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OAK RIDGE
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LOCKHEED MARTIN

Availability of Uranium Feed for the Fissile Materials Disposition Program

Volume 1 : Depleted Uranium Hexafluoride

V. S. White

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AVAILABILITY OF URANIUM FEED FOR THE FISSILE MATERIALS DISPOSITION PROGRAM

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Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37831-6285
managed by
LOCKHEED MARTIN ENERGY RESEARCH CORP.
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ACRONYMS

ADU	ammonium diuranate
AEA	Atomic Energy Act of 1954
AHF	anhydrous hydrogen fluoride
ANL	Argonne National Laboratory
ANSI	American National Standards Institute
ARIES	Advanced Recovery and Integrated Extraction System
ASME	American Society for Mechanical Engineers
ATR	Advanced Test Reactor
AUC	ammonium uranyl carbonate
B&W	Babcock & Wilcox
CFR	*Code of Federal Regulations*
DNFSB	Defense Nuclear Facilities Safety Board
DOE	U.S. Department of Energy
DOE–EH	DOE Office of Environment, Safety and Health
DOE–EM	DOE Office of Environmental Management
DOE–MD	DOE Office of Fissile Materials Disposition
DOE–NE	DOE Office of Nuclear Energy, Science, and Technology
DOT	U.S. Department of Transportation
EIS	environmental impact statement
EPA	U.S. Environmental Protection Agency
EPACT	Energy Policy Act of 1992
FMDP	Fissile Materials Disposition Program
FY	fiscal year
GDP	gaseous diffusion plant
HaMTES	Hazardous Material Transportation Expert System
HazMAT	hazardous materials
HF	hydrogen fluoride (hydrofluoric acid)
HS&E	health, safety, and environmental
HVAC	heating, ventilation, and air conditioning
IAEA	International Atomic Energy Agency
IDR	integral dry route
INEEL	Idaho National Engineering and Environmental Laboratory
LANL	Los Alamos National Laboratory
LEU	low-enriched uranium
LLNL	Lawrence Livermore National Laboratory
LLW	low-level waste
LWR	light-water reactor
MIN	Materials in Inventory Initiative
MOX	mixed oxide
MT	metric tons
NEPA	National Environmental Policy Act of 1969
NOI	Notice of Intent
NRC	U.S. Nuclear Regulatory Commission
O&M	operations and maintenance
ORNL	Oak Ridge National Laboratory
PEIS	programmatic environmental impact statement
Q-CEP	Quantum-Catalytic Extraction Process
R&D	research and development
RCRA	Resource Conservation and Recovery Act of 1976
ROD	Record of Decision
SAIC	Science Applications International Corporation

TIGR	Thermally Induced Gallium Removal
USEC	United States Enrichment Corporation

AVAILABILITY OF URANIUM FEED FOR THE FISSILE MATERIALS DISPOSITION PROGRAM

VOLUME I: DEPLETED URANIUM HEXAFLUORIDE

V. S. White

ABSTRACT

Uranium dioxide (UO_2) powder makes up more than 95 wt % of the feedstock needed for the domestic mixed-oxide (MOX) fuel fabrication facility to be constructed by the U.S. Department of Energy's (DOE's) Fissile Materials Disposition Program (FMDP) as part of its "dual-path" plutonium disposition strategy. The needed uranium feed can be derived from natural or depleted uranium compounds. This first volume considers domestic sources of depleted urania in the form of uranium hexafluoride (UF_6). Depleted UF_6, a by-product of the uranium enrichment process, is now stored primarily in solid form in 14-ton cylinders located at the three U.S. gaseous diffusion plant sites. The FMDP's depleted UF_6 requirements are a very small fraction (less than 0.3%) of the total depleted UF_6 available. More problematical is the need for a facility to convert the depleted UF_6 to a stable, high-quality depleted UO_2 powder.

This first volume in a series of reports on FMDP urania feed materials discusses the UF_6 storage site inventories, cylinder conditions, and transportation/regulatory issues in detail. A generic discussion of issues associated with the chemical conversion of depleted UF_6 to depleted UO_2 powder is also included.

The purpose of this document is to support the DOE's FMDP procurement activity for the reactor-based MOX option. This report is one of several topical reports generated to provide background information on various subjects related to manufacturing and burning MOX fuel. Because the uranium component of MOX is 95% or more of the fuel materials, this document provides information on the uranium source inventory and subsequent handling and processing of uranium feed. This volume assumes the use of depleted uranium as the diluent for the weapons-grade plutonium. Companion reports to this report may deal with the use of natural uranium and different chemical forms of depleted uranium.

1. OVERVIEW

The U.S. Department of Energy (DOE) currently owns more than 500,000 metric tons (MT) of uranium inventory in the chemical form of depleted uranium hexafluoride (UF_6) resulting from historical uranium enrichment activities at the U.S. gaseous diffusion complexes. This is approximately equivalent to 385,000 MT of depleted uranium dioxide (UO_2). Between 5 and 10 kg of depleted uranium were historically produced for each kilogram of reactor-grade, enriched uranium product as a result of the low initial concentration of ^{235}U in the uranium feed input to the process and the depleted or tails material selected to remain following enrichment operations. The gaseous diffusion process separates isotopes according to atomic weight by processing through multistage converters housing the porous diffusion barrier. During processing, the lighter uranium isotopes in UF_6 are separated to increase the concentration of ^{235}U.

Natural uranium consists of 0.006 wt % ^{234}U, 0.711 wt % ^{235}U, and the majority as ^{238}U. The fissile isotope is ^{235}U; uranium is considered depleted if the total ^{235}U content is less than 0.711 wt % as found in nature. The percentage composition, referred to as assay, of low-enriched uranium (LEU) necessary for controlled fission in nuclear power reactors is 1.8 to 5.0 wt % ^{235}U; the average composition of ^{235}U in depleted uranium is 0.20 wt %.

Resulting from a combination of changes in DOE's nuclear materials and weapons programs, decreasing federal budgets, and the enactment of the Energy Policy Act (EPACT) of 1992, DOE is reviewing options for disposition of depleted UF_6 resulting from historical, civilian and military nuclear power operations. Among other requirements, EPACT instructed DOE to (1) perform a comprehensive inventory of all DOE-owned uranium, including depleted material, and (2) determine the availability of conversion services and possible commercial uses with recommendations for disposition of such inventories. DOE's Depleted UF_6 Management Program is developing a programmatic environmental impact statement (PEIS) to fulfill these mandates. The PEIS consists of five steps:

1. Data and information gathering through the process of requesting recommendations.
2. Review and acceptance of recommendations.
3. Preparation of the draft environmental impact statement (EIS).
4. Receipt and resolution of comments received on the draft EIS.
5. Preparation of the final EIS followed by the Record of Decision (ROD).

On November 10, 1994, DOE requested recommendations[1] for potential management, strategies, and uses of depleted UF_6. The Notice of Intent (NOI) to prepare the EIS was published in the *Federal Register* on January 25, 1996.[2] DOE's Depleted UF_6 Management Program under the Office of Nuclear Energy, Science, and Technology (DOE–NE) is reviewing the recommendations for conversion processes, uses, storage options, disposal alternatives, transportation/packaging issues, and potential environmental impacts. The first phase of the PEIS will result in a strategy selected for implementation. The second phase will be project specific, incorporating site assessments, particular transportation issues relative to the site(s), and construction and operation decisions. The final EIS will contain the selected alternative(s) for cylinder disposition.

Even though depleted UF_6 is the tails stream from the enrichment process, it is a by-product that is not considered waste. Section 11(z) of the Atomic Energy Act (AEA) of 1954, in concurrence with the Nuclear Regulatory Commission (NRC) in the *Code of Federal Regulations* (10 CFR 40.4), defines uranium in any physical or chemical form as source material. The AEA further defines depleted uranium as source material uranium with less than 0.711 wt % ^{235}U, thus excluding it from jurisdiction under the U.S. Environmental Protection Agency (EPA) and the Resource Conservation and Recovery Act (RCRA) of 1976 regulations. DOE management of depleted uranium by DOE–NE is not under the control of EPA or any other government agency.

The fluoride portion of depleted UF_6, once separated, is a RCRA-regulated material. RCRA Section 3001 authorizes the EPA to regulate the identification and listing of hazardous wastes according to toxicity, persistence, natural degradation, health impacts from accumulation in tissue, flammability, corrosiveness, and other potential hazards. Furthermore, RCRA Section 3004(a) authorizes EPA to regulate the storage, treatment, or disposal of hazardous wastes identified under Section 3001.

Urania constitutes 95% or more of mixed-oxide (MOX) fuel. The other component of MOX, plutonium, is composed primarily of the ^{239}Pu and ^{240}Pu isotopes and is classified in three basic grades, for use in (1) weapons (7.0 wt % or less ^{240}Pu content), (2) breeder reactors (7.0 to 19.0 wt % ^{240}Pu content), and (3) light-water reactors (LWRs) (greater than 19.0 wt % ^{240}Pu content). Approximately 38.2 MT of weapons-quality plutonium (plutonium of 93.0 wt % ^{239}Pu or greater) has been declared surplus to defense program requirements. Additional quantities of weapons plutonium may become surplus in the future.[3]

DOE's Office of Fissile Materials Disposition (DOE–MD) is currently beginning implementation of options for disposing of weapons-program plutonium that is surplus to national defense requirements based on the *U.S. Nonproliferation and Export Control Policy*[4] and the *Joint Statement Between the United States and Russia on Nonproliferation of Weapons of Mass Destruction and Means of Their Delivery.*[5] These policies focus on five primary efforts:[6]

- security of nuclear materials located in the former Soviet Union,
- long-term, safeguarded storage and disposition of surplus fissile materials,
- nuclear arms reductions that are transparent and irreversible,
- stronger nuclear nonproliferation actions, and
- control of nuclear material exports.

Diluting surplus plutonium with DOE-owned depleted uranium for use as LWR fuel is one of two disposition alternatives being pursued as part of the Fissile Materials Disposition Program's (FMDP's) "dual-path" strategy. The plutonium would be the primary fissile material (5% or less of the contents) combined with depleted uranium to produce MOX fuel for commercial reactors. This approach provides a feasible solution that accomplishes the plutonium disposition mission and affords the Depleted UF_6 Management Program a disposal method for some depleted uranium for which there are few designated uses.[7] Depending on the selection of alternatives for cylinder disposition, the future availability of feed obtained from DOE-owned depleted UF_6 is an unknown factor.

The plutonium composition subsequent to usage as fuel would be elevated in ^{238}Pu (1.5 wt %), ^{240}Pu (2.2 wt %), ^{241}Pu (13.5 wt %), and ^{242}Pu (5.0 wt %) and rendered less reactive and more difficult to handle than weapons plutonium. While disposition of plutonium as MOX fuel in commercial LWRs does not destroy a high percentage of plutonium, fuel irradiation results in increased radioactivity of fission products that, coupled with the fabricated assembly form containing the material, minimizes the potential for unauthorized removal of plutonium from the reactor or repository site.

The primary steps involved in using the depleted UF_6 resulting from the enrichment process as feed-stock in the chemical form of depleted UO_2 for the weapons-grade plutonium are as follows:

1. selecting and retrieving the cylinders from their storage location;
2. transferring depleted UF_6 to transportable cylinders of acceptable size for the conversion facility if current cylinders are unsatisfactory for either transportation or feeding, including purchasing new cylinders and contracting with the United States Enrichment Corporation (USEC) for cylinder emptying if necessary;
3. inspecting and certifying cylinders for shipping;
4. preparing cylinders for transport by inserting the cylinder into an approved overpack or fitting with a valve protector and loading onto the transportation source (truck or train);
5. transportation, including unloading functions, by road or rail service from current location (Paducah, Kentucky; Portsmouth, Ohio; or Oak Ridge, Tennessee) to a commercial facility or DOE site housing the conversion or MOX facility. [The Hanford Reservation, Idaho National Engineering and Environmental Laboratory (INEEL), Pantex, and Savannah River sites are under consideration for the MOX facility];
6. transferring the depleted UF_6 to the receiving and storage facility at the conversion facility;
7. converting the depleted UF_6 to depleted UO_2 by commercial converter with approved environmental permits and licenses. Alternatives to existing domestic commercial conversion consist of (1)construction of domestic, commercial facility; (2)construction of DOE/private industry joint venture facility; and (3) initially contracting with Europeans for depleted UF_6 conversion services while awaiting construction of domestic facility;
8. preparing depleted UO_2 powder for blending process; this step involves (1) filling clean containers for transporting to MOX facility if not collocated with conversion facility; (2) transporting, including loading and unloading functions, to the DOE site housing the MOX facility if not collocated with conversion facility; and (3) transferring materials accountability to MOX facility;
9. transferring depleted UO_2 to the receiving and storage facility at the MOX facility; and
10. adhering to EPA and RCRA approved disposal methods for wastes generated.

In summary, DOE owns surplus depleted UF_6 that could be used as feed with plutonium for a MOX facility. It is unknown which alternative(s) for depleted UF_6 disposition will be selected. The recommendation from the National Research Council in 1996 was "… if consistent with the prioritized cost- and risk-reduction process, *the depleted UF_6 should be converted to the more stable chemical form*, U_3O_8, for storage and disposal."[8]

This report is in concurrence with the National Research Council. The only additional recommendation from the FMDP would be the **possible conversion of sufficient quantities of depleted UF_6 to the chemical form of depleted UO_2 to accomplish the requirements of both DOE programs simultaneously.**

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2. DEPLETED URANIUM INVENTORY

The majority of the most easily accessible and convertible depleted uranium is in the form of 99.9% pure UF_6 stored at the two operating gaseous diffusion plants (GDPs) in Paducah, Kentucky, and Portsmouth, Ohio, and at the former Oak Ridge GDP (K-25 Site) on the Oak Ridge Reservation in Tennessee.[9] The K-25 Site was renamed the East Tennessee Technology Park on February 21, 1997. However, the facility will be referred to as the K-25 Site in this report. Depleted UF_6 is stored primarily in 14-MT cylinders. A discussion on depleted UF_6 cylinders is provided in Chap. 3 of this report.

The majority of the government-owned inventory of depleted UF_6 is stored at the Paducah GDP. The Paducah plant was designated to produce the lower assay (maximum 2.75 wt % ^{235}U) feed for the Portsmouth GDP and the now shutdown Oak Ridge GDP (K-25 Site) on the Oak Ridge Reservation. Assays required for nuclear reactor LEU fuel range up to 5.0 wt %; and due to the nature of operations, the Paducah GDP produced the bulk of the depleted UF_6. The percentage composition of ^{235}U contained in the depleted UF_6 ranges from ~0.1 wt % to natural at all three sites.

Although depleted UF_6 is not a waste material, it is the tails stream or by-product of the gaseous diffusion process in which uranium is elevated in ^{235}U content for use in fabricating nuclear reactor fuel. The UF_6 is composed of uranium and fluorine and can be solidified from a gaseous phase through desublimation or from the liquid state by lowering the temperature to less than 64.2°C. In solid form, UF_6 takes on the appearance of white, opaque crystals similar to rock salt at normal atmospheric pressure conditions and temperature less than 56°C.[10] Water is a reactant for both the vapor, liquid, and solid phases, and care is taken to avoid inadvertent contact with moisture. The UF_6 is stable up to relatively high temperatures. The UF_6 is heated and usually liquefied to provide gas feed to a diffusion cascade. In storage at ambient temperatures, it is a solid with a vapor pressure below atmospheric pressure.

Depleted UF_6 is stored and transported in metal cylinders of differing sizes directly related to the physical quantities and ^{235}U enrichment levels involved. Oversight of depleted UF_6 by the DOE–NE consists of complying with all applicable orders, laws, and regulations to ensure that nuclear materials safeguards, control, and accountability measures are followed. Regulations and policies pertinent to depleted UF_6 are listed in Chap. 8 of this report.

The current DOE depleted UF_6 inventory is summarized in Table 1. Nearly 68% of the 503,000 MT of DOE-owned depleted UF_6 is stored at DOE's Paducah GDP in Kentucky. The combination of inventory at the two operating plants at Paducah and Portsmouth approaches 90% of the total.

The operating GDP facilities are currently leased by the USEC and operated by Lockheed Martin Utility Services, Inc. After passage of EPACT, which mandated that the enrichment enterprise would be commercialized, USEC took over enrichment operations on July 1, 1993, as a government corporation to eventually become private. The privatization process is currently under way. The USEC Privatization Act of 1996, part of the Omnibus Consolidated Recessions and Appropriations Act of 1996, provides that the liabilities associated with the disposal of all depleted UF_6 produced after July 1, 1993, but prior to the date of privatization, shall also be the responsibility of DOE.[11] Depleted UF_6 generated by USEC operations is not included in Table 1.

Table 1. Total inventory of DOE-owned depleted UF_6 as of February 24, 1997 (MT of UF_6)

Assay range (%)	Oak Ridge K-25 Site	Paducah GDP	Portsmouth GDP	Total inventory
0.001 < 0.30	53,315	203,165	52,020	308,500
0.30 < 0.36	793	103,910	55,335	160,038
0.36 < 0.41	168	14,869	505	15,542
0.41 < 0.46	8	16,479	71	16,558
0.46 < 0.711	12	1,678	722	2,412
Total	54,296	340,100	108,653	503,049

More than 60% of the total depleted UF_6 inventory contains ^{235}U assays of less than 0.30 wt %. According to the National Research Council in its response to DOE's request for a cost reduction study relative to decontamination and decommissioning of the GDPs, ~33% of the inventory is at assays less than 0.21 wt %.[8] Depleted UF_6 assays relate to the operations tails assay stream used during the historical DOE enrichment operations. Table 2 provides greater detail relative to types, quantities, and availability of cylinders used for storage.

"Readily Available" implies ease of removal from storage, contents filled at less than maximum levels, and in transportable condition. Of the 36,500 MT readily available for conversion, nearly 90% has weighted assays less than 0.30 wt %. The 0.46–0.710 wt % and the 0.30–0.36 wt % ranges are ~6% and 4% of the readily transportable depleted UF_6, respectively. Even though the largest amount of DOE-owned depleted UF_6 is stored at the Paducah GDP, ~75% of the *available* material is at the Portsmouth GDP.

Table 3 provides the depleted UO_2 equivalencies for the government-owned depleted UF_6 inventories. Approximately 28,000 MT depleted UO_2 could be converted from the readily available cylinders with a total of more than 385,000 MT potentially available. Assuming a 5.0 wt % fissile composition, the readily available cylinders contain sufficient inventory to accomplish a blend ratio of 1 part plutonium to 20 parts depleted uranium. A 50-MT plutonium program would require ~1000 MT depleted uranium, equating to 1135 MT depleted UO_2 or slightly less than 1500 MT depleted UF_6. Less than 3% of the readily available depleted UF_6 would be required for blending the presently identified weapons program surplus of 38.2 MT plutonium. Cylinders are available for shipping from any of the three locations. The contents may need to be transferred to other cylinders at one of the operating GDPs before transporting to the conversion facility because of cylinder condition or failure to meet shipping criteria.

Several UF_6 cylinder disposition alternatives are under review by DOE's Depleted UF_6 Management Program. These are summarized in Chap. 3 of this report. The option relative to this report relates to blending depleted UF_6 with surplus weapons-quality plutonium to produce enriched material for fabrication into nuclear reactor fuel.

There are additional depleted uranium inventories at several government sites in forms of alloyed and unalloyed metals, oxides, nitrates, hydrides, and aqueous solutions. Many of these quantities have classified histories and may have undesirable chemical compositions because of their origination in either weapons production or dismantlement. For example, depleted UF_6 from the GDPs was shipped to the Fernald Facility in Ohio and converted into metal, which was subsequently transported to the Oak Ridge Y-12 Plant in Tennessee for weapons component production. The forms of Fernald and Y-12 Site inventories are not as UF_6. Total Fernald depleted uranium inventory quantities can be found in Ref. 12 with additional background in Ref. 13. The depleted uranium inventory at the Y-12 Plant is classified "Confidential–Restricted" and is not available to the general public for review.

Even through inventories have routinely been classified at most weapons facilities, facilities no longer in production mode are releasing inventory data subsequent to the U.S. Department of Energy Openness Initiative.[3] An example of one weapons facility releasing data is the Rocky Flats Plant near Denver, Colorado, which reports 262 MT depleted uranium in various forms remaining at its facility.[14] Additional sources of depleted uranium may be located at other weapons facilities and national laboratories.

National laboratories have inventories resulting from research experiments and isotope production. Because this report does not examine the feed potential of depleted uranium forms other than UF_6, individual government-site inventories have not been requested and are not provided in this report. The exception is the Oak Ridge National Laboratory's (ORNL's) inventory, contained in *Materials in Inventory: Depleted Uranium,*[15] which details all Oak Ridge Reservation depleted inventories. ORNL's depleted uranium inventory was assessed by the DOE Materials in Inventory Initiative (MIN) along with inventories at the enrichment complex and the K-25 Site. These other chemical forms of depleted uranium are not discussed further in this report.

Table 2. Inventory of DOE-owned depleted UF_6 as of February 24, 1997

		Oak Ridge K-25 Site				Paducah GDP				Portsmouth GDP				Total	
Assay range[a]	Cylinder model[b]	Number of cylinders	Total (MT)	Readily available (%)	Readily available MT	Number of cylinders	Total (MT)	Readily available (%)	Readily available (MT)	Number of cylinders	Total (MT)	Readily available (%)	Readily available (MT)	Readily available (Cylinders)	Readily available (MT)
0.000010	12A	30	5	0.0	0	4	0	0.0	0	0	0	0.0	0	0	0
–0.002999	30A	14	14	100.0	14	1,634	3,693	32.5	1,136	6	8	100.0	8	551	1,159
	48A	2	20	0.0	0	10	88	10.0	1	6	57	50.0	27	4	28
	48G	146	1,770	98.6	1,745	4,942	62,102	3.2	1,453	1,945	24,245	100.0	24,245	2,249	27,443
	48HI	0	0	0.0	0	0	0	0.0	0	1	12	0.0	0	0	0
	48O	172	2,162	0.0	0	4,417	56,097	0.0	20	85	1,077	1.2	12	3	31
	48OHI	0	0	0.0	0	1	12	0.0	0	0	0	0.0	0	0	0
	48OM	2,818	35,347	6.4	2,132	5,717	72,468	0.9	599	4,108	5,206	1.2	569	281	3,300
	48T	1,442	13,997	2.4	323	503	4,922	0.2	0	2,096	21,394	1.9	363	75	687
	48X	0	0	0.0	0	8	66	37.5	18	2	20	0.0	0	3	18
	Other	0	0	0.0	0	287	3,716	0.0	0	0	0	0.0	0	0	0
Range subtotal		4,624	53,315	8.1	4,214	17,523	203,165	4.3	3,227	8,249	52,020	24.8	25,224	3,166	32,665
0.003000	30A	1	1	100.0	1	0	0	0.0	0	0	0	0.0	0	1	1
–0.003599	48A/X	0	0	0.0	0	2	19	100.0	19	0	0	0.0	0	2	19
	48G	45	547	33.3	173	6,599	83,641	0.1	64	4,378	54,583	1.4	733	81	970
	48H	0	0	0.0	0	1	13	0.0	0	0	0	0.0	0	0	0
	48O/OM	15	180	100.0	180	1,583	20,028	0.0	0	61	752	44.3	320	42	500
	48T	7	65	100.0	65	15	148	0.0	0	0	0	0.0	0	7	65
	48Y	0	0	0.0	0	5	61	0.0	0	0	0	0.0	0	0	0
Range subtotal		68	793	55.9	419	8,205	103,910	0.1	83	4,439	55,335	2.0	1,053	133	1,554
0.003600	30A	3	3	100.0	3	1	0	100.0	0	0	0	0.0	0	4	3
–0.004099	48G	6	71	100.0	71	1,026	13,005	0.0	0	599	417	0.2	12	7	83
	48O/OM	8	94	100.0	94	147	1,864	0.0	0	7	88	14.3	12	9	106
Range subtotal		17	168	100.0	168	1,174	14,869	0.1	0	606	505	0.3	24	20	192
0.004100	30A	2	2	100.0	2	0	0	0.0	0	0	0	0.0	0	2	2
–0.004599	48G	1	6	100.0	6	1,190	15,084	0.0	0	6	62	0.0	0	1	6
	48O/OM	0	0	0.0	0	112	1,395	0.0	0	1	9	100.0	9	1	9
Range subtotal		3	8	100.0	8	1,302	16,479	0.0	0	7	71	14.3	9	4	17
0.004600	30A	1	2	100.0	2	10	2	100.0	2	0	0	0.0	0	11	4
–0.007100	48A/X	1	9	100.0	9	3	23	100.0	23	0	0	0.0	0	4	32
	48G	1	1	100.0	1	20	248	30.0	72	7	86	14.3	12	8	85
	48O/OM	1	0	100.0	0	65	731	100.0	731	3	38	0.0	0	66	731
	48Y	0	0	0.0	0	55	674	100.0	674	48	598	100.0	598	103	1,272
Range subtotal		4	12	100.0	12	153	1,678	90.8	1,502	58	722	84.5	610	192	2,124
Grand total		4,716	54,296	9.1	4,821	28,357	340,100	3.0	4,811	13,359	108,653	13.4	26,920	3,515	36,552
Average assay					0.00197				0.00189				0.00213		0.00208

[a]In addition, a total of 3 MT with assays between 0.0030 end 0.0071 are available in 12-in. cylinders at the three sites.
[b]"Cylinder Model—Other" are 12.8-, 17-, and 19-ton cylinders fabricated from converter shells (not ANSI-approved cylinders).
Source: "UF_6 Cylinder Location, Inspection, and Management (UCLIM) Database," 3-Site UF_6 Cylinder Program, February 24, 1997.

Table 3. Depleted UO_2 equivalent inventory of DOE-owned depleted UF_6 as of February 24, 1997 (MT of UO_2)

	Oak Ridge K-25 Site		Paducah GDP		Portsmouth GDP		Equivalent inventory	
Assay range (%)	Total	Readily available	Total	Readily available	Total	Readily available	Total	Readily available
0.001 < 0.30	40,898	3,233	155,849	2,475	39,905	19,349	236,652	25,057
0.30 < 0.36	608	321	79,710	63	42,448	808	122,766	1,192
0.36 < 0.41	129	129	11,406	0	387	18	11,923	148
0.41 < 0.46	6	6	12,641	0	54	7	12,702	13
0.46 < 0.711	9	9	1,287	1,152	554	468	1,850	1,629
Total	41,651	3,698	260,893	3,691	83,349	20,650	385,892	28,039

3. DEPLETED UF_6 STORAGE CYLINDERS AND TRANSPORTATION TO CONVERSION FACILITY

The storage media for the majority of depleted UF_6 are 14-ton, thin-walled (5/16-in. wall thickness), carbon steel cylinders, 4 ft in diameter, 12 ft in length, and designed for 100-psig service pressure rating.[10] Each cylinder is filled with ~12 MT depleted UF_6. The models in this classification are the 48G, 48H, 48X, 48O, and 48OM.[16] Most older models are thick-walled (5/8-in. wall thickness) with 10-MT capacity. Depleted UF_6 in solid form is stored in enclosed yards at the K-25 Site, Paducah GDP, and Portsmouth GDP within security fenced areas. Because consideration must be given to chemical compositions and radiological activity, storage yards are typically located a distance from activities with human involvement at the site.

Cylinders used for storage and transportation of depleted UF_6 must meet American National Standards Institute (ANSI) requirements. In addition, depleted UF_6, relative to the quantity and assay involved, is packaged, transported, and stored in cylinders adhering to regulations and policies provided in the various publications listed in Chap. 8 of this report. Depleted UF_6 packaging, labeling, and transportation regulations have been incorporated in CFR Title 49. The U.S. Department of Transportation (DOT) Research and Special Program Administration is responsible for maintaining and requiring adherence to these policies. According to the Ultimate Disposition of Depleted Uranium Task team, more than 60% of the depleted UF_6 cylinders are approved for transport by DOT. The remaining cylinders either have not been evaluated or have contents that would require transfer to approved cylinders prior to shipment.

Cylinders must be identified by manufacturer, serial number, certified filling limit, tare weight, maximum working pressure and temperature, and date of most current hydrostatic inspection. Precise materials accountability and status are maintained for each cylinder with ongoing inspection programs. Cylinders are moved on-site through use of a cylinder handler (either a straddle buggy or NCH-35), which drives over a cylinder, picks up the cylinder, and moves it to a different location. Figures 1 and 2 are pictures of a straddle buggy and NCH-35, respectively.

A cylinder is considered overfilled if, when heated, the contents expand such that the gas volume is less than 5%. Prior to 1986, maximum limits for filling cylinders were specified by the DOE Oak Ridge Operations Office in ORO-651[10] and in ANSI 14.1[17] as 61% for all cylinders except Model 48G, whose limit is 63.4%. In 1987, following an accident involving a ruptured cylinder, CFR Title 49 was modified to fill limits of 62% for all cylinders being transported. In most cases, cylinders prior to 1987 are filled above the current standards. Less than 8% of depleted UF_6 cylinders have met the standards under the revised DOT guidance in 49 CFR 173.474 and 49 CFR 173.475. Requests for exemption from transportation regulations from the DOT can and have been made for cylinders that have contents filled in excess of specifications. An overfilled cylinder may be safely emptied to meet standards by vacuum transfer of the overfilled amount. If the cylinder is acceptable in all other regards, it would then be transportable.

It should be recognized that some cylinder models have higher certified volumes than ANSI regulations. This higher volume may result in cylinders being described as overfilled when, in fact, they are not. The ANSI fill limits are based on liquid filling at 250°F. The GDPs routinely fill cylinders at 235°F, which serves to increase the capacity limit.

Table 2 provides an inventory report as of February 24, 1997, classifying the depleted UF_6 by physical location, cylinder type, quantity of cylinders, readily available material, and assay. Readily available implies those cylinders that have the following characteristics: (1) easily accessible from storage, (2) having appropriate fill levels, and (3) in relatively good physical condition for transportation. According to *Depleted Uranium: A DOE Management Challenge*,[9] the cost of storage and cylinder maintenance is approximately $10 million a year. Depleted UF_6 disposition alternatives are estimated to range in cost to more than $11 billion.

Table 4 provides a listing of DOE-owned cylinders. The majority are Models 48G and 48OM. Procedures for handling and shipping cylinders, physical descriptions, and volume and weight limits can be found in Ref. 18. Cylinders must be identified by manufacturer, serial number, certified filling limit, tare weight, maximum working pressure and temperature, and date of most current hydrostatic inspection. Precise materials accountability and status is maintained for each cylinder with ongoing inspection programs.

Fig. 1. Straddle buggy moving a 14-ton UF_6 cylinder.

Fig. 2. NCH-35 14-ton nuclear cylinder handler.

Table 4. DOE-owned depleted UF_6 cylinders as of February 24, 1997

Cylinder model	Total cylinders	Number available for transport	Diameter (in.)	Weight limit (MT)
12A	34	0	12	0.209
30A	1,672	569	30	2.245
48A	18	4	48	9.539
48A/X	6	6	48	9.539
48G	20,911	2,346	48	12.174
48H	1	0	48	12.261
48HI	1	0	48	N/A
48O	4,674	3	48	12.261
48OHI	1	0	48	N/A
48OM	12,643	281	48	12.261
48O/OM	2,003	118	48	12.261
48T	4,063	82	48	12.261
48X	10	3	48	9.539
48Y	108	103	48	12.501
Other	287	0	N/A	N/A
Total	46,432	3,515		

In addition to the cylinders listed in Table 4, there are more than 3,500 "empty" cylinders containing residual quantities after the cylinders were emptied, bringing the total to 50,000. The quantities remaining in the cylinders are referred to as "heels."

Depleted UF_6 reacts with moisture in air, and, as with any sealed container, cylinders can develop problems during handling or with age. A cylinder breach results in the formation of hydrofluoric acid (HF) and solid uranyl fluoride (UO_2F_2) if the contents come in contact with moist air. Breaks rectify themselves through a self-seal process. When negative pressure allows air into the rupture, the UO_2F_2 fills and closes the opening. Patches secured with metal bands around the cylinder are used to fortify the weakened areas of the cylinder.

Cylinders must comply with strict design, fabrication, and certification standards and regulations. Currently, transportation by truck or train can occur once depleted UF_6 is solidified with a vapor pressure less than atmospheric. For general information and a better appreciation of the size of cylinders, Fig. 3 captures the loading of a depleted UF_6 cylinder onto a truck flatbed for highway movement, and Fig. 4 shows cylinders being readied for rail transportation.

Beginning as early as 2001, depleted UF_6 cylinders must comply with International Atomic Energy Agency (IAEA) safety standards,[19] which include thermal, pressure, and drop tests, as summarized below. This change in compliance results from increased concern over chemical hazards rather than radiological problems.

- Cylinders designed to contain 0.1 kg or more of UF_6 must meet structural, thermal, and containment tests specified by the International Organization for Standardization.
- Cylinders designed to contain 0.1 kg or more of UF_6 cannot have pressure relief valves.
- Subject to approval, cylinders designed to contain 0.1 kg or more of UF_6 may be transported if they meet the above requirements and can pass a pressure test without leaking or showing unacceptable stress.

The majority of DOE cylinders, which are thin-walled models with structural degradation, will not pass the testing requirements. Even though the cylinders will not meet the IAEA regulations in their current conditions, they could be placed in approved overpacks meeting specifications. An overpack designed to accommodate cylinder models 48G, 48X, and 48Y has been proposed to DOE by the ORNL Transportation Technologies Group[20] for moving four breached cylinders from the K-25 Site to the Paducah GDP where

Fig. 3. Loading cylinder onto flatbed truck at K-25 Site on Oak Ridge Reservation.

Fig. 4. Cylinders being prepared for rail transportation at K-25 Site on Oak Ridge Reservation.

the contents could be safely transferred to other cylinders. This design complies with ANSI N14.1[17] and the American Society for Mechanical Engineers (ASME) guidance in ASME NQA-1.[21] The overpack could be handled and transported, meeting operational requirements, the same as if the cylinder were new. The design allows for UF_6 removal by vaporization with steam or electrically heated air or through liquid transfer using existing equipment. If the proposal is accepted, this overpack will meet IAEA regulations.[19]

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4. DEPLETED UF_6 TO UO_2 CONVERSION PROCESS

For the purposes of the MOX fabrication plant acquisition strategy and conceptual design, it is assumed that the MOX fabrication facility will receive a dry, free-flowing depleted or natural UO_2 powder capable of being readily blended with a PuO_2 powder. The PuO_2 will be derived from a hydride process such as the Advanced Recovery and Integrated Extraction System (ARIES)/Thermally Induced Gallium Removal (TIGR). This report considers the use of depleted UO_2 as blend stock.

As stated earlier, most DOE and commercial depleted uranium is in the form of UF_6, metal, or UO_3. No commercial or DOE materials inventories contain the 1000 MT uranium or more of high-quality depleted UO_2 powder needed for the MOX plutonium disposition mission. [This report does not consider the near-term problem of providing UO_2 blend stock for the MOX test rods required for irradiation in the INEEL Advanced Test Reactor (ATR).] The challenge for FMDP is to provide assurance to potential consortium bidders that a depleted UF_6 to depleted UO_2 conversion service or facility will be available in a few years to meet this need.

In the LEU fuel cycle, the word "conversion" usually refers to the process of transforming natural uranium ore concentrates or "yellowcake" to natural UF_6. This UF_6 is then fed to a uranium enrichment process, such as gaseous diffusion or gas centrifuge, for the preparation of enriched UF_6. The process of converting enriched UF_6 to enriched UO_2 powder is handled by the LEU fuel fabricator as part of the overall process and is termed the "powder preparation" step. In the United States, the commercial LEU fabricators are ABB–Combustion Engineering (ABB–CE) at Hematite, Missouri; Framatome Cogema Fuels [formerly Babcock & Wilcox (B&W) Fuels Company] at Lynchburg, Virginia; GE Nuclear Energy at Wilmington, North Carolina; Siemens Power Corporation at Richland, Washington; and Westinghouse Electric Corporation at West Columbia, South Carolina. B&W obtains its powder and pellet supply from another fabricator. Table 5 provides UF_6-to-UO_2 conversion capacity available in the United States.

Because we are dealing with depleted UF_6 rather than enriched UF_6 and a depleted UF_6 to depleted UO_2 powder process that does not presently exist on a commercial scale in the United States, we will retain the word "conversion" for this step. This is analogous to the conversion step for converting plutonium "pits" or other materials to clean, free-flowing PuO_2 powder for ultimate blending with the depleted UO_2 powder. If such a service is not available elsewhere, the DOE-funded MOX fabrication facility will be required to provide this depleted UF_6 to depleted UO_2 conversion step as part of the MOX fuel fabrication facility. This will mean additional investment costs for the government. There are also environmental consequences of adding the conversion step, which would have to be addressed in the National Environmental Policy Act (NEPA) of 1969 process. If such a step is included, the MOX fuel fabrication process becomes more analogous to the LEU fabrication process, which, as noted above includes an enriched UF_6 to enriched UO_2 step.

The overall generic fuel-fabrication flow sheet consists of feed receipt; powder preparation (blending, milling, granulating, and incorporating additives); pellet fabrication (sintering, grinding, and inspection); rod fabrication; packaging; and assembling of fuel bundles required by the specific reactor's core loading requirements. The chemical conversion of the depleted UF_6 to oxide powder for subsequent blending with PuO_2 powder is an initial step for MOX fuel processing as shown in Fig. 5. This is true whether it is accomplished at the MOX fabrication facility or at a separate location. In basic terms, depleted UF_6 conversion involves processing to obtain depleted UO_2 with recovery or disposal of the fluoride values. The health, safety, and environmental (HS&E) risks involved in the conversion process and handling of materials are not discussed in this report.

Before the depleted UF_6 enters the depleted UO_2 conversion facility, the contents may need to be removed from the current cylinders and transferred to other cylinders. The commercial UF_6 to UO_2 conversion facilities are set up to handle 2.5-ton cylinders. The Portsmouth plant has four liquid transfer autoclaves to transfer the depleted UF_6 from 14-ton to the 2.5-ton cylinders. Enriched UF_6 utility customers generally have a witness on site to confirm the filling and weighing of the 2.5-ton cylinders. Because these customers are assessed charges by the pound of UF_6, this is economically advantageous. However, the need for a witness for the depleted UF_6 transfers does not exist for two reasons: (1) there is ample government-owned, depleted UF_6; and (2) the charge will most likely be based on a "per cylinder filled" basis. DOE or the consortium will have to negotiate a contract with USEC, the lessee of

Table 5. UF_6 to UO_2 powder conversion capacity in the United States

Fabricator	Location	Powder capacity (MT uranium)	Available capacity in 2006	Comments
ABB–Combustion Engineering	Hematite, Missouri	700	Yes	Capacity is from a dry conversion process (data supplied by ABB–Combustion Engineering, June 25, 1997)
Framatome Cogema Fuels (formerly B&W Fuel Company)	Lynchburg, Virginia	None	No	Powder and pellets are purchased from another fuel fabricator
GE Nuclear Energy	Wilmington, North Carolina	1000	Yes	In 1997, dry conversion lines will replace the wet (ADU) process lines (data supplied by GE Nuclear Energy, June 5, 1997)
Siemens Power Corporation	Richland, Washington	1400	Yes	Capacity includes operations from both the currently operating wet process and completion of dry process conversion scheduled to be fully operational in 1998 (data supplied by Siemens Power Corporation, June 23, 1997)
Westinghouse Electric Corporation	West Columbia, South Carolina	1150	Yes	Capacity includes operations from both integral dry route (IDR) and wet (ADU) processing lines (data supplied by Westinghouse Electric Corporation, June 26, 1997)

the DOE GDPs, to perform this service. Because of the condition of many of the cylinders, it will be appropriate to perform a safety analysis before insertion into autoclaves. It is possible that a slower, low-pressure transfer would be required for many of the older cylinders.

Standard forklifts are used to move 2.5-ton cylinders. The forklift tongs are set fairly close together in order to slide the tongs under a cylinder from one end. The rules for movement are "keep as low as possible" and do not exceed 30 in. at any time.

Once converted, the depleted UO_2 would be available for transportation to the MOX fabrication facility for further processing if the conversion plant is not collocated. The MOX facility does not necessarily require collocation with the depleted UF_6 conversion plant, which will have a small depleted UO_2 product storage vault for inventory awaiting transport to the MOX fuel fabrication plant. According to *Resume of Uranium Alloy Data-XI*[22], the chemical shelf life of UO_2 depends on exposure to water and oxygen. The amount of exposure allowable is a function of the method of preparation of the powder as well as storage conditions. Studies indicate that powders prepared from ammonium diuranate (ADU) were most susceptible to air; however, water was of minor importance in all UO_2 samples regardless of conversion method. Estimates for chemical shelf life range from 1 year to an indefinite period if the storage container is maintained in an air- and moisture-controlled environment. The economic shelf life is of primary importance to the LEU owner because of the inventory carrying costs associated with enriched uranium. It is of less concern to the depleted uranium owner.

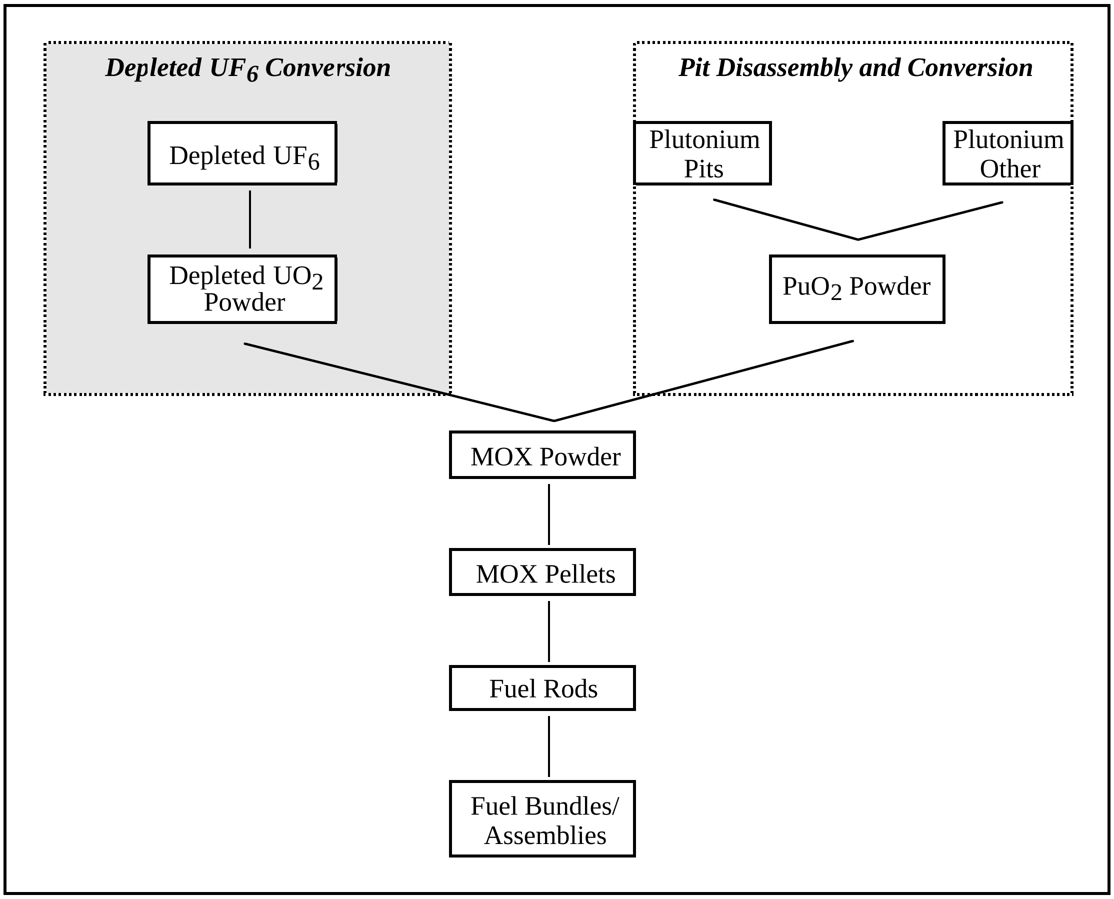

Fig. 5. Material process flow for MOX fuel.

The depleted UO_2 is not a fissile material and does not have a packaging limit to prevent criticality. The primary considerations for the packaging for depleted UO_2 will be to protect the powder from moisture and air to preserve product quality and to protect the environment and personnel from inadvertent release. A 55-gal drum with a closed inner container or sealed heavy plastic liner and an airtight seal on the lid will be required. The maximum weight capacity for a UO_2 drum is approximately 880 lb. Used drums can be returned to the fabricator for refilling or disposed of as low-level waste (LLW).

The proven conversion methods currently available for converting enriched UF_6 to enriched UO_2 could be used to convert depleted UF_6 to depleted UO_2. The UO_2 can be formed by anhydrous or "dry" processing (free of H_2O as a liquid stream; also known as vapor-phase pyrohydrolysis-reduction) or by aqueous or "wet" processing (dissolving in water; precipitating with ammonia, ammonia plus carbon dioxide (CO_2), or hydrogen peroxide; and calcining the precipitate). The terms "dry" and "wet" are analogous to the same terms used for plutonium conversion processes. The major difference is that the plutonium processes do not involve fluorine or plutonium fluorides. A primary commercial objective in the conversion process will be recovery of the fluoride values. The hydrogen fluoride (HF) portion is classified by RCRA as a hazardous waste if it cannot be sold commercially as a viable product.

Additional conversion processes are in developmental stages, such as hydrogen plasma reduction technology. Research is under way at INEEL for conversion to oxide form using plasma technology. These other untested processes are not discussed in this report.

Figure 6 shows the two predominant conversion processes. The dry process usually recovers 70% of HF through application of superheated steam and hydrogen (from dissociated ammonia) to UF_6 gas, which reacts to form solid UO_2F_2 powder and gaseous HF. The powder is defluorinated through heat addition, and steam is used to reduce the UO_2F_2 to triuranium octaoxide (U_3O_8). Hydrogen (H_2) is used in the stripping procedure in place of steam to reduce U_3O_8 to UO_2. Equipment items utilized in the dry process are gas-phase (flame), rotary kiln, or fluidized-bed reactors. A screw conveyor may be used to move the

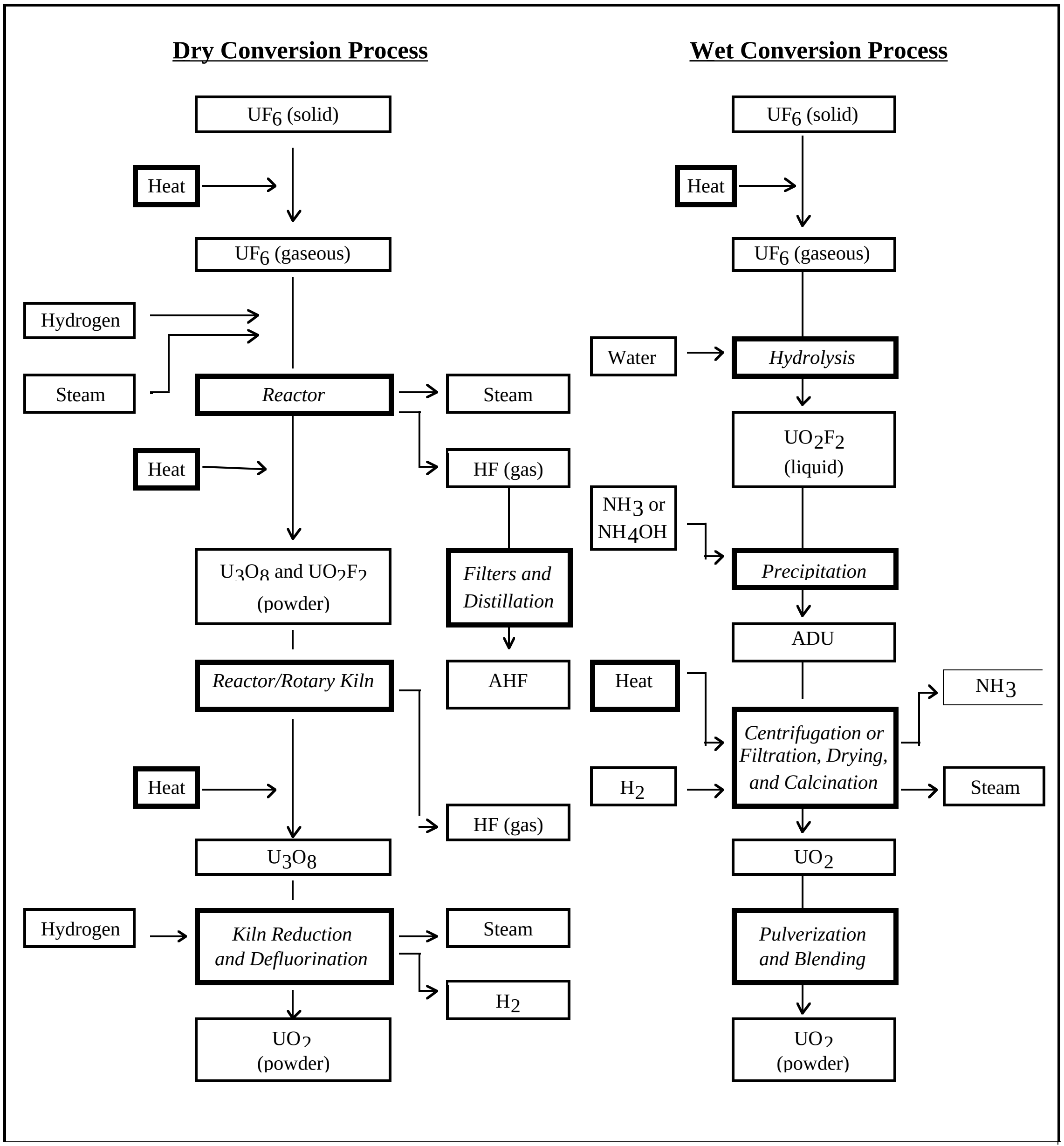

Fig. 6. Comparison of steps involved in anhydrous and aqueous UF_6 conversion.

solids between process stages. One such dry process is the integral dry route (IDR) used by Westinghouse for LEU UO_2 fabrication. The steps in the dry conversion process are represented by the following set of equations:

$$UF_6 + 2H_2O \text{ (steam)} \rightarrow UO_2F_2 + 4HF \ .$$

$$3UO_2F_2 + 3H_2O \text{ (steam)} \rightarrow U_3O_8 + 6HF + 1/2O_2 \ .$$

$$U_3O_8 + 2H_2 \rightarrow 3UO_2 + 2H_2O \text{ (steam)} \ .$$

The wet process transforms UF_6 gas into UO_2F_2 solution. The UO_2F_2 can be readily dissolved to generate a solution for use in the precipitation processes. The wet process in Fig. 6 continues through precipitation to ADU with further conversion through centrifugation, calcination, pulverizing, and blending to produce UO_2 powder. Filters and centrifuges collect precipitates, which may then be dried and calcined. The wet process generally results in large amounts of fluoride and other wastes and increased costs. Several variations of the wet process exist, depending on the precipitating agent used. Other agents can be used to precipitate ammonium uranyl carbonate (AUC) or oxalate powders. The choice of which wet process to use depends on the desired morphology and quality of the UO_2 powder derived from the precipitation.

The steps in the wet conversion process precipitating to ADU are represented chemically by the following equations:

$$UF_6 + 2H_2O\ (\text{liquid}) \rightarrow UO_2F_2\ (\text{solution}) + 4HF\ .$$

$$2UO_2F_2\ (\text{solution}) + 6NH_4OH \rightarrow 4NH_4F\ (\text{solution}) + (NH_4)_2U_2O_7\ (\text{ADU precipitate}) + 3H_2O\ ,$$

$$\text{ADU} + 2H_2 \rightarrow 2UO_2 + 3H_2O\ (\text{steam}) + 2NH_3\ .$$

The steps in the AUC aqueous conversion process are represented by the following set of equations:

$$UF_6 + 2H_2O\ (\text{liquid}) \rightarrow UO_2F_2\ (\text{solution}) + 4HF\ .$$

$$UO_2F_2\ (\text{solution}) + 4HF + 10NH_3 + 3CO_2 + 3H_2O$$

$$\rightarrow (NH_4)_4UO_2(CO_3)_3\ (\text{AUC precipitate}) + 6NH_4F\ (\text{solution})\ .$$

$$\text{AUC} + H_2O\ (\text{steam}) \rightarrow UO_2 + CO_2 + NH_3\ .$$

The UO_2 powder will be transferred to either short-term storage or an homogenization process. Homogenization ensures chemical and physical homogeneity. The powder will subsequently be sent through a blending process for addition of a pore former and/or lubricant. The UO_2 will be either returned to short-term storage or transferred for pressing and granulating. After powder preparation is completed, the depleted UO_2 will be packaged in a heavy-plastic lined, 55-gal drum. The lining, secured with a wrapping tie, is used to prevent powder contamination from contact with the drum. The UO_2 will be stored at the LEU fuel fabricator until shipment to the MOX fuel fabrication facility occurs.

After powder preparation, the UO_2 will be available for blending with the PuO_2 powder. There are four basic blending processes for producing MOX suitable for nuclear reactor fuel:

- **Mechanical blending** of depleted UO_2 and PuO_2 powders to obtain the correct physical properties such as particle size, form, density, structure, and chemical and physical reactivity.
- **Coconversion** of depleted uranium and plutonium nitrates in aqueous solution to a mixture of oxides followed by thermal and chemical treatments to form MOX. In coprocessing, the plutonium and depleted uranium never exist as a separate stream, and the product mix can occur at the fuel fabrication plant to effect the specific enrichment assay necessary. This is also known as coprecipitation.
- **Two-stage mixing** with the preparation of an intermediate master blend of plutonium-uranium as the first step and blending with depleted UO_2 as the second step.
- A **combination** of these processes.

The selection of processing options depends on factors such as nonproliferation objectives, considerations of criticality, quality control factors, generation of wastes, and cost. MOX production is discussed in separate FMDP topical and NEPA reports.

DOE's Office of Environmental Management (DOE–EM) is investigating the long-term problem of depleted UF_6 conversion for all the enrichment process tails material. The results of its studies and research and development (R&D) could have an impact on the needed depleted UF_6 conversion step for MOX fabrication. The *Summary of the Technology Assessment Report for the Long-Term Management of Depleted Uranium Hexafluoride*[23] lists recommendations submitted to DOE–EM for feasible uses of depleted UF_6. The generic responses applicable to conversion options relative to this report are as follows:

- two-part process for the dry conversion of depleted UF_6 to depleted UO_2 with the dehydration of off-gases to produce anhydrous hydrogen fluoride (AHF);
- defluorination to recover AHF and depleted UO_2 and multistage pyrohydrolysis process with steam and hydrogen or ammonia to produce depleted U_3O_8 and depleted UO_2;
- conversion to depleted UO_2 using the same process for converting isotopically enriched UF_6 to UO_2, using either a wet or dry process; and
- conversion to depleted UO_2 based on gelation methods.

At least two commercial, domestic companies have shown interest in converting depleted UF_6 to another form. Molten Metal Technology, one of the applicants submitting a proposal to DOE, signed a contract in May 1995 with USEC for conversion of USEC's depleted UF_6 into AHF and either metal or oxide form using the Quantum-Catalytic Extraction Process (Q-CEP). Molten Metal Technology is the parent company of M4 Environmental L.P. in Tennessee that holds the license for Q-CEP, which uses molten metals to separate radioactive wastes into viable products. Following a pilot-scale demonstration, which ended in mid-1996, discussions have halted on formation of a joint venture to process USEC's depleted UF_6 with the Q-CEP process with facilities built by Molten Metals on site at one of the GDPs under a 10-year service agreement.[24,25] Details on the possible applicability of this process to the FMDP requirements are not known. In addition, Molten Metals has recently undergone corporate restructuring; no cost estimates are available at this time.

More information is available about the second company showing interest in conversion of the government-owned tails material. AlliedSignal, Inc., in Metropolis, Illinois, which has commercial capabilities to convert natural U_3O_8 to UF_6 using HF and fluorine as reactants, is expanding its current operations, in conjunction with General Atomics, to include a small-scale, pilot facility to convert depleted UF_6 to both U_3O_8 and UO_2.

Financing for the pilot facility is $6.8M, with AlliedSignal and General Atomics jointly providing one-half and DOE providing the other half. The DOE funding is divided between DOE–NE and DOE–EM. This pilot facility will require ~2% of the total internal space of AlliedSignal's existing natural UF_6 conversion facility, with the HF handling facility located in close proximity external to the building. Equipment installation began in the summer of 1997 with the facility scheduled to begin operations in late 1997 or early 1998 and run for 4 to 6 months. Initial capacity will approach 100-lb depleted UF_6 feed (31 kg uranium) per hour.[26]

The pilot run will convert natural UF_6 rather than depleted to avoid possible contamination of the collocated large natural uranium conversion facility and to eliminate the necessity of AlliedSignal's requesting modification to its NRC license. To introduce depleted UF_6 into the pilot plant, AlliedSignal would have to totally segregate the pilot facility from its natural uranium operations. This would require duplicating systems for utilities; heating, ventilation, and air conditioning (HVAC); waste disposal; and personnel. By using natural uranium, which is already routinely handled and processed at this site, the NRC license requires only a license amendment and eliminates the risk of contamination. AlliedSignal has been granted a NEPA environmental categorical exclusion based on its current operations and use of the same nuclear and other materials existing at the site. In addition, use of depleted UF_6 would require that AlliedSignal purchase an independent autoclave to evacuate the depleted UF_6 from the 14-ton cylinders. The cost of conversion services using this process at the pilot facility for depleted UF_6 would include the cost for installation of an autoclave. The facility is also designed for process testing as opposed to economic operation. The cost is estimated at $17/kg UF_6 ($25/kg uranium).

A flow diagram showing AlliedSignal's deconversion process is provided as Fig. 7. After completion of the pilot run, AlliedSignal plans to keep the pilot plant running for production of the by-product fluorine, which will be used/recycled in its natural uranium conversion process. The majority of AlliedSignal's fluorine supply, generated from the mineral fluorspar (CaF_2), is imported. Only about 5% is produced in the United States. As a by-product, the commercial operations will be able to produce 10,000 tons of AHF for reuse in its current UF_6 production process and a variety of fluorine products. One of these fluorine products is Genetrons®, which are hydrofluorocarbon (HFC) replacements for chlorinated fluorocarbons (CFCs).[27]

AlliedSignal is analyzing whether to have a one-step or two-step process for conversion to depleted UO_2 (i.e., direct conversion from depleted UF_6 to depleted UO_2 or using two steps from depleted UF_6 through U_3O_8 to depleted UO_2). The extra step involves injection of hydrogen at the end of the second reactor. The process is represented by the following equations:

$$UF_6 + 2H_2O \text{ (steam)} + HF \rightarrow UO_2F_2 + 4HF + H_2O \ .$$

$$3UO_2F_2 + 3H_2O \text{ (steam)} + HF \rightarrow U_3O_8 + 6HF + 1/2O_2 \ .$$

$$U_3O_8 + 2H_2 \rightarrow 3UO_2 + 2H_2O \text{ (steam)} \ .$$

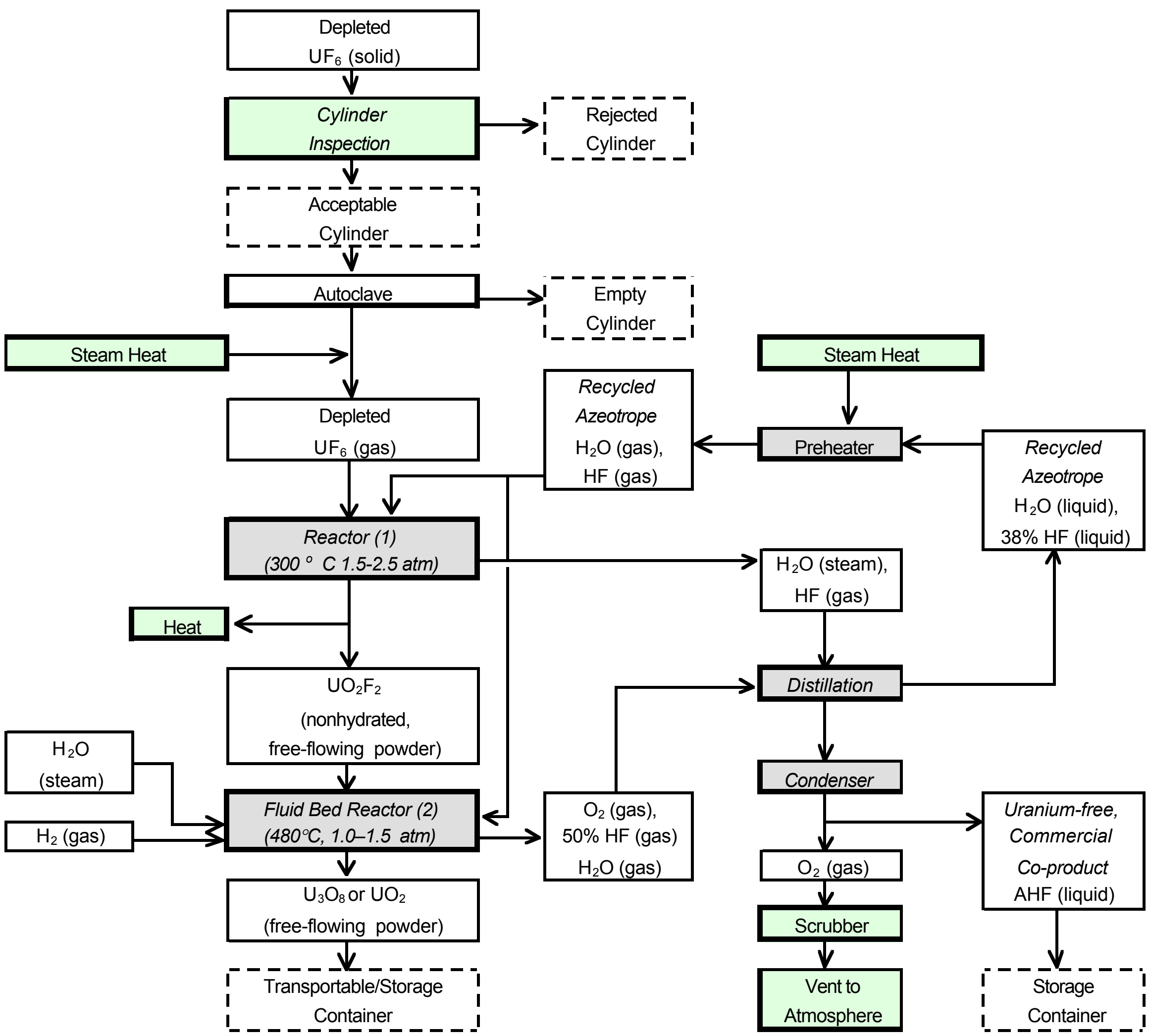

Fig. 7. AlliedSignal/General Atomics depleted UF_6 deconversion process.

If a full-scale facility is constructed, FMDP could use capacity to meet the FMDP's requirements because one of the final products will be UO_2. The timing and construction of a commercial facility will be based on DOE's decision regarding processing of its tails material. AlliedSignal and General Atomics will not pursue construction of the facility without assurance of economic incentives and/or joint government funding.

Use of the commercial-scale facility for deconversion of depleted UF_6 for MOX fuel fabrication would be an economical option because it will be constructed strictly for conversion of depleted UF_6. The capacity has not been determined, but the facility would be located near the operating GDPs in either Paducah, Kentucky, or at the nearby AlliedSignal plant in Metropolis, Illinois. Because autoclaves would be included linearly in the overall cost of the facility, the cost for processing FMDP's requirements would be substantially less using the commercial facility than the cost for processing and modifications to the pilot facility. The cost of conversion services using the commercial facility is estimated at \$2.70/kg UF_6 (\$4/kg uranium; 1997 dollars).[28] This estimate could vary due to scale of operations, the preliminary planning stage of this facility, and the FMDP requirement for reactor-grade UO_2 powder.

5. DEPLETED UF_6 TO UO_2 CONVERSION FACILITIES

As mentioned in the previous section, before transporting depleted UF_6 to a depleted UO_2 conversion facility, the solidified depleted UF_6 may require transfer to other cylinders if the current cylinders cannot meet safety standards. Presently, the only domestic facility capable of transferring the depleted UF_6 from the 14-ton tails cylinders to 2.5-ton product cylinders for the LWR fuel fabrication facilities is the GDP at Portsmouth, Ohio. The transfer facility at the Paducah GDP has not operated since 1989. Because autoclaves are required and because the Portsmouth GDP is currently leased to USEC, DOE or the consortium will be required to contract with USEC for the service of emptying the depleted UF_6 cylinders and transferring the contents. The charge for the service will have to be negotiated. The current charge associated with this transfer is $2000 per 2.5-ton cylinder filled. Because a 14-ton tails cylinder will nominally fill five 2.5-ton cylinders, the total charge per 14-ton cylinder emptied is approximately $10,000.

Even though there currently exist depleted UF_6 to depleted uranium tetrafluoride (UF_4) and uranium metal commercial conversion facilities, there are no existing commercial-scale facilities[9] in the United States for the conversion of depleted UF_6 to depleted UO_2. Facilities with lines capable of handling 200 MT of uranium per year or less for converting enriched UF_6 to UO_2 are in use at domestic LWR fuel fabrication plants; but the fuel fabricators have not yet formally expressed interest in using these lines for large-volume conversion of depleted uranium. For those fabricators with excess capacity, this task represents a viable business opportunity.

To use the powder conversion facilities at one of the LWR fuel fabrication plants, the contents of the 14-ton cylinders would need to be transferred to 2.5-ton cylinders. As standard operations, the Portsmouth GDP routinely fills 2.5-ton feed cylinders with enriched UF_6. This procedure is also used for natural and depleted UF_6 as necessary in the course of operations. The transfer process involves increasing the temperature of the UF_6 to above 64.1°C in one of the four autoclaves. The transfer rate is 2400–2500 lb/h with four 2.5-ton cylinders being filled in a standard, 8-h shift. During transfer procedures, a liquid sample is extracted to determine assay. Following transfer, a "heel" of slightly more than 1000 lb is left in the 14-ton parent cylinder. The 14-ton cylinder is moved to a "heels" storage yard, and the 2.5-ton cylinders are moved to a cooling yard awaiting transportation.

Following conversion, the depleted UO_2 would be available for transportation to the MOX fabrication facility if it is not collocated with the conversion plant. The emptied 2.5-ton cylinders would be returned to Portsmouth for reuse. The conversion facility would have a small product storage vault for inventory awaiting transport to the MOX fuel fabrication plant. The UO_2 will be transferred from the storage vault to 55-gal drums and loaded onto a flatbed truck for shipment to the MOX fuel fabrication facility's fuel feed safeguards storage area. The associated materials accountability for the UO_2 will be assigned to the MOX facility. The drums will be subsequently returned to the conversion facility for refilling.

A possible short-term alternative to a domestic conversion facility would be contracting with an experienced non-U.S. converter with operating facilities. COGEMA, which has operated facilities in Cadarache, France, since 1984, has limited excess capacity in depleted uranium conversion and is interested in supplying commercial aqueous-process conversion services for DOE-owned depleted uranium. Contracting for conversion services with COGEMA could be a viable alternative. Estimates of conversion costs by COGEMA are in the range of $3 to $4.50/kg depleted UF_6 ($4.50–$6.50/kg uranium, converted to 1997 dollars).[29] Costs do not include a reduction offset for revenue received from sale of HF.

Plans for building two separate NRC-licensed, pilot-scale conversion plants for DOE–EM and USEC are under way. The AlliedSignal pilot facility for converting depleted UF_6 to HF and U_3O_8 will be collocated in Metropolis, Illinois, with its current UF_6 conversion operations.[30] A process discussion for this facility can be found in Chap. 4 of this report. This pilot plant could prove the process commercial success with final products of U_3O_8, UO_2, and HF. The U_3O_8 could be safely buried; UO_2 could be used to form the uranium portion of MOX powder or ceramic pieces for use in place of rocks in Ducrete, a form of concrete; and the HF gas could be recycled for use in the UF_4 process. Ducrete is being assessed as a shielding material in spent fuel storage canisters.

The second company, Molten Metals, has been involved with USEC for conversion of USEC's depleted UF_6 into AHF and either metal or oxide form using the patented Q-CEP process. Discussions with

USEC concerning formation of a joint venture with facilities being built by Molten Metals at one of the GDPs have ceased.

Summarizing the information from both Chaps. 4 and 5, conversion services for depleted UF_6 to depleted UO_2 are estimated to cost between \$3 and \$7/kg depleted UF_6 (\$4.50–\$10/kg uranium, 1997 dollars) for *large-scale operations* based on the available commercial natural uranium conversion services, French depleted uranium conversion services, estimated domestic commercial facilities resulting from pilot-scale processes, and assumptions of similarity among the costs.[9,29,30] No reduction has been given for HF sales revenues, which are estimated at \$12–\$15/ton of AHF.

6. STATUS OF DEPLETED UF_6 MANAGEMENT PROGRAM

DOE is currently reviewing several alternatives for disposition of the more than 46,000 DOE-owned depleted UF_6 and 3,500 "heels" cylinders. Phase 1 of the Depleted UF_6 Management Program consists of a technology assessment, engineering and costs analyses, and preparation of PEIS. The objective of the technology assessment was to identify and evaluate alternatives submitted by interested parties for the conversion, storage, use, and disposition of government-owned depleted UF_6. This step was completed June 30, 1995, with publication of the summary of findings dated November 7, 1995.[23] The recommendations received were reviewed in the technology assessment by a group of independent technical reviewers.

The technology assessment has been completed, and the engineering and cost analyses are being performed as part of PEIS to evaluate the management strategies for the DOE-owned depleted UF_6 cylinders. Of the 57 recommendations received under the technology assessment, 51 were considered technically feasible. Because of the diversity of the alternatives, cost estimates based on vendor quotes and engineering economic analysis for R&D, construction, licensing, operations and maintenance, waste disposal, and eventual D&D are being developed. After thorough review, process selection will be made by DOE-NE in fiscal year (FY) 1998. Technologies submitted in response to DOE's Depleted UF_6 Management Program's PEIS will eventually result in a facility design and process description. The selected process and location will be released in the implementation phase.

An engineering analysis is being performed for each option resulting from the technology assessment step. This analysis will identify designs for facilities and processes, estimate resources required and wastes produced, and determine hazards and regulations associated with each option. The Cost Analysis step will provide total life-cycle costs for planning, designing, operations and maintenance, waste processing, and D&D relative to each alternative. Lawrence Livermore National Laboratory (LLNL) and Science Applications International Corporation (SAIC) are preparing the engineering and cost analyses, and Argonne National Laboratory (ANL) is developing the EIS on long-term strategies for management and use of depleted UF_6.

The last step of Phase 1 is the EIS preparation. The EIS will analyze the environmental impacts of each option and will be used for selection of the optimal management strategy for depleted UF_6 disposition. This will consist of conversion, use, storage, disposal, packaging, and transportation alternatives. Phase 2 will be a site-specific evaluation of the alternative(s) selected; and if siting, construction, and operations are associated with the option(s), preparation of all the NEPA documents will be included. Strategies can consist of any combination of the alternatives submitted.

The Depleted UF_6 Management Program PEIS lists the following courses of action, in no particular order of preference:[31]

1. Continuation through at least 2039 of current "no action" management activities: handling, inspection, monitoring, and maintenance only. A decision will be postponed until 2010 for implementation of a strategy starting no earlier than 2020.
2. Long-term storage as depleted UF_6 beyond 2020, including repackaging and transport to new locations: yards, buildings, and/or underground retrievable storage facilities.
3. Long-term storage as oxide beyond 2020, including transport to a conversion facility, conversion to oxide, packaging, transport to a storage facility, and storage in buildings, cement vaults, and/or underground retrievable storage facilities.
4. Use as an oxide, including transport to a conversion facility, conversion to oxide, transport to fabrication plant, fabrication of an end product, transport to the user, and ultimate usage as radiation shielding.
5. Use as metal, including transport to a conversion facility, conversion to metal, transport to fabrication plant, fabrication of an end product, transport to the user, and ultimate usage as radiation shielding.
6. Disposal of depleted UF_6, including transportation to a conversion facility, conversion to oxide, packaging, transport to a disposal facility, and final disposal.

Regardless of the alternative selected with the exception of the "no action" plan, conversion to another chemical form and transportation to other facilities will be required.

The PEIS will address the impacts of the various alternatives, which must comply with terms of NEPA. NEPA sets policies, goals, and the methods for carrying out actions to protect the environment and the population. The draft PEIS, which will be followed by a final site-specific EIS and a ROD following the final EIS by 30 days, is currently being prepared. The DOE Office of Environment, Safety and Health (DOE-EH) approved publication and distribution of the draft PEIS for Alternative Strategies for the Long-Term Management and Use of Depleted Uranium Hexafluoride in November 1997. Final comments from DOE-EH and the DOE Office of General Counsel will be incorporated prior to public dissemination. Public hearings will be held in January 1998 at the three affected sites storing the depleted UF_6.

7. RECOMMENDATIONS FOR FMDP

Because a full evaluation on use of depleted or natural uranium as feed has not been performed under DOE's FMDP, a comprehensive technical feasibility and cost analysis would be necessary to obtain a better understanding of the issues. Use of depleted UF_6 as feed for a MOX facility is not one of the alternatives under DOE–EM's Depleted UF_6 Management Program; thus, the required evaluation will not occur for that program's PEIS. Some components needed for the analysis relating to conversion processes and transportation issues will, however, be available from the technical and cost analyses from EIS.

The technical study would involve an interest search among DOE and commercial uranium facilities to obtain a better understanding of chemical, isotopic, and powder morphology requirements. Planning for the following activities could be started: R&D for potential conversion processes, facility design and licensing, construction, and decommissioning. These planning activities would require close interaction with the commercial sector interested in providing conversion services for DOE and the commercial sector providing LEU fuel fabrication services. (Some of these corporate entities may become part of the MOX fabrication irradiation consortium.) Issues relating to transportation to the conversion and MOX facilities, cylinder size and handling, feed storage, and waste disposal would need to be resolved in connection with program requirements. The recommended cost analysis would include model development for total life-cycle costing relative to possible R&D, conversion facility construction, depleted UF_6 feed preparation, operations and maintenance (O&M) of the conversion facility, and site decommissioning. The contents of these five components are as follows:

- **R&D** costs include feasibility studies and process comparisons for the conversion facility and feed quality required for the MOX facility.
- **Capital construction** is composed of items that impact building the conversion facility: scheduling, design, economic parameters, labor rates and required hours, materials and equipment, land purchase, and any other items determined to directly impact the project cash flow.
- **Depleted UF_6 feed** consists of expenditures relating to the cylinders and/or contents: storage retrieval, manufacture of overpacks, purchase of cylinders, USEC contract for transfer services, cylinder inspections and certifications for shipping, preparation and loading of cylinders for transport, transportation services by truck or train, unloading and transferring depleted UF_6 to the receiving and storage facility at the conversion or MOX facility, and any other items relating to feed delivery at the conversion facility.
- **O&M** includes contracting for conversion services, environmental permits and licenses for the facility, materials accountability, processing depleted UF_6 to depleted UO_2, transportation and storage considerations, waste disposal methods that adhere to EPA and RCRA regulations, and any other operational considerations that may be determined from either the FMDP or Depleted UF_6 Management Program.
- **Site decommissioning** includes final decontamination, disposal of equipment, and site reclamation.

In conclusion, a portion of DOE's surplus depleted UF_6 could be converted to the oxide form of depleted UO_2. The depleted UO_2 could be used as feed in combination with plutonium for a MOX fuel fabrication facility.

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8. REGULATORY REQUIREMENTS

Handling, disposition, packaging, and transportation of cylinders must adhere to the following laws, policies, and regulations.

Document	Description of Document
ANSI N14.1	*American National Standard for Nuclear Materials—Uranium Hexafluoride Packaging for Transport,* American National Standards Institute, 1990.
ASME NQA-1	*Quality Assurance Program Requirements for Nuclear Facilities,* American Society for Mechanical Engineers.
DOE 1270.2	*Safeguards Agreement with the International Atomic Energy Agency,* U.S. Department of Energy, June 1992.
DOE 1540.1	*Materials Transportation/Traffic Management,* U.S. Department of Energy, July 1992.
DOE 1540.2	*Hazardous Material Packaging for Transport—Administrative Procedures,* U.S. Department of Energy, September 1986.
DOE 5480.3	*Safety Requirements for the Packaging and Transportation of Hazardous Materials, Hazardous Substances, and Hazardous Wastes*, U.S. Department of Energy, July 1985.
DOE 5630.11	*Safeguards and Security Program,* Department of Energy, August 1994.
IAEA ST-1	*Regulations for the Safe Transport of Radioactive Material*, IAEA Safety Standards Series, International Atomic Energy Agency, No. ST-1, 1996 [effective date is 2001].
ORO-651, Rev. 6	*Uranium Hexafluoride: A Manual of Good Handling Practices*, U.S. Department of Energy, October 1991.
USPS Pub. 52	*Acceptance of Hazardous or Perishable Articles*, U.S. Postal Service, Publication 52.
10 CFR	Parts 40.4, 50.34, 70, 71(H), and Appendix B to Part 50, *Code of Federal Regulations*, U.S. Nuclear Regulatory Commission.
42 USC 2296b-5	*Energy Policy Act (EPACT) of 1992*, Public Law 102-486, Section 1016—Uranium Inventory Study, October 24, 1992.
49 CFR	Parts 173.420, 173.425, 173.474, 173.475, *Code of Federal Regulations,* U.S. Department of Transportation, Research and Special Program Administration.

Both materials, UF_6 and UO_2, are classified according to the DOT Hazardous Materials (HazMat) Regulations. These classifications were determined through use of the Hazardous Material Transportation Expert System (HaMTES) developed at ORNL. HaMTES determined that the depleted UF_6 can be shipped from the Portsmouth GDP to an LWR fuel fabrication facility as follows:

- Identified as RQ, Uranium Hexafluoride, UN2978
- Classified as Primary Hazard Class 7, Container Type A

- Packaged and shipped in a cylinder designed in accordance with ANSI N14.1, *American National Standard for Nuclear Materials—Uranium Hexafluoride Packaging for Transport*
- Regulated under Title 49 CFR 173.420
- Marked with primary hazard label as “Radioactive Yellow-II” and secondary hazard label as “Corrosive”
- Identified by primary placard as “Radioactive” and secondary placard as “Corrosive”
- Shipped by commercial carrier by highway

HaMTES determined that the depleted UO_2 will be shipped from the LWR fuel fabrication facility to the MOX fuel fabrication facility as follows:

- Identified as radioactive material, low specific activity, n.o.s., UN2912
- Classified as Primary Hazard Class 7, Container Type LSA-I
- Packaging and shipped in a IP-1 Type or Strong Tight Package with exclusive use, domestic only exception. A strong, tight packaging could be an open-head drum or a fiberboard box equipped with a plastic bag liner. A sealed, open-head, 55-gal drum with a heavy plastic liner for contamination control is the recommended packaging method.
- Regulated under Title 49 CFR 173.425
- No primary or secondary hazard labels required
- Identified by primary placard as “Radioactive” but no secondary placard required
- Shipped by commercial carrier by highway

Standard nuclear industry specifications, including allowable impurity limits and equivalent boron content factors, for UO_2 powder can be found in the following ASTM publication:

C753-94 Standard Specification for Nuclear-Grade, Sinterable Uranium Dioxide Powder

Other standard nuclear industry specifications, practices, and test methods for uranium can be found in the following ASTM publications:

C698-92 Standard Test Methods for Chemical, Mass Spectrometric, and Spectrochemical Analysis of Nuclear-Grade Mixed Oxides [$(U, Pu)O_2$]

C788-93 Standard Specification for Nuclear-Grade Uranyl Nitrate Solution

C996-96 Standard Specification for Uranium Hexafluoride Enriched to Less than 5% ^{235}U

C1287-95 Standard Test Method for Determination of Impurities in Uranium Dioxide by Inductively Coupled Plasma Mass Spectrometry

C1296-95 Standard Test Method for Determination of Sulfur in Uranium Oxides Uranyl Nitrate Solutions by X-Ray Fluorescence (XRF)

C1334-96 Standard Specification for Uranium Oxides with a ^{235}U Content of Less than 5% for Dissolution Prior to Conversion to Nuclear-Grade Uranium Dioxide

C1347-96 Standard Practice for Preparation and Dissolution of Uranium Materials for Analysis

C1348-96 Standard Specification for Blended Uranium Oxides with a ^{235}U Content of Less than 5% for Direct Hydrogen Reduction to Nuclear-Grade Uranium Dioxide

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ADDENDUM

PURITY OF DEPLETED UF_6 FOR MIXED-OXIDE FUEL FABRICATION

Background

One option for obtaining the depleted uranium dioxide (UO_2) required for blending with surplus weapons-grade plutonium for the mixed-oxide (MOX) fuel program is to use a portion of the U.S. Department of Energy's (DOE's) stockpile of uranium hexafluoride (UF_6) tails located at the Portsmouth Gaseous Diffusion Plant (PORTS). The depleted UF_6 is presently stored in 14-ton 48G cylinders at PORTS. The MOX project will need 130 to 140 14-ton cylinders of depleted UF_6 to complete the currently identified mission. It is desirable to have a consistent assay of depleted UF_6 for blending with the surplus plutonium. A consistent depleted assay level cannot be achieved by using current production of tails because the tails stream assay varies from cylinder to cylinder depending on the enriched UF_6 assay being produced at any particular time.

To supply a consistent depleted UF_6 assay, information on cylinders from the past 20 years was researched. The analysis determined that all of the required cylinders of depleted UF_6 with an assay range of 0.25 to 0.251 could be found in four rows in Storage Yard C at PORTS.

Purity of Depleted UF_6 for MOX Fuel

Purity is always higher in depleted UF_6 relative to enriched UF_6 from the same batch. The impurities, due to similar molecular weights to the enriched UF_6, move up the enrichment cascade with the product rather than down the cascade with the depleted UF_6.

Because the depleted UF_6 analyzed for the MOX fuel project has been in storage since between 1980 and 1985, the question of impurities formed by daughter products arises. Fortunately, the generation of daughter products in an approximately 20-year period is very small. Also, because the depleted UF_6 is stored in 14-ton 48G cylinders and the UF_6-to-UO_2 conversion line at a low-enriched uranium (LEU) fabrication facility is only capable of accepting 2.5-ton 30B cylinders, the depleted UF_6 will have to be transferred from the 48G cylinders to 30B cylinders. The transfer process entails heating the 14-ton cylinder to make a liquid transfer of depleted UF_6 to the 2.5-ton cylinders. This process tends to leave daughter product impurities in the 14-ton cylinder because they do not liquefy under the process conditions. Much of the unliquified impurities remains behind in the 14-ton cylinder and is called heels.

Additionally, at the UF_6-to-UO_2 conversion facility, the UF_6 is vaporized and withdrawn for feed for the conversion process. Again, the unvaporized impurities remain behind as heels in the 2.5-ton cylinder. The heels material consists of UF_5 and various fluoride compounds of metals, which include the daughter products.

Conclusion

This analysis determined that the purity of the depleted UF_6, which DOE is offering to supply to the consortium for MOX fuel fabrication, will meet or exceed the American Society for Testing and Materials (ASTM) standard C787-96, "Standard Specification for Uranium Hexafluoride for Enrichment."

Author: R. D. Michelhaugh
Chemical Technology Division
Oak Ridge National Laboratory
February 3, 1998

Principle Investigator: V. S. White
Engineering Technology Division
Oak Ridge National Laboratory