would be expressed as the projected percent increase in the unit cost above the mean "conventional SWU price" depicted in Module C1**. Since there is no present market or production capacity for this HALEU material, the projection discussed in this section is also based on the authors' rough estimation of the cost penalties imposed for increased regulatory, nuclear safety, and security factors for a CAT-II facility. These factors are likely to be much more serious for CAT II SWUs, hence the CAT-II SWU cost premium is expected to be somewhat higher than that for CAT-III HALEU SWUs.
3. **The unit cost of deconversion or metallization (combined defluorination/alkali metal reduction) of HALEUF6 to HALEU metal from both CAT-III and CAT-II Nth-of-a-kind (NOAK) facilities capable of handling 500 MTU per year.** Deconversion is mentioned since the fuel fabricator's desired pre-fuel fabrication uranium form might also be a halide, specialized oxide (such as UOC), silicide, or nitride compound instead of metal. Because the deconversion process from HALEUF6 also operates in a CAT-II environment, the unit cost of deconversion is expected to be of the same order of magnitude as for metallization. The unit cost for both is expressed in US$/kgU assuming year 2020 constant dollars.
4. The unit cost of 19.95% HALEUF6 including all of the costs of the front-end fuel cycle materials and services needed for its production: ore mining and milling, natural $U_3O_8$ to $UF_6$ conversion, and enrichment. In order to perform this calculation, a flowsheet with a front-end fuel cycle material balance is required and provided in the sections below.

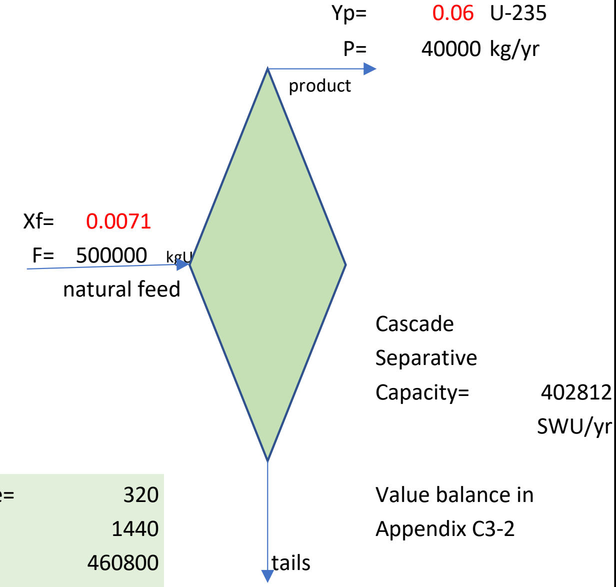
**Historical SWU premium for HEU in the USAEC Weapons Complex**. As depicted on Figure C3.4, the PORTS formerly produced enriched HEU (NPR 1991). At the same time, the other GDPs were increasingly producing LEU for commercial reactors at around $117/SWU in 1988$. (That would be over $350/SWU in today's dollars). SWUs were more expensive prior to the introduction of centrifuge technology because of the huge amount of electric power required to operate the GDPs and the lack of significant foreign competition (i.e. a U.S. enrichment monopoly). Today's centrifuge plants use less than 5% of the kwh per SWU than enrichment by the gaseous diffusion method. The USAEC finance office had developed an "imputed" SWU price of $922/SWU (in 1988$) for the "more expensive to produce" Portsmouth SWUs above 10.5% U-235. (Today, these would be called CAT-I and CAT-II SWUs). This higher "Portsmouth Top" penalty reflected the much higher security, MCP&A, safety, and smaller equipment inefficiency costs associated with CAT-II HALEU and HEU. The "premium" in this case would be 688% for the unit SWU price ratio of 922/117 = 7.88. It should be noted that the "Portsmouth Top" was a highly secure CAT-I facility handling strategically sensitive amounts of UF6 at assays 90% (weapons-grade U) and above, i.e. what would be considered "direct use" SNM from a non-proliferation standpoint. Material could only be withdrawn in small cylinders of less than 20 kgU capacity, and manpower, safety, and security overheads were very high. These considerations would account for the very high CAT I/II SWU premium.

**More Recent Data and Analyses on Conventional LEU and CAT-III HALEU Enrichment Facilities.** In an October 2015 "Report to Congress" (USDOE 2015), the DOE-NNSA published an analysis and management plan regarding their needs for uranium of all types for defense applications. The need to provide domestic unencumbered LEU (i.e., LEU not co-utilized for defense purposes such as tritium production) was identified. NNSA needs approximately 40 MT of <7% U-235 LEU/yr to provide LEUO2 reloads to the two TVA Watts Bar Reactors, which are now irradiating tritium-producing burnable absorber rods (TPBARs) for eventual tritium extraction at the SRS. Because of the dual defense and commercial power production missions, these reactors cannot use SWU produced by URENCO, TENEX, ORANO, or any other foreign enrichers. The TVA reactors are assumed to burn an "LEU-plus," 6% U-235 higher burnup fuel to compensate for neutron absorption by the TPBARs. In 2014, NNSA prepared a rough life-cycle cost estimate for a new "government-owned greenfield" special purpose gas centrifuge enrichment plant which could provide the approximately 400,000 to 500,000 SWUs per year required to provide this LEU-plus to TVA and for possible special reconfiguration/production campaigns for higher enrichments. Figure C3.8 presents the capital and operations cost ranges from the "Report to Congress" (USDOE 2015), escalates them to 2020$, and, using a low 3% real discount rate for capital recovery, calculates the unit SWU cost for a plant that operates for 50 years. This calculation results in a unit SWU cost range of 338 to 844 $/SWU. (This wide unit cost range comes from the fact that NNSA considered the use of both large [CENTRUS-type] and small [URENCO-type] centrifuges in two separate estimates). One might ask why this unit SWU cost is so high compared to the market unit SWU price range of 126 to 164 $/SWU in the 2020 AFC-CBR. The following are possibilities:

- The AFC-CBR projects SWU prices (126 to 164 $/SWU) for a LEU-only stable market that includes multiple international enrichers with amortized facilities where the addition of more centrifuges is marginally inexpensive.
- The NNSA would like their facility to also be able to periodically produce HEU > 20% U-235 for weapons and maritime propulsion applications. Even if short HEU campaigns are envisioned, there would be some CAT-I plant design and operational characteristics involved which would incur additional life cycle costs above CAT-II. No detailed design data from the NNSA cost study was available which specifically delineated and documented these additional HEU-related costs.
- The special purpose NNSA enrichment plant design has a separative capacity of 0.4 to 0.5 million SWUs per year, which is much smaller than for a purely commercial plant such as the New Mexico URENCO facility which is over 4 million SWUs annually and services ~20 large LWRs.

**NNSA "Unecumbered LEU-Plus" CENTRIFUGE ENRICHMENT PLANT**

(Relatively small E-plant, but enough to supply reloads for two TVA PWRs)




| | |
|---|---|
| SWUs/machine= | 320 |
| # of machines | 1440 |
| Unadj SWU/yr | 460800 |
| Adjusted SWU/yr* | 402812 |

(* 87% cascade eff due to large # of machines & near ideal "taper")

| | |
|---|---|
| Yr of NNSA estimate | 2014 |
| Yr for this calculation | 2020 |
| 2014 to 2020 Esc factor from AFC-CBR | 1.105 |

| **NNSA cost data from Tritium and EU planning document (USDOE 2015)** | 2014$ | 2020$ |
|---|---|---|
| Ave Capital cost in $M for $3.2B to $4.8B range | 4000 | 4420 |
| Ave Recurring costs for $100/yr to $200/yr range in $M/yr | 150 | 165.75 |

| | | |
|---|---|---|
| Total in 2020$ for 50-yr Life cycle cost with no interest >> | 12708 | $M |
| Unit SWU cost with no interest | 631 | $/SWU |

**Calculation with interest:**

| | |
|---|---|
| Assumed yrs of ops and capital recovery (amortization) | 50 |
| Assumed real discount rate for amortization (Gov't) | 3% |
| Annual production in kgSWU/yr (rounded) | 403000 |
| Fixed charge rate (calculated) | 0.039 |

| **Annualized costs including interest** | **$M/yr** | **$/SWU** |
|---|---|---|
| Capital | 172 | 426 |
| Recurring (incl O&M) | 166 | 411 |
| **Total** | **338** | **838** |

Figure C3.8. Derivation of a unit SWU cost for a U.S. government-owned small gas centrifuge enrichment plant for production of unencumbered LEU for tritium co-production in domestic TVA power reactors (case in diagram assumes large CENTRUS-type centrifuges at 320 SWU/yr each).

**Derivation of incremental CAT-III Unit SWU cost increase based on rudimentary analysis of staffing increases and capital cost modifications for transitioning from conventional LWR-LEU enrichments (4.95% U-235 or less) to CAT-III HALEU enrichments (5 to 9.75% U-235).** Since CAT-II HALEU facilities are likely to cost much more per SWU than CAT-III HALEU facilities, it is assumed that an enrichment plant enriching to above 10% U-235 would be an entirely separate facility. This prevents the need to apply CAT-II regulations to the enrichment of CAT-III HALEU (0.71% U-235 to 9.75% U-235) if all enrichment from natural feed to 19.75% U-235 were done in one large enrichment plant. Presently, U.S. enrichment facilities are licensed for CAT-III enrichments up to 5% U-235 as presently configured. URENCO-USA's license specifies up to 8% U-235; however, some plant modifications of unknown scope would be required. There will soon be a need to produce LEU (sometimes called LEU-plus) at enrichments from 5 to 8% U-235 for accident-tolerant LWR fuels (ATFs). One such advanced ceramic fuel using 6% U-235 is being tested at Plant Vogtle in Georgia. The small quantity of "LEU plus" needed for the four lead test assemblies (LTAs) was prepared from blend-down of unused, clean government HEU such as unirradiated Zero Power Physics Reactor (ZPPR) fuel plates from INL. Commercial enrichers such URENCO understand that there eventually will be a need for their facilities to eventually enrich to the CAT-III limit of < 10% U-235 (assumed to be actually 9.75% U-235). The regulatory rulemaking, however, for enhanced CAT-III HALEU facilities is not in place, hence no enrichment upgrade efforts are currently under construction. In addition to ATFs, another major demand for CAT-III HALEU will arise because it is the likely precursor for dedicated CAT-II HALEU production; 9.75% U-235 enhanced CAT-III HALEUF6 would be the ideal feedstock to a CAT-II enrichment facility going form >10% U-235 up to 19.75% U-235. (This CAT-II enrichment facility is discussed in another subsection below).

It should be noted that no "bottom up" engineering designs and cost estimates are available for enhanced CAT-III HALEU enrichment facilities, either for an "add-on" or a stand-alone facility. Commercial enrichers, such as CENTRUS, ORANO, or URENCO, may have produced such or be in the process of doing so; however, such information would be highly proprietary. It is most likely that a commercial enricher would want to add CAT-III enrichment to an existing LEU enrichment facility or add more centrifuge capacity and switch production over to entirely 9.75% U-235 LEU. Since this latter option, with only a single 9.75% LEU product, is easier to evaluate from the standpoint of cascade material balance calculations, it is the one considered in this section. The following is assumed:

- A URENCO-USA-sized plant of 4.95 MSWU/yr with small (100 SWU/yr centrifuges) is switched entirely from conventional LEU production (here considered 4.95% U-235) to the production of 9.75% "enhanced CAT-III LEUF6", the required precursor feed to a separate CAT-II enrichment plant capable of 19.75% HALEUF6 production.
- As a result, the product annual flow is reduced by approximately half from ~600 MTU of 4.95% material to ~300 MTU of 9.75% material. In a separate CAT-II cascade, this production rate will again be reduced by nearly half to produce ~150 MTU of 19.75% HEUF6, which is still a significant fraction of the anticipated 500 MTU/yr market.
- Additional centrifuges, floor space, and feed/withdrawal capability will be needed to allow such a conversion. The additional separative capacity required is ~10% of the URENCO-USA capacity of 4.9 MSWU or ~0.5 MSWU/yr. Additional operational personnel will also be required. The amount of additional SWU and UF6 feed required is minimized by removing tails in the upper stages at an assay of 0.711% U-235 and recycling it to the lower stages.

Figures C3.9a and C3.9b show how this might be accomplished. Figure C3.9a shows how this expanded plant can be represented as two cascades: one, the conventional 0.71% to 4.95% enrichment mission, and the second smaller one, the enhanced CAT-III HALEU mission. Figure C3.9b shows the material balance data for the cascade drawings in Figure C3.9a. A 9.75% CAT-III product rate of 1 kgHALEU/yr is assumed; however, a constant multiplier can be applied to all these normalized material balance streams for sizing enrichment facilities to meet market needs. The right columns of the material balance table show the flows for an enhanced URENCO-USA-sized facility.

The question now arises: what "CAT-III SWU premium" needs to be applied to ~10% of all SWUs for the modified facility? One needs to determine what incremental costs (above those which would be incurred for conventional LEU additional SWU capacity) are incurred in this enhanced CAT-III HALEU plant additional capacity. An attempt to calculate the premium was made by assuming a URENCO-USA sized plant (4.9 million SWU) would have an additional 0.49 million SWU of centrifuge capacity (10%) added to allow an enhanced CAT-III HALEU production campaign. The following assumptions are made:

- The same size (~100 SWU/yr) and same unit cost per machine centrifuges could be safely added to the "top" stages of the existing cascade. Inside-the-rotor centrifuge UF6 inventories are low enough that nuclear criticality should not pose an issue; however, more non-destructive surveillance of U-compound deposition in piping and vacuum system components may be warranted.
- An additional building would be needed to house these centrifuges and the additional product withdrawal stations. Because of what are anticipated to be more stringent security, safety, and environmental regulations, the building enclosing these higher assay centrifuges might need to be more robust (at a higher cost per square foot). The incremental cost of this space above that for a conventional industrial building housing high-tech equipment is calculated. One should note that the requirements for CAT-III structure "robustness" are anticipated to be much less stringent than for CAT-II or CAT-I structures. Literature sources for $/ft2 estimating for various building types are cited.
- The present Type-30B product withdrawal cylinder for 5% U-235 or less will not suffice for CAT-III HALEUF6 because of criticality concerns. Significant up-front expenditures will be needed to design, develop, certify, and manufacture the "modified 30B's." One might need to purchase enough of these smaller capacity cylinders to store 1 year's worth of product (~300 MTU) unless product cylinder contents could be quickly utilized by a fabricator or CAT-II enricher, and the empty cylinders transported back to the CAT-III enricher for reuse. These one-time costs will need to be amortized to make them mor representative of a NOAK facility operating for 50+ years.
- Additional personnel would be required to handle the more numerous cylinder feed and withdrawals, higher security level, and more stringent MPC&A requirements for higher assay UF6.

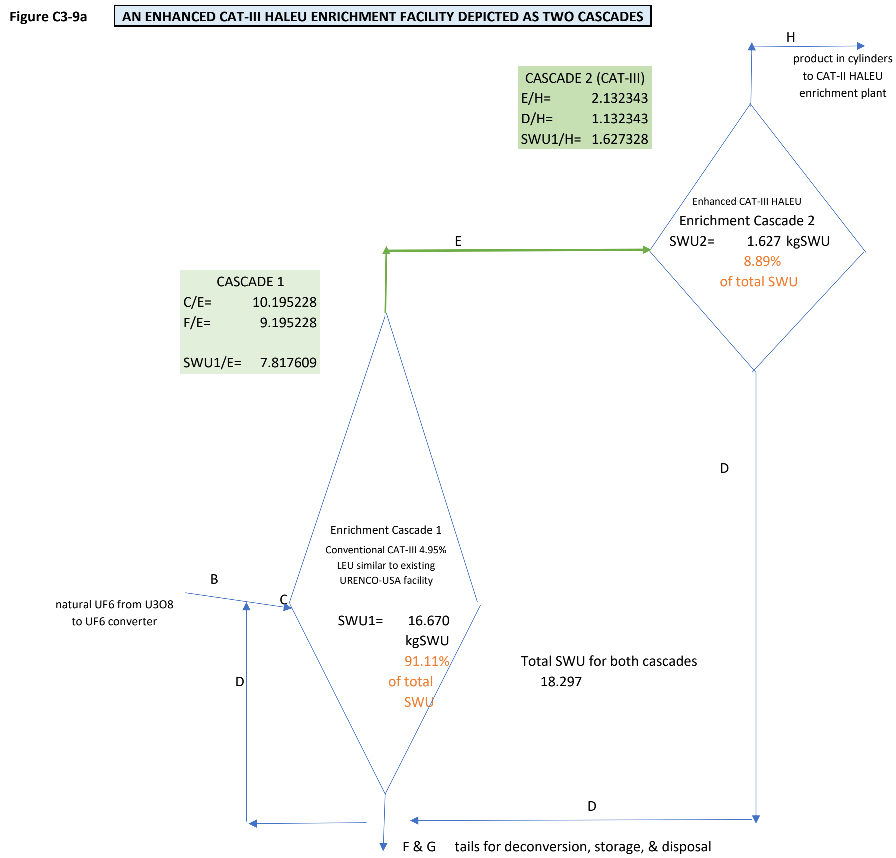



**Figure C3-9b**

**MATERIAL BALANCE FOR ENHANCED CAT-III PRODUCT OF 1 kgU/yr (NORMALIZED) AND FOR POSSIBLE TWO-CASCADE ARRANGEMENT WITH CASCADE 1 SIZED SIMILAR TO URENCO-USA CAT-III FACILITY**

| Streams B - G | Form | U-235 Assay | Normalized Annual Flow for H=1 kgU/yr | Units | Flows normalized to a URENCO-USA-sized Cascade 1 | Units |
|---|---|---|---|---|---|---|
| | | | | | | |
| B (total feed for both cascades) | Nat UF6 | 0.00711 | 20.607 | kgU/yr | 6119 | MTU/yr |
| C (cascade 1 feed) | Nat UF6 | 0.00711 | 21.740 | kgU/yr | 6455 | MTU/yr |
| D (cascade 2 tails for recycle as Cascade 1 feed) | Nat UF6 | 0.00711 | 1.132 | kgU/yr | 336 | MTU/yr |
| E (cascade 1 product & cascade 2 feed) | LEUF6 | 0.0495 | 2.132 | kgU/yr | 633 | MTU/yr** |
| F (cascade 1 tails) | DUF6 | 0.0025 | 19.607 | kgU/yr | 5822 | MTU/yr |
| G (cascade1 tails) | DU3O8 | 0.0025 | 19.607 | kgU/yr | 5822 | MTU/yr |
| H (cascade 2 product) | HALEUF6 | 0.0975 | **1.000** | kgU/yr | 297 | MTU/yr |
| | | | | | | |
| Cascade 1 SWU | | | 16.670 | kgSWU | **4.95** | MTSWU |
| Cascade 2 SWU | | | 1.627 | kgSWU | 0.48 | MTSWU |
| Total SWU | | | 18.297 | kg SWU | 5.43 | MTSWU |

Multiplier to adjust from normalized material balance to large plant case= 296944

**URENCO-USA Annual Conventional LEU Product is likely to be on this order

Figure C3.9. (part a at left) A hypothetical CAT-III HALEU cascade represented as two cascades; (part b at right) material balance data to accompany Figure C3-9 part a above.

A major item needed for this rough analysis is the amount of additional building space required for 10% more centrifuges. Since the authors of this report do not have any URENCO drawings or data, they used public photos from inside a URENCO centrifuge plant to estimate the average square footage (i.e., footprint) required by a single machine, adjusting for aisle and instrumentation space. Figure C3.10 shows two photographs which allow some estimates, given that the machine casing outer diameter is assumed to be approximately 1 foot (30.48 cm).

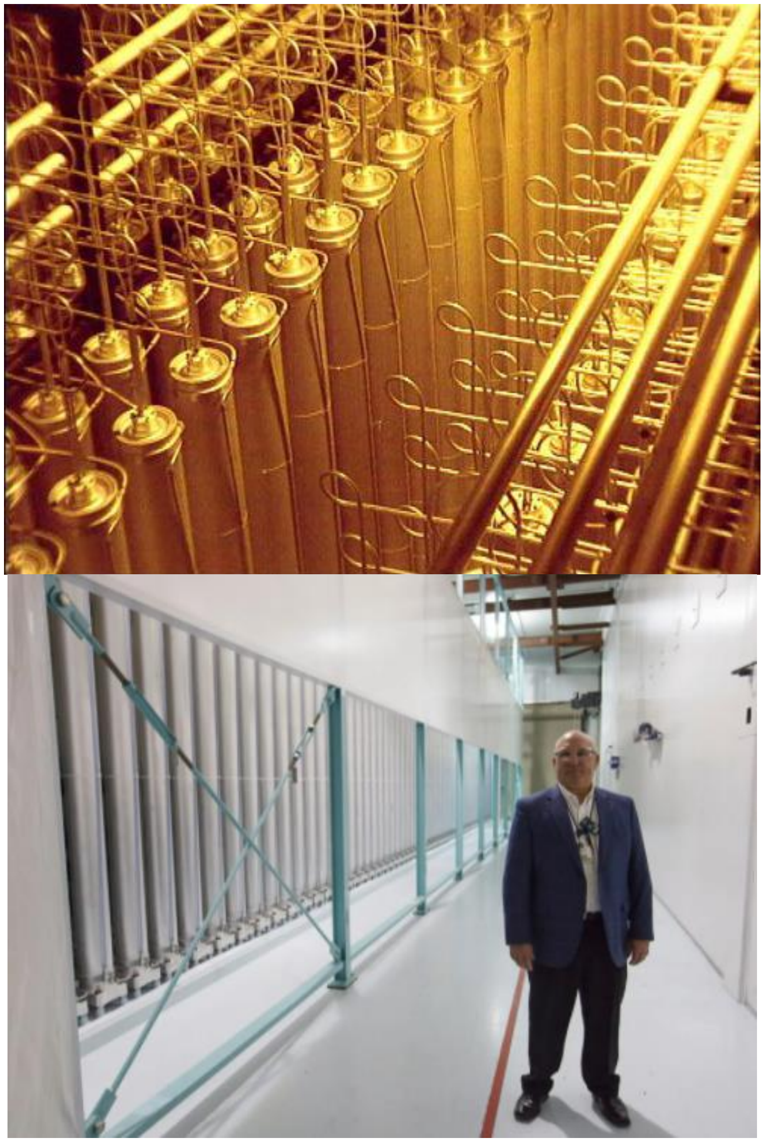


Figure C3.10. A URENCO centrifuge cascade hall.

Figure C3.11 represents the authors' concept of a replicate four-machine "unit cell" (shaded in yellow) which is representative of the thousands in the main cascade halls. From this schematic, an average value of ~5 ft2 of footprint per centrifuge is obtained. If 0.49 MSWU are to be added, and each machine is 100 SWU/yr, then 4,900 new machines are required, along with 24,500 ft2 of additional floor space for mounting them.

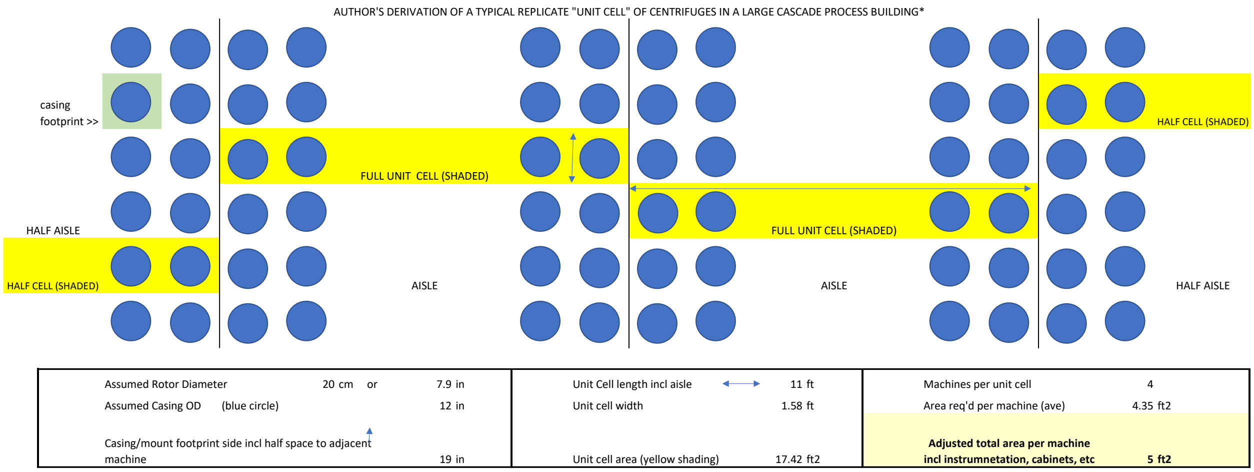


Figure C3.11. Determination of average building footprint required for one centrifuge machine.

Also required for this analysis are building costs per square foot (not including centrifuges) for the existing CAT-III building and those anticipated for an enhanced CAT-III structure housing the additional machines. Table C3.5 lists recent $/ft2 costs found in the literature for various industrial building types. The existing CAT-III building would have special lifting (cranes), seismic, chemical safety, and heating, ventilating, and air conditioning (HVAC) considerations present in its design, well beyond those of a typical warehouse or light industrial facility. For this reason, the authors estimate the building cost at $100 to $200/ft2. The question is now what modifications might be required by enhanced CAT-III licensing, and the fact that higher enrichment material is being handled. The following should be noted as far as the extended building design:

- The 4.95% UF6 can be piped directly from the conventional LEU cascade directly into the enhanced CAT-III cascade. A wall separating the two sections will probably not be necessary. The 0,711% UF6 tails from the added cascade can be piped directly back to the feed station part of the existing LEU cascade.
- Product cylinders for the 9.75% UF6 will be significantly smaller than the 30B cylinders used for a conventional LEU enrichment plant. This means more withdrawal stations, more cylinders, and more operating staff will be required than if the capacity expansion were only for 4.95% or less UF6 product capability. For purposes of additional security and chemical safety (associated with more UF6 handling), the new building will likely have more internal concrete and steel walls associated with increased product withdrawal operations and higher 9.75% product cylinder inventory. Effectively, this will increase the average cost per square foot for the additional building space.

As will be shown below, a cost model was constructed to see how the "incremental costs above a conventional LEU facility" could translate into a unit cost for the "incremental SWUs required to go from 4.95 to 9.75% U-235". Important input parameter ranges (optimistic if results in lower cost, and pessimistic if results in higher cost) to this model are as follows:

- Cost per square foot for the additional enhanced CAT-III building space (estimated to vary from $200 to $400/ft2).
- Up-front cost to design and certify a new, smaller Type-30B cylinder and estimated cost of single cylinder once multiple replicate units are available. These capital costs should be amortized over the estimated life of the enrichment plant additional capacity (assumed to be 50 years as is done for most fuel cycle facilities in the AFC-CBR). Modified 30B cylinder capacity for 5 to 9.75% U-235 HALEUF6 is estimated to be in the range of 300 kgU to 1,000 kgU as compared to 1,540 kgU for a regular 30B product cylinder handling up to 4.95% U-235. These lower capacity values were chosen

arbitrarily based on lack of design data but still consistent with the data in Table C3.4, such as that for HEU cylinders. This range means that anywhere from 75 to 1,000 cylinders per year are needed to withdraw the 294 MTU of 9.75% HALEU product. For the pessimistic case, it is assumed that a CAT-II HALEU cascade may not be ready to accept these smaller modified 30B cylinders as feed, hence a year's worth of product might have to stored onsite. The optimistic case assumes the 9.75% product cylinders can be shipped, emptied, and returned within 3 months.

- A plant producing 9.75% material with more product withdrawal positions and smaller product cylinders will mean more personnel will be required than if the capacity addition were for 4.95% material. All shifts will need to be covered. Given that the present highly automated URENCO facility requires 228 FTEs total, the authors presume a 10% capacity addition for 9.75% material will require 40 to 80 FTEs above the same hypothetical staff addition for 4.95% material. No time and motion studies are available to support these estimates, so an educated guess was necessary.

Table C3.5. Data on cost per square foot for industrial buildings.

| Building Type | $/square foot | Comments |
|---|---|---|
| Simple metal Butler building | 15 -18 | Probably not appropriate for large nuclear facility. Typical for small light-duty manufacturing or warehousing in warm climate. |
| Modular steel building range | 36-40 (General Steel 2022) | Not likely to include seismic modifications needed for structure with high-speed, tall, floor-mounted rotating equipment. |
| Large warehouse in Denver | 142 | Significant wind and snow load location. |
| High tech factory/laboratory | 479 to 635 (Scalisi 2022) | Probably higher than what is needed for enhanced CAT-III facility. |

Table C3.6 summarizes economic analysis for calculating the CAT-III SWU cost premium. Individual costs for items such as additional building space, product cylinders, and additional staff are not based on actual bottom-up designs and cost estimates prepared by an architect-engineering organization, but rather on educated guesses made by the authors based on cost estimating "rules-of-thumb" and other information gleaned from work on other AFC-CBR Cost Modules and life-cycle cost evaluations for NNSA programs, such as fissile materials disposition (Williams 2009). Up-front capital costs are amortized and annualized over 50 years at a low 5% real discount rate typical of government-supported projects. All of the annualized costs, including incremental staffing, are summed and divided by the additional 0.49 million SWU of capacity to calculate the incremental $/SWU unit cost. Both an optimistic (low cost) and pessimistic (high cost) set of assumptions are presented in the table. The low and high values of 6.6 $/SWU and 28.4 $/SWU are then divided by the mean conventional enrichment cost of $145/SWU (2020$) to obtain optimistic and pessimistic SWU premiums rounded to 5 and 20%, respectively. **A mean or average SWU premium of 13% is calculated, and for uncertainty analysis a uniform distribution for these uncertain SWU premiums is suggested**. This SWU premium would apply only to the 8.9% of the overall LEU-CAT-III enrichment facility separative capacity that operates above 4.95% U-235. The question of whether one needs to "wall-off" the enhanced CAT-III HALEU centrifuges from the conventional CAT-III LEU centrifuges is one for regulators to consider in "LEU-plus" enrichment rulemaking.

The reader should note that in this “SWU premium” analysis, we are dealing only with incremental costs (i.e., the HALEU-related costs above those required to produce the same amount of conventional LEU SWUs at < 5% U-235). It is assumed the centrifuges used for HALEU production cost no more per unit than those used for conventional LEU production. The same is assumed for cascade piping modules. (Very low UF6 gas pressure ensures that criticality should not be an issue that mandates a new, more expensive machine or more expensive cascade piping module design.) The building “footprint” housing these HALEU machines, however, may cost more because of regulatory mandated safety and security requirements for enhanced CAT-III or CAT-II facilities. It should be kept in mind that the SWU premium is the unit cost of SWU above the unit cost needed to produce an equivalent amount of conventional LEU. Unit SWU cost is interpreted to be the same as unit SWU price in a perfect market where the unit SWU cost includes a return on investment to the owners.

Table C3.6. SWU premium range calculation for LEU e-plant expanded for CAT-III HALEU production.

| **Calculation of an incremental $/SWU (aka "premium") to add enhanced CAT-III HALEU (aka "LEU-plus") capability to a URENCO-USA sized conventional CAT-III HALEU enrichment plant using European centrifuge technology (Costs in FY 2020 constant $)** | | | | | |
|---|---|---|---|---|---|
| % increase in plant separative capacity in going from 4.95 to 9.75% U-235 | | 9.8% | | | |
| Rounded to >> | | 10% | | | |
| Price Range for Conventional LEU SWUs from Module C in 2020$ ($/SWU) | Low<br>126 | Mode<br>145 | High<br>164 | mean<br>145 | |
| Present capacity of URENCO USA Plant (basis for typical size): | 4.90E+06 | SWU/yr | ( assumes all product is 4.95% U-235) | | |
| Hypothetical separative capacity that could be added to produce 9.75% U-235 from 4.95% feed: | 4.90E+05 | SWU/yr | (note: all product now becomes 9.75% U-235) | | |
| Total Separative capacity of modified URENCO-type plant: | 5.39E+06 | SWU/yr | | | |
| Amount of 9.75% UF6 product available from CAT-III HALEU enhanced plant: | 2.95E+05 | kgEU/yr | | | |
| | 295 | MTU/yr | as HALEUF6 | | |
| **Incremental Capital costs for additional, somewhat more robust process building space** | | | | optimistic (resulting in lower costs) | pessimistic (resulting in higher costs) |
| Number of 100 SWU/yr centrifuges to be added (machines) | 4900 | | | | |
| Square feet of add'l bldg footprint per centrifuge (ft2/machine) | est ave =5 | | | 4 | 10 |
| Additional building footprint required (ft2) | | | | 19600 | 49000 |
| Cost per sq foot of more robust CAT-III building ($/ft2) | | | | 200 | 400 |
| Cost per sq foot of normal CAT-III building ($/ft2) | | | | 100 | 200 |
| Incremental cost of robust CAT-III over conventional CAT-III bldg ($/ft2) | | | | 100 | 200 |
| Total incremental cost of add'l building footprint ($M) | | | | 1.96 | 9.8 |
| **Process Building-related Capital Recovery Component of Unit Cost of SWU($/SWU) for annual fixed charge rate of** | 5.5% | | | **0.22** | **1.10** |

Table 3.6. (continued).

| Capital Costs for Initial Higher Assay Product Withdrawal Cylinders | | | | optimistic | pessimistic |
|---|---|---|---|---|---|
| Maximum capacity of 30B prod cylinder for ~5% U-235 (kgU): | 1540 | | | | |
| Estimated capacity of modified 30B for 9.75% U-235 (kgU): | | | | 1000 | 300 |
| (neutron absorber rods added to cylinder) or in MTU: | | | | 1 | 0.3 |
| Cylinders required annually to withdraw annual product | | | | 74 | 983 |
| [Pess: if not returned and reused Opt: if returned in 3 mo for reuse] | | | | | |
| Estimated one-time cost to design and certify modified 30B cylinder ($M) | | | | 15 | 30 |
| Estimated cost to purchase, modify, and inspect one modified 30B cyl ($/cylinder) | | | | 15000 | 40000 |
| Total product cylinder-related cost ($M) | | | | 16.1 | 69.3 |
| **Cylinder-related Capital Recovery Component of Unit Cost of SWU ($/SWU) for fixed charge rate of** | 5.5% | | | **1.80** | **7.75** |
| **Recurring costs for additional personnel** | | | | optimistic | pessimistic |
| Number of additional personnel needed to handle greater # of cylinders and address add'l crit safety, security, and storage issues (FTEs). (Incremental to what would be required for 10% expansion of 4.95% LEU production capacity) | | | | 25 | 80 |
| Number of present URENCO onsite employees in NM (FTEs) = | 230 | | | | |
| Estimated # of FTEs if 4.95% LEU production were increased 10%; | 250 | | | | |
| Ave annual fully-loaded salary of an employee ($/FTE/yr) | | | | 90000 | 120000 |
| Annual incremental full time employee cost ($M/yr) | | | | 2.25 | 9.6 |
| Incremental SWU cost (recurring cost component) ($/SWU) | | | | **4.59** | **19.59** |
| **Total Incremental $/SWU** | | | | **6.61** | **28.44** |
| % above mean enrichment cost (price) from Module C1 (range for CAT-III HALEU SWU premium) | | | | 4.6% | 19.6% |
| Round SWU premium upward to >> | | | | 5% | 20% |
| **SWU Premium Rounded values for use in analyses** | **Low** | **Mean** | **High** | | |
| **%** | **5** | **12.5** | **20** | | |

**Derivation of a unit SWU cost for the CENTRUS CAT-II HALEU pilot plant.** As part of a DOE program, the U.S. corporation, CENTRUS, has been conducting an R&D program related to possible HALEU enrichment at both Oak Ridge, TN and Piketon, OH (former PORTS site). This $115 million program will culminate in the operation of a 16 centrifuge HALEU CAT-II pilot plant operating at the PORTS site. Based on news releases and other articles such as (Nuclear News 2020a), the authors of this report have constructed a likely material balance for this pilot facility and assume it produces ~600 kg of 19.75% HALEU (as HALEUF6) per year (Figure C3.12). Sixteen 320 SWU/yr large centrifuges times 16 units totals to 5120 SWU/yr; however, the small number of machines implies a less than ideal "taper" to the interstage flows and the need to adjust the overall separative capacity down to ~3600 SWU/yr by means of a 0.71 cascade efficiency factor.

If the total program costs are divided by the pilot plant separative capacity, a unit SWU cost of over 30,000 $/SWU results. This of course includes fixed costs such as R&D and licensing that would not normally be encountered in a large Nth-of-a-kind (NOAK) facility, so this high number **is not all indicative of how much a large, efficient, optimized, and state-of-the-art facility would cost**, especially if capital costs could be recovered (i.e., amortized) over many decades instead of the few years a pilot plant would operate. (For the fuel cycle steps covered in the AFC-CBR fuel cycle modules, fuel cycle facilities are assumed to operate for 50 years and are amortized over the same 50 years.

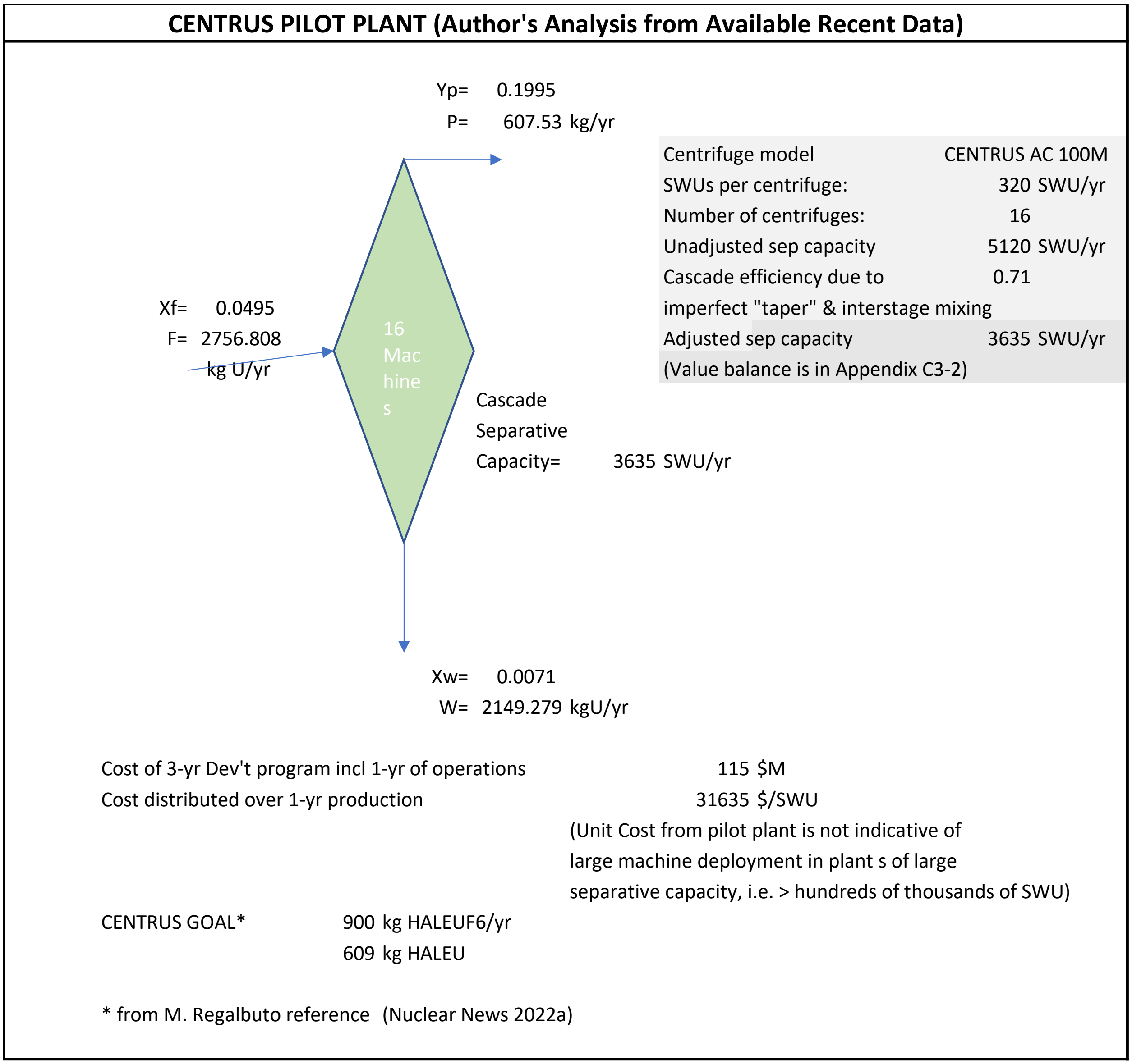



Figure C3.12. Authors' estimated material balance and performance information for 16-machine CENTRUS pilot plant in Portsmouth, OH.

It should be noted that the CENTRUS pilot plant in Figure C3.12 is fed 4.95% LEUF6 instead of 0.71% natural UF6 feed. In this way, the size of the more expensive CAT-II part of the facility is minimized. A CAT-II HALEU facility would likely buy conventional LEUF6 from (1) a fuel broker, (2) a utility which encounters fuel reloading delays, or (3) contract individual ore purchases, U3O8 to UF6 conversion, and conventional LEU enrichment. In any case, provision of this already partly enriched CAT III feed material will be the highest expense associated with CAT-II HALEU production. Once CAT-III enrichment facilities capable of enriching to 9.75% U-235 are available, this material would become the preferred feed to the CAT-II enrichment plant. In this way, the CAT-II regulations will apply to all of the facility, hence obviating the possibility of having to handle CAT-III LEU in an expensive CAT-II environment. It should also be noted that the "tails" for a CAT-II enrichment plant might not be depleted U, but rather clean natural UF6 which can be resold to a CAT-III or conventional enrichment plant. Selection of tails assay will depend on multiple factors depending on ore and conversion costs, relationships with other enrichers, and the possibilities of underfeeding and overfeeding the cascade to optimize the eventual HALEUF6 unit cost. Participants in a DOE-HALEU program would very likely conduct sensitivity and optimization studies before selecting a final cascade configuration. Table C3.7 presents the unit costs of the various steps needed to prepare the 4.95 or 9.75% U-235 feeds to a CAT-II enrichment facility. The last case shows the effect of a CAT-III HALEU SWU premium on the feed cost, which it turns out is very small.

Table C3.7. Derivation of unit costs for conventional LEUF6 and enhanced CAT-III HALEUF6 feeds to a CAT-II HALEU enrichment facility (tails assay of 0.25% U-235 assumed for CAT-III facilities).

| | Low, Mode, High, and Mean **Unit Costs** for Front-end Fuel Cycle Steps from 2020 AFC-CBR (fuel fabrication not included, product is LEUF6) | | | | | | | Material Balance from SWU Calculator for 1 kg U of product | | | Unit Cost Contribution of front-end Fuel Cycle Steps to unit cost of CAT-III LEU | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Mining & Milling (divide value below by 2.6 to express in $/lbU3O8) | U3O8 to UF6 conversion | standard comm'l LEU enrichment price up to 4.95% U-235 | CAT-III HALEU SWU premium for enrichment >5% and <10% U-235 | SWU cost with HALEU premium applied | Tails deconversion, storage | Tails U3O8 geologic disposal | Enrichment feed req'd per unit of product (multiplier for "mining & milling" + "conversion to UF6" unit costs) | Enrichment tails produced per unit of product (multiplier for tails treatment unit costs (deconversion, storage,pkg, & geologic disposal) | SWUs required per unit of product (applies to enrichment unit costs) | Feed (U3O8) component of LEUF6 product | Tails disposition component of LEUF6 product | Enrichment (SWU) component of LEUF6 product (where SWU premium is applied, it applies only to SWUs in portion of cascade > 4.95% U-235) | **Total front-end FC Cost up to and including enrichment** |
| Units >>> AFC-CBR Module >> Data set from AFC-CBR V | ($/kgNATU) A | ($/kgNATU) B | ($/SWU) C1 | (%) premium above C1 | ($/SWU) C3 | ($/kgDU) K1-1 | ($/kgDU) K1-2 | "F/P" ratio | "W/P ratio" | "SWU/P ratio" | ($/kgLEU) | ($/kgLEU) | ($/kgLEU) | **($/kgLEU) as CAT-III LEUF6** |
| Typical Commercial Enricher: 4.95% Std LWR LEU product (tails assay=0.25% U-235) | | | | | | | | | | | | | | |
| Low | 35.8 | 6 | 126 | n/a | n/a | 5 | 5 | 10.217 | 9.217 | 7.826 | 427 | 92 | 986 | **1505** |
| Mode | 89.5 | 11.9 | 145 | n/a | n/a | 7 | 14 | 10.217 | 9.217 | 7.826 | 1036 | 194 | 1135 | **2364** |
| High | 310.2 | 17.9 | 164 | n/a | n/a | 9 | 45 | 10.217 | 9.217 | 7.826 | 3352 | 498 | 1284 | **5134** |
| Mean | 145.2 | 11.9 | 145 | n/a | n/a | 7 | 21 | 10.217 | 9.217 | 7.826483 | 1605 | 258 | 1135 | **2998** |
| 9.75% CAT-III HALEUF6 product (tails assay=0.25% U-235) No SWU premium on SWUs produced > 4.95% | | | | | | | | | | | | | | |
| Low | 35.8 | 6 | 126 | 0% | 126 | 5 | 5 | 20.652 | 19.652 | 18.315 | 863 | 197 | 2308 | **3367** |
| Mode | 89.5 | 11.9 | 145 | 0% | 145 | 7 | 14 | 20.652 | 19.652 | 18.315 | 2094 | 413 | 2656 | **5163** |
| High | 310.2 | 17.9 | 164 | 0% | 164 | 9 | 45 | 20.652 | 19.652 | 18.315 | 6776 | 1061 | 3004 | **10841** |
| Mean | 145.2 | 11.9 | 145 | 0% | 145 | 7 | 21 | 20.652 | 19.652 | 18.315 | 3244 | 550 | 2656 | **6450** |
| 9.75% CAT-III HALEUF6 product (tails assay=0.25%) SWU premium on SWUs produced from 4.95% to 9.75% U-235 | | | | | | | | | | | | | | |
| Low | 35.8 | 6 | 126 | 5.0% | 132.3 | 5 | 5 | 20.652 | 19.652 | 18.315 | 863 | 197 | 2318 | **3378** |
| Mode | 89.5 | 11.9 | 145 | 12.5% | 163.1 | 7 | 14 | 20.652 | 19.652 | 18.315 | 2094 | 413 | 2685 | **5192** |
| High | 310.2 | 17.9 | 164 | 20.0% | 196.8 | 9 | 45 | 20.652 | 19.652 | 18.315 | 6776 | 1061 | 3057 | **10894** |
| Mean | 145.2 | 11.9 | 145 | 12.5% | 163.1 | 7 | 21 | 20.652 | 19.652 | 18.315 | 3244 | 550 | 2685 | **6480** |

8.9% of SWUs are used to enrich from 4.95 to 9.75% U-235 (CAT-III HALEU)
91.1% of SWUs are used to enrich from 0.71% to 4.95% U-235 (Conventional CAT-III LEU SWUs)

**Derivation of incremental CAT-II unit SWU cost increase based on rudimentary analysis of staffing increases and capital cost modifications for transitioning from conventional LWR-LEU enrichments (4.95% U-235 or less) to CAT-II HALEU enrichments (9.75% to 19.95% U-235).** Note "bottom up" engineering designs are not publicly available, but cost estimates are available for large CAT-II HALEU enrichment facilities, either for an "add-on" or a stand-alone facility. Commercial enrichers, such as CENTRUS, ORANO or URENCO, may have produced some, or be in the process of doing so; however, such information would be highly proprietary. It is most likely that an aforementioned facility would be a stand-alone plant on a site and within a building that meets CAT-II safeguards, security, and safety regulations. Presently, no such "CAT-II only" regulations are available; however, they are likely to be not too dissimilar to CAT-I facility requirements. (It should be noted that X-Energy recently submitted a 10CFR70 license application for a 8 to 14 MTU/yr HALEU TRISO fuel fabrication facility to be constructed in Oak Ridge, TN based on a Category II design (X-energy 2022a; X-energy 2022b). No information was available on the assumed regulatory requirements upon which their application's design submittal is based.

Figure C3.11a shows how a CAT-II enrichment facility might be supported by a predecessor's much larger CAT-III facility which can provide the needed 9.75% U-235 HALEU feed. Figure C3.11b shows the material balance data for the two-enrichment plant drawing in Figure C3.11a. A 19.75% CAT-II product rate of 500 MT HALEU/yr is assumed; however, a constant multiplier can be applied to all streams for sizing enrichment facilities to meet other, perhaps smaller, product requirements. The two enrichment plants in Figure C3.11a need not be on the same site, especially since one plant is CAT-III and the other CAT-II. Even if they are on the same physical site, HALEUF6 from the one CAT-III plant is highly unlikely to be piped directly into the CAT-II plant as feed. At these enrichments, large quantity provision of vapor-phase tank-type "buffer storage" between plants is not possible for criticality reasons, and material balance will need to be confirmed by sampling and weighing at all feed and withdrawal points at each plant. Safe and secure rack-type storage for multiple "enhanced type 30B" cylinders of 300 to 1,000 kgU each (for 9.75% U-235) will be needed at both the CAT-III facility product area and the CAT-II facility feed area. These modified Type-30B product cylinders containing solid-phase UF6 from the CAT-III plant will need to be safely moved, perhaps after overpacking, to the CAT-II plant for use in its feed sublimation station. Tails cylinders at 0.71% U-235 assay from the CAT-II facility will need to be transported to the CAT-III facility to provide more feed or sold on the NATUF6 feed market. A credit for this byproduct material will be assumed. If other tails assays from the CAT-II facility are assumed, similar provisions for tails reuse or disposal must be made. Industrial participants in the HALEU program will likely develop their own flowsheets based on economic optimization and market relationships with other enrichers and HALEU fuel fabricators.

The question now arises: what "CAT-II SWU premium" needs to be applied to 100% of the SWUs for a CAT-II HALEU enrichment facility? Once again, one needs to determine what incremental costs (above those which would be incurred for a same-sized conventional LEU facility of the same separative capacity) are incurred for this new CAT-II HALEU plant capacity. It should be noted that the CAT-II SWU premium for the plant shown on the right side of Figure C3.11a will only need to be applied to ~6% of the total two-plant SWU capacity needed to go from natural feed (0.711% U-235) to 19.75% U-235 (i.e. the total SWUs for both plants [CAT-III and CAT-II]) in the figure. Note that this two plant total separative capacity is very large at 19.3 million SWU/yr, which constitutes approximately half of the world's non-Russian separative capacity. It is very important to note that increasing use of HALEU fuel at the 500 MTU/year level will require significant expansion of worldwide existing ore, U3O8 to UF6 conversion, and CAT-III enrichment capacity in order to provide the CAT-III LEUF6 feed to CAT-II enrichment facilities!

An attempt to calculate the premium was made by assuming a 1.2 million SWU CAT-II plant capable of providing 500 MTU of 19.75% U-235 annually. Figures C3.13a and C3.13b provide the material balance data for this case. This is about 20% of the separative capacity of the URENCO-USA plant (4.9 million SWU) and would have several thousand centrifuge machines if European smaller-machine technology is used. The following assumptions are made:

- The same size and same unit cost per machine centrifuges could be safely used in a CAT-II cascade. Centrifuge UF6 inventories are low enough that in-machine nuclear criticality should not pose an issue, provided that possible points for uranium chemical compound accumulation within the piping and vacuum system are carefully monitored.
- A CAT-II building would be needed to house these centrifuges and the product withdrawal stations. Because of what are anticipated to be much more stringent security, safety, and environmental regulations the building enclosing these higher assay centrifuges would need to be much more robust (at a higher cost per square foot than for CAT-III or conventional LEU facilities). The incremental cost of this CAT-II space above that for a conventional CAT-III industrial building is calculated. One should note that the requirements for CAT-II "robustness" have not yet been developed; however, they will probably be guided by CAT-I requirements. Three CAT-I U.S. uranium-handling facilities come to mind in this regard: the Oak Ridge Y-12 Plant, the BWXT nuclear facility at Lynchburg VA, and the Nuclear Fuel Services (NFS) facility at Erwin, TN. Their operating contractors may be able to provide further guidance in this regulatory area. X-energy has also submitted a license application to the USNRC for a CAT-II TRISO fuel fabrication facility in Oak Ridge, TN (X-energy 2022a; X-energy 2002b). Once the USNRC provides a redacted, non-proprietary version of the X-energy license application on their website, some insight to CAT-II design requirements might be gained.
- A CAT-II facility may utilize the PIDAS fence which is now required for CAT-I facilities. This feature has been added to the authors' "pessimistic" cost estimate in Table C3.8 below. It should be noted that the product cylinder storage portion of the process building will likely contain tens of metric tons of CAT-II HALEUF6 and is likely to require significant "guns, gates, and guards" because of its attractiveness to another country-level actor that could enrich it further to weapons-grade HEU. Anti-theft and MPC&A measures for CAT-II HALEUF6 product in small, human-transportable, low weight cylinders will be very important in the design. Hopefully, however, the fact that CAT-II HALEUF6 is not "direct-use" weapons material may eliminate the need for a PIDAS (optimistic case from a cost standpoint).
- The modified 30B product withdrawal cylinder of estimated 300 to 1,000 kgU capacity for 5% up to 9.75%% U-235 will not suffice for CAT-II HALEUF6 because of criticality concerns. Significant up-front expenditures will be needed to design, develop, certify, and manufacture the much smaller, critically safe container which will probably be able to contain only 32 to 80 kgU of 19.95% HALEU as UF6. A CAT-II enricher might need to purchase 6,000 to 16,000 of these smaller capacity cylinders to store 1 year's worth of HALEU product (~500 MTU). If the product cylinders can be quickly transported to and emptied by the recipient metallization, deconversion, or fuel fabrication facilities, they can be returned and reused, thus reducing the number of cylinders initially required.
- More personnel are required to operate a CAT-II facility as opposed to a CAT-III facility. In addition to the more numerous chemical operators at feed and withdrawal stations, many of these will be in security, health physics, and material accountability areas. In Table C3.8 below, these costs are in the "Recurring Life Cycle Costs" category. This facility is assumed to operate for 50 years.

Table C3.8 also summarizes the economic analysis for calculating the CAT-II SWU cost premium. Individual costs for items such as additional building space, products cylinders, and additional staff are not based on actual bottom-up designs and cost estimates prepared by an architect-engineering organization, but rather on the authors' educated "top-down estimating" guesses based on "rules-of-thumb" and other information gleaned from work on other AFC-CBR cost modules and work for NNSA programs having CAT-I facilities, such as HEU handling, surplus weapons-grade plutonium disposition, and tritium production. As an example of useful "top-down" estimating data, the $/per ft2 for a facility can be calculated if the building footprint dimensions are known, and the total capital cost (building plus equipment) is known. Two examples are shown here:

- Y-12 Highly Enriched Uranium Materials Facility (HEUMF at Oak Ridge, TN) is a 300 ft by 475 ft reinforced concrete CAT-I facility with a PIDAS fence and vault type indoor rack storage for storing specially packaged weapons grade uranium metal and oxides. Its cost at completion was ~450$M, resulting in $3160/ft2. Most of this cost is for the massive building capable of withstanding an armed terrorist attack, very severe weather phenomena, and an airplane crash.
- Using life-cycle cost data from Module D1-1 (LWR UOX Fuel Fabrication), a greenfield 500 MTU/yr CAT-III plant with the process building occupying 100,000 ft2 would cost $677M. A cost of $677/ft2 results, with the process building structure accounting for ~$290/ft2 of this total.

Data of this type guides the selection of optimistic and pessimistic model inputs in Table C3.8.

Up-front capital costs for incremental capital modifications are amortized and annualized over 50 years at a low real discount rate typical of government-supported projects. All of the annualized costs, including incremental staffing, are summed and divided by the 1.2 million SWU of CAT-II capacity to calculate the incremental $/SWU unit costs. Both an optimistic (low cost) and pessimistic (high cost) set of assumptions are presented in the table. The low and high values of 5.0 and 38.64 $/SWU are then divided by the mean conventional enrichment cost of $145/SWU (2020$) to obtain optimistic and pessimistic SWU premiums rounded to 3 and 27% respectively. **A mean or average SWU premium of 15% is calculated, and a uniform distribution for these uncertain premiums is suggested.** This SWU premium would apply to **all** of the CAT-II enrichment facility separative capacity. One must keep in mind, however, that only 6% of the overall separative capacity for two enrichment facility CAT III + CAT-II HALEU enterprise is needed to enrich 0.7% U-235 to 19.95% U-235. As will be shown later, it is the unit cost of the 5 to 9.75% U-235 CAT-III LEU feed (a recurring operating cost) to the CAT-II plant that drives the life cycle cost, including operations, of the CAT-II enrichment facility and not the relatively smaller number of SWUs to go from 9.75% U-235 to 19.95% U-235.

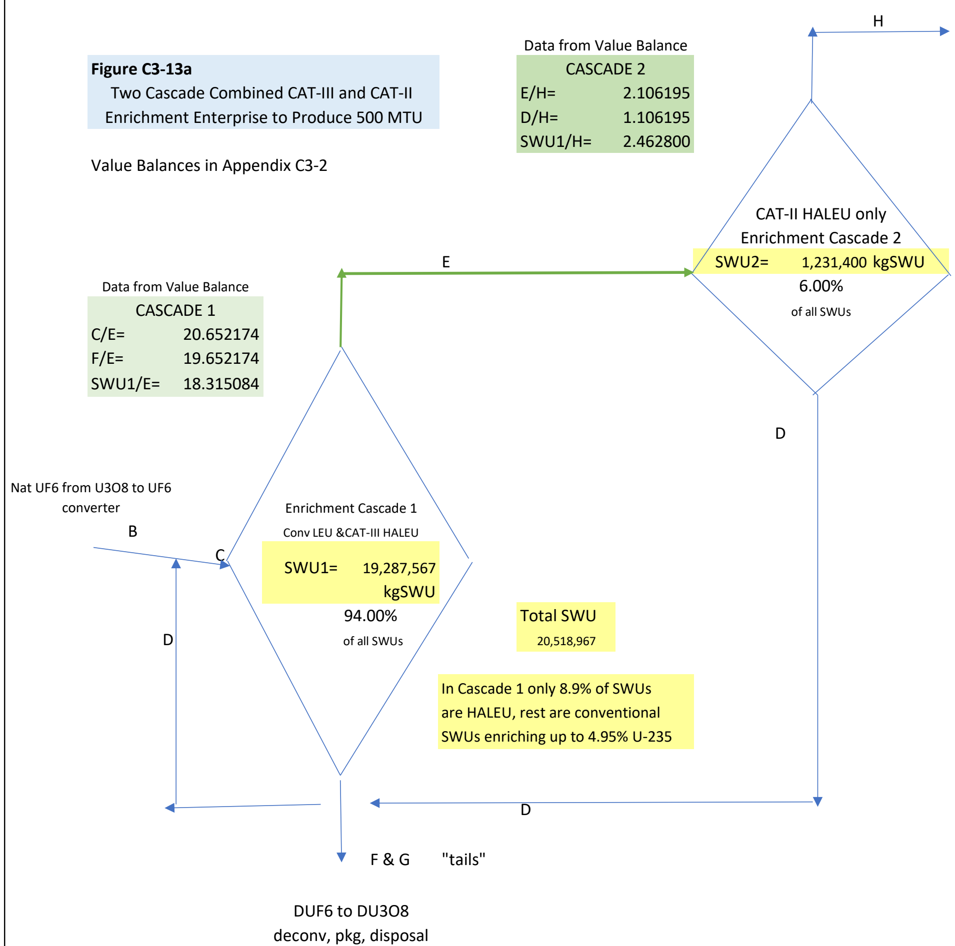



**Fig C3-13b Material Balance for Configuration in Figure C3-13a**

| SUMMARY MATERIAL BALANCE TO SUPPLY 500 MT HALEU PRODUCT PER YEAR | | | | |
|---|---|---|---|---|
| **Stream** | **Form** | **U-235 Assay** | **Annual Flow** | **Units** |
| | | | | |
| B (total cascade feed) | Nat UF6 | 0.0071 | 21,195,652 | kgU/yr |
| C (cascade 1 feed) | Nat UF6 | 0.0071 | 21,748,750 | kgU/yr |
| D (cascade 2 tails) | Nat UF6 | 0.0071 | 553,097 | kgU/yr |
| E (cascade 1 product & cascade 2 feed) | CAT-III HALEUF6 | 0.0975 | 1,053,097 | kgU/yr |
| F (cascade 1 tails) | DUF6 | 0.0025 | 20,695,652 | kgU/yr |
| G (Cascade 1 tails) | DU3O8 | 0.0025 | 20,695,652 | kgU/yr |
| H (cascade 2 product) | CAT-II HALEUF6 | 0.1975 | 500,000 | kgU/yr |
| | | | | |
| SWU1 Sep. Capacity | | | 19.29 | MSWU |
| SWU2 Sep. Capacity | | | 1.23 | MSWU |
| SWU1+SWU2 | | | **20.52** | **MSWU** |

Figure C3.13.(part a left) enrichment plant configuration for production of 500 MTU/yr of 19.95% U-235 HALEUF6; (part b right) material balance for e-plant configuration in part a.

Table C3.8. SWU premium range calculation for CAT-II HALEU enrichment.

| | | | | |
|---|---|---|---|---|
| **CAT-II HALEU SWU PREMIUM: Derivation of Incremental unit SWU costs of 19.75% U-235 CAT-II SWUs above SWU costs for conventional LEU (up to 4.95% U-235) CAT-III SWUs (European Centrifuge Technology Assumed)** | | | | |
| **Annual product (CAT-II HALEU @19.95% U-235)** | **500 MTU as HALEUF6** | | | |
| SWUs required if receiving 9.75% U-235 CAT-III HALEU feed (separative capacity) | 1,231,400 kgSWU | (@ tails assay= | 0.71% U-235) | |
| Centrifuge type | European (URENCO) | | | |
| | | | Optimistic | Pessimistic |
| SWU per machine (kgSWU/yr): affects building size since process building footprint driven by number of centrifuges needed to meet desired plant separative capacity | | | 120 | 80 |
| **INCREMENTAL CAPITAL FOR CAT-II Facility** | | | | |
| **CAT-II DESIGN and LICENSING** | | | Optimistic | Pessimistic |
| CAT-II Facility design costs and licensing costs above those for a conventional new CAT-III centrifuge facility ($M) | | | 20 | 80 |
| Incremental $/SWU based on amortization of this up-front cost | | | 0.89 | 3.56 |
| **INCREMENTAL CAT-II BUILDING VS CAT-III BLDG** | | | Optimistic | Pessimistic |
| Square foot of cascade hall bldg footprint per machine incl hallways (ft2) [same as for CAT-III] | | | 4 | 10 |
| Number of machines required in cascade hall bldg | | | 10262 | 15393 |
| Total square feet of cascade hall required (ft2) | | | 41047 | 153925 |
| Additional CAT-II space needed for feed & product withdrawal area, indoor cylinder storage, & facility maintenance (ft2) | | | 30000 | 50000 |
| Total area of CAT-II building (ft2) | | | 71047 | 203925 |
| Cost per ft2 of CAT-II building | | | 600 | 2500 |
| Cost per ft2 of CAT-III building | | | 100 | 200 |
| Cost oer ft2 difference (CAT-II minus CAT-III) | | | 500 | 2300 |
| Total incremental CAT-II Bldg cost ($M) | | | 36 | 469 |
| Assumed yrs of ops and capital amortization | | | 50 | 50 |
| Assumed real discount rate for amortization (assuming Gov't backed loan) | | | 5% | 5% |
| Annual production in kgSWU/yr from above | | | 1,231,400 | 1,231,400 |
| Fixed charge rate (annual) for amortization | | | 0.055 | 0.055 |
| **Incremental $/SWU attributable to more robust CAT-II bldg** | | | 1.58 | 20.86 |
| **POSSIBLE ADDITION of PIDAS FENCE FOR CAT-II FACILITY SECURITY** | | | Optimistic | Pessimistic |
| Distance from fence to wall (ft) | | | 0 | 50 |
| Length of building side if square bldg (ft) | | | 267 | 392 |
| One side of square PIDAS layout (ft) | | | 267 | 492 |
| Total perimeter to be protected (ft) | | | 1066 | 1969 |
| Unit cost of PIDAS ($/ft) | | | 0 | 20000 |
| Total capital cost of PIDAs ($M) | | | 0.00 | 39.39 |
| Fixed charge rate for amortization | | | 0.055 | 0.055 |
| **$/SWU attributable to PIDAs req't for CAT-II** | | | 0.00 | 1.75 |

Table C3.8 (continued).

| SMALLER, MORE NUMEROUS CAT-II HALEUF6 PRODUCT WITHDRAWAL CYLINDERS | | Optimistic | | Pessimistic |
|---|---|---|---|---|
| Amount of 19.95% HALEU allowable in one product cylinder (kgU as UF6) | | 80 | | 32 |
| Cylinders req'd to hold one yr's worth of product | | 6250 | | 15625 |
| Reduced cyl req't if cyls can be reused more than 1/yr (cyls/yr): Optimistic is 4 cycles/yr, Pessimistic is only one use per year | | 1563 | | 15625 |
| One time cost to design and certify cylinders ($M) | | 15 | | 30 |
| Cost per cylinder if mass-produced ($/cylinder) | | 500 | | 2000 |
| Total cylinder-related costs (SM) | | 15.78 | | 61.25 |
| **$/SWU attributable to amortized initial cylinder purchase and other amortized cylinder-related costs ($/SWU)** | | 0.70 | | 2.72 |
| TOTAL CAPITAL CONTRIBUTION TO UNIT COST ($/SWU) | | 3.17 | | 28.90 |
| INCREMENTAL ANNUALIZED RECURRING COSTS FOR CAT-II Facility | | | | |
| **Additional** personnel (security, safeguards, MPC&A, criticality safety) (FTEs) | | 25 | | 100 |
| Fully-loaded annual salary per additional FTE ($/FTE-y) | | 90000 | | 120000 |
| Total additional staffing cost ($M/yr) | | 2.25 | | 12 |
| Incremental $/SWU | | 1.83 | | 9.75 |
| TOTAL INCREMENTAL RECURRING CONTRIBUTION ($/SWU) | | 1.83 | | 9.75 |
| GRAND TOTAL UNIT COST (INCREMENTAL TO CONVENTIONAL CAT-III) IN $/SWU | | 5.00 | | 38.64 |
| Mean $/SWU Unit Price from 2020 AFC-CBR Update Module C1 for conventional CAT-III LEU (incl esc from 2017$ to 2020$) | 145 $/SWU | For a "perfect market" unit SWU cost with return to investors included is assumed to equal unit SWU price | | |
| **% premium for CAT-II above Conv LEU mean price from AFC-CBR (2017 Module C1 escalated to 2020$)** | | **3.4%** | | **26.7%** |
| **ROUNDED SWU PREMIUMS FOR USE IN ANALYSES** | | **Low** | **Mean** | **High** |
| **% >>** | | **3%** | **15%** | **27%** |

**Status of CAT-II HALEUF6 deconversion/metallization unit cost estimation.** For use in nuclear reactors, the HALEUF6 product from the CAT-II enrichment facility must be deconverted from the UF6 form to a chemical form acceptable as feed to a fuel fabrication facility. For metal-fueled reactor fuel cycles, this deconversion step is usually called “metallization” or “chemical reduction.” The following HALEU forms are anticipated for various reactor types:

- For HTRs (gas-cooled or salt-cooled) using TRISO fuels, the deconversion step may become part of the overall TRISO fabrication process. The TRISO fabrication flowsheet may start with an aqueous solution, and one can be prepared by hydrolysis of UF6 into a UO2F2 solution which can then be further treated by ammonium diuranate (ADU) precipitation to produce UCO for TRISO kernels. (See AFC-CBR Module D1-3 on particle fuels for TRISO flowsheet information and [Benedict, Pigford and Levi 1980] for UF6 to oxide preparation). Another option is to construct a generic CAT-II deconversion/TRISO plant which can sell packaged TRISO particles to various fuel fabricators for embedment into their particular fuel geometries. Such a TRISO particle plant could be collocated with the CAT-II enrichment facility on a common protected site as shown on Figure C3.5. A consortium type agreement could be an economically attractive mode for constructing and operating such a complex with shared overhead costs.
- For liquid-fuel reactors such as molten-salt reactors (MSRs), a HALEU halide compound such as UCL3 or UF4 (green salt) might be required. These can be produced by continuous chemical processes that must operate in a CAT-II environment.
- Specialized research and military reactors might use uranium silicides, carbides, or nitrides as feed for fuel fabrication.
- For metal-fueled reactors, such as SFRs or seed/blanket LWRs, the fuel fabricator will need relatively pure uranium shards or billets that can be melted and alloyed with other elements, such as zirconium, molybdenum, or even other fissile materials like plutonium. Section C3-2 described the metallization/reduction chemistry which is likely to be a more-difficult-to-implement batch process in which equipment sizes for items such as crucibles are limited by criticality considerations and the need to remove the high heat of reaction. Co-location of this CAT-II facility with the CAT-II enrichment plant could provide the economic benefits of sharing security and other overhead costs and minimizing transportation costs.

It should be noted that very large-scale deconversion for enrichment plant tails (depleted UF6 [i.e., DUF6]) disposition is presently underway at both the Portsmouth and Paducah, former GDP sites, by Midwest Deconversion Services, a DOE-EM contractor. Metallization processes have been recently conducted by private firms for natural and depleted UF6 to provide special radiation shielding and armor-penetrating munitions. Because of the low U-235 assays, any unit costs available from such operations would not be applicable to CAT-II material. The 2017 AFC-CBR Module K1-1 discusses the unit cost of dispositioning large quantities (1,000s of MTU/yr) of depleted UF6. As an example, large-scale deconversion of DUF6 to DU3O8 is expected to cost 4 to 9 $/kgDU (geologic disposal as low level waste not included). NNSA is considering a facility at Portsmouth, OH to deconvert legacy enrichment plant tails DUF6 to high-purity DU metal for non-fissile weapons components. Based on data in (GAO 2020), these authors estimate a cost of ~$25/kgDU to accomplish this task.

On the other side of the U-235 assay spectrum, NNSA and its predecessor agencies have over many years contracted multiple CAT-I facilities to provide HEU. These specialized facilities would handle much smaller annual flowrates than the 500 MTU/yr anticipated CAT-II HALEU demand for advanced reactors. For this reason, fixed costs with the high overheads associated with CAT-I operations are a larger component of the unit product costs. Unit costs in the range $5,000 to $10,000/kgHEU would be expected.

Presently there are no private or government CAT-II only facilities in the United States. The closest type of EU operation would be the preparation and handling of HALEU research reactor fuel. As an example, the Oak Ridge Y-12 Plant blends surplus HEU metal down to HALEU to provide feed material to BWXTs research reactor fuel fabrication plant in Lynchburg, VA. Both the Y-12 Plant and the BWXT facilities are CAT-I, however.

Finally, note that “bottom up” engineering designs are not yet available, nor are detailed cost estimates are available for HALEU deconversion or metallization facilities. Commercial research reactor fuel manufacturers, such as BWXT Lynchburg, or specialty converters, such as NFS in Erwin, TN, may have produced such estimates or be in the process of doing so; however, such information would be highly proprietary.

**Historical costs for chemical conversion costs for HEU in the USAEC Complex as a surrogate for possible deconversion/metallization costs.** In the late 1980s and early 1990s, DOE Defense Programs were considering the construction of new production reactors (NPRs) at DOE sites (for tritium and weapons-grade plutonium) which would use HEU fuels. The *Life Cycle Cost* report (NPR-1991) discusses the assumptions used to calculate projected fuel cycle costs. In this report, a rough estimate from the Oak Ridge Y-12 Plant indicates that under evolving regulations (at that time) and DOE Orders, deconverting clean reprocessed HEUO3 to metal might cost $3,500/kgU in 1990$, which would correspond to $10,000/kgU in 2020$. There are three considerations which could lead one to lower this unit cost:

- Any material for deconversion would likely be clean UF6 rather than reprocessed U that would contain trace fission products, transuranics, and U-232 decay daughter isotopes.
- The plant anticipated for Advanced Reactor fuel production would be larger, and economies of scale are possible.
- The material handled is CAT-II rather than CAT-I.

**Uranium metal fuel fabrication costs as an upper bound on deconversion/metallization unit costs.** Soon-to-be-published Module D1-6A of the AFC-CBR estimates the unit cost of fabricating clean (contact-handled) SFR uranium metal alloy fuel from HALEU and lower-assay (20 to 35% U-235) HEU billet feed. These costs include alloying, casting, cleaning, sodium-bonding, cladding, and bundle fabrication. Metallization by bomb reduction of HALEUF6 involves fewer process steps than fuel fabrication; however, the metallization steps are more hazardous and difficult than for the casting of small SFR fuel pins. Figure C3.14 below from AFC-CBR Module D1-6A shows the anticipated $1,000 to $3,000/kgU range anticipated for CAT-II HALEU metal fuel fabrication. The author of this Module C3 suggests that this range would also be an acceptable range for HALEU metallization. A mean value of $2,000/kgU for metallization is used in a fuel cycle analysis in the next subsection of this HALEU report.

If a non-metal deconversion product is desired, it may be possible that a more economic continuous process can be implemented. The $2,000/kgU unit cost for metallization would probably be an upper bound. Table C3.9 and Table C3.10 below present the author of this report’s estimated unit cost ranges for both CAT-II and CAT-III metallization and deconversion, recognizing that some advanced reactor fuel concepts require fuel in the 6 to 9.75% U-235 range.

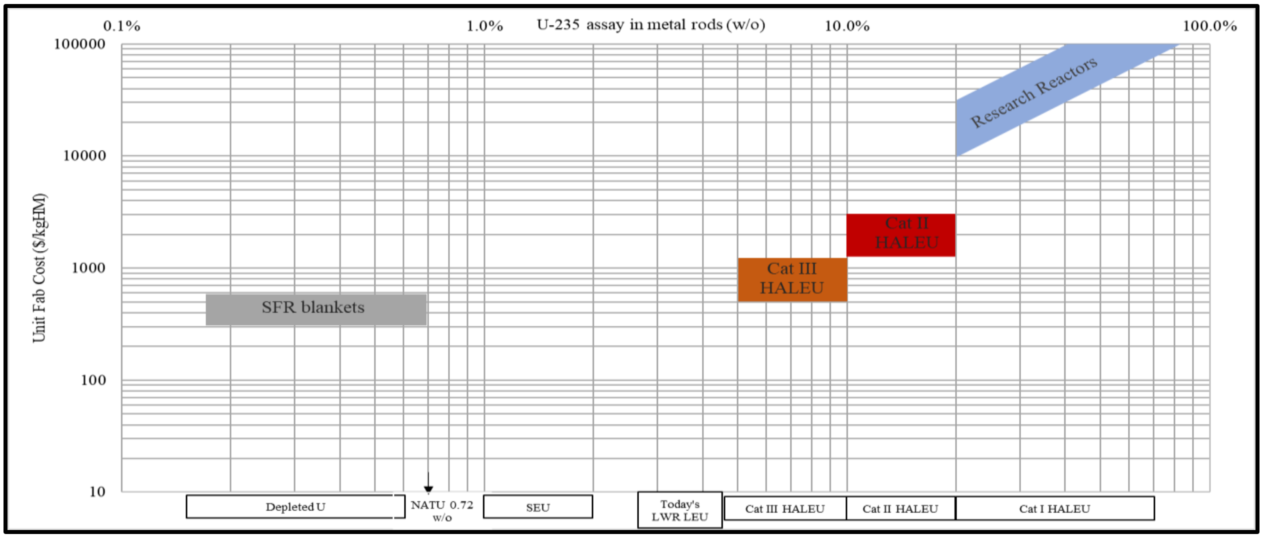



Figure C3.14. Chart used for determination of unit fuel fabrication costs for U-metal alloy fuels (from draft 2020 AFC-CBR Module D1-6A).

# C3-7. DATA LIMITATIONS

**Identification of Gaps**. Because of the sensitive nature of enrichment and metallization technology, both needed for nuclear weapons production, there is little plant design and life-cycle cost data available even from old USAEC, ERDA, or DOE-NNSA archives. Commercial centrifuge technology, such as that owned by URENCO, ORANO, and CENTRUS, is highly proprietary since uranium enrichment is now an established, highly competitive international business. The following steps are suggested for obtaining higher quality cost estimates for both HALEU enrichment and deconversion/metallization:

- Consultation with commercial enrichers and possible HALEU fuel fabricators, including their comments on this document.
- Consultation with NNSA planners and NNSA-owned uranium-handling GOCO contractors. Access to any NNSA studies on gas centrifuge facility costs would be especially helpful.

# C3-8. COST SUMMARY

## C3-8.1. 2021 AFC-CBD Cost Summary

Table C3.9 below shows the new 2021 What-it-takes (WIT) unit HALEU SWU cost premiums above the usual SWU cost for conventional LEU SWUs (up to 4.95% U-235 product) as percentages.

Table C3.9. “What-it-takes” unit SWU premiums for both CAT-III and CAT-II HALEU SWU (% increase over normal commercial LEU SWUs).

| E-plant Type | Low | High | Mean |
|---|---|---|---|
| CAT-III HALEU | 5 | 20 | 13 |
| CAT-II HALEU | 3 | 27 | 15 |
| Uniform distributions assumed | | | |

One might note that the SWU premium low range for CAT-II HALEU is smaller than for CAT-III HALEU, which seems counter-intuitive. This can be explained as follows. The CAT-III SWU and CAT-II SWU premiums were calculated from two different sized plants. The CAT-III plant was assumed to be a 0.5 million SWU add-on to an existing 4.95 million SWU plant similar to the URENCO-USA one in

New Mexico.  This plant could produce around 295 MT of 9.75% U-235 product annually.  All costs were distributed over 0.5 million SWU to arrive at incremental $/SWU for low, mode, and high cases, which are presented in  the above tables in this report.   The CAT -II case is for a stand-alone 1.23 million SWU plant capable of producing 500 MTU annually at 19.75% U-235. In this case costs are distributed over a much larger incremental SWU amount (1.23 MSWU).  Not all costs scale linearly with size, i.e. plant throughput.  For both plants there we relatively fixed costs such as for regulatory matters and security.  If these fixed costs are distributed over a larger SWU base for CAT-II, the incremental S/SWU can be lower, especially if optimistic cost parameters are chosen for the low case. A lower incremental $/SWU results, therefore, in a lower % SWU premium above normal commercial enrichment.

Table C3.10 below shows the new 2021 WIT unit metallization costs in $/kgU for HALEU defluorination and batch reduction to metal.

Table C3.10. "What-it-takes" unit metallization costs for both CAT-III and CAT-II HALEU ($/kgU as metal product).

| Conversion-plant Type | Low | High | Mean |
|---|---|---|---|
| CAT-III HALEU | 200 | 1000 | 600 |
| CAT-II HALEU | 1000 | 3000 | 2000 |
| Uniform distribution assumed | | | |

Table C3.11 below shows the new 2021 WIT unit deconversion costs in $/kgU for HALEUF6 to a non-metal uranium compound.

Table C3.11. "What-it-takes" unit chemical deconversion costs for both CAT-III and CAT-II HALEU ($/kgU as a uranium compound).

| Conversion-plant Type | Low | High | Mean |
|---|---|---|---|
| CAT-III HALEU | 100 | 1000 | 550 |
| CAT-II HALEU | 500 | 2000 | 1250 |
| Uniform distribution assumed | | | |

Table C3.11 below shows the overall front-end fuel cycle cost components for the production of both 9.75% (CAT-III) and 19.75% (CAT II) HALEU as UF6. It can be seen that the feed cost to the HALEU enrichment plant is by far the largest component of the overall HALEUF6 cost. The SWU-related costs in going from 4.95 to 9.75% U-235 and from 9.75 to 19.95% U-235 are small because the separative capacity required is very small compared to that needed to go from 0.71% U-235 to 4.95% U-235. For this reason, the contribution of the SWU premium is even smaller, as shown by comparing the top and bottom parts of Table C3.11. This table forms the basis for the selection of the "What-it-Takes" (WIT) data below for production of 19.95% HALEU.

Table C3.12. Breakdown of HALEUF6 production costs.

**Breakdown of Costs of Production for 1 kgU of 9.75% U-235 and 1 kgU of 19.75% U-235 HALEU based on front-end fuel cycle unit cost data from *2020 Advanced Fuel Cycle Cost Basis Report* and application of appropriate SWU price premiums (Transportation and Interest on inventory charges not included)**

**Contribution of Front-end Fuel Cycle Material and Service Purchases to the Production of One Kilogram of 9.75% CAT-III HALEUF6 with and without SWU Premium* ($/kgU)**

| Case | AFC-CBR Unit Cost Parameter Set Used (from Table C3-7) | NATU3O8 feed related (mining & milling) component of unit cost | Tails disposition component of unit cost (tails assay=0.25% U-235) | Enrichment component of unit cost (All CAT-III SWUs) | **Total front-end unit cost for 9.75% U-235 HALEUF6 (Same as last column of Table C3-7)** |
|---|---|---|---|---|---|
| No SWU premium | Low >> | 863 | 197 | 2308 | **3368** |
| | Mode >> | 2094 | 413 | 2656 | **5163** |
| | High >> | 6776 | 1061 | 3004 | **10841** |
| | Mean >> | 3244 | 550 | 2656 | **6450** |
| Includes SWU premium | Low >> | 863 | 197 | 2318 | **3378** |
| | Mode >> | 2094 | 413 | 2685 | **5192** |
| | High >> | 6776 | 1061 | 3057 | **10894** |
| | Mean >> | 3244 | 550 | 2685 | **6479** |

*SWU premium applied only to separative capacity above 4.95% U-235 (Enhanced CAT-III SWUs)

Material and Value Balance based on Figure C3-9a

**Contribution of Front-end Fuel Cycle Material and Service Purchases to the Production of One Kilogram (P=1 kg U/yr) of 19.75% CAT-II HALEUF6 with and without SWU Premium** ($/kgU)**

| Case | AFC-CBR Unit Cost Parameter Set Used (from Table C3-7) | 9.75% HALEUF6 feed related component of unit cost (based on last column of Table half at left) | 0.71% U-235 Tails credit component of unit cost (tails assay=0.71% U-235): includes ore and conversion components as if natural feed) | Enrichment component of unit cost (All CAT-II SWUs): based on conventional SWU prices in Table C3-7 with CAT-II SWU premium added in lower rows | **Total front-end unit cost for 19.75% U-235 HALEUF6** |
|---|---|---|---|---|---|
| No SWU premium | Low >> | 7094 | -46 | 310 | **7358** |
| | Mode >> | 10874 | -112 | 357 | **11119** |
| | High >> | 22833 | -363 | 404 | **22874** |
| | Mean >> | 13585 | -174 | 357 | **13768** |
| Includes SWU premium | Low >> | 7115 | -46 | 320 | **7388** |
| | Mode >> | 10935 | -112 | 411 | **11234** |
| | High >> | 22945 | -363 | 513 | **23095** |
| | Mean >> | 13646 | -174 | 411 | **13883** |

**SWU premium applied only to all SWUs in CAT-II facility

Material and Value Balance based on upper right corner of Figure C3-13a

| F/P = 2.1062 | W/P= 1.1062 | SWU/P = 2.4628 |
|---|---|---|

Table C3.13 below shows the estimated unit cost of 19.95% HALEU (as HALEUF6) including all of the front-end feed costs for 9.75% U-235 and the applicable SWU costs including premiums. It should be noted that a recent April 2022 unit cost estimate for CAT-II HALEU by the Nuclear Innovation Alliance (NIA 2022) gives a value of $15,000/kgU as UF6, which falls well within the range shown below.

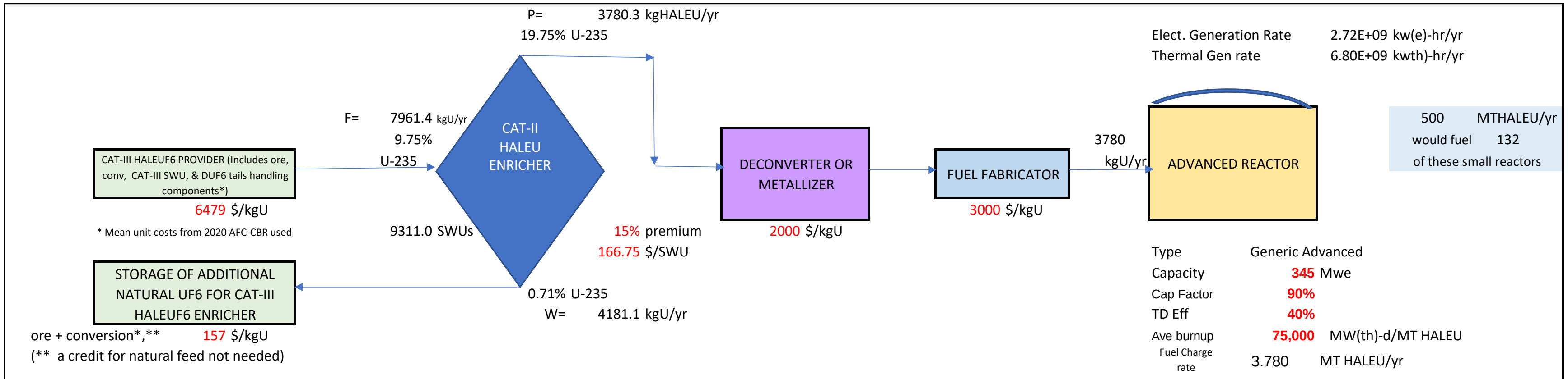
Table C3.13. What-it-takes unit cost for 19.95% HALEUF6 including all front-end fuel cycle costs.

| | Low | Mode | High | Mean |
|---|---|---|---|---|
| Unit cost of 19.95% HALEUF6 ($/kgU) | 7400 | 11000 | 23000 | 14000 |

The use of a uniform distribution is suggested.

## C3-9. EXAMPLE FRONT-END FUEL CYCLE COST CALCULATION FOR A GENERIC ADVANCED REACTOR FUELED WITH HALEU

Figure C3.15 below shows the unit cost contribution to the cost of electricity (in $/Mwe-h) for all of the front-end steps for the fuel cycle of a generic advanced reactor using CAT-II HALEU fuel. Note that the production of CAT-III LEU feed to the CAT-II enrichment plant is the largest contributor. For this feed, 94% of the SWUs are required are from the CAT-III E-plant , with most of them going from 0.71 to 4.95% U-235. The 26 $/Mwe front-end fuel cycle component is over twice that for a UOX LWR with ~4% U-235 LEU fuel; however, other unique benefits associated with HALEU-fueled advanced reactors, such as the availability of high temperature for process heat, small size, and special applications, may still make the overall system unit energy cost economically attractive. A forthcoming report (Kim et al. 2020) will contain more of these type studies along with sensitivity analyses.




| Front-end step | Amt processed (kgU/yr or kgSWU/yr) | Unit cost ($/kgU or $/kgSWU) | Annual $M cost | Cost per kg of fabricated fuel ($/kgHALEU) | Cost per kw(e)-hr of generation ($/MWe-hr) |
|---|---|---|---|---|---|
| CAT-III HALEU feed UF6 (9.75%) | 7961.4 | 6479 | 51.582 | 13645 | 18.95 |
| Enrichment in CAT-II Cascade | 9311.0 | 166.75 | 1.553 | 411 | 0.57 |
| Natural assay "tails" credit | 4181.1 | -157 | -0.656 | -174 | -0.24 |
| Subtotal for HALEUF6 | n/a | n/a | **52.478** | **13882** | **19.28** |
| Deconversion | 3780.3 | 2000 | 7.561 | 2000 | 2.78 |
| Fuel Fabrication | 3780.3 | 3000 | 11.341 | 3000 | 4.17 |
| Total cost where applicable >> | n/a | n/a | **71.380** | **18882** | **26.22** |

| Total SWUs for this front-end cycle including conventional, CAT-III, and CAT-II >> | 155124 | % of all SWUs |
|---|---|---|
| Conv SWU from .71 to 4.95% | 132836 | 85.6% |
| Cat-III SWU from 4.95 to 9.75% | 12977 | 8.4% |
| Cat-II SWUs | 9311 | 6.0% |
| | 155124 | 100.0% |

SWUs for 132 reactors = 20.5 million SWU/yr

Figure C3.15. Breakdown of generic advanced reactor front-end fuel cycle cost by various steps including HALEU enrichment and deconversion.

# C3-10. SENSITIVITY AND UNCERTAINTY ANALYSES

Insufficient base process cost data exist for accurate sensitivity studies to be initiated. Bottom-up design and life-cycle cost estimates are needed. There are many cascade configurations and multiple tail assay choices available to accomplish the HALEU mission. Once bottom-up design data are available, economic optimization may be possible.

In light of the many uncertainties associated with this HALEU analysis, the following conclusions can be made:

- The additional enrichment above that required to produce conventional LEU < 5% U-235 is a small fraction of the overall unit cost of HALEUF6 if all predecessor fuel cycle steps are included. The total feed cost to the HALEU facility (and its constituent ore, U3O8 to UF6 conversion, and conventional LEU enrichment costs) is the major contributor to the unit cost of HALEUF6.
- Because the "HALEU SWUs" are such a small portion of the HALEUF6 unit cost, the SWU premium is an even smaller contributor to the unit HALEUF6 cost. This can be seen by examining Table C3.12.
- Some preliminary information from URENCO (NARUC 2022) obtained just prior to this document draft indicates that they could add an unspecified amount of HALEU SWU capacity by an addition to their URENCO-USA Lea County, New Mexico facility at a capital cost of around $300M. This compares to the original conventional LEU plant capital cost of $5B for their 4.95 MSWU plant. This HALEU addition could share existing plant functions such as centrifuge assembly, plant maintenance, some personnel, and overhead costs. In this case, there may be no SWU premium necessary.
- Conversion/metallization of the HALEUF6 is likely to add an additional 10 to 20% to the total unit cost of HALEU metal or other chemical forms to the fuel fabricator. (HALEU metal fuel fabrication unit costs are discussed in Modules D1-4 and Modules D1-6 and are for the fabrication step only).

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# Appendix C3-1
# Regulatory Considerations for HALEU Fuel Cycle Facilities

The large scale deployment of HALEU-fueled reactors will require enrichment and metallization facilities that can produce at least tens of metric tons of HALEUF6 and heavy metal (HM) per year in the early years and perhaps hundreds of MTU as fleets of HALEU-fueled reactors are deployed in later years. What needs to be considered is how the use of HALEU affects the design and operations of such facilities, and how the life cycle costs are likely to compare to the life cycle costs for standard enrichment SWUs. In the United States, fuel cycle facilities are licensed under Title 10 of the Code of Federal Regulations (10 CFR) Part 70, “Domestic Licensing of Special Nuclear Material,” and reviewed by the Nuclear Regulatory Commission as prescribed in NUREG-1520 Rev 1 (U.S. Nuclear Regulatory Commission, 2010), which is the standard review plan (SRP). NRC-regulated fuel cycle facilities generally fall into three classes from the standpoint of security and safeguards depending on the “attractiveness level” (to a proliferator or terrorist) of the type of SNM handled:

1. Category I facilities handle "high strategic significance" SNM which would be plutonium, U-233, or HEU (uranium with U-235 content 20% or higher). There are two fuel fabrication facilities in the United States which handle HEU, NFS in Erwin, Tennessee and BWXT Nuclear in Lynchburg VA. The latter also handles HEU for fabrication of research reactor fuel. NFS has also blended down legacy reprocessed HEU from military production reactors to produce LWR UOX fuel for use in U.S. commercial reactors. The Oak Ridge National Security Complex (i.e., Y-12 Plant) can do specialty blending of HEU metal with DU metal to produce HALEU feed billets for the manufacture of research reactor fuel.
2. Category II facilities handle "moderate strategic significance" uranium in quantities of 10 kg or more falling in the assay range 10 to 19.75% U-235. A domestic facility fabricating HALEU fuel for most advanced reactor concepts would fall under this designation.
3. Category III facilities handle "low strategic significance" uranium in quantities of 10 kg or more of U-235 assay less than 10% U-235. Today's three existing U.S. UOX fabrication plants (GNF - Wilmington, NC, Westinghouse - Columbia, SC, and AREVA/Framatome - Hanford, WA) fall in this category. If today's UOX fuel fabricators want to produce material in the U-235 range 5 to 10% U-235, such as for higher burnup UOX fuel or some accident tolerant fuels (ATFs), there would likely be some USNRC relicensing required despite the fact that the facility would still be a Category III facility.

Transitioning from a Category III facility to a Category II will likely require significant changes in the physical structure, security perimeter, equipment, and operations of the plant. These changes are dictated by regulations in the areas listed in the bullets below. All of these considerations are likely to incur significantly higher levelized life cycle costs for a kilogram of uranium processed ($/SWU, $/kgU or $/kgHM).

- Nuclear criticality and radiation safety: higher fissile content will require redesign of some process systems and procedures. Existing criticality design codes may need to be re-benchmarked by critical experiments or the application of NRC-approved criticality codes and the applicability of these studies extended to the Category II regime.
- Material control and accountability (MC&A): the USNRC requirements for MC&A are described in NUREG-2159 (U.S. Nuclear Regulatory Commission, 2022). Since HALEU is of a higher "attractiveness level" for theft or diversion, the MC&A software and procedures will require upgrading from the practices associated the Category III commercial enrichment facilities.

- **Physical protection of materials and the facility** (from both natural phenomena and human threats): USNRC regulations under 10 CFR 70.22(h) require the development of a physical security plan, a part of the licensing procedure. The 10 CFR 73.67, “Physical Protection of Special Nuclear Material of Moderate and Low Strategic Significance,” spells out the requirements for a Category II (CAT-II) facility. A CAT-II facility will need to be more robust to protect against the consequences of manmade threats such as a terrorist attack and against natural phenomena such as earthquakes, fires tornadoes, floods, and hurricanes.
- **Transportation of UF6 from the enricher to the fabrication plant**: Because of their large batch size present EUF6 shipping casks, such as the standard 30B cylinder, will not meet criticality safety requirements. A new HEUF6 shipping cask and overpack will need to be designed, tested, and certified for use on railcars and commercial highway transport. The 10 CFR 71, “Packaging and Transportation of Radioactive Nuclear Material,” covers the USNRC regulations for transportation. Co-location of the HALEU fuel fabrication facility with the HALEU enrichment facility would be desirable from the standpoint of eliminating transportation-related security and NIMBY (not-in-my-backyard) issues.
- **Transportation from the HALEU fuel fabrication plant to the reactor users**: the higher fissile content of the finished fuel bundles also will require shipping package redesign, testing, and certification.
- **Conversion of the HALEUF6 to the chemical form required to feed the fuel fabrication process (could be U-metal, U-metal alloys, or non-U02 ceramic forms such as UOC TRISO)**: the "front-end" processes in the HALEU fabrication plant may require significantly different conversion chemistry from today's semi-continuous "dry" UF6 to pellet-grade UOX powder process. Batch processes with smaller "in-process" inventories may be required, especially for metal HALEU fuels.
- All of the above factors will affect the recurring operations costs and ultimately the eventual decontamination and decommissioning (D&D) costs in addition to the front-end capital design and construction life-cycle costs.

# Appendix C3-2
# Material Balance and Value Balance Data for Cascades Discussed in Module C3

All of the centrifuge cascade figures and tables in the main part of this Module C3 required a material and "value" balance for calculation of annual uranium flowrates. The SWU calculation methodology and value-function algorithms for the tables below are described in Section 2.4 of ORNL/TM-2019/1311 ISPO-553: *Uranium Enrichment Plant Characteristics-A Training Manual for the IAEA* (Whitaker 2019). Each table assumes a product amount of 1 kg/yr, and the algorithms calculate the normalized amount of necessary feed (F), tails (waste or W), and SWUs necessary for the separation. By appropriate scaling of these normalized results, cascades can be interconnected so that the product of one cascade can become the feed for another. Multipliers on the normalized F/P, W/P, and SWU/P values in the tables can be used to design cascades for larger amounts of product, which will of course require more separative capacity (SWUs). Table AC3-2.1 is for a cascade (Figure C3.8) producing 6% U-235 "unencumbered" LEU plus for use in reactors where in-core TPBAR targets are irradiated for tritium production. Table AC3-2.2 is for two cascades (Figure C3.9a) where LEU Cascade 1 produces 4.95 % U-235 to be further enriched in Cascade 2 to 9.75% U-235 enhanced CAT-III HALEU. The third of the three small tables in Table AC3-2.2 shows how two linked cascades can be represented as a single cascade where the separative capacity is the sum of the individual separative capacities for Cascade 1 and Cascade 2. Table AC3-2.3 presents the same data for the authors' assumption of how the CENTRUS Pilot Cascade at Portsmouth, OH (Figure C3.12) is configured. Table AC3-2.4 is for two cascades (Figure C3.13a) where Enhanced HALEU Cascade 1 produces 9.75 % U-235 to be further enriched in Cascade 2 to 19.75% U-235 CAT-II HALEU. The third of the three small tables in Table AC3-2.4 shows how these two linked cascades can be represented as a single cascade where the separative capacity is the sum of the individual separative capacities for Cascade 1 and Cascade 2.

Table AC3-2.1. Material and value balance for designing centrifuge cascade depicted in Figure C3.8.

| NNSA UNENCUMBERED LEU ENRICHMENT PLANT | | | | |
|---|---|---|---|---|
| SWU Calculator for Figure C3-8 | | | | |
| P = Amount of Desired Product in kgU | 1 | | | |
| Tails Assay (% U-235) | 0.25 | % | (Value Fct. | 5.959 |
| Desired Product Enrichment (%U-235) | 6 | % | (Value Fct. | 2.421 |
| F/P ratio | 12.500 | | | |
| W/P ratio | 11.500 | | | |
| Feed Assay for Cascade (%U-235) | 0.71 | % | (Value Fct. | 4.87 |
| Total SWU/KgU product (SWU/P) | 10.070 | | | |

Table AC3-2.2. Material and value balance for designing centrifuge cascade depicted in Figure C3.9a and C3.9b.

| URANIUM ENRICHMENT PLANT | | | |
|---|---|---|---|
| SWU Calculator for Cascade 2 (CAT-III HALEU) | | | |
| Assay Data | %U-235 | Calculated value Functions | |
| Product assay | 9.75 | (Value Fct.) | 1.7914 |
| Feed Assay | 4.95 | (Value Fct.) | 2.6625 |
| Tails Assay | 0.711 | (Value Fct.) | 4.8689 |
| Material Balance Results from Value Balance | | | |
| F/P ratio (P=1) | 2.13 | | |
| W/P ratio | 1.13 | | |
| Total SWU/KgU product | 1.63 | | |

| URANIUM ENRICHMENT PLANT | | | |
|---|---|---|---|
| SWU Calculator for Cascade 1 (Conventional CAT-III LEU ) | | | |
| Assay Data | %U-235 | Calculated value Functions | |
| Product assay | 4.95 | (Value Fct.) | 2.6625 |
| Feed Assay | 0.711 | (Value Fct.) | 4.8689 |
| Tails Assay | 0.25 | (Value Fct.) | 5.959 |
| Material Balance Results from Value Balance | | | |
| F/P ratio (P=1) | 10.20 | | |
| W/P ratio | 9.20 | | |
| Total SWU/KgU product | 7.82 | | |

| URANIUM ENRICHMENT PLANT | | | |
|---|---|---|---|
| SWU Calculator for Combined Cascades (as if one cascade) | | | |
| Assay Data | %U-235 | Calculated value Functions | |
| Product assay | 9.75 | (Value Fct.) | 1.7914 |
| Feed Assay | 0.711 | (Value Fct.) | 4.8689 |
| Tails Assay | 0.25 | (Value Fct.) | 5.959 |
| Material Balance Results from Value Balance | | | |
| F/P ratio (P=1) | 20.61 | | |
| W/P ratio | 19.61 | | |
| Total SWU/KgU product | 18.30 | | |

Table AC3-2.3. Material and value balance for designing centrifuge cascade depicted in Figure C3.12.

| CENTRUS PILOT URANIUM ENRICHMENT CASCADE FOR HALEU | | | |
|---|---|---|---|
| **VALUE BALANCE & SWU Calculator** | | | |
| **Feed Assay to Enichmentr Plant (w/o U-235)** | **4.95** | (Value Fct. | 2.662 |
| **Tails Assay (w/o U-235)*** | **0.71** | (Value Fct. | 4.87 |
| **Desired Product Enrichment (w/o U-235** | **19.95** | (Value Fct. | 0.835 |
| **F/P ratio for enrichment** | **4.538** | | |
| **W/P ratio** | **3.538** | | |
| **Total SWU/KgU product** | **5.984** | | |

Table AC3-2.4. Material and value balance for designing centrifuge cascade depicted in Figure C3.13a and C3.13b.

| URANIUM ENRICHMENT PLANT | | | |
|---|---|---|---|
| **SWU Calculator for Cascade 2 (CAT-II HALEU)** | | | |
| | %U-235 | | |
| Product flow "P" in kgU/yr | 1 | | |
| Product assay | 19.75 | (Value Fct.) | 0.848 |
| Feed Assay | 9.75 | (Value Fct.) | 1.791 |
| Tails Assay | 0.71 | (Value Fct.) | 4.87 |
| F/P ratio | 2.106 | | |
| W/P ratio | 1.106 | | |
| Total SWU/KgU product | 2.463 | | |

| URANIUM ENRICHMENT PLANT | | | |
|---|---|---|---|
| **SWU Calculator for Cascade 1 (Conv. LEU & CAT-III HALEU)** | | | |
| | %U-235 | | |
| Product flow "P" in kgU/yr | 1 | | |
| Product assay | 9.75 | (Value Fct.) | 1.791 |
| Feed Assay | 0.71 | (Value Fct.) | 4.87 |
| Tails Assay | 0.25 | (Value Fct.) | 5.959 |
| F/P ratio | 20.652 | | |
| W/P ratio | 19.652 | | |
| Total SWU/KgU product | 18.315 | | |

| URANIUM ENRICHMENT PLANT | | | |
|---|---|---|---|
| **SWU Calculator for Combined Cascades as if One Cascade** | | | |
| | %U-235 | | |
| Product flow "P" in kgU/yr | 1 | | |
| Product assay | 19.75 | (Value Fct.) | 0.848 |
| Feed Assay | 0.71 | (Value Fct.) | 4.87 |
| Tails Assay | 0.25 | (Value Fct.) | 5.959 |
| F/P ratio | 42.391 | | |
| W/P ratio | 41.391 | | |
| Total SWU/KgU product | 41.038 | | |

Table AC3-2.5. Material and value balance for designing centrifuge cascades depicted in Figure C3.7.

| URANIUM ENRICHMENT PLANT | | | |
|---|---|---|---|
| | | | |
| SWU Calculator for Cascade producing 4.95% LEU from Natural feed UF6 ( P=1 kgU/yr) | | | |
| | **%U-235** | | |
| Product assay | **4.95** | (Value Fct.) | 2.66247 |
| Feed Assay | **0.71** | (Value Fct.) | 4.87038 |
| Tails Assay | **0.25** | (Value Fct.) | 5.95902 |
| **F/P ratio** | **10.217** | | |
| **W/P ratio** | **9.217** | | |
| **Total SWU/KgU produ** | **7.826** | | |

| URANIUM ENRICHMENT PLANT | | | |
|---|---|---|---|
| | | | |
| SWU Calculator for Cascade producing 9.75% LEU from Natural feed UF6 ( P=1 kgU/yr) | | | |
| | **%U-235** | | |
| Product assay | **9.75** | (Value Fct.) | 1.79138 |
| Feed Assay | **0.71** | (Value Fct.) | 4.87038 |
| Tails Assay | **0.25** | (Value Fct.) | 5.95902 |
| **F/P ratio** | **20.652** | | |
| **W/P ratio** | **19.652** | | |
| **Total SWU/KgU produ** | **18.315** | | |

# Appendix C3-1 References

U.S. Nuclear Regulatory Commission. 2010. NUREG 1520 rev 1; "Standard Review Plan for the Review of a License Application for a Fuel Cycle Facility – Final Report NUREG-1520, Revision 1." https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1520/r1/index.html.

U.S. Nuclear Regulatory Commission. 2022. Draft NUREG-2159; "Acceptable Standard Format and Content for the Fundamental Material Control and Accounting Plan Required for Special Material of Moderate Strategic Significance – Final Report (NUREG-2159, Revision 1)." https://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr1520/r1/index.html.

# Appendix C3-2 References

(Whitaker 2019) Whitaker, J. M. 2019. "Uranium Enrichment Plant Characteristics-A Training Manual for the IAEA." ORNL/TM-2019/1311 ISPO-553, Oak Ridge National Laboratory. https://info.ornl.gov/sites/publications/Files/Pub132067.pdf.