

**MARTIN MARIETTA**

KET

#45

## The Ultimate Disposition of Depleted Uranium

### TASK TEAM

T. R. Lemons, Chairman

C. R. Barlow  
J. M. Begovich  
F. C. Huffman

P. M. Kannan (Legal Advisor)

L. D. Trowbridge

J. D. McGee  
J. H. Faste  
J. J. Saley  
W. J. Speer

### OTHER CONTRIBUTORS

N. M. Baldwin  
R. L. Pearson  
R. W. Schmidt

F. W. Stout  
M. S. Taylor  
J. P. Voumans

*Martin Marietta Energy Systems, Inc.*

W. A. Pryor  
*PAI Corporation*

K. T. Ziehlke  
*MJB Technical Associates, Inc.*

MANAGED BY  
MARTIN MARIETTA ENERGY SYSTEMS, INC.  
FOR THE UNITED STATES  
DEPARTMENT OF ENERGY

U. S. NUCLEAR REGULATORY COMMISSION

Enrichment Technical Operations

THE ULTIMATE DISPOSITION OF DEPLETED URANIUM

TASK TEAM

T. R. Lemons, Chairman

C. R. Barlow	J. D. McGaugh
J. M. Begovich	J. H. Pashley
F. C. Huffman	J. J. Staley
P. M. Kannan (Legal Advisor)	W. J. Spetnagel
L. D. Trowbridge	

OTHER CONTRIBUTORS

N. M. Baldwin	F. W. Stout
R. L. Pearson	M. S. Taylor
R. W. Schmidt	J. P. Vournazos

*Martin Marietta Energy Systems, Inc.*

W. A. Pryor  
*PAI Corporation*

K. T. Ziehlke  
*MJB Technical Associates, Inc.*

Date Published—December 1990

Prepared by the  
URANIUM ENRICHMENT ORGANIZATION  
Oak Ridge, Tennessee 37831-7605  
managed by  
MARTIN MARIETTA ENERGY SYSTEMS, INC.  
for the  
U.S. DEPARTMENT OF ENERGY  
under contract DE-AC05-84OR21400

## CONTENTS

ACRONYMS AND TECHNICAL TERMS .....	v
ACKNOWLEDGMENTS .....	vii
EXECUTIVE SUMMARY .....	ix
A. INTRODUCTION .....	1
A.1 BACKGROUND INFORMATION .....	1
A.2 CURRENT STATUS .....	1
A.3 FUTURE PROSPECTS .....	2
A.4 PURPOSE OF REPORT .....	2
B. LEGAL/REGULATORY REVIEW .....	3
B.1 DEPLETED URANIUM REGULATORY STATUS .....	3
B.2 FOREIGN-ORIGIN ACCOUNTABILITY .....	4
C. DISPOSITION OPTIONS ANALYSIS .....	7
C.1 BASIS FOR DEPLETED URANIUM MANAGEMENT STRATEGIES .....	7
C.2 WORKING INVENTORY MANAGEMENT .....	8
C.2.1 Storage As $UF_6$ .....	8
C.2.1.1 Current status .....	8
C.2.1.2 Upgraded cylinder storage requirements .....	9
C.2.1.3 $UF_6$ storage costs .....	10
C.2.1.4 Indoor storage .....	11
C.2.2 Management Strategy .....	12
C.2.2.1 Break-even tails assays for natural uranium .....	12
C.2.2.2 Partially depleted feed recycle economics .....	12
C.2.2.3 Decision criteria for ultimate disposition .....	13
C.3 ULTIMATE DISPOSITION .....	14
C.3.1 Optimum Form of Uranium for Ultimate Disposal .....	14
C.3.2 Other Chemical Conversion Options .....	14
C.3.3 Commercial Facilities .....	15
C.3.4 Permanent Disposal Versus Long-Term Storage .....	17
C.3.5 Ultimate Disposition Plan .....	18
D. CONCLUSIONS .....	19
E. RECOMMENDATIONS .....	21
APPENDIX I REGULATORY ANALYSIS OF DEPLETED URANIUM .....	23
APPENDIX II RISK CHARACTERIZATION OF ALTERNATE CHEMICAL FORMS OF URANIUM .....	31

APPENDIX III. INDOOR STORAGE OF UF, .....	43
APPENDIX IV. BREAK-EVEN TAILS ASSAYS .....	47
APPENDIX V. CONVERSION PROCESSES .....	53

## ACRONYMS AND TECHNICAL TERMS

ACGIH	American Conference of Governmental Industrial Hygienists
AEA	Atomic Energy Act of 1954, as amended
AEC	U.S. Atomic Energy Commission
ANSI	American National Standards Institute
Assay	$^{235}\text{U}$ content as a percent or fraction of total uranium
AVLIS	Atomic Vapor Laser Isotope Separation
BETA-1	Economic break-even tails assay for gaseous diffusion process
BETA-2	Economic break-even tails assay for AVLIS process
CFR	Code of Federal Regulations
CRADA	Cooperative Research and Development Agreement
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DU	Depleted uranium
EPA	U.S. Environmental Protection Agency
ES&H	Environmental, safety, and health
FDU	Fully depleted uranium (i.e., all of the economically recoverable $^{235}\text{U}$ has been extracted by the enrichment process)
GDP	Gaseous diffusion plant
LLW	Low-level radioactive waste
LSA	Low specific activity
MTU	Metric tons of uranium (1000 kg U)
NRC	U.S. Nuclear Regulatory Commission
NTS	Nevada Test Site
NU	Natural uranium, containing about 0.71% $^{235}\text{U}$
ORO	Oak Ridge Operations Office of DOE
PDF	Partially depleted (in the $^{235}\text{U}$ isotope) feed material
RCRA	Resource Conservation and Recovery Act of 1976, as amended
SWU	Separative work unit
TCLP	Toxicity Characteristic Leaching Procedure (a test specified by the EPA for identifying hazardous material)

TLV

Threshold limit value

UE

Uranium enrichment, as in uranium enrichment program, etc.

## ACKNOWLEDGMENTS

We wish to extend our appreciation to the numerous components of Martin Marietta Energy Systems who contributed to this report and also to the management and staff of other DOE prime contractors and various commercial uranium processing companies for their assistance in providing much of the data on which the study is based. Special thanks are extended to Clara Y. White for typing the initial draft of this report and to Janice M. Asher for technical editing and preparation of the final report.

## EXECUTIVE SUMMARY

Significant amounts of the depleted uranium (DU) created by past uranium enrichment activities have been sold, disposed of commercially, or utilized by defense programs. In recent years, however, the demand for DU has become quite small compared to quantities available, and within the U.S. Department of Energy (DOE) there is concern for any risks and/or cost liabilities that might be associated with the ever-growing inventory of this material. As a result, Martin Marietta Energy Systems, Inc. (Energy Systems), was asked to review options and to develop a comprehensive plan for inventory management and the ultimate disposition of DU accumulated at the gaseous diffusion plants (GDPs). An Energy Systems task team, under the chairmanship of T. R. Lemons, was formed in late 1989 to provide advice and guidance for this task.

The first milestone objective was to commission a thorough review of laws and regulations pertaining to DU. Eminently qualified outside counsel was retained for the legal/regulatory review. It was concluded that the management of DU working inventories at the DOE sites is not constrained by current regulations of other government agencies. In addition, DOE Oak Ridge Operations (DOE/ORO) has formally advised the Ohio Environmental Protection Agency (EPA) that DU is "source material," which is exempt from Resource Conservation and Recovery Act (RCRA) regulation.

The principal objective for both inventory management and the ultimate disposition of DU is to protect the health and safety of workers and the public and to minimize degradation of the environment. The most important aspect of this is the chemical form of the uranium in storage. Our technical analysis indicates that it is acceptable and desirable to maintain DU working inventories as UF<sub>6</sub> as long as they remain potential feed resources for the GDPs and as long as cylinders and storage facilities are adequately monitored and maintained. Some, perhaps all, of the DU inventories may be recycled through the Atomic Vapor Laser Isotope Separation (AVLIS) process before they become fully depleted (criteria to be defined) and ready for ultimate disposition. Whether DU is recycled through AVLIS or declared surplus to DOE needs, chemical conversion will be required at some time in the future. Integrated planning for enrichment processing and the ultimate disposition of DU will be necessary to minimize costs and risks.

The ultimate disposition of DU relative to the uranium enrichment program could be transfer/sales to other government programs (e.g., defense programs), commercial sales, or long-term storage or disposal. It appears that commercial and government demands will use only a small fraction of the DU available in the foreseeable future; so a plan for permanent disposition will be required for the vast bulk of the DU.

---

<sup>1</sup>R. O. Hultgren, DOE/ORO, Oak Ridge, Tennessee, letter to K. W. Sommerfeld, Martin Marietta Energy Systems, Inc., Oak Ridge, Tennessee, "Disposition of Tails Material at the GDPs," dated July 12, 1989.

This report reviews options and recommends actions and objectives in the management of working inventories of partially depleted feed (PDF) materials and for the ultimate disposition of fully depleted uranium (FDU). Actions that should be considered are as follows:

1. Inspect UF<sub>6</sub> cylinders on a semiannual basis.
2. Upgrade cylinder maintenance and storage yards.
3. Convert FDU to U<sub>3</sub>O<sub>8</sub> for long-term storage or disposal. This will include provisions for partial recovery of costs to offset those associated with DU inventory management and the ultimate disposal of FDU.

Another recommendation is to drop the term "tails" in favor of "depleted uranium" or "DU" because the "tails" label implies that it is "waste." Consistent with this recommendation, the DU terminology is used throughout this report. Other recommendations are given in the text.

## A. INTRODUCTION

### A.1 BACKGROUND INFORMATION

Natural uranium exists primarily as the stable isotope  $^{238}\text{U}$ . Only 0.71% of naturally occurring uranium is the fissile isotope  $^{235}\text{U}$ . For most military or commercial purposes, the uranium must be enriched—that is, the concentration of the  $^{235}\text{U}$  isotope must be increased. The U.S. uranium enrichment (UE) program began during World War II, as a part of the Manhattan Project, to provide highly enriched uranium for military needs. The first plant to use the gaseous diffusion process began operation at Oak Ridge in the mid-1940s. The Portsmouth and Paducah Gaseous Diffusion Plants (GDPs) were built in the 1950s to increase the United States' capacity to enrich uranium. In the 1960s and 1970s, the primary emphasis shifted from production for military needs to providing fuel for nuclear power plants. The three GDPs operated continuously until 1985, when the Oak Ridge plant was shut down for economic reasons. The Portsmouth and Paducah plants continue to enrich uranium for the nuclear power industry, supplying about one-half of worldwide UE production. According to an article in *Scientific American*,<sup>2</sup> nuclear power now supplies approximately 16% of the world's electricity. The Portsmouth plant also provides highly enriched uranium to fuel some research reactors and to supply U.S. defense program requirements, including those for the Navy's nuclear fleet.

Enriching uranium involves splitting a feed stream into a product stream enriched in  $^{235}\text{U}$  and a by-product stream depleted in  $^{235}\text{U}$ . The enriched product is used for commercial and military nuclear applications. Significant quantities of the DU have been used in a few military and commercial applications, but the demand has become quite small in recent years. Because of the low concentration of  $^{235}\text{U}$  in natural uranium, 5 to 10 kg of DU are produced for every kilogram of uranium enriched for commercial applications, while about 200 kg of DU are produced for each kilogram of highly enriched uranium. These proportions hold true regardless of the process used for enrichment (gaseous diffusion, gas centrifuge, AVLIS, etc.). Since uranium enrichment activities produce much more DU than is required by existing applications, the excess DU requires disposal or storage.

### A.2 CURRENT STATUS

Essentially all of the DU currently stored at the GDPs is in the form of solid  $\text{UF}_6$ —primarily in 14-ton cylinders. By the end of FY 1990, the enrichment enterprise had accumulated about 320 million kgU of depleted  $\text{UF}_6$  in storage. The  $^{235}\text{U}$  assays of the stockpiled DU generally range from 0.2% to 0.5%  $^{235}\text{U}$ . The depleted  $\text{UF}_6$  is stored in about 40,000 cylinders, mostly at the Paducah site. (Because Paducah was designed to produce low-assay feed for the other enrichment plants, most of the DU is produced there.) Current plans call for the GDPs to continue to produce a total of about 20 million kgU per year of depleted  $\text{UF}_6$ , requiring about 2500 14-ton cylinders per year for storage.

---

<sup>2</sup>Wolf Hafele, "Energy from Nuclear Power," *Scientific American* 263(3), 137-144 (September 1990).

### A.3 FUTURE PROSPECTS

Some, perhaps all, of the DU inventory may be recycled through UE facilities in the future. There have been several major recycling campaigns in the past when there was a perceived shortage of DOE-owned natural uranium, and thus the internal DOE cost of feed was high relative to the cost of separative work. However, recycling (stripping additional  $^{235}\text{U}$  from partially depleted uranium) can reduce the total quantity of DU by only a few percent. Other means must be found to use or dispose of the bulk of the material. The inventory of DU is a highly refined resource that could be of significant use to future generations. The most promising long-term use for DU is as feed for an advanced breeder or other type of reactor when other energy sources have been depleted. Foreign breeder reactor programs have demonstrated the potential for energy production from DU.

Nonnuclear uses for DU are currently limited to military applications and a very few specialized civilian applications, requiring very dense materials (uranium is 1.6 times as dense as lead). In the past, a substantial amount of the DU stockpile has been used by the military, primarily to produce penetration projectiles. The Department of Defense Appropriations Act for FY 1991 requires that an additional 16 million kgU be placed in the national defense stockpile over the next 10 years. Recent studies of alternative uses for DU have failed to reveal any significant new uses in the immediate future. The most promising new long-term use suggested is to replace the sand and aggregate in concrete with depleted  $\text{UO}_2$ . This would produce concrete with a density greater than that of cast iron. Such a concrete might be useful as ballast or in radiation shielding, although development and acceptance of this material could take years.

### A.4 PURPOSE OF REPORT

Since no end use is currently foreseeable for most of the fully depleted uranium (FDU) that has been and will be created by the U.S. uranium enrichment programs, the U.S. Department of Energy (DOE) requested an analysis of management options and development of a plan for the ultimate disposition of this material (see Ref. 1). An Energy Systems technical task team was formed in late 1989 to provide guidance for the DU disposition study. The purpose of this report is to present the recommended management plan to DOE. The report also documents details and conclusions from the legal review and technical/economic analysis on which the recommendations in this report are based.

## B. LEGAL/REGULATORY REVIEW

Regulatory compliance concerns in the management of depleted uranium have been raised by changes in federal law, which created the U.S. Nuclear Regulatory Commission (NRC) and the DOE (which superseded the U.S. Atomic Energy Commission, or AEC) and which established environmental laws such as the Resource Conservation and Recovery Act (RCRA). The state of Ohio recently questioned whether DU storage might have to comply with RCRA hazardous waste regulations.<sup>3</sup> The concern raised by the state of Ohio was answered in a letter to the Director of the Ohio EPA by the manager of the Oak Ridge Operations Office. Prior to this letter, and at the suggestion of DOE, expert outside counsel was retained to review and evaluate present laws and regulations as they apply to the DU inventory.

### B.1 DEPLETED URANIUM REGULATORY STATUS

Current regulations do not impair DOE's inventory management prerogatives for DU material. In the review of applicable laws and regulations, outside counsel concluded<sup>4</sup> that DU is "source material" as defined by the Atomic Energy Act<sup>5</sup> (AEA) and thus that U.S. Environmental Protection Agency (EPA) regulations do not apply. "Source, special nuclear and by-product materials" as defined in the AEA are specifically excluded in the RCRA statute.<sup>6</sup> In the opinion of outside counsel, the exclusion exempts DU from the regulatory jurisdiction of both the federal EPA and state agencies. These legal findings were verified by DOE in the letter from the manager of Oak Ridge Operations to the Ohio EPA<sup>7</sup> (see Appendix I). However, it is imperative to maintain safe containment of DU so that no environmental insult occurs. Loss of containment of this material in its present form, UF<sub>6</sub>, would generate a hazardous material, hydrogen fluoride (HF); and a significant release would be of great concern to DOE and Energy Systems (see Appendix II for a summary of the risks and hazards of uranium compounds). Thus, the principal near-term objective of the proposed DU management plan is to implement actions that will assure that no hazardous releases of UF<sub>6</sub> occur.

Other legal and regulatory issues are related to the proposed management plans for storage of partially depleted feed (PDF) as UF<sub>6</sub> and for conversion of FDU to an oxide. Examples include U.S. Department of Transportation (DOT) shipping regulations and DOE orders

---

<sup>3</sup>Donna Goodman, Inspector, Division of Solids & Hazardous Waste Management, Ohio EPA, letter to E. W. Gillespie, Site Manager, U.S. DOE, Portsmouth, Ohio, dated September 27, 1990.

<sup>4</sup>R. J. Szyduhar, Vorys, Sater, Seymour, and Pease, Attorneys-at-Law, Columbus, Ohio; letter to P. M. Kannan, Martin Marietta Energy Systems, Inc., Oak Ridge, Tennessee, "Uranium Hexafluoride (UF<sub>6</sub>) Tails," dated May 9, 1990.

<sup>5</sup>42 U.S.C., Sect. 2014 (z), 1982.

<sup>6</sup>42 U.S.C., Sect. 6903 (27), 1982.

<sup>7</sup>Joe La Grone, Manager, DOE Oak Ridge Operations, letter to Richard Shank, Director, Ohio EPA, dated October 29, 1990.

on handling  $UF_6$ . DOE, in ORO 651, requires a minimum wall thickness of 1/4 in. for the thin-wall storage cylinders in order to liquefy  $UF_6$  and transfer it from the cylinder. External corrosion to the extent that the wall thickness would be less than this minimum will require an alternate, more costly transfer method. DOT, by reference to ANSI N14.1, also requires a minimum wall thickness of 1/4 in. when DU is transported in thin-wall cylinders.<sup>9</sup> Approximately two-thirds of the DU inventory is contained in cylinders that are approved as DOT Specification 7A, Type A- packages for offsite transport. The remaining DU cylinders that have not been evaluated by DOT would require similar approval, or the contents would have to be transferred to approved cylinders if offsite transport were necessary.

## B.2 FOREIGN-ORIGIN ACCOUNTABILITY

DOE also requested<sup>9</sup> that this DU disposition study consider how most effectively to handle accountability for foreign-origin depleted uranium. Agreements with Australia and Canada require maintenance of a DU physical inventory corresponding to the amount of feed used from those countries. An appropriate quantity of DU at any assay would satisfy the commitment since DU is considered to be fungible by all parties to the agreements. The cumulative total amount of Australian- and Canadian-origin DU accounted for by DOE at this point amounts to less than 20% of the current depleted  $UF_6$  inventory. There should be no difficulty in continuing to account for the Australian/Canadian-origin material in the future. Even when FDU is converted to  $U_3O_8$  and placed in long-term storage, an accounting procedure can be set up that will physically account for the required amount of DU material in one location.

The suggested procedure is to identify an appropriate amount of 0.20% DU in storage at Paducah as the stockpile of Australian/Canadian-origin DU. This is the DU inventory category least likely to be moved and should be undisturbed for many years. The cylinders included in the Australian/Canadian-origin account can be identified by cylinder number and can be physically segregated by simply roping off these cylinders from the rest of the 0.20% inventory. A DOE office or individual would need to be made responsible for notifying Paducah Material Accountability of quantities to be added to this account. In turn, Paducah would be responsible for notifying DOE of which cylinders were added for accountability and for moving the rope or other boundary marker for physical segregation.

No change in the procedure would be necessary until 0.20% DU is either recycled or converted for long-term storage. If conversion of FDU to  $U_3O_8$  is implemented, the next and last step would be to transfer physical accountability to the long-term storage facility. The transfer of Australian/Canadian accountability should begin as soon as significant quantities of FDU are converted and placed in long-term storage. When a quantity of FDU is converted, a like amount of 0.20%  $UF_6$  could be transferred or operationally used.

---

<sup>9</sup>49 CFR 173.420.

<sup>9</sup>J. W. Parks, DOE/ORO, Oak Ridge, Tennessee, letter to T. R. Lemons, Martin Marietta Energy Systems, Inc., Oak Ridge, Tennessee, "Tails Disposition Study," dated February 28, 1990.

If  $U_3O_8$  conversion is not implemented and 0.20% DU is recycled, the Australian/Canadian origin account would have to be tracked through the recycling facility.

Both the working inventory management plan for PDF and the long-term storage plan for FDU should address the above legal and regulatory issues in order to maximize their flexibility. Since regulations continually change, it is also essential that the legislative/regulatory developments be monitored for any new or revised requirements that could affect DOE inventory management plans for the future.

## C. DISPOSITION OPTIONS ANALYSIS

### C.1 BASIS FOR DEPLETED URANIUM MANAGEMENT STRATEGIES

A complete DU disposition plan must address both near-term DU inventory management objectives and the ultimate disposition of surplus DU. The scope of the ultimate disposition program will be of the same magnitude as the near-term inventory management program because quantities of DU will be reduced only slightly by presently foreseeable uses. Just a small fraction of the current depleted UF<sub>6</sub> inventories and future DU production will be needed to fill known demands for DU metal. Some or all of the excess DU may be processed through AVLIS, but this cannot be considered as an option for permanent disposition. Even if all of the DU is recycled through the GDPs and/or AVLIS for further stripping of the <sup>235</sup>U isotope, the quantity of DU will be reduced by only a few percent.

Working inventory management issues—that is, management of DU as a resource for existing government programs—will be considered first. DOE is free to manage DU inventories for the benefit of its programs until the material is declared a waste. The legal/regulatory review and the assessment of environmental, safety, and health (ES&H) risks did not reveal any reason to depart from the current strategy of maintaining the working inventories as UF<sub>6</sub> for as long as they may be needed for future recycle and other government uses. There is no existing basis in law for other government agencies to regulate or control DOE inventories of DU, and the risks associated with cylinder storage of UF<sub>6</sub> are manageable.

The purpose in managing the DU working inventories is to maintain high ES&H standards while using the inventories for the greatest economic benefit to the enrichment enterprise and other government programs. The working inventory management issue of the greatest immediate concern is upgrading current UF<sub>6</sub> storage practices to achieve high standards of excellence for primary containment and for monitoring of the storage yards. This will involve upgrading cylinder maintenance and inspection programs and cylinder storage facilities. Cost estimates are given for the recommended upgrading program. The economics of PDF recycling are also addressed—that is, how to determine (1) when and what to refeed to the diffusion or AVLIS processes and (2) when depleted uranium can no longer be economically used in uranium enrichment and should be classified as FDU.

Options for the ultimate disposition of FDU and associated costs are the final topics covered in this section (see Sect. C3).

## C2 WORKING INVENTORY MANAGEMENT

### C2.1 Storage As UF<sub>6</sub>

#### C2.1.1 Current status

The present practice for retention of PDF materials is to store them as UF<sub>6</sub> in 48-in. steel cylinders of 10- and 14-ton capacity,<sup>10</sup> most of which are coded pressure vessels. These cylinders currently qualify as "strong, tight containers" for transport of low-specific-activity (LSA) radioactive materials under DOT regulations. The term of storage has never been fixed or defined, but corrosion observations on the nominally unprotected steel cylinders in outdoor storage indicate a remaining service life of at least 30 years for cylinders now in storage before the cylinder wall thickness decreases to the minimum allowable value for present liquid transfer procedures.<sup>11</sup> Based on these observations, new cylinders could have a service life of as much as 70 years. The inventory management program must provide for monitoring the progress of corrosion in order to schedule transfers of UF<sub>6</sub> to new cylinders on a safe and timely basis.

The storage cylinder inventory at the end of FY 1990 included 34,400 standard 14-ton cylinders at the three diffusion plant sites, with 22,300 at Paducah, 8,900 at Portsmouth, and 3,200 at Oak Ridge. In addition, a few thousand cylinders of other types were included in the inventory. The total PDF inventory contained 322,100 metric tons of uranium (MTU). Most of the cylinders are stacked in two-high arrays, in double rows, with the plug ends of the cylinders separated by about 1 ft and the valve ends by 3 to 4 ft. In this array, the single-cylinder space requirements are about 38 ft<sup>2</sup> of storage surface. The geometric arrangement was intended only to facilitate inventory and accountability requirements, with little consideration for other monitoring or inspection needs. Storage experience with 48-in. cylinders since the late 1950s has shown the necessity for stable storage surfaces, and, at present, nearly all of the PDF cylinders are stored on either concrete-paved or compacted-gravel yards. Also, nearly all are in the stacked (two-tier) configuration. The lower tier of cylinders utilizes creosote-treated wooden saddles for above-ground support. (In the Paducah storage facilities, cast concrete saddles have been

---

<sup>10</sup>The principal UF<sub>6</sub> storage container is a 48-in.-diameter cylinder of 14-ton capacity designated as a thin-wall cylinder (working pressure rating of 100 psig, with a wall thickness of 5/16 in.) and produced in several minor design variations as Models 48 H and 48 HX, Model O, Model OM, and Model 48 G. More than 51,000 of these cylinders have been procured since 1958. Approximately 34,400 of these are currently in DU storage service. Over 7,000 cylinders of other types are also being used for DU storage. This includes thin-wall and heavy-wall 10-ton cylinders and miscellaneous cylinder types.

In addition, the Paducah plant fabricated a number of DU storage containers from surplus converter shells, 142 of 19-ton capacity and 150 of 12.8-ton capacity.

<sup>11</sup>J. H. Alderson, *Remaining Life of Uranium Hexafluoride Tails Storage Cylinders*, KY/L-1482, Paducah Gaseous Diffusion Plant, April 1988.

used for the past several years, but the wood saddles have not been replaced with concrete ones.) Spacing between adjacent rows of stacked cylinders is variable, both among the three storage sites and within the individual sites. Since cylinder inventories depended only on the cylinder serial numbers, the valve-end spacing was controlled to allow for walk-through observation of the cylinder name plates. Plug end spacing was not controlled to the same degree and was often targeted at a nominal 1-ft separation. However, many of the stacking arrays permit walk-through access to the plug end for inspection.

#### C2.1.2 Upgraded cylinder storage requirements

Storage area requirements are increasing at a rate of about 2.2 acres per year if present stacking configurations continue to be used. This figure is derived from the earlier described double-tier arrangement, with the  $3\frac{1}{2}$ -ft separation between valve ends and 1-ft separation between plug ends of double rows of cylinders. The cylinders are nominally spaced on 62-in. centers. In an infinite array (i.e., ignoring dead space at the edges), this gives an area requirement of 38 ft<sup>2</sup> per cylinder, exclusive of the area for manipulation of the cylinder handling equipment. The estimated yearly increase of 2500 cylinders thus requires 2.2 acres of new storage space.

The PDF storage facilities at the three diffusion plant sites have been scrutinized closely in the past several months, and a number of situations have been identified as problems that require attention in any long-term storage situation. Evidence (or suspicion) of valve leaks; the possibility of plug leaks; the promotion of corrosion by, and deterioration of, wooden support saddles; and general corrosion of the storage cylinder walls all indicate the need for a formal maintenance and surveillance program for PDF storage.

Although cylinder procurement specifications over the past several years have required a painted surface, the paint used has not held up well in outside storage and is not very resistant to steam in the autoclave cycle. Thus, the net effect of the initially specified paint coating is to extend the cylinder life by a few years at best, not a significant amount in the storage service life of a thin-wall steel cylinder. Preparing the new steel cylinders for extended storage in order to essentially eliminate atmospheric corrosion would require cleaning all surfaces by abrasive blasting and then priming and painting them. Presently, available paint systems have life expectancies in outdoor service that may exceed 25 years, and with spot repair and effective monitoring, use of such systems could reduce atmospheric corrosion losses to zero.

The new cylinders are stacked for storage; this should be done using durable, long-life support saddles. The stacking should include quality control of each cylinder's placement to avoid the eccentric and possibly unstable stacking configurations noted in recent surveys. Finally, the stacking should provide the full-cylinder access necessary to assure adequate surveillance—access to both ends and some measure of visual access to the support points for each cylinder.

Cylinder handling carries with it the risk of damage through accidental contact with adjacent cylinders or rough placement on support surfaces. These accidental contacts are responsible for dents, and if impacts are strategically located and of sufficient force, they can crack the

cylinder wall, leading to loss of internal vacuum and eventual release of a portion of the cylinder contents. The accidental contacts can also damage valves (or plugs), with similar consequences. In the two known instances in which handling damage apparently cracked a cylinder wall, material loss and reaction with atmospheric moisture were so slow that the breaches were not detected until years later. The UF<sub>6</sub> reaction products tended to self-seal these minor breaches.

### C2.1.3 UF<sub>6</sub> storage costs

To assure safe, long-term storage (i.e., storage for periods that exceed the anticipated life of an unpainted thin-wall cylinder in off-ground outdoor storage), it is necessary to consider modifications in the present storage philosophy and methodology. At the outset, the corrosion process that determines the present cylinder life cycle must be slowed or eliminated. For example, one of the simplest ways to accomplish this is by surface protection through painting. Although painting is presently specified (one coat of zinc chromate primer plus one enamel topcoat) for new cylinders, the paint is not protective for extended time periods; and damage incurred from in-plant handling operations is generally not repaired before the cylinders are deployed in storage. Corrosion problems could be avoided if the painting were specified to include a zinc-rich topcoat that can provide galvanic protection for steel exposed to scuffs and scratches, and cylinder deployment in storage yards should also be followed by inspection and touch-up of handling damage. Zinc-rich paints used on a few dozen cylinders placed in K-1066-K (Oak Ridge) in 1980 are still in excellent condition and, with proper substrate preparation, would probably eliminate atmospheric corrosion for storage periods of 25 years or more. Preparation and painting with this level of quality should be obtainable for new cylinders at a reasonable incremental cost and should be made standard for all newly procured cylinders.

Painting or other durable protective coatings can be used to extend the service life of existing cylinders indefinitely. Cost elements of such a program would include moving the cylinder to a preparation facility, abrasive blasting to remove accumulated oxide scale, application and curing of the protective coating, and returning the cylinder to the storage yard. The painting cycle, at an estimated cost of \$300-\$500 per cylinder, could be repeated at approximately 25-year intervals for extended storage, as the need is indicated by annual visual inspections for rust and physical condition of the protective coating.

Nearly all of the cylinders are presently stored on stable surfaces, that is, either concrete pavement or compacted gravel. The cylinders at Portsmouth and Oak Ridge and many of those at Paducah are stacked on wooden saddles and may not be fully accessible for visual inspection in their present configuration. A cost/benefit analysis should be made for restacking these cylinders on concrete or steel saddles and in a manner that provides easy inspection access.

Monitoring activities related to cylinder storage are currently estimated to require annually about one-fourth man-hour per stored cylinder to (a) inspect in detail for valve and plug leaks and perform repairs as necessary, (b) perform occasional cold pressure checks, and (c) determine cylinder wall thickness and assess corrosion rates. There is also some need for housekeeping and weed control, for run-off monitoring, and for inventory and

accountability activities. While the distribution of effort may vary from year to year, the overall rate of time investment is expected to remain constant; and this should be considered to be an annual cost of cylinder storage and maintenance. If the cylinders are not painted, as the storage system matures and cylinders approach the end of their service life, provisions must be made for transfer of contents to new cylinders and for disposal of the expended scrap cylinders. The necessary exchange rate could exceed 1000 cylinders per year and would require new transfer facilities for the enrichment complex; therefore, the cylinder transfer activities would have to begin in advance to accommodate the required transfers. Initial transfer activities should target the nonstandard containers (see footnote 10 in Sect. C.2.1.1) and a group of older cylinders of noncertified volume, as well as some storage cylinders that are known to have been overfilled. All of these will require special handling to provide for safe removal of the contents. The painting of new cylinders before deployment for long-term storage would eliminate the need for periodic transfer to new cylinders. This would also preserve the liquid transfer capability for an indefinite period of time until the UF<sub>6</sub> is removed for conversion.

Facility expansion at Portsmouth and Paducah to accommodate the yearly growth of 2500 storage cylinders is estimated to cost \$6 to \$8 million/year if designed to meet recommended IAEA standards. Cylinder and facility inspection and maintenance (including the replacement of any leaking valves and plugs) are estimated at \$500,000 to \$1 million/year. Total storage costs for upgrading, expansion, and maintenance of the storage facilities are thus \$6.5 to \$9.0 million/year. It should be noted that these cost figures represent very preliminary estimates that are intended only to develop order-of-magnitude costs.

Consolidation of storage facilities for DU was not considered in the evaluation of storage costs. Within the UE complex, the Paducah GDP produces most of the DU, is the site where most of the DU is currently stored, and is designed to recycle large quantities of PDF. Consolidation of the DU at the Paducah GDP would reduce the total capital and annual operating costs of storage. The duplication of maintenance facilities and equipment and the number of operating, maintenance, and other support personnel could be optimized by this consideration; however, there would be significant costs associated with the transport of the depleted UF<sub>6</sub> to consolidate storage. While consolidation of DU storage could result in significant cost savings, further evaluation is required in order to determine the optimum storage site(s) and the probable magnitude of cost savings.

DU storage facilities must also be planned for AVLIS and for chemical conversion of FDU to U<sub>3</sub>O<sub>8</sub>. Optimization of the management plan for DU storage can be finalized only after the sites for AVLIS and chemical conversion have been selected.

#### **C.2.1.4 Indoor storage**

There are no current requirements for indoor storage of PDF; however, since requirements are subject to changes in the future, this option was reviewed (see Appendix III). The need to provide utilities, temperature and humidity control, the development and procurement of specialized cylinder handling equipment, and storage density requirements would combine to drive the cost of indoor storage in existing facilities far above that of upgraded outdoor facilities.

Preliminary estimates for indoor storage in new buildings at the Portsmouth plant suggest capital costs exceeding \$300 million to accommodate the present total inventory of stored  $UF_6$ . Indoor storage would require new building construction for the Paducah inventory whether the other sites utilized existing buildings or new buildings, since there is no present capacity for indoor storage at Paducah. Upgraded outdoor storage appears to be adequate for the retention of DU for an indefinite period of time, at a fraction of the cost of indoor storage. Indoor storage would only marginally improve the quality of storage of the  $UF_6$ ; therefore, the additional cost is not presently justified.

## **C.2.2 Management Strategy**

This section addresses PDF recycle economics and how to determine when depleted uranium is of no further value to the uranium enrichment program. The relevant decision criteria are related to the optimum, or break-even, tails assay, which balances the costs of separative work and normal feed so as to minimize the total cost of the enriched product.

### **C.2.2.1 Break-even tails assays for natural uranium**

The economic objective for tails assay optimization is to minimize the overall cost of enriched uranium production by striking an optimum balance between feed and separative work costs. This balance is quantified as the optimum, or break-even, tails assay. The break-even tails assay (BETA) is a function of the ratio of feed costs to separative work costs and is completely independent of the enriched product assay. The origin and form of the break-even tails assay equation, as well as a plot of break-even tails assays versus cost ratio, are given in Appendix IV.

Partially depleted uranium at any assay greater than a given BETA is a candidate for recycle. That is, it may be economic to use it as partially depleted feed to the enrichment facilities to produce enriched product and depleted uranium at the BETA. Depleted uranium at an assay less than or equal to the BETA cannot be economically refed. The PDF assay must be a minimum increment above the BETA to make production costs for PDF attractive when compared to production costs for normal feed.

### **C.2.2.2 Partially depleted feed recycle economics**

When calculating the current BETA, the feed and separative work unit (SWU) costs used should be incremental costs that apply to the specific circumstances. For example, if separative work cost is \$100/SWU and feed cost is \$50/kgU as  $UF_6$ , the optimum tails assay is 0.30%. If the cost of feed climbs to \$75/kgU as  $UF_6$ , the optimum tails assay becomes 0.26%. However, DOE can currently produce SWUs at a marginal cost of about \$40/SWU. For DOE operating at the marginal SWU cost and paying \$50/kgU as  $UF_6$  for feed, then BETA is 0.20%. In the long term, it is conceivable that feed cost will escalate relative to SWU cost and will reduce BETA even further. For example, if feed cost is \$75/kgU and SWU cost is \$40/SWU, the BETA would be reduced to 0.16%.

### C2.2.3 Decision criteria for ultimate disposition

A final requirement for the DU management plan will be to determine a decision BETA to use for designating when DU becomes FDU and is ready to be converted for final disposition. Since a BETA can easily be determined at any point in time from current feed and SWU costs, the difficulty lies in determining how the BETA will change with time. The decision BETA must reflect changes anticipated in SWU production costs as well as feed costs over the operating lifetime of the enrichment enterprise. Consequently, selection of a decision BETA for UE is complicated by the expectation that AVLIS will replace gaseous diffusion as the DOE UE process. The AVLIS program will have significantly different economics than gaseous diffusion; so BETA for AVLIS will be different, and presumably lower, than BETA for diffusion. This clouds the decision on when to convert DU from  $UF_6$  and also affects the decision about what form the  $UF_6$  should be converted to. At present, it is not known which chemical form of uranium will be required by the AVLIS program. If, as expected, the AVLIS BETA (BETA-2) is lower than the diffusion BETA (BETA-1), then the decision tree would look like this:

- For DU above BETA-1, maintain the DU as  $UF_6$ , refeed to the GDPs, and strip to BETA-1.
- For DU above BETA-2 but at or below BETA-1, determine if it is desirable to feed it to AVLIS. If so, convert to the desired chemical form for AVLIS feed, refeed to AVLIS, and strip to BETA-2.
- For DU at or below BETA-2, convert to  $U_3O_8$  for ultimate disposition.

The AVLIS process uses uranium metal as the process medium; however, other chemical forms of uranium, including  $U_3O_8$ , are being considered for feed to the AVLIS site. The other forms would have to be converted to uranium metal at the AVLIS site for use in the process. If  $U_3O_8$  is acceptable for PDF delivery to AVLIS, then BETA-1 will be the only significant factor to consider for determining the assay at which to convert DU to  $U_3O_8$ . However, if  $U_3O_8$  is not acceptable for PDF delivered to AVLIS, then projecting the value of BETA-2 will be critical in determining the assay at which to convert to  $U_3O_8$  for long-term storage or disposal. It would be desirable to convert any DU that will be recycled to AVLIS directly from  $UF_6$  to the AVLIS feed compound to avoid double conversion costs.

A decision BETA can be determined for gaseous diffusion economics in the near term. However, a meaningful evaluation of a BETA for the AVLIS process cannot be made until that process nears commercialization. PDF inventories held for GDP recycle should be managed as  $UF_6$  to avoid the costs of chemical conversion to  $U_3O_8$  and then back to  $UF_6$  for GDP recycle. Therefore, it follows that a major campaign of converting DU from  $UF_6$  to  $U_3O_8$  should not be initiated until either  $U_3O_8$  is determined to be an acceptable feed source for AVLIS or a decision BETA is available based on AVLIS economics. This may not impact the start of the conversion campaign, however, since it will take several years to establish and implement the conversion program.

### C3 ULTIMATE DISPOSITION

The principal question addressed in this section is the safest form of uranium to use for ultimate disposition. Other topics addressed in this section are permanent disposal versus long-term storage as disposition options and a basis for cost recovery for the ultimate disposition of FDU.

#### C3.1 Optimum Form of Uranium for Ultimate Disposal

Environmental, safety, and health issues clearly favor  $U_3O_8$  as the uranium form for long-term storage or disposal of DU.  $U_3O_8$  is the most inert chemical form of uranium, can be stored safely, and has the lowest potential impact on people and the environment in the event storage or disposal facilities are abandoned in the future. Major advantages of  $U_3O_8$  are the relatively low chemical reactivity, solubility, and risks compared to alternate uranium forms.  $U_3O_8$  is insoluble even in weak acids and bases typically found in soils and groundwaters. A literature search has indicated that studies documented in foreign countries support the conclusion that  $U_3O_8$  is the preferred form for long-term disposition.<sup>12</sup> More details concerning risk characterization of alternate chemical forms of uranium can be found in Appendix II.

A major objective of a DU oxide conversion/disposition program should be to recover and recycle the fluorine. This is important both for economics and for minimizing waste for the industry as a whole. The French have demonstrated the commercial feasibility of recovering the fluorine, primarily as aqueous HF. However, the aqueous HF would likely be slightly contaminated with uranium and may not be marketable in this country. The most efficient way to utilize recovered HF would be in the conversion of natural uranium to  $UF_6$  for feed to the diffusion plants. Uranium contamination would not be a concern in this process. However, this conversion process requires anhydrous HF. Consequently, there is an imminent need to start development on a conversion process that will permit full recovery of fluorine as anhydrous HF. As backup, an effort should be made to develop a market for recovered aqueous HF.

#### C3.2 Other Chemical Conversion Options

Other chemical forms of uranium can certainly be handled and stored safely in an industrial environment and were evaluated as possible options. Those forms which were considered in addition to  $U_3O_8$  are uranium tetrafluoride ( $UF_4$ ), uranium dioxide ( $UO_2$ ), uranium trioxide ( $UO_3$ ), and uranium metal. The advantages that  $UF_4$  offers are that it is an intermediate in existing processes for the production of uranium metal, the fraction of recovered HF is easily recycled in the  $UF_4$  production process, existing commercial facilities

---

<sup>12</sup>M. F. Michallet, "A New Approach to Uranium Chemistry Completing the Nuclear Fuel Cycle," Canadian Nuclear Society, Proceedings—International Symposium on Uranium and Electricity, *The Complete Nuclear Fuel Cycle*, September 18–21, 1988, Saskatoon, Canada, K. H. Talbot and V. I. Lakshmanan, eds., ISBN 0-919784-16-X.

are readily expandable to meet the current GDP production rate of depleted uranium, and the cost of conversion (approximately \$2/kgU) is relatively low. A fully developed production process is already in use, and commercial facilities for converting  $UF_6$  to  $UF_4$  with capacities more than 4,000 MTU/year are in operation; so the implementation of this option could begin immediately. This capacity could readily be expanded to more than 25,000 MTU/year. Containers for the storage of the  $UF_4$  are currently in use, so experimentation and development of new containers would not be required. Protection from the elements is essential for proper storage, however, since  $UF_4$  reacts slowly with moist air, forming oxides and releasing corrosive HF.

Conversion of the DU to alternative oxide forms ( $UO_2$  or  $UO_3$ ) was another possibility considered. This option would permit recovery of virtually all of the fluorine content of the  $UF_6$  and would decrease the volume about 25% compared to  $UF_6$ . This would reduce the requirement and cost for containers and storage space. The oxides are relatively stable chemically, noncorrosive, and resistant to leaching by groundwater (see Appendix II).  $UO_2$  is more difficult to produce in the pure form and will hydrolyze in air at ambient temperatures.  $UO_2$  is the chemical form used for power reactor fuel, but powdered  $UO_2$  must be stabilized to prevent reaction with oxygen in air, which will cause  $U_2O_5$  to form.  $UO_2$  pellets sintered for reactor fuel show enhanced stability to further oxidation.

The final conversion form considered was uranium metal. Uranium metal is virtually insoluble in water, requires less storage space than the other forms (about 80% less than  $UF_6$ ), and is the only form of DU with an end use at the present time. Commercial conversion facilities are already in existence for processing  $UF_6$  into metal. However, known demands for metal will use only a small fraction of the DU being stockpiled; and the current commercial  $UF_6$ -to-uranium metal conversion process requires  $UF_6$  as an intermediate step. This double conversion ( $UF_6$  to  $UF_4$  then  $UF_4$  to uranium metal) requires increased handling costs over the more direct conversion options. It also involves a batch thermite bomb process that generates large quantities of contaminated  $MgF_2$  slag, which requires disposal as low-level waste (LLW). This process does not allow recovery of the majority of the fluorine in the depleted product, and the uranium metal "derby" product readily undergoes surface oxidation to  $U_2O_5$ . To prevent or minimize this oxidation, uranium metal placed in long-term storage would have to be given a protective coating. Even uranium metal ingots constitute a hazard in a sustained fire. Current U.S. metal capacity is more than 8,000 MTU/year, which is expandable to 12,000 MTU/year. The present cost of conversion to metal is greater than \$10/kgU, including the cost to convert to  $UF_6$ . The two-step process, along with the LLW disposal costs, are reflected in this conversion cost. The unit cost would be substantially reduced by a large-volume conversion program but would likely remain unattractive for disposition of the entire DU stockpile.

A detailed description of the processes for converting  $UF_6$  to other forms of uranium can be found in Appendix V.

### C3.3 Commercial Facilities

There are existing domestic commercial facilities for converting depleted  $UF_6$  to  $UF_4$  and  $UF_4$  to uranium metal (originally established for military applications). Table C1

summarizes the capacities of the three domestic facilities that are currently producing depleted  $UF_6$  and/or uranium metal and include current military commitments. The capacities are readily expandable, as indicated by facility management.

Domestic nuclear fuel fabricators also operate conversion facilities that use enriched  $UF_6$  to produce uranium dioxide. However, these are small-scale and expensive operations; and these companies have not expressed any interest in DU conversion. COGEMA, the French uranium processor with extensive experience with large-scale depleted  $UF_6$  conversion to  $U_3O_8$ , has expressed interest in doing conversion work for DOE.

Table C.1. Commercial capabilities				
Facility	$UF_6$ to $UF_6$		$UF_6$ to U metal	
	Current (MTU/year)	Expandable (MTU/year)	Current (MTU/year)	Expandable (MTU/year)
Aerojet Ordnance, Jonesboro, TN			3,000*	
Carolina Metals, Inc., Barnwell, SC	2,700	22,700	4,500	9,000
Sequoyah Fuels Corp., Gore, OK	3,400	6,800		
Total	6,100	29,500	7,500	9,000
*Capacity in excess of current commitments.				

A continuing program for converting depleted  $UF_6$  to  $UF_6$  or metal could maintain existing U.S. commercial facilities in a viable state and in a position to expand capacity quickly to meet future needs. Overall, some waste reduction for the uranium industry is currently being achieved through recovery of HF for recycle to the natural feed conversion process. However, HF recovery is not feasible from the thermite process now in use for reducing  $UF_6$  to metal. Direct conversion of  $UF_6$  to oxide would permit recovery of essentially all of the fluorine as aqueous HF, but no commercial process or facilities have been established in the United States. While AVLIS is based on uranium metal feed, current plans are to transport the material as oxide and then convert to and from the metal at the AVLIS plant site.

There are no existing commercial facilities in this hemisphere for the conversion of depleted  $UF_6$  to oxide. Current AVLIS planning is based on transportation of the feed material as oxide and conversion to metal at the AVLIS site. The AVLIS site may also include facilities for conversion of the enriched product from metal to oxide. Since similar facilities will be required for conversion of DU for ultimate storage, construction and operation of the disposition facilities should be integrated with construction and operation of enrichment facilities to the extent feasible.

### C3.4 Permanent Disposal Versus Long-term Storage

The major DU management question remaining is whether the ultimate disposition of FDU should be permanent disposal or long-term retrievable storage. The cost of disposal versus that of long-term retrievable storage and philosophical considerations will form the basis for making that decision. This section addresses the cost for permanent disposal compared to that of long-term storage, including the cost of converting to  $U_3O_8$ .

By far the greatest cost associated with ultimate disposition of DU is the conversion of  $UF_6$  from the GDPs or of uranium metal from AVLIS to  $U_3O_8$ . Since the French process is the only available commercial process for  $UF_6$  conversion to  $U_3O_8$ , the best estimate of conversion cost is provided by their information. A cost of 22 French francs/kgU (\$4.20/kgU) for this conversion, assuming recovery and credit for the fluorine, has recently been quoted by French sources.<sup>13</sup> An earlier communication had indicated a conversion cost of 17 French francs/kgU,<sup>14</sup> which is equivalent to \$3.30/kgU.<sup>15</sup> The difference between the two values could represent profit margin, cost escalation, rate of exchange anomalies, or a combination of all these factors. The higher number (\$4.20/kgU) is considered more sound as the basis for estimating disposal costs since it was obtained more recently.

The second largest cost for ultimate disposition is expected to be for disposal or permanent storage. This cost is estimated utilizing the waste disposal fees at the two government disposal sites, the Nevada Test Site (NTS) near Las Vegas and the Hanford site in Washington. Information from a waste acceptance seminar at Hanford and discussions with personnel at Hanford and at NTS provided waste disposal criteria and costs. Personnel at both sites agreed that  $UF_6$  is not acceptable for permanent disposal since it is reactive if released to the environment. It was also agreed that  $U_3O_8$  is an acceptable uranium disposal form. NTS currently charges \$9/ft<sup>3</sup> for disposal of LLW, while Hanford's fee is \$35/ft<sup>3</sup>. These fees are for containerized disposal and are calculated for the total volume of the waste package. Therefore, even with efficient packaging, low-density  $U_3O_8$  (Appendix II) would cost about \$0.25/kgU for NTS disposal and about \$1.00/kgU for disposal at Hanford. Personnel at both sites cautioned, however, that rapidly changing regulations and disposal requirements made it impossible to project disposal fees, even for the near future. The higher-cost disposal option (\$1.00/kgU) is therefore seen as a prudent basis for current estimates of disposal costs.

Other costs associated with the ultimate disposition of FDU are handling, packaging, transportation, and storage costs. Packaging and handling costs should be similar whether the ultimate disposition is permanent disposal or long-term storage. Transportation costs would be very dependent on the location of the AVLIS plant, conversion facilities, and the ultimate disposal or storage sites with respect to the Paducah GDP site. Since the sites for these new facilities have not been selected, a precise estimate of transportation costs is not

---

<sup>13</sup>R. H. Dyer, DOE/ORO, Oak Ridge, Tennessee, letter to J. W. Parks, "Plant Visit to French Tails Defluorination Facility," dated May 1, 1990.

<sup>14</sup>R. L. Hoglund, Martin Marietta International, Inc., Brussels, Belgium, letter to F. C. Huffman, "Enrichment Tails Forms," dated January 10, 1990.

<sup>15</sup>October 10, 1990, foreign exchange rate.

possible at this time. Rail transport cost estimates are based on a present cost of about \$5.500 for moving a flat car from Paducah to a west coast location. With a capacity of four or five storage cylinders per car, transportation costs therefore amount to about \$0.15/kgU when transported as UF<sub>6</sub> to the conversion plant/disposal site. Transportation costs are thus seen to add only a small increment to the total cost of permanent storage or disposal of DU. Without a detailed engineering analysis, there is no basis for estimating storage costs as being significantly different from those for permanent disposal. Therefore, the same \$1.00/kgU should be applied to the cost of long-term retrievable storage as U<sub>3</sub>O<sub>8</sub>. Total costs for disposal or storage of DU, therefore, amount to approximately \$6.00/kgU.

### C3.5 Ultimate Disposition Plan

Since there are no existing domestic facilities and no spare capacity in existing French facilities for conversion of UF<sub>6</sub>/uranium metal to U<sub>3</sub>O<sub>8</sub>, eventually a plan will have to provide for the establishment of these facilities. Either a suitable process will have to be developed, or the technology will have to be purchased. There are several options for the development and operation of a government DU disposition program. The viable options are as follows:

- Develop an in-house conversion process that permits fluorine recovery as anhydrous HF; construct government-owned, contractor-operated conversion and storage facilities.
- Same as above, but use joint DOE/private industry process development. This would involve the establishment of a cooperative research and development agreement (CRADA) with an interested private industry partner.
- Contract with private industry for UF<sub>6</sub>/uranium metal to U<sub>3</sub>O<sub>8</sub> conversion service; construct government-owned, contractor-operated storage facilities.
- Utilize the French conversion process; construct government-owned, contractor-operated conversion and storage facilities.
- Contract with the French uranium processor (COGEMA) for DU conversion service; construct government-owned, contractor-operated storage facilities.

All of these options should be pursued with the objective of selecting the most cost-effective option for a complete long-term DU disposition program. DOE should also promote the sale of DU to help reduce the disposition cost liability.

Several support activities would also facilitate management decision-making on the structure of the disposition program. Process development would be necessary to obtain cost information for comparison with the licensing and contracting options. Since transportation and inventory maintenance costs will be a significant, but controllable, contributor to the overall cost, the early site selection for AVLIS, the conversion facilities, and the permanent DU storage site would permit optimum placement of inventories to minimize costs. The advanced completion of the conceptual design of retrievable storage facilities for the permanent disposition of the U<sub>3</sub>O<sub>8</sub> would also aid the site selection process.

## D. CONCLUSIONS

The most important conclusions that are apparent from the legal/regulatory review and from the technical/economic study are as follows:

- Under existing laws and regulations, DOE is free to manage the DU resource (PDF) for the benefit of its uranium enrichment program until it becomes fully depleted of economically recoverable  $^{235}\text{U}$ .
- A DU inventory management plan is needed which provides for periodic cylinder inspections and steps for upgrading  $\text{UF}_6$  cylinders and storage yards.
- Indoor storage of DU cylinders could be costly and is unnecessary.
- The ultimate disposition form of FDU which is determined to be surplus to UE and defense needs should be as  $\text{U}_3\text{O}_8$  in long-term, retrievable storage as a national FDU reserve for the potential benefit of future generations.
- Stewardship of a national FDU reserve transcends the mission of DOE as presently defined and has not been addressed in the political/legislative arena.

## **E. RECOMMENDATIONS**

Our DU management recommendations are given below in categories of general, working inventory management, and long-term disposition.

### **I. GENERAL**

- Use "depleted uranium" or "DU" terminology in preference to "tails" or "waste" whenever possible.
- Support ongoing commercial and military uses of DU, for example, the stockpiling of DU for national defense applications.
- Promote and support the development of new and innovative uses of DU.

### **II. DU WORKING INVENTORY MANAGEMENT PLAN**

- Immediately implement a cylinder inspection program. This program should provide for semiannual inspection of cylinders.
- Evaluate protective coating options for new cylinders as well as old cylinders currently in storage and upgrade protective coating requirements for new cylinders.
- Establish criteria for upgraded cylinder storage facilities. This should include an evaluation of cost savings for DU inventory consolidation at one or two sites.
- Design and construct improved storage facilities when criteria are completed.
- Evaluate the economic break-even tails assay for gaseous diffusion (BETA-1) and consolidate inventories above this assay at Paducah for future recycle. Evaluate BETA-2 for the AVLIS process as a preliminary guideline on FDU inventories.
- Periodically update the break-even tails assay evaluations (BETA-1 and BETA-2) for operational and envisioned future enrichment facilities; maintain inventory figures for the respective categories of DU.
- Reevaluate the DU inventory management program when process economics and chemical conversion steps for AVLIS are determined.
- Continue monitoring legislative/regulatory developments for possible implications related to DOE inventory management practices.
- Consolidate, review, and update all safety assessments to provide a single document that applies to all storage facilities.

- On each of the above recommendations, perform a benefit/risk/cost analysis to develop an appropriate schedule of implementation.

### III. ULTIMATE DISPOSITION PLAN

- Initiate long-range planning for converting FDU to  $U_3O_8$  and for retrievable storage. This includes the following:
  - Determining when to start development work on full fluorine recovery from the conversion process and exploring the possibility of using the CRADA joint venture approach for process development.
  - Exploring possibilities of utilizing the French process and for contracting for chemical conversion of DU by private industry.
  - Conceptual design study of a retrievable storage facility, including an evaluation of single-site versus multi-site facilities.
  - Exploring the parameters for a site selection process for a  $UF_6/U_3O_8$  conversion facility and retrievable storage facility.
- Implement FDU conversion program when facilities are readied.
- Design and implement PDF feed options that will recover DU storage and disposition costs. Options include the following:
  - GDP recycle at marginal SWU cost for uncommitted (last 30%) commercial requirements.
  - Recycle as feed for military demands.
  - Alternative feed source for AVLIS enrichment.
- Explore the possibility of a new, independently funded government program for long-term, retrievable storage of FDU as a backup option.

**Appendix I REGULATORY ANALYSIS OF DEPLETED URANIUM**



## Department of Energy

Oak Ridge Operations  
P.O. Box 2001  
Oak Ridge, Tennessee 37831-9510

October 29, 1990

Dr. Richard Shank  
Director, Ohio Environmental  
Protection Agency  
1800 Watermark Drive  
Post Office Box 1049  
Columbus, Ohio 43266-1049

Dear Dr. Shank:

Representatives of the Department of Energy (DOE) and your staff met in Columbus on October 12, 1990, to discuss a number of issues involving the Portsmouth Gaseous Diffusion Plant (PORTS) in Piketon, Ohio. I understand that progress was made toward resolution of a number of issues confronting our agencies.

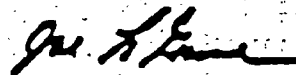
A most important issue was raised by your staff in a recent letter from the Southeast District Office of Ohio Environmental Protection Agency (OEPA) to the effect that cylinders of depleted uranium at PORTS were no longer exempt from regulation as a hazardous waste under OAC 3745-51-04. The cylinders of depleted uranium hexafluoride are exempt from regulation because uranium hexafluoride is "source material" under the Atomic Energy Act of 1954, as amended (68 Stat. 923) [42 U.S.C. § 2011 et seq.]. Your staff requested that we provide our position in a letter so that you could give it full and due consideration. The enclosed analysis is provided in response to that request.

In order for you to become more familiar with the safety practices followed by us in storing depleted uranium at PORTS, we would welcome you and any of your representatives to the facility to inspect the cylinders and discuss storage practices with PORTS personnel. We would also provide a briefing concerning the studies we have undertaken to review our storage practices including the experimental and analytical work underway to evaluate the remaining useful life of the cylinders and the investigation concerning the two cylinders found to have holes. We want to demonstrate to you our continuing concern that the depleted uranium is safely stored and handled.

October 29, 1990

Finally, I understand that you expressed an interest in the funding status for the activities planned for PORTS. We are evaluating options to transfer funds from other work to PORTS for the completion of the activities planned for fiscal year 1991. This evaluation of funding alternatives is based on closure options submitted to and approved by OEPA. It does not include the additional cost if more expensive options are utilized. If problems arise, we will be in touch with you or your staff as soon as we identify them.

Sincerely,



Joe La Grone  
Manager

Enclosure:

"Regulatory Analysis of  
Depleted Uranium Stored  
at DOE PORTS Facility"

cc w/enclosure:

William Young, NE-1, Forst  
Richard A Claytor, DP-1, Forst  
Leo Duffy, EM-1, Forst  
Paul Ziemer, EH-1, Forst  
Stephen Wakefield, GC-1, Forst  
Steven Blush, NS-1, Forst

**REGULATORY ANALYSIS  
OF  
DEPLETED URANIUM  
STORED AT DOE PORTS FACILITY**

Depleted uranium is generated by the gaseous diffusion process used to enrich uranium. The gaseous diffusion process uses uranium hexafluoride (UF<sub>6</sub>) containing 0.7 percent U-235 as feed material. The feed material, which arrives in cylinders in solid form, is heated in its cylinder to a gaseous state and fed into a cascade, which consists of a series of compressors and separation barriers. By physical separation only, the cascade increases the percent of U-235 in the UF<sub>6</sub> product stream typically from 0.7 to 3-4%. No chemical substances are added or used in this process. While a portion of the UF<sub>6</sub> feed material is enriched in U-235, the remainder becomes depleted in U-235 to a concentration less than 0.7 percent. This material consists solely of UF<sub>6</sub>, and no chemicals or other substances are added to it prior to storage. The solid depleted uranium is stored in steel cylinders and maintained by DOE as inventory, because it is capable of being used as feed material to produce enriched uranium. The depleted uranium is not corrosive to the steel cylinders used for storage.

Depleted uranium is a "source material" subject to regulation under the Atomic Energy Act of 1954 (AEA), as amended. Section 11(z) of the AEA, as amended [42 U.S.C. § 2014(z)] defines "source material" as follows:

The term "source material" means (1) uranium, thorium, or any other material which is determined by the [Atomic Energy] Commission pursuant to the provisions of section 61 to be source material; or (2) ores containing one or more of the foregoing materials, in such concentration as the Commission may by regulation determine from time to time. (Emphasis added.)

Section 61 of the AEA, as amended, authorized the Atomic Energy Commission to define the term "source material." The Atomic Energy Commission promulgated the following regulatory definition at 10 C.F.R. 40.4:

"Source material" means (1) uranium or thorium, or any combination thereof, in any physical or chemical form; or (2) ores which contain by weight one-twentieth of one percent (0.5%) or more of: (i) uranium; (ii) thorium; or (iii) any combination thereof. Source material does not include special nuclear material. (Emphasis added.)

The Atomic Energy Commission further defined the term "depleted uranium" at 10 C.F.R. § 40.4(o) as follows:

"Depleted uranium" means the source material uranium in which the isotope uranium-235 is less than 0.711 weight percent total uranium present. Depleted uranium does not include special nuclear material. (Emphasis added.)

Consistent with these definitions, DOE treats depleted uranium as source material.

Materials defined as "source material" under the AEA are not hazardous wastes. Under the federal system of regulation of hazardous waste, a material must first be defined as a "solid waste" before it may be regulated as a "hazardous waste." 42 U.S.C. § 6903(5). Section 1004(27) of the Resource Conservation and Recovery Act of 1976 (RCRA), as amended [42 U.S.C. § 6903(27)], excludes source material from the definition of "solid waste":

The term "solid waste" . . . does not include . . . source, special nuclear or byproduct material as defined by the Atomic Energy Act of 1954, as amended (68 Stat. 923) [42 U.S.C. § 2001 et seq.].

In regulations (40 C.F.R. § 261.4) implementing the RCRA, the U.S. Environmental Protection Agency (USEPA) states the exclusion as follows:

The following materials are not solid wastes for the purpose of this part:

- (4) Source, special nuclear or byproduct material as defined by the Atomic Energy Act of 1954, as amended, 42 U.S.C. 2011 et seq.

Consistent with the federal framework, the Ohio Legislature has excluded source material from the definition of hazardous waste. Section 3734.01(J)(2) of the Ohio Revised Code provides:

Hazardous waste includes any substance identified by regulation as hazardous waste under the "Resource Conservation and Recovery Act of 1976," 90 Stat. 2806, 42 U.S.C. 6921, as amended, and does not include any substance that is subject to the Atomic Energy Act of 1954." 68 Stat., 919. 42 U.S.C. 2011. (Emphasis added.)

Source material clearly is a substance that is subject to the AEA. Therefore, depleted uranium, having been defined by the Atomic Energy Commission as a source material, is not a hazardous waste under Ohio law.

The depleted uranium stored at PORTS also is not a mixed waste subject to regulation as a hazardous waste, because the depleted uranium is not mixed with a RCRA hazardous waste. There is no other material, waste or otherwise, in the storage cylinders of uranium hexafluoride.

USEPA announced its mixed waste policy in the Federal Register on July 3, 1986 (51 FR 24504). That policy and subsequent clarifications issued by USEPA indicate that USEPA intended to regulated as "mixed wastes" those radioactive materials that become mixed with a non-AEA material that is a hazardous waste. Radioactive materials, such as the depleted uranium stored at our Portsmouth facility, that have not been mixed with a non-AEA material that is a hazardous waste are not considered "mixed wastes" regulated by RCRA. See "Guidance on Identification of Low-Level Radioactive and Hazardous Waste," 52 FR 11147.

In summary, the UF<sub>6</sub> tails qualify as "source material" under the AEA. Source materials are exempt from regulation under RCRA and Ohio law by statute. USEPA's "mixed waste" policy does not apply to depleted uranium, because this material has not been mixed with a listed hazardous waste or non-AEA material which exhibits a hazardous waste characteristic.

**Appendix II RISK CHARACTERIZATION OF ALTERNATE  
CHEMICAL FORMS OF URANIUM**

## Appendix II RISK CHARACTERIZATION OF ALTERNATE CHEMICAL FORMS OF URANIUM

Depleted uranium is presently contained as solid  $UF_6$  in thin-walled steel cylinders that are stored outdoors exposed to the elements. Although  $UF_6$  can be handled and stored safely in a well-managed industrial environment, other uranium compounds or uranium metal may be more appropriate for long-term storage or permanent disposal in a less structured environment. Other potential storage forms besides  $UF_6$  include  $UF_4$ ,  $UO_2$ ,  $U_3O_8$ ,  $UO_3$ , and uranium metal.

It is the purpose of this appendix to discuss the risks associated with each of these storage forms.

### A. PHYSICAL PROPERTIES

Those physical properties of interest for risk assessment of the pertinent depleted uranium storage options are shown in Table II.1.<sup>1,2</sup>

#### A.1 Uranium Hexafluoride<sup>3,4</sup>

Solid  $UF_6$  is readily transformed into the gaseous or liquid states by application of heat.

All three phases—solid, liquid, and gas—coexist at 64°C (the triple point). Or, the gaseous phase exists above 230°C (the critical temperature) at which the critical pressure is 4.61 MPa. The vapor pressure above the solid reaches 1 atm (0.1 MPa) at 56°C, the sublimation temperature.

A large decrease in  $UF_6$  density occurs in changing from the solid to the liquid state, which results in a large increase in volume. The thermal expansion of the liquid with increasing temperature is also high. It is always essential to maintain control of the total mass and physical state of  $UF_6$  throughout an operation cycle. When restricted volumes such as traps and containers are filled with  $UF_6$ , full allowance must be made for the volume changes that will arise over the working temperature range to which the vessels will be subjected in order to avoid hydraulic rupture.

Since the sublimation temperature lies below the triple point, the pressure must be in excess of 0.15 MPa (1.5 atm), and the temperature must be above 64°C for  $UF_6$  to be handled as a liquid. Thus, any process using liquid  $UF_6$  is above atmospheric pressure and will be subject to a potential leakage of  $UF_6$  to the environment, with vapor loss and cooling occurring simultaneously. Solidification occurs exothermically when the pressure falls below 1.5 × atmospheric. Thus, if a cylinder heated above the triple point is breached, a rapid outflow of the  $UF_6$  occurs until the pressure drops sufficiently to start the solidification process. The rate of outflow then decreases but continues until the contents cool to about 56°C,

which is the atmospheric sublimation temperature. Some release of material may continue, depending on the type and location of the breach.

Table II.1. Physical properties of pertinent uranium compounds

Compound	Melting point (°C)	Density, g/cm <sup>3</sup>		Solubility in H <sub>2</sub> O <sup>b</sup>
		Crystal	Bulk <sup>a</sup>	
UF <sub>6</sub>	64.1	4.68	4.6	Decomposes to UO <sub>2</sub> F <sub>2</sub>
UF <sub>4</sub>	960 ± 5	6.7	2.0-4.5	Very slightly soluble
UO <sub>3</sub>	Decomposes to U <sub>3</sub> O <sub>8</sub> when heated	7.29	1.5-4.5	Insoluble
U <sub>3</sub> O <sub>8</sub>	Decomposes to UO <sub>2</sub> at 1300	8.30	1.5-4.0	Insoluble
UO <sub>2</sub>	2878 ± 20	10.96	2.0-5.0	Insoluble
U	1132	19.05	19	Insoluble

<sup>a</sup>Bulk densities of UF<sub>4</sub>, UO<sub>3</sub>, U<sub>3</sub>O<sub>8</sub>, and UO<sub>2</sub> are highly variable, depending on the production process and the properties of the starting uranium compounds.

<sup>b</sup>At ambient temperature.

UF<sub>6</sub> is hygroscopic and will decompose to UO<sub>2</sub>F<sub>2</sub> immediately when in contact with H<sub>2</sub>O. When heated to decomposition, UF<sub>6</sub> emits toxic fluoride fumes.

#### A.2 Uranyl Fluoride

UO<sub>2</sub>F<sub>2</sub> is very soluble in H<sub>2</sub>O. When heated to decomposition, UO<sub>2</sub>F<sub>2</sub> emits toxic fluoride fumes.

#### A.3 Uranium Tetrafluoride

UF<sub>4</sub> is very slightly soluble in H<sub>2</sub>O.

#### A.4 Uranium Trioxide

When heated in air, UO<sub>3</sub> decomposes and converts to U<sub>3</sub>O<sub>8</sub>.

#### A.5 Uranium Oxide

When heated to 1300°C, U<sub>3</sub>O<sub>8</sub> decomposes and converts to UO<sub>2</sub>.

#### A.6 Uranium Dioxide

There are no hazardous physical properties that are significant.

#### A.7 Uranium Metal

There are no hazardous physical properties that are significant.

### B. CHEMICAL PROPERTIES

#### B.1 Uranium Hexafluoride<sup>2-7</sup>

UF<sub>6</sub> is a highly reactive material. It reacts with H<sub>2</sub>O to form the soluble reaction products uranyl fluoride (UO<sub>2</sub>F<sub>2</sub>) and hydrogen fluoride (HF), both of which are very toxic. Aqueous hydrogen fluoride is also an extremely corrosive acid.

When released to the atmosphere, gaseous UF<sub>6</sub> reacts with humidity to form a cloud of particulate UO<sub>2</sub>F<sub>2</sub> and HF fumes. The reaction is very fast and is dependent on the availability of water. Following a large-scale release of UF<sub>6</sub> in an open area, the dispersion is governed by meteorological conditions, and the plume could still contain unhydrolyzed material even after travelling a distance of several hundred meters. After hydrolysis, uranyl fluoride (UO<sub>2</sub>F<sub>2</sub>) can be deposited as a finely divided solid, while HF remains as part of the gas plume. External contact with HF results in chemical burns of the skin, while exposure to airborne HF causes chemical burns/irritation of the eyes, nose, and throat. Significant inhalation can result in pulmonary edema. Individuals can smell HF at levels of 0.02–0.2 mg/m<sup>3</sup>. The threshold limit value (TLV) of HF is 2.5 mg/m<sup>3</sup>. No person can tolerate an airborne concentration of 10 mg/m<sup>3</sup>. Exposure for as little as 15 min to an airborne concentration of 20–30 mg/m<sup>3</sup> may prove fatal (pulmonary edema).

In enclosed situations, the reaction products form a dense fog, seriously reducing visibility for occupants of the area and hindering evacuation and emergency response. Fog can occur in unconfined areas if the humidity is high.

In a fire, the reaction of UF<sub>6</sub> with water is accelerated because of the increased UF<sub>6</sub> vapor pressure and the large quantities of H<sub>2</sub>O formed in combustion of organic materials or hydrocarbons. Reaction of liquid UF<sub>6</sub> with hydrocarbon vapors is extremely vigorous in flames, with formation of UF<sub>6</sub> and low-molecular-weight fluorinated compounds. More heat is generally released in these hydrocarbon interactions with UF<sub>6</sub> than in the corresponding reactions of hydrocarbons with O<sub>2</sub>.

#### B.2 Uranyl Fluoride<sup>8</sup>

UO<sub>2</sub>F<sub>2</sub> is a yellow hygroscopic solid that is very soluble in water.

In accidental releases of  $UF_6$ ,  $UO_2F_2$  as a solid particulate compound may deposit on the ground over a large area. There are no internationally accepted values for uranium contamination levels for uncontrolled residence. However, the value of  $0.38 \text{ Bq/cm}^2$  ( $10^{-3} \text{ } \mu\text{Ci/cm}^2$ ) is accepted in many countries for unlimited occupancy of uncontrolled areas. This is equivalent to a ground concentration of approximately  $0.1 \text{ g/m}^2$  for natural uranium.

### B.3 Uranium Tetrafluoride

$UF_6$  reacts slowly with moisture at ambient temperature, forming  $UO_2$  and  $HF$ .

### B.4 Uranium Trioxide

There are no hazardous chemical properties that are significant.

### B.5 Uranium Oxide

There are no hazardous chemical properties that are significant.

### B.6 Uranium Dioxide

$UO_2$  will ignite spontaneously in heated air and burn brilliantly. It will slowly convert to  $U_3O_8$  in air at ambient temperature. Its stability in air can be improved by sintering the powder in hydrogen.

### B.7 Uranium Metal

Uranium powder or chips will ignite spontaneously in air at ambient temperature. During storage, uranium ingots can form a pyrophoric surface because of reaction with air and moisture. It will also react with water at ambient temperature, forming  $UO_2$  and  $UH_3$ . The metal swells and disintegrates. Hydrogen gas can be released.

Solid uranium, either as chips or dust, is a very dangerous fire hazard when exposed to heat or flame.

Uranium can react violently with  $Cl_2$ ,  $F_2$ ,  $HNO_3$ ,  $Se$ ,  $S$ ,  $NH_3$ ,  $BrF_3$ , trichlorethylene, or nitryl fluoride and similar compounds.

## C. CHEMICAL CONVERSION

The risks involved in converting  $UF_6$  to other chemical forms for storage or disposal are relatively small. The processes involved in chemical conversion include transporting the cylinders of solid  $UF_6$  to the conversion facility, emptying the  $UF_6$  cylinders, performing the chemical conversion, packaging the final product, transporting to the storage or disposal location, and monitoring of this location.

Aside from nuclear considerations,  $UF_6$  can be safely handled in essentially the same manner as any other corrosive and/or toxic industrial chemical. With good procedures and careful, attentive operations, handling depleted  $UF_6$  is a comparatively low-risk operation. Safe handling procedures have been developed and evaluated in DOE and commercial facilities during the more than 40 years of experience in handling vast quantities of  $UF_6$ .

Risks due to transporting solid  $UF_6$  are small. Transporting cylinders of depleted  $UF_6$  for conversion or disposal entails a slightly increased risk of release because of the possibility of a vehicle accident. However, a rapid release of  $UF_6$  is not likely unless an accident is accompanied by a sustained fire engulfing the cylinder. Risks for chemical conversion are also likely to be small, although they depend heavily on the chemical conversion route and specific process being considered, as well as the design and operation of the conversion facility. Several companies, both in the United States and abroad, routinely convert depleted  $UF_6$  to a variety of other chemical forms. Some special precautions are required when emptying  $UF_6$  cylinders that have been in storage for many years. Used storage cylinders and valves must be carefully inspected for corrosion or damage prior to transport or heating. In some old cylinders, a slight possibility exists that hydrocarbons may have contaminated the cylinder. Some hydrocarbons react violently with liquid  $UF_6$ .

As discussed above, all of the alternative forms of uranium listed, except for the oxides, exhibit some hazardous characteristics. Because of their stability, noncorrosiveness, and resistance to leaching, the oxides,  $U_3O_8$  in particular, are the most desirable chemical forms for long-term storage or disposal from an environmental and safety point of view.

#### D. RADIOACTIVITY

Depleted uranium differs from natural uranium only in that it contains less  $^{235}U$  and  $^{234}U$  than natural uranium. The specific activity of any given lot of DU will be dependent on the isotopic makeup of that material; for example, the specific activity of DU with 0.45 wt %  $^{235}U$  is only 70.8% the specific activity of natural uranium (see Table 173.434 in CFR 49). DU with less  $^{235}U$  would have an even lower specific activity. The radiation exposure varies greatly depending on its physical form but not significantly due to the chemical form. The radiation exposure also varies depending on whether the uranium is enclosed in a container.

It is the policy of DOE to implement radiation protection standards consistent with presidential guidance to federal agencies. According to DOE Order 5480.11, Radiation Protection for Occupational Workers,<sup>8</sup> the limiting value of the annual effective dose equivalent is 5 rem for occupational workers and 0.1 rem for the public.

Those who have worked with depleted uranium for long periods of time have had no difficulty meeting DOE policies as long as the depleted uranium is stored in a controlled area and the operating personnel limit their residence time in the controlled area. At GenCorp's Aerojet Ordnance Tennessee facility in Jonesboro, Tennessee, those handling large quantities of unenclosed depleted uranium have experienced penetrating radiation exposures of 60 to 260 mrem/year.<sup>9</sup> The average for the

approximately 100 occupational workers is 115 mrem/year. Surface surveys of several 48-in. storage cylinders filled with depleted UF<sub>6</sub> (0.2% <sup>235</sup>U) at DOE's gaseous diffusion plant in Paducah, Kentucky, gave dose rates of 10.5–12.25 rem/year.<sup>10</sup> Measurements of filled 48-in. shipping cylinders containing depleted UF<sub>6</sub> (0.2% <sup>235</sup>U) at NUKEM in Hanau, Germany, gave dose rates of 12.25–30.6 rem/year, depending on the wall thickness of the cylinders.<sup>11</sup> For a large UF<sub>6</sub> storage facility, these surface dose rates would require a controlled area of about 3 m around the cylinders in order to meet DOE's limiting value of radiation for occupational workers.

Sequoyah Fuels Corporation of Gore, Oklahoma, experienced surface radiation readings as high as 1000 mR/h after emptying Paducah GDP UF<sub>6</sub> tails cylinders.<sup>12</sup> These high readings were due to the <sup>235</sup>U decay products, <sup>231</sup>Th and <sup>231</sup>Pa, which emit more penetrating beta and gamma radiation. When UF<sub>6</sub> is vaporized from a vessel or transport cylinder, these nonvolatile decay products remain and can concentrate at surfaces. Without the shielding and absorption of the bulk UF<sub>6</sub>, the gamma radiation levels are much higher immediately after emptying than for the filled vessel. However, the radiation level decreases with time relative to the half-lives of <sup>231</sup>Th and <sup>231</sup>Pa, which are 24.1 days and 1.17 min, respectively. Acceptable dose rates are reached in a few months.

#### E. TOXICITY

Uranium is a highly toxic element on an acute basis.<sup>6</sup> It is chemically toxic to kidneys, and high exposure to soluble (transportable) compounds can result in renal injury. In addition, intake of uranium must not exceed the radiological limits discussed in Sect. II.C. The transportability of an inhaled or ingested material determines its fate within the body and therefore the resulting internal radiological dose or chemical effect. Table II.2 lists potential inhaled depleted uranium storage forms and their assigned transportability classes.<sup>7</sup> Airborne concentration limits for transportable uranium have been set by the NRC and the American Conference of Governmental Industrial Hygienists (ACGIH) at 0.2 mg/m<sup>3</sup>. At this airborne concentration, all inhaled or ingested storage forms of depleted uranium, except high-fired UO<sub>2</sub>, reach the threshold limit of chemical toxicity before they reach the threshold limit of radiotoxicity.

#### F. CRITICALITY

Depleted uranium in any form will be criticality safe in any configuration.<sup>13</sup>

#### G. SUMMARY

Both the positive and negative features of potential storage forms of uranium are summarized in Table II.3. The forms of uranium are listed in preferred order in regard to storage hazards.

Table II.2. Inhalation classification for depleted uranium storage forms

Storage form	Abbreviation	Inhalation solubility class <sup>a</sup>
Uranium hexafluoride	UF <sub>6</sub>	Class "D"
Uranyl fluoride	UO <sub>2</sub> F <sub>2</sub>	Class "D"
Uranium trioxide	UO <sub>3</sub>	Class "D"
Uranium tetrafluoride	UF <sub>4</sub>	Class "W"
Uranium oxide <sup>b</sup>	U <sub>3</sub> O <sub>8</sub>	Class "W"
Uranium dioxide <sup>b</sup>	UO <sub>2</sub>	Class "W"
High-fired uranium dioxide <sup>b</sup>	UO <sub>2</sub>	Class "Y"

"D," "W," and "Y" are inhalation solubility classes established by the International Commission on Radiological Protection. "D" class material is very soluble; lung retention time is days. "W" class material is moderately soluble; lung retention time is weeks. "Y" class material is relatively insoluble; lung retention time is years.<sup>a</sup>

<sup>a</sup>The solubility of uranium oxides is very dependent on heat treatment.

Table II.3. Summary of positive and negative features for alternate uranium storage<sup>a</sup>

Feature	U <sub>3</sub> O <sub>8</sub>	UO <sub>2</sub> <sup>b</sup>	UO <sub>3</sub>	UF <sub>4</sub>	U <sub>metal</sub>	UF <sub>6</sub>
Reactive	++ <sup>c</sup>	++	++ <sup>d</sup>	+	+	--
Ignitable	++	+	++	++	-	++
Corrosive	++	++	++	++ <sup>e</sup>	+	++ <sup>e</sup>
Soluble	++	++	++	+	++	NA
Radiotoxicity <sup>f</sup>	NA	-	NA	NA	NA	NA
Chemical toxicity <sup>g</sup>	-	NA	--	-	--	--
Containment <sup>h</sup>	++	+	++	-	-	--

<sup>a</sup>Symbols used: ++, strong positive feature; +, positive feature; -, negative feature; --, strong negative feature; NA, not applicable.

<sup>b</sup>Sintered at high temperature.

<sup>c</sup>Decomposes to UO<sub>2</sub> at 1300°C.

<sup>d</sup>Decomposes to U<sub>3</sub>O<sub>8</sub> when heated.

<sup>e</sup>Reaction with H<sub>2</sub>O releases HF, which is very corrosive.

<sup>f</sup>Decomposes to UO<sub>2</sub>F<sub>2</sub> and HF when exposed to H<sub>2</sub>O.

<sup>g</sup>Depleted uranium forms are dependent upon TLV (threshold limit value) and are either radiotoxic or chemically toxic but not both.

<sup>h</sup>Container integrity requirement is considered to be a negative feature.

## H. REFERENCES

1. Chemical Rubber Company, *CRC Handbook of Chemistry and Physics*, 67th Ed., Robert C. Weast, Editor-in-Chief, CRC Press, Inc., Boca Raton, Fla., 1986.
2. *Lange's Handbook of Chemistry*, 13th Ed., J. A. Dean, Ed., McGraw-Hill Book Company, New York, 1985.
3. S. M. Leone et al., *Long-Term Disposal of Enrichment Plant Tails*, K/ET-131, Martin Marietta Energy Systems, Inc., ORGDP, December 1978.
4. U.S. Department of Energy, *Uranium Hexafluoride: Handling Procedures and Container Descriptions*, ORO-651, Rev. 5, U.S.DOE, Oak Ridge Operations Office, September 1987.
5. International Atomic Energy Agency, *A Guidebook to Safe Production, Transportation, Handling, and Storage of UF<sub>6</sub>*, 2nd Draft, Proposed, IAEA, Vienna, Austria, to be issued.
6. N. I. Sax and R. J. Lewis, Sr., *Dangerous Properties of Industrial Materials*, Vol. III, 7th Ed., Van Nostrand Reinhold, New York, 1989.
7. U.S. Department of Energy, *Health Physics Manual of Good Practices for Uranium Facilities*, EGG-2530, Idaho Falls, Idaho, June 1988.
8. U.S. Department of Energy, "Radiation Protection for Occupational Workers," DOE Order 5480.11, Washington, D.C., Dec. 21, 1988.
9. G. V. Bowling, GenCorp Aerojet, Jonesboro, Tenn., letter to T. R. Lemons, Martin Marietta Energy Systems, Inc., Oak Ridge, Tenn., describing handling of depleted uranium at Aerojet Ordnance Tennessee plant, received May 1990.
10. C. D. Ecklund, Martin Marietta Energy Systems, Paducah, Ky., facsimile to Ray Pearson, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., Oak Ridge, Tenn., "Nuclear Materials Tally-out Sheets," dated May 16, 1990.
11. L. Aumueller and J. Hermann, *Accumulation, Use, Storage, and Final Disposal of Depleted Uranium*, NUKEM-292, November 1977.
12. D. R. Allen, Martin Marietta Energy Systems, Paducah, Ky., to J. R. Story, Martin Marietta Energy Systems, Paducah, Ky., Occurrence Report, #MMES-90-58-PAD-90-3, entitled "UF<sub>6</sub> Tails Cylinder High Radiation," July 26, 1990.
13. J. L. Feuerbacher, *Nuclear Safety Guide for the Portsmouth Gaseous Diffusion Plant*, GAT-225, Rev. 4, Goodyear Atomic Corp., Piketon, Ohio, March 1981.

### Appendix III INDOOR STORAGE OF UF<sub>6</sub>

### Appendix III. INDOOR STORAGE OF UF<sub>6</sub>

The principal advantage of indoor storage of cylinders containing UF<sub>6</sub> is the prevention of continuous exposure to the elements, which could reduce the corrosion rate or extend the times between repainting cylinders and thus reduce overall handling and maintenance costs. Two types of indoor storage were briefly examined: currently available facilities and new buildings. With the limitations inherent in the use of existing building space and the sophistication required in atmosphere control in new buildings, indoor storage of DU as UF<sub>6</sub> appears to be considerably more costly than upgraded outdoor storage.

#### EXISTING BUILDINGS

Large areas are available for development of alternate uses in no-longer-used process buildings at Portsmouth and Oak Ridge. These buildings present possibly attractive sites for long-term storage of PDF cylinders. The K-31 and K-33 building basements at Oak Ridge and the Portsmouth centrifuge facility buildings contain enough area for all (Oak Ridge) or nearly all (Portsmouth) current storage cylinder inventories. A rather detailed engineering evaluation would have to be conducted to determine whether these areas are actually suited to cylinder storage. This evaluation would include the development and procurement of specialized handling equipment for cylinder transport over existing floors and placement in close quarters, adaptation of building ventilation systems to cope with possible leaks as well as for maintenance of low relative humidity to minimize corrosion, and emergency plans to deal with accidents in transport and placement of cylinders in storage.

Examination of building drawings shows that the storage density is seriously reduced by the presence of support columns, particularly in the K-25 diffusion process buildings. These columns also limit the maneuverability of any cylinder handling equipment employed in the storage task. Furthermore, ground floor loading limits would be severely taxed, if not exceeded, by existing handling equipment. Load limits on equipment floors of the K-25 buildings would not appear to permit storage of full cylinders in dense single-tier arrays. Less dense arrays might be feasible, however, particularly if the building cranes, which were used for installing and replacing the original process equipment, are still available. It should be noted that some of the K-25 process areas are presently being used for storage of wastes generated locally and at other DOE sites and are not presently available for UF<sub>6</sub> cylinder storage.

An additional requirement for indoor storage is that of humidity control. Seasonal temperature changes, and even a wide range in the diurnal cycle, can result in condensation of highly oxygenated (and thus highly corrosive) moisture on the cylinder surfaces, resulting in higher corrosive rates than those encountered in outside storage with freer air exchange. For effective reduction in the overall corrosion rates, a relative humidity level of less than 50% must be maintained, and this would probably require some level of temperature control as well.

Thus, while many of these adverse factors may be overcome through engineered design, it is evident that utilization of existing indoor space for DU storage as UF<sub>6</sub> would be very expensive. The need to provide ventilation facilities for management of material releases and for temperature and humidity control, the development and procurement of specialized cylinder handling equipment, and the decreased storage density requirement would appear to combine to drive the cost of indoor storage in existing facilities above that of upgraded outdoor facilities.

## NEW BUILDINGS

Storage in new buildings would appear to be more viable than use of existing buildings since the new buildings would be engineered to be compatible with the approved storage arrangements and the handling and maintenance operations. As envisioned, the buildings would be a "Butler-type," which would provide protection from the elements and would have humidity control. The buildings could be designed and engineered to optimize building size with the storage arrangement. A detailed cost evaluation would be required for a comparison with the use of existing buildings and with the present system of outdoor storage. A rough estimate of the cost of housing the Portsmouth DU inventory in Butler-type buildings is about \$100 million; scaling this up to accommodate the total three-site inventory of stored cylinders gives a capital cost of about \$360 million.

**Appendix IV. BREAK-EVEN TAILS ASSAYS**

#### Appendix IV. BREAK-EVEN TAILS ASSAYS

The economic objective of both DOE and its customers is to minimize the overall cost of enriched uranium production by striking an optimum balance between feed and separative work costs. This point is identified as the optimum or break-even tails assay (BETA). BETA is defined as the tails assay at which the cost of enriched product is minimized. The cost of enriched product comes primarily from two components: the cost of feed and the cost of separative work. If the derivative of the total cost of enriched product with respect to the tails assay is set equal to zero, the resulting equation defines the break-even tails assay. That equation is

$$\frac{C_{Feed}}{C_{SWU}} = V(x_f) - V(x_w) - (x_f - x_w) \cdot V'(x_w),$$

where

$C_{Feed}$  = cost of feed in dollars per kilogram of uranium,

$C_{SWU}$  = cost of SWU in dollars per kilogram SWU,

$x_f$  = feed assay in weight fraction  $^{235}\text{U}$ ,

$x_w$  = tails assay (BETA) in weight fraction  $^{235}\text{U}$ ,

and where

$$V(x) = (2 \cdot x - 1) \cdot \ln\left(\frac{x}{1-x}\right),$$

$$V'(x) = \left[ \frac{2 \cdot x - 1}{x \cdot (1-x)} \right] + 2 \cdot \ln\left(\frac{x}{1-x}\right).$$

This set of equations condenses to

$$\frac{C_{Feed}}{C_{SWU}} = (2 \cdot x_f - 1) \cdot \ln\left[\frac{x_f \cdot (1 - x_w)}{x_w \cdot (1 - x_f)}\right] + \left(1 - \frac{x_f}{x_w}\right) \cdot \left(\frac{2 \cdot x_w - 1}{1 - x_w}\right).$$

Note that, for a given feed assay, the break-even tails assay is a function of the ratio of feed costs to separative work costs and is completely independent of the enriched product assay. Since the normal uranium feed assay (0.711%  $^{235}\text{U}$ ) is essentially a constant of nature, BETA becomes a direct function of the feed-to-SWU cost ratio. Therefore, the absolute values of the feed and SWU costs are not important—only the cost ratio. This means that BETA is the same for any product assay and that, if both feed and SWU costs increase by the same percentage (e.g., due to inflation), the BETA is unchanged. Figure IV.1 is a plot of BETA versus the cost ratio.

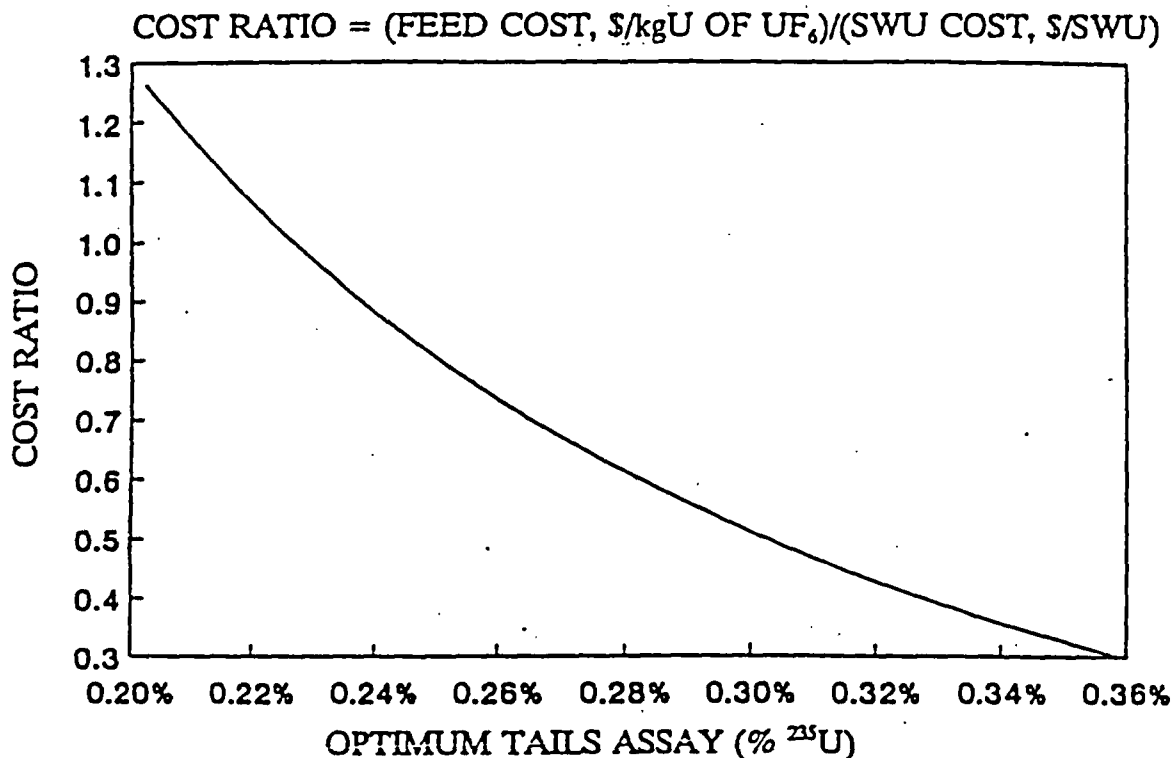


Fig. IV.1. Break-even tails assay (BETA).

The feed and SWU costs used should be the incremental costs that apply to the specific circumstances. Therefore, enrichment customers with different feed costs will have different optimum transaction tails assays. Likewise, DOE's incremental production cost and the value of feed to DOE are different than the costs to our customers; so DOE's optimum operating tails assay (BETA-1) will be different than our customers' optimum transaction tails assays.

The nature of the break-even tails equation implies that depleted uranium at any assay greater than the current BETA can be economically refed. That is, the depleted uranium can be used as partially depleted feed (PDF) to the cascade to produce enriched product and depleted uranium at the BETA assay. The cost of additional SWU required to enrich PDF rather than normal uranium is offset by the savings in normal feed purchases. Depleted uranium at an assay less than or equal to the BETA cannot be economically refed.

The above discussion does not include the cost of storage or other disposal of the depleted uranium. If the disposal cost is considered, the only change is to add the cost of disposal to the feed cost in calculating the cost ratio. The break-even tails equation then becomes

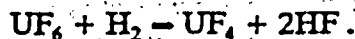
$$\frac{(C_{Feed} + C_{Disp})}{C_{SWU}} = (2 \cdot x_f - 1) \cdot \ln \left[ \frac{x_f \cdot (1 - x_w)}{x_w \cdot (1 - x_f)} \right] + \left( 1 - \frac{x_f}{x_w} \right) \cdot \left( \frac{2 \cdot x_w - 1}{1 - x_w} \right),$$

where  $C_{Disp}$  is the cost of disposal in dollars per kilogram of uranium. Note that the right side of the equation is unchanged. Therefore, Fig. IV.1 is still applicable—only the calculation of the cost ratio has changed. Note also that, as expected, increased disposal costs will reduce the optimum tails assay—thereby reducing the amount of depleted uranium to be disposed of. The units on the disposal cost must, of course, match the units on the feed and SWU costs.

**Appendix V. CONVERSION PROCESSES**

## Appendix V. CONVERSION PROCESSES

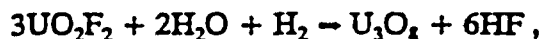
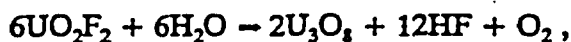
Several routes exist for converting  $\text{UF}_6$  to  $\text{UF}_4$ , uranium metal, or the oxides. The  $\text{UF}_6$  to  $\text{UF}_4$  reduction process reacts hydrogen ( $\text{H}_2$ ) with  $\text{UF}_6$  in a tower (vertical pipe) reactor according to the equation



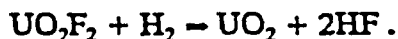
This reaction becomes self-sustaining at approximately 800°F, which is achieved either by heating the reactor wall or by injecting fluorine with the  $\text{UF}_6$ . Once ignited, the reaction proceeds vigorously and requires considerable cooling to maintain a wall temperature below 1000°F, the upper temperature limit for Monel (a common material of construction for fluoride environments). The products are dense, finely divided  $\text{UF}_4$  powder and anhydrous HF. This is the process used by Sequoyah Fuels Corporation and Carolina Metals, Inc., to produce  $\text{UF}_4$  for later conversion to uranium metal for the military.

Any of the uranium oxides ( $\text{UO}_2$ ,  $\text{UO}_3$ , or  $\text{U}_3\text{O}_8$ ) can be formed from  $\text{UF}_6$  either by vapor-phase (dry) pyrohydrolysis-reduction or by dissolution in water followed by precipitation with a variety of reagents such as ammonia, ammonium carbonate, or hydrogen peroxide and then subsequent calcination of the collected precipitate. The flowsheet and equipment selected depend on the product characteristics desired and design of the HF by-product recovery system. Fluidized beds, rotary kilns, and screw reactors are used in the vapor phase process. In the wet process, filters and centrifuges collect precipitates, which may then be dried and calcined in screw or rotary kiln equipment.

In the dry process, the  $\text{UF}_6$  is fed to the reactor in the presence of superheated steam at 300°C to 500°C, causing the  $\text{UF}_6$  to react to form uranyl fluoride ( $\text{UO}_2\text{F}_2$ ). The uranyl fluoride is then reacted with more superheated steam, sometimes augmented with hydrogen, at about 750°C to produce the desired oxide. These two steps can occur either in two separate reactors or in a single multizone reactor, depending on the design selected. The dry processes typically recover most of the fluoride as aqueous (70%) HF, which can be sold or recycled to convert natural-assay  $\text{U}_3\text{O}_8$  feed to  $\text{UF}_6$  for enrichment. The basic reactions involved in converting  $\text{UF}_6$  to oxide in the vapor phase are



and

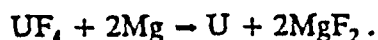


UF<sub>4</sub> can be converted to oxide in a similar fashion. However, the UF<sub>4</sub>-to-oxide reaction is reversible; so operating conditions must be carefully controlled to provide good yields:



The wet conversion processes result in the generation of considerable fluoride waste, which introduces extra processing costs. These processes start by dissolving gaseous UF<sub>6</sub> in water. The uranium hexafluoride and water quickly react as above to form uranyl fluoride, which is highly soluble in water. A precipitating agent is then added to the solution to recover the uranium product, which is converted to oxide by calcining (roasting) in the presence of suitable reducing agents (typically, hydrogen or steam).

The current standard method of reducing UF<sub>6</sub> to uranium metal, the thermite process, is to reduce the UF<sub>6</sub> to UF<sub>4</sub> as described above and then react the finely powdered UF<sub>4</sub> with magnesium in a batch reactor:



The reactor and its contents are heated to between 550°C and 700°C to initiate the reaction. When the reaction is complete and the contents are cooled, the uranium derby and MgF<sub>2</sub> are removed. The uranium yield is approximately 96%. Of the remaining 4%, about half can be recovered as crude metal product by mechanical means (grinding, screening). Exhaustive leaching of the MgF<sub>2</sub> can then reduce the residual uranium content. In this process, all of the fluoride from the UF<sub>4</sub> is lost as MgF<sub>2</sub> waste.

INTERNAL DISTRIBUTION

**MARTIN MARIETTA  
ENERGY SYSTEMS**

Oak Ridge

1. J. M. Asher
2. N. M. Baldwin
3. C. R. Barlow
4. J. M. Begovich
5. C. R. Bieber
6. D. J. Bostock
7. J. T. Bradbury III
8. T. M. Butler
9. J. H. Devan
10. R. S. Eby
11. R. L. Faulkner
12. G. G. Fee
13. J. M. Googin
14. C. A. Hall
15. L. E. Hall
16. H. M. Henson
17. R. L. Higgins
18. C. C. Hopkins
19. F. C. Huffman
20. J. D. James
21. P. S. Johnson
22. M. L. Jones
23. P. M. Kannan

**ENERGY SYSTEMS  
(continued)**

24. J. K. Keith
- 25-44. T. R. Lemons, Jr.
45. D. C. Landguth
46. J. D. McGaugh, Jr.
47. D. L. Mason
48. J. R. Merriman
49. M. E. Mitchell
50. H. M. Oakes
51. J. H. Pashley
52. R. L. Pearson
53. R. C. Riepe
54. J. E. Rushton
55. R. W. Schmidt
56. K. W. Sommerfeld
57. D. L. Stansberry
58. F. W. Stout
59. M. S. Taylor
60. L. D. Trowbridge
61. R. L. Walker
62. H. D. Whitehead, Jr.
63. R. E. Upchurch

Paducah

64. J. H. Alderson

**ENERGY SYSTEMS**  
(continued)

- 65. S. C. Blue
- 66. C. D. Ecklund
- 67. R. A. Green
- 68. S. A. Polston
- 69. H. Pulley
- 70. J. J. Staley
- 71-75. W. E. Sykes
- 76. C. W. Walter

Portsmouth

- 77. R. A. Boelens
- 78. D. E. Boyd
- 79. J. G. Crawford
- 80. R. G. Donnelly
- 81. R. E. Dorning
- 82. R. D. McDermott
- 83. W. D. Netzer
- 84. J. E. Shoemaker, Jr.
- 85. W. J. Spetnagel
- 86. J. P. Vournazos

**DOE**

Headquarters

- 87. J. W. Bennett

**DOE (continued)**

- 88. E. C. Schmidt
- 89. P. G. Sewell
- 90-93. D. C. Thomas

**DOE-ORO**

Oak Ridge

- 94. W. R. Bibb
- 95. D. C. Booher
- 96. R. H. Dyer
- 97. J. C. Hall
- 98. M. M. Heiskell
- 99. D. B. Howard, Jr.
- 100. R. O. Hultgren
- 101-103. J. W. Parks
- 104. R. R. Nelson
- 105. J. R. Russell

Paducah

- 106. D. R. Allen

Portsmouth

- 107. E. W. Gillespie

**CONSULTANTS**

**MJB Technical Associates**

108. K. T. Ziehlke

**PAI Corporation**

109. W. A. Pryor

**Vorys, Sater, Seymour, and Pease**

110. R. J. Styduhar

**EXTERNAL DISTRIBUTION**

111-302. Given distribution as shown in DOE/OSTI-4500-R75 under Category 515, Nuclear Materials Security and Management.