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Technical Competencies for the Safe Interim Storage and Management of ^{233}U at U.S. Department of Energy Facilities

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LOCKHEED MARTIN ENERGY RESEARCH CORPORATION
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

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ACRONYMS AND ABBREVIATIONS

AEC	Atomic Energy Commission
ALARA	as low as reasonably achievable
Am	americium
ANL	Argonne National Laboratory
ANSI	American National Standards Institute
B&W	Babcock & Wilcox
BAPL	Bettis Atomic Power Laboratory
Bi	bismuth
CEUSP	Consolidated Edison Uranium Solidification Program
Cm	curium
DNFSB	Defense Nuclear Facilities Safety Board
DOE	U.S. Department of Energy
DP	Defense Programs
DU	depleted uranium
FTE	full-time equivalent
HEU	highly enriched uranium
HQ	Headquarters (DOE)
IAEA	International Atomic Energy Agency
ICPP	Idaho Chemical Processing Plant
INEEL	Idaho National Engineering and Environmental Laboratory
LANL	Los Alamos National Laboratory
LEU	low-enriched uranium
LLNL	Lawrence Livermore National Laboratory
LWBR	light-water breeder reactor
LWR	light-water reactor
MeV	million electron volts
MSRE	Molten Salt Reactor Experiment
MT	metric tonnes
Np	neptunium

ACRONYMS AND ABBREVIATIONS, cont'd.

NRC	U.S. Nuclear Regulatory Commission
ORNL	Oak Ridge National Laboratory
PEP	Program Execution Plan
PNNL	Pacific Northwest National Laboratory
PWR	pressurized-water reactor
Pu	plutonium
PUREX	plutonium/uranium extraction
RDF	Radiochemical Development Facility (ORNL)
RFETS	Rocky Flats Environmental Technology Site
RWMC	Radioactive Waste Management Complex
SNF	spent nuclear fuel
SNL	Sandia National Laboratory
SNM	special nuclear materials
SRS	Savannah River Site
TBP	tri-*n*-butyl phosphate
Th	thorium
Tl	thallium
ThO_2	thorium oxide
THOREX	thorium extraction process
TRU	transuranic
U	uranium
VA	Vulnerability Assessment
WAC	waste acceptance criteria
WGP	weapons-grade plutonium
WIPP	Waste Isolation Pilot Plant
Y-12	Oak Ridge Y-12 Plant

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EXECUTIVE SUMMARY

This report was prepared as a commitment identified in the 1997 U.S. Department of Energy (DOE) *Implementation Plan for the Safe Storage of Uranium-233,* in response to the Defense Nuclear Facilities Safety Board Recommendation 97-1. This recommendation to DOE, which addresses the safe storage of uranium-233- (^{233}U-) bearing material, was issued March 3, 1997. Subrecommendation 8 of Recommendation 97-1 concerns the retention of technical knowledge and competence needed to ensure safe storage of ^{233}U-bearing material in the short and long term. This report addresses the short-term issues of Subrecommendation 8 by providing the present status of relevant competencies that are still available to the DOE complex.

The key personnel with direct ^{233}U-related work experience at each major ^{233}U site are documented. Personnel with other actinide experience, but no ^{233}U experience, have been excluded from the list. To provide more specific information and detail regarding the key personnel with direct ^{233}U experience, six major categories of expertise were defined: handling, remote handling, processing, process support, radiological safety, and materials management. Information on the major ^{233}U and related actinide programs at each DOE site was compiled as well. While the primary focus of the report is on ^{233}U, it was deemed that experience and knowledge in handling and processing related actinides such as neptunium (Np), plutonium (Pu), americium (Am), curium (Cm), and the general category of transcurium elements — which possess similar characteristics in terms of criticality, specific activity, and radiation — should also be covered. Thus, information on the programs (current, recent, and major historical) for ^{233}U, Np, Pu, Am, Cm, and transcurium elements conducted at each site is provided, where available, to indicate the institutional experience with related actinides.

Highly enriched uranium (HEU) handling and processing expertise has not been included. The handling requirements and experience for ^{233}U were judged to more closely resemble those of the higher actinides. It is recognized that the experience associated with handling and processing irradiated HEU (i.e., spent nuclear fuel) would have relevance to ^{233}U handling but would not be as closely related as heavy actinide processing.

Uranium-233 is a man-made isotope of uranium primarily formed by neutron bombardment of naturally occurring thorium-232 (^{232}Th). The inventory of separated ^{233}U in the United States totals about 790 kg and is contained in 1505 packages. ("Separated ^{233}U" refers to reprocessed ^{233}U or ^{233}U that has been separated from fission products, and "packages" refers to external containers.) Most of the separated ^{233}U and most of the packages are located at Oak Ridge National Laboratory (ORNL) in the DOE National Repository for ^{233}U. Savannah River Site (SRS) has ^{233}U inventory in spent fuel and other materials.

The DOE sites were included in the survey based primarily on the level of ^{233}U experience and secondarily on the scale of major related actinide programs. The DOE sites included were Argonne National Laboratory (ANL), Bettis Atomic Power Laboratory, DOE Headquarters and site offices, Idaho National Engineering and Environmental Laboratory (INEEL), Los Alamos National Laboratory (LANL), Lawrence Livermore National Laboratory (LLNL), Mound Plant, ORNL (including Y-12 Plant involvement), Pacific Northwest National Laboratory (PNNL)–Hanford, Rocky Flats Environmental Technology Site, Sandia National Laboratory–Albuquerque, and SRS.

The survey for key personnel (defined as those with direct ^{233}U experience) identified a total of 82 individuals. These key personnel are from DOE sites with either current ^{233}U holdings or significant past ^{233}U program involvement. Twelve of the key personnel, or 15%, were identified as being retired. The breakdown of key personnel identified at the various DOE sites is provided in the table that follows..

Number of key personnel at DOE ^{233}U sites

Site	Number of key personnel	Number of retirees listed as key personnel
ANL–West	2	0
DOE	8	0
INEEL	8	0
PNNL–Hanford	6	2
LANL	5	0
LLNL	9	3
ORNL	43	7
SRS	1	0
Total	82	12

Slightly more than half of the key personnel have M.S. or Ph.D. degrees. Ten senior technicians were identified as key personnel. Approximately 40% of all the identified personnel have degrees in either chemistry or chemical engineering. The next largest representation in academic backgrounds is in nuclear engineering. The following table shows the distribution of key personnel currently involved with DOE ^{233}U programs and projects, identified by their years of direct ^{233}U experience.

Number of key personnel, identified by years of direct ^{233}U experience

< 5 years	5 to 10 years	11 to 20 years	21 to 40 years	Retired
26	20	15	9	12

Of the programs listed by the six DOE sites that provided such information, only two sites, ORNL and INEEL, list current programs related to ^{233}U. The ^{233}U program at INEEL currently consists of storage while ORNL programs include Molten Salt Reactor Experiment (MSRE) remediation, serving as the National ^{233}U Repository, fissile material disposition, and thorium recovery from ^{233}U for medical applications. Five of the sites responding to the survey reported having current programs in the related actinides; these sites are LANL, LLNL, ORNL, PNNL-Hanford, and SRS. Other ^{233}U activities at the remaining DOE sites include, to varying degrees, inspection, consolidation, and repackaging actions that are part of DOE's Implementation Plan for 97-1.

The core knowledge base needed for safe storage of ^{233}U is still available, and much of this expertise is involved in current ^{233}U programs (i.e., safe storage, MSRE remediation, fissile material disposition, and medical radioisotope research and development). Since many of these programs are relatively recent, the number of personnel with ^{233}U experience has been increasing. Many retirees are serving as consultants on the ^{233}U programs. SRS, however, does not have any retirees serving as consultants or any plans to do so. Over the next few years, these retirees will continue to provide valuable experience, knowledge, and mentorship through their involvement with the ^{233}U projects. In the short term, their participation in current ^{233}U work will result in the transfer of knowledge to a new generation of technical personnel and will help perpetuate the technical knowledge and competencies in this area. In addition, experience in processing other actinides, such as Am, Cm, Np, and ^{238}Pu, is applicable to the ^{233}U work. Through this or a similar strategy, an appropriate base of knowledge will continue to exist.

1. INTRODUCTION

1.1 BACKGROUND

This report was prepared as a commitment identified in the U.S. Department of Energy (DOE) *Implementation Plan for the Safe Storage of Uranium-233* (U.S. Department of Energy 1997), in response to the Defense Nuclear Facilities Safety Board (DNFSB) Recommendation 97-1. This recommendation, which addresses the safe storage of uranium-233- (^{233}U-) bearing material, was issued by the DNFSB on March 3, 1997. The U.S. Secretary of Energy accepted the DNFSB recommendation on April 25, 1997.

The recommendation describes actions that the DNFSB considers necessary to improve the safe storage of ^{233}U-bearing materials in the interim and the longer term. Eight subrecommendations detail those actions:

1. Establish a single line project to deal with issues attached to safe storage of ^{233}U.
2. Develop the standards to be used for packaging, transportation, and interim and long-term storage.
3. Characterize the items of ^{233}U presently in storage in DOE's defense nuclear facilities as to material, quantity, and type and condition of storage container.
4. Evaluate the conditions and appropriateness of the vaults and other storage systems used for the ^{233}U at DOE's defense nuclear facilities.
5. Assess the state of storage of the items of ^{233}U in light of the standards mentioned in Subrecommendation 2 above.
6. Initiate a program to remedy any observed shortfalls in ability to maintain the items of ^{233}U in acceptable interim storage.
7. Establish a plan for the measures that can eventually be used to place the ^{233}U in safe permanent storage.
8. Until these ultimate measures are taken, ensure that the DOE complex retains the required technical knowledge and competence to implement all of the measures needed to ensure safe storage of the ^{233}U-bearing material in the short and the long term.

The recommendation had been preceded in February 1997 by a DNFSB technical report entitled *Uranium-233 Storage Safety at Department of Energy Facilities* (U.S. Defense Nuclear Facilities Safety Board 1997). The report described the DNFSB perspective on the safety of ^{233}U stored at various sites in the DOE complex and formed the basis for the DNFSB subrecommendations. The report also acknowledged the DOE's highly enriched uranium (HEU) Vulnerability Assessment (VA), which had been completed in August 1996. As a result of that assessment, DOE was aware of the legacy issues surrounding the storage of ^{233}U-bearing material.

1.2 SCOPE

This report addresses the DOE Implementation Plan commitment related to Subrecommendation 8 of the DNFSB's Recommendation 97-1. Subrecommendation 8 is concerned with the retention of technical knowledge and competency to ensure safe storage of ^{233}U-bearing material in the short and long term. This report addresses the first part of Subrecommendation 8 by providing an assessment of relevant competencies in the DOE complex. The second part of Subrecommendation 8 deals with the long-term retention of technical knowledge and competency. That issue will be addressed in the Program Execution Plan (PEP) for safe storage of ^{233}U, which will describe an approach to maintain technical competencies over the extended periods of storage of the ^{233}U.

The technical expertise to handle, process, and safely store ^{233}U is similar to the expertise required for handling and processing other high-specific-activity alpha emitters, such as selected isotopes of neptunium (Np), plutonium (Pu), americium (Am), curium (Cm), and the general category of transcurium elements. While the primary focus of the report is ^{233}U, it was deemed that experience and knowledge in handling and processing these related actinides, in substantial quantities (i.e., kilograms), should also be covered. These related actinides possess similar characteristics in terms of criticality, specific alpha activity, and radiation (see Table 1.1). DOE has programs involving these other nuclides, which provide continuing experience for technical, facility, and operational personnel. In addition, there is a substantial body of literature on the handling and processing of ^{233}U. This report documents the key personnel (with direct ^{233}U experience) and expertise available to perform ^{233}U-related work at each major ^{233}U site. Information on the programs (current, recent, and major historical) for ^{233}U, Np, Pu, Am, and transcurium elements conducted at each site is also provided.

Table 1.1. Nuclear characteristics of selected isotopes

Isotope[a]	Specific activity (GBq/g)	Specific gamma-ray dose constants at 1 m (mSv/h/MBq)	ANSI/ANS-8.1[b] subcritical limits on mass of metal units (kg)	(alpha,n) Yield in oxide (n/s-g)	Power generation (W/g)
^{232}U	8.29×10^{2}	2.40×10^{-5}		1.49×10^{4}	6.75×10^{-1}
^{233}U	3.57×10^{-1}	7.87×10^{-6}	6.00×10^{0}	4.80×10^{0}	2.75×10^{-4}
^{235}U	7.10×10^{-5}	9.16×10^{-5}	2.01×10^{1}	7.10×10^{-4}	5.56×10^{-4}
HEU (20% ^{235}U)	6.11×10^{-4}	3.24×10^{-5}			3.48×10^{-7}
HEU (50% ^{235}U)	4.11×10^{-4}	5.46×10^{-5}			9.28×10^{-7}
HEU (80% ^{235}U)	2.06×10^{-4}	7.68×10^{-5}			1.54×10^{-6}
^{239}Pu	2.29×10^{0}	8.14×10^{-6}	5.00×10^{0}	3.81×10^{1}	1.89×10^{-3}
^{238}Pu	6.33×10^{2}	2.14×10^{-5}		1.34×10^{4}	5.57×10^{-1}
^{237}Np	2.61×10^{-2}	1.25×10^{-4}		3.40×10^{-1}	1.91×10^{-5}
^{241}Am	1.27×10^{2}	8.48×10^{-5}		2.69×10^{3}	1.11×10^{-1}
^{244}Cm	2.99×10^{3}	1.74×10^{-5}		7.73×10^{4}	2.78×10^{0}
^{246}Cm	1.14×10^{1}	1.55×10^{-5}			9.75×10^{-3}
^{252}Cf	1.98×10^{4}	1.13×10^{-5}		6.00×10^{5}	1.89×10^{1}

[a] HEU = highly enriched uranium.

[b] ANSI = American National Standards Institute.

HEU processing and handling expertise has not been included in this report. The handling requirements and experience for ^{233}U were judged to more closely resemble those for the higher actinides than HEU. Although the chemistry aspects of ^{233}U and HEU are the same, handling ^{233}U involves two additional precautions. First, the specific activity of ^{233}U (which is higher than that for HEU by 1000-fold) necessitates handling in high-integrity alpha-containment enclosures. Second, ^{233}U with the contaminant uranium-232 (^{232}U) introduces an additional shielding problem. Uranium-232 has a high specific activity, and its radioactive daughter, thallium-208 (^{208}Tl), emits highly energetic 2.6 million electron volt (MeV) photons during decay. Hence, the high radiation exposure rates encountered in ^{233}U handling and processing require biological shielding and usually necessitate the use of remote-handling techniques. Another set of technical competencies, that associated with handling and processing irradiated HEU [i.e., spent nuclear fuel (SNF)], would have relevance to ^{233}U handling and processing. This irradiated HEU group is not addressed.

Some technical background and history of ^{233}U are described, but this report does not attempt to provide a comprehensive background on ^{233}U production and technology. This information will be compiled and provided in a technical handbook as a separate DOE commitment to the DNFSB.

Finally, it should be noted that personnel training and qualifications were considered to be relevant to the long-term goal of maintaining technical competencies. Thus, personnel training and qualification issues will be considered in the PEP. DOE Order 5480.20A (U.S. Department of Energy 1994) currently defines requirements for selection, qualification, and training of personnel involved in the operation, maintenance, and technical support of DOE-owned Category A and B reactors and moderate hazard, nonreactor nuclear facilities. DOE Order 5480.20A–based training programs and materials currently exist and are in use for facilities handling ^{233}U, such as ORNL Building 3019 [Radiochemical Development Facility (RDF)] or the Molten Salt Reactor Experiment (MSRE). These training programs and materials are relevant to those competencies required to support the safe storage of ^{233}U and will be included as inputs to future actions for maintaining ^{233}U technical knowledge and competencies in the DOE complex.

1.3 TECHNICAL OVERVIEW OF ^{233}U

Uranium-233 is a man-made isotope of uranium primarily formed as a result of neutron bombardment of naturally occurring thorium-232 (^{232}Th). The key properties of ^{233}U are summarized in Sects. 1.3.1 through 1.3.4. More detailed information is available in *Strategy for Future Use and Disposition of Uranium-233:*

Technical Information (Bereolos 1997). Additional references for ^{233}U technology are provided in the appendix to the present report.

1.3.1 Chemical Characteristics

Uranium-233 is chemically identical to natural, depleted, and enriched uranium. Consequently, the same chemical processes used for natural, depleted, and enriched uranium are applicable to ^{233}U. The ^{233}U isotope, however, has a higher specific radioactivity than the naturally occurring isotopes of uranium [i.e., uranium-234 (^{234}U), uranium-235 (^{235}U), and uranium-238 (^{238}U)]. Thus, certain radiation-induced chemical reactions are faster in uranium containing significant quantities of ^{233}U. This knowledge is important in situations such as long-term storage, where the higher radiation levels of ^{233}U require that storage containers and ^{233}U storage forms not contain organics (plastics, etc.) or water, which reacts radiolytically to form potentially explosive concentrations of hydrogen gases.

1.3.2 Radiological Characteristics

The radiological worker-protection requirements for high-quality ^{233}U (i.e., low concentrations of ^{232}U) are similar to those for weapons-grade plutonium (WGP). The primary hazard from such ^{233}U is alpha radiation, which is also the primary health hazard from WGP. The alpha activity of isotopically pure ^{233}U (with no ^{232}U present) is three orders of magnitude higher than that of HEU and about one order of magnitude less than that of WGP. Consequently, the handling and containment requirements (glove boxes, etc.) for ^{233}U are similar to those for WGP.

All ^{233}U contains some ^{232}U, which is produced during production of ^{233}U. The concentrations of ^{232}U depend upon the specifics of the production techniques for ^{233}U. The ^{232}U has a decay product, ^{208}Tl, which decays through a complex chain to stable lead, while producing a high-energy (2.6-MeV) gamma ray. The concentration of ^{232}U determines the radiation shielding required to protect workers. Ultrapure ^{233}U contains very low levels (~1 part per million or less) of ^{232}U and has correspondingly low levels of gamma radiation. Low-quality ^{233}U with high concentrations of ^{232}U (tens to hundreds of parts per million) and associated radioactive decay products requires heavier radiation shielding and remote-handling operations to protect workers from gamma radiation.

There is an important radiochemical characteristic of this system. If uranium is chemically purified and its decay products are removed, freshly separated ^{233}U with significant concentrations of ^{232}U can be processed and converted into desired forms in unshielded glove boxes and other enclosures without significant radiation exposure to workers. Depending on the ^{232}U concentration, it takes days or weeks for the ^{232}U radioactive decay products that emit gamma rays to build up to sufficient concentrations such as to require radiation shielding to protect the workers.

The radiological characteristics of ^{233}U have historically determined what uranium was to be managed as ^{233}U. If a mixture of uranium contains several isotopes, the mixture is handled as ^{233}U provided that the ^{233}U is the primary hazard. In practice, this procedure implies that uranium materials containing substantially >1 wt % ^{233}U would be handled as ^{233}U.

1.3.3 Nuclear Characteristics

The nuclear characteristics of ^{233}U are significantly different from those of WGP or HEU. The minimum critical mass of ^{233}U, in a uniform fluoride aqueous solution, is 0.54 kg (American National Standards Institute 1983). This is less than that of WGP or HEU; thus, facilities designed for WGP or HEU might not be suitable for storage or processing of ^{233}U unless more restrictive criticality precautions are instituted.

1.3.4 Institutional Characteristics

Although ^{233}U has been investigated for many applications, it has not been used on a large scale in the United States. The total inventory of separated ^{233}U is very small relative to that of HEU and WGP and is limited to a few sites. Because there have been no large-scale uses of ^{233}U outside of the light-water breeder reactor (LWBR), an institutional structure for long-term management of ^{233}U has not been implemented.

National and international safeguards requirements [DOE orders, U.S. Nuclear Regulatory Commission (NRC) regulations, International Atomic Energy Agency (IAEA) agreements] for weapons-usable fissile materials [i.e., special nuclear materials (SNM)] have been developed for HEU and WGP; however, the requirements are not developed fully for disposition of surplus ^{233}U. For uranium containing ^{235}U, these regulatory requirements recognize that only HEU can be made into nuclear weapons. Natural uranium, depleted uranium (DU), and low-enriched uranium (LEU) do not require the safeguards and security required of weapons-usable HEU. For disposition of surplus HEU, the U.S. policy is to blend HEU with DU to make LEU for fuel in commercial nuclear power plants. It is universally recognized that this process eliminates the use of this material for nuclear weapons and eliminates the need for SNM-type security.

1.4 FACILITIES AND CURRENT INVENTORY

DOE has an inventory of ~ 2 metric tonnes (MT) of ^{233}U in many different forms stored under a variety of conditions throughout the complex. The majority is located at the Oak Ridge National Laboratory (ORNL) and the Idaho National Engineering and Environmental Laboratory (INEEL); significantly lesser quantities are located at Los Alamos National Laboratory (LANL). Even smaller quantities of material exist at numerous other sites. The material exists as solid oxides, metal, and fluorides, or in solution.

The unclassified, separated inventory of ^{233}U within the DOE complex is shown in Table 1.2. ("Separated ^{233}U" refers to reprocessed ^{233}U or ^{233}U that has been separated from fission products.) Detailed inventory information is available in a companion report (Bereolos 1997). Uranium-233 in SNF, irradiated targets, and wastes is not included in these numbers. The unclassified separated inventory contains 1800 kg of total uranium in 1505 packages (external containers) at multiple sites, of which 790 kg is ^{233}U. Most of the separated ^{233}U and its packages are located at ORNL in the DOE National Repository for ^{233}U, primarily in the chemical form of oxides stored in stainless steel or aluminum cans. The ^{233}U is typically packaged in welded double-metal containers with the inner container made of stainless steel or aluminum.

The total inventory of separated ^{233}U is expected to increase by several percent (or by ~31 kg ^{233}U in a total of ~37 kg uranium) over the next several years as material associated with the MSRE at ORNL is processed to resolve safety concerns identified in DNFSB Recommendation 94-1. The MSRE contains irradiated ^{233}U, which will be separated from this fuel to minimize long-term safety concerns. (Natural processes are slowly separating the ^{233}U from the fuel with the potential of creating significant safety problems.) There are several other batches of waste from which ^{233}U may be recovered to minimize safeguards or specific safety concerns. The resultant ^{233}U would be added to the national inventory.

Table 1.2. Uranium-233 inventories and characteristics[a]

Site	No. of pkgs.	Total U[b] (kg)	^{233}U[b,c] (kg)	^{235}U[b,c] (kg)
Argonne National Laboratory (ANL)–East	5	*	*	0
ANL-West	63	<0.2	<0.2	0
Bettis Atomic Power Laboratory[d]	13	0.4	0.4	*
General Atomics	2	*	*	*
Hanford	3	0.6	*	0
Idaho National Engineering and Environmental Laboratory/Idaho Chemical Processing Plant[e,f]	186	359	352	0
Lawrence Livermore National Laboratory	50	3	3	0
Los Alamos National Laboratory	109	7.2	7.1	0
Oak Ridge National Laboratory	1049	1387	427	796
Pacific Northwest National Laboratory	15	*	*	0
Oak Ridge Y-12 Plant	5	43	0.8	39
Rocky Flats Environmental Technology Site	5	*	*	0
Total	1505	1800	790	835

[a] Excludes ^{233}U in materials classified as waste (unless specifically noted), spent nuclear fuel, and irradiated thorium targets.

[b] An asterisk (*) is used to represent mass quantities of material <0.1 kg.

[c] Accountable amounts only for safeguards and security.

[d] Includes transuranic waste materials, which are stored in four 55-gal drums. The mass of waste material is currently known to be in excess of 21 kg.

[e] Some additional materials are categorized as waste or spent nuclear fuel may be candidate ^{233}U materials.

[f] Includes contributions from 145 drums of unirradiated fuel materials (<35.1 kg uranium) stored at the INEEL Radioactive Waste Management Complex.

1.5 HISTORY OF THE ^{233}U PROGRAM

1.5.1 Production of ^{233}U

Uranium-233 was first recovered in quantity during the early 1950s by processing irradiated thorium oxide (ThO_2) at ORNL. Approximately 60 kg of ^{233}U was produced for experiments regarding (1) the feasibility of nuclear reactors based on the ^{233}U fuel cycle and (2) other purposes. Subsequently, during the 1965–1970 time frame, about 1250 kg of ^{233}U was recovered from some 840 tons of irradiated ThO_2 during special production campaigns in the plutonium/uranium extraction (PUREX) plants at Hanford and Savannah River.

The thorium extraction process (THOREX), which used tri-*n*-butyl phosphate (TBP) to separate thorium and uranium from each other and from fission products, was developed at ORNL for the initial work. This process is related to the PUREX process, but there are significant differences because of the different properties of thorium. The irradiated fuel is first dissolved in fluoride-catalyzed nitric acid — typically 13 *M* HNO_3 containing 0.01 to 0.1 *M* fluoride ion (to catalyze the thorium dissolution) — and aluminum (to complex the fluoride ion to prevent excessive corrosion of stainless steel equipment). Two different THOREX processes, one using a nitric acid feed solution and the other an acid-deficient solution, were eventually developed at Oak Ridge, and these were modified to fit the particular equipment available at the Hanford and Savannah River sites. These processes are described in detail in references dating from 1953 (Bond 1984), and the production operations have been summarized (Rathvon et al. 1968; Jackson and Walser 1977; Orth 1979).

The important features of this work are that (1) ^{233}U was produced by irradiating thorium and (2) the irradiated fuel was processed successfully in full-scale PUREX reprocessing plants with modifications required for the THOREX flow sheets. Such production requires the methods, equipment, shielding, controls, etc. that are normal for commercial or defense-fuel reprocessing operations. However, compared with conventional fuel reprocessing or the WGP cycle, certain complicating factors must be taken into account. Of primary concern are (1) the relatively long life of the protactinium-233 (^{233}Pa) parent of ^{233}U compared with neptunium-237 (^{237}Np), which occupies the same position in the more common U-Pu fuel cycle (which mandates longer decay), and (2) the presence of ^{232}U in the product stream that includes in its decay chain ^{208}Tl, which emits highly penetrating 2.6-MeV gamma radiation (which prevents removal of this gamma emitter from the product stream).

1.5.2 Uranium-233–Thorium Fuel Cycle

Starting in the 1950s, there was major interest in developing a fuel cycle based on thorium (Th) and ^{233}U. The initial driver was to provide an alternative fuel cycle in anticipation of a projected rapid growth in nuclear power, along with concern about a potential shortage of uranium to supply the existing uranium fuel cycle. Later, during the 1970s, the emphasis shifted to the development of proliferation-resistant fuel cycles. The projections from the earlier era did not turn out to be correct, but several tests were made that included producing ^{233}U in power reactors. These tests included the Indian Point 1 pressurized-water reactor (PWR), Fort St. Vrain gas-cooled reactor, Peach Bottom gas-cooled reactor, Sodium Reactor Experiment, and Shippingport PWR thermal breeder reactor test. Of these reactors, only the Shippingport reactor was fueled with ^{233}U. The other reactors used fuel fabricated from enriched uranium and thorium, in which ^{233}U is produced during irradiation. The idea was that, after sufficient ^{233}U was produced, the fuel cycle would convert from the initial Th-^{235}U to Th-^{233}U. Relatively pure ^{233}U could be recovered from this spent fuel.

In the early 1960s, work on a liquid-fueled reactor concept, the molten salt breeder reactor, was initiated at ORNL. A test reactor, the MSRE reactor, was operated from 1965 to 1969 to test reactor operation, materials compatibility, and fuel processing for a thermal breeder concept. The MSRE reactor was initially fueled with ^{235}U. In 1968, the ^{235}U was replaced with ^{233}U in an on-site processing campaign.

1.5.3 Summary of ^{233}U Processing

Usually, most processing of recovered ^{233}U has been primarily related to the preparation of mixed oxide containing thorium and ^{233}U and secondarily by fabrication of fuel rods for reactor irradiation. Such fuel has been prepared at ORNL; Bettis Atomic Power Laboratory (BAPL); and Babcock and Wilcox (B&W), in Lynchburg, Virginia. Two core loadings for the Shippingport reactor were fabricated, and one was irradiated. Both are stored at INEEL. Excess uranium oxide powder is stored at ORNL.

Various techniques have been used to make reactor fuel, including conventional pellets produced from powders and methods based on processes for forming sol-gel microspheres. Because powder processes generate dust that accumulates in equipment and containment enclosures, and because the ^{232}U daughter activity will build up from such dust, there was enhanced interest in the sol-gel methods, which largely avoid the dusting problem. This is an important consideration for future stabilization work. There are extensive publications regarding these processes (U.S. Atomic Energy Commission 1968).

In addition, the fuel irradiated by the Indian Point 1 reactor was processed for ^{233}U recovery at the West Valley, New York, reprocessing plant operated by Nuclear Fuel Services, Inc., but no account of this large-scale operation has been published. The recovered uranium was shipped as a nitrate liquid to ORNL, stored for over 15 years in liquid form, and finally processed to produce a stable oxide form in the Consolidated Edison Uranium Solidification Project (McGinnis et al. 1987). In this process, the uranium solution was concentrated by evaporation with addition of formaldehyde to destroy nitrates and the uranium was finally calcined to U_3O_8 in situ in stainless steel storage cans. The process was operated remotely without prior processing to break the ^{232}U decay chain at ORNL. This demonstrated a potential stabilization process for other ^{233}U-bearing materials.

2. KEY PERSONNEL AND PROGRAMS

2.1 IDENTIFICATION OF KEY PERSONNEL AND PROGRAMS

A series of scoping and planning discussions with experts in ^{233}U and related actinide technologies led to the conclusion that two sets of information — (1) key personnel *with direct ^{233}U experience* within the DOE complex and (2) the *program experience* for ^{233}U and related actinides (i.e., Np, Pu, Am, Cm, and the general category of transcurium elements) — will be identified in this report.

Identifying the key personnel will provide an indication of the currently available expertise and the skills relevant to addressing technical issues on ensuring safe handling and interim storage ^{233}U. To provide more specific information and detail regarding each individual's direct ^{233}U experience, the experience was broken down into six major categories of expertise. These categories of expertise are as follows:

Handling. Consists of technical knowledge and competence in the areas of package receipt, inspection, sampling, storage, and repackaging for ^{233}U.

Remote handling. Consists of technical knowledge and competence in the area of remote handling of ^{233}U.

Processing. Consists of technical knowledge and competence in the areas of radiochemical processing such as dissolution, separation, and stabilization of ^{233}U.

Process support. Consists of technical knowledge and competence in the areas of support functions needed for ^{233}U programs. These support functions include chemical/radiochemical analysis and laboratory-scale development of processes for ^{233}U.

Safety. Consists of technical knowledge and competence in safety-related areas for the ^{233}U programs. The safety-related areas include nuclear criticality analysis, radiological safety, and nuclear facility safety.

Materials management. Consists of technical knowledge and competence in areas related to ^{233}U materials management such as safeguards, inventory management, waste classification/disposal, and nuclear facility support.

Along with identifying the key personnel with direct ^{233}U experience available within the DOE complex, information on the major ^{233}U and related actinide programs at each DOE site was compiled. The intent of providing a list of current, recent historical (within the past 5 years), and major historical programs is to present a general indication of the range of activities conducted at each DOE site. The type of programs, as mentioned in Sect. 1.2 of this report, was expanded to include not only ^{233}U but related actinides (i.e., Np, Pu, Am, Cm, and the general category of transcurium elements) as well.

The sites within the DOE complex from which information on key personnel and programs for ^{233}U and related actinides was compiled were identified based on the level of ^{233}U experience and the scale of major related actinide programs. The list of DOE sites meeting these criteria is as follows:

- Argonne National Laboratory (ANL)
- BAPL
- DOE Headquarters (HQ) and site offices
- INEEL
- LANL
- Lawrence Livermore National Laboratory (LLNL)
- Mound Plant
- ORNL (including the Y-12 Plant)
- PNNL-Hanford
- Rocky Flats Environmental Technology Site (RFETS)
- Sandia National Laboratory (SNL)–Albuquerque
- Savannah River Site (SRS)

A survey was conducted to expediently obtain technical competencies information from each of the identified DOE sites. In the survey, it was requested that each site identify its key personnel and provide information on the person's direct experience and expertise in ^{233}U. A brief ^{233}U-related biography of each person was also requested. In addition to information on key personnel, information relating to programs in ^{233}U, related actinides, and heavy elements (e.g., Am, Np, Pu, Cm, and transcurium) was requested. The program experience indicates current, recent (within the past 5 years), and historic (for major programs only) work involving the radionuclides identified. For ^{233}U and the related radioactive materials, criticality safety, high alpha activity, and substantial gamma radiation are the main handling and processing issues of concern.

2.2 TECHNICAL REPRESENTATIVES FOR RECOMMENDATION 97-1

The technical representatives of each DOE site who were contacted to facilitate the technical competencies survey are listed in Table 2.1.

Table 2.1. Technical representatives for DNFSB Recommendation 97-1 surveys

Site[a]	Name	Phone No.	Electronic mail
ANL	S. Brown-Van Hoozer	208-533-7906	alenka@anl.gov
BAPL	C. Detrick	412-476-6193	
DOE	J. Arango	202-586-7599	joseph.arango@hq.doe.gov
DOE	R. Cooperstein	301-903-5353	
DOE	R. Felt	208-526-8241	feltre@inel.gov
DOE	H. Johnson	202-586-0191	hoyt.johnson@em.doe.gov
INEEL	G. Christian	202-475-2237	chrigf@inel.gov
INEEL	L. Lewis	208-526-3295	llewis@inel.gov
INEEL	J. Nail	202-475-2236	nailjh@inel.gov
LANL	J. Nielsen	505-665-8763	nielsen@lanl.gov
LLNL	B. Ives	510-423-2636	ives1@llnl.gov
ORNL	C. Forsberg	423-574-6783	cwf@ornl.gov
ORNL	A. Krichinsky	423-574-6940	amk@ornl.gov
ORNL	B. Patton	423-576-0603	bdp@ornl.gov
ORNL	J. Rushton	423-576-7000	rushtonje@ornl.gov
PNNL-Hanford	J. Tingey	509-376-2580	jm_tingey@pnl.gov
RFETS	G. Thompson	303-966-6419	
SNL-Albuquerque	K. Reil	301-415-3050	koreil@sandia.gov
SRS	D. McWhorter	803-952-4547	donaldmcwhorter@srs.gov

[a] ANL = Argonne National Laboratory; BAPL = Bettis Atomic Power Laboratory; DOE = Department of Energy; INEEL = Idaho National Engineering and Environmental Laboratory; LANL = Los Alamos National Laboratory; LLNL = Lawrence Livermore National Laboratory; ORNL = Oak Ridge National Laboratory; PNNL = Pacific Northwest National Laboratory; RFETS = Rocky Flats Environmental Technology Site; SNL = Sandia National Laboratory; and SRS = Savannah River Site.

2.3 KEY PERSONNEL WITHIN THE DOE COMPLEX

The information on key personnel with direct ^{233}U experience gathered from the survey is provided in Tables 2.2–2.9 for the various DOE sites. Other personnel with experience in related actinides have not been included in the listings. The names of the key personnel have been withheld due to concerns regarding personal privacy. Instead, an identification number is provided.

No information on key personnel or programs is available for BAPL, Mound Plant, RFETS, and SNL-Albuquerque. These sites, which have small or no ^{233}U inventories, identified no workers that met the definition of key personnel.

SRS identified one current employee with direct ^{233}U experience. In addition, 17 SRS retirees with direct ^{233}U experience were identified. Due to privacy protection concerns, the background information on the SRS retirees is available only upon written request.

Table 2.2. Key personnel at Argonne National Laboratory (ANL)–West

Key personnel identifier	Highest degree earned	Academic major	Position[a]	Direct ^{233}U experience in years: Handling	Remote handling	Processing	Process support	Safety	Materials management
ANL-1	Ph.D.	Human factors engineering	Engineer	1	2			3	
ANL-2	*b*	*b*	Nuclear materials representative						20

[a] Position is intended to reflect each person's role at time of involvement with ^{233}U.

[b] Not available.

Table 2.3. Key personnel at the U.S. Department of Energy (DOE)

Key personnel identifier	Highest degree earned	Academic major	Position[a]	Direct ^{233}U experience in years: Handling	Remote handling	Processing	Process support	Safety	Materials management
DOE-1	Ph.D.	Chemistry/ ceramics	Physical scientist	10		15		30	25
DOE-2[b]									
DOE-3	M.S.	Nuclear engineering	Facility representative	3	3	3	3	3	3
DOE-4	B.S.	Mechanical engineering	Facility representative				1	1	
DOE-5	B.S.	Mechanical and electrical engineering	Facility representative	6	6			8	5
DOE-6	Ph.D.	Nuclear engineering	Nuclear safety engineer					3	
DOE-7	M.S.	Chemistry	General engineer	8	5	8	8	7	8
DOE-8	B.S.	Mechanical engineering	Safeguards engineer						3

[a] Position is intended to reflect each person's role at time of involvement with ^{233}U.

[b] No information available at time of publication.

Table 2.4. Key personnel at Idaho National Engineering and Environmental Laboratory (INEEL)

Key personnel identifier	Highest degree earned	Academic major	Position[a]	Direct ^{233}U experience in years					
				Handling	Remote handling	Processing	Process support	Safety	Materials management
INEEL-1	B.S.	Nuclear engineering	Supervisor, criticality safety	15		15		15	
INEEL-2	M.S.	Nuclear engineering	Criticality safety engineer	20		20		20	
INEEL-3	Ph.D.	Chemistry	Technical			1			
INEEL-4	Ph.D.	Physical chemistry	Supervisor/ manager		25	30	20		
INEEL-5	M.S.	Inorganic chemistry	Technical		4	15	7	20	
INEEL-6	M.S.	Nuclear engineering	Technical			29	7		29
INEEL-7	M.S.	Mechanical engineering	Manager	10	10	5		10	5
INEEL-8	B.S.	Management science	*b*	15	15	15		15	15

[a] Position is intended to reflect each person's role at time of involvement with ^{233}U.

[b] Not available.

Table 2.5. Key personnel at Los Alamos National Laboratory (LANL)

Key personnel identifier	Highest degree earned	Academic major	Position[a]	Direct ^{233}U experience in years: Handling	Remote handling	Processing	Process support	Safety	Materials management
LANL-1	Ph.D.	Chemistry	Staff	3	0	0	8	3	5
LANL-2	Ph.D.	Chemistry	Staff	5	0	5	5	0	3
LANL-3	Ph.D.	*b*	Staff	10	0	10	15	0	0
LANL-4	Ph.D.	*b*	Staff	10	0	15	15	0	0
LANL-5	Ph.D.	*b*	Staff	15	15	10	20	0	0

[a] Position is intended to reflect each person's role at time of involvement with ^{233}U.
[b] Not available.

Table 2.6. Key personnel at Lawrence Livermore National Laboratory (LLNL)

Key personnel identifier	Highest degree earned	Academic major	Position[a]	Direct ^{233}U experience in years					
				Handling	Remote handling	Processing	Process support	Safety	Materials management
LLNL-1	[b]	[b]	Chemical technician	10	10		10		10
LLNL-2	Ph.D.	Chemistry	Chemist	10	10	5	10		
LLNL-3[c]	[b]	[b]	[b]	15	15				
LLNL-4[c]	[b]	[b]	[b]	25	25	10			25
LLNL-5[c]	M.S.	[b]	[b]	5	5				
LLNL-6	M.S.	Nuclear engineering	Criticality engineer					16	
LLNL-7	M.S.	Health physics	Health physicist					4	
LLNL-8	Ph.D.	Chemistry	Staff chemist	4			4		4
LLNL-9	B.S.	Management	Deputy section leader	4					7

[a] Position is intended to reflect each person's role at time of involvement with ^{233}U.
[b] Not available.
[c] Retired.

Table 2.7. Key personnel at Oak Ridge National Laboratory (ORNL)

Key personnel identifier	Highest degree earned	Academic major	Position[a]	Direct ^{233}U experience in years					
				Handling	Remote handling	Processing	Process support	Safety	Materials management
ORNL-1	Ph.D.	Chemical engineering	Project engineer						2
ORNL-2	Sc.D.	Chemical engineering	Senior staff member			10	10		
ORNL-3[b]	Ph.D.	Physical chemistry	Group leader			3	5		
ORNL-4[b]	B.S.	Chemical engineering	Section chief	30	25	30	30	25	25
ORNL-5	A.S.	Chemical engineering	Operator/ supervisor	23	15	15	23	15	15
ORNL-6	M.S.	Nuclear engineering	Staff member				1		
ORNL-7	B.S.	Nuclear technology	Radiation engineering technician	7		7		6	3
ORNL-8	B.S.	Chemical engineering	Repository manager	6	6	6	6	6	6
ORNL-9	A.S.	Nuclear medicine	Radiation control technician	6				6	
ORNL-10	*c*	*c*	Operator / technician	19	2	19			19
ORNL-11	B.S.	Mechanical engineering	Facility manager	3	1	3		3	3
ORNL-12	Sc.D.	Nuclear engineering	Staff scientist					2	3

Table 2.7 (continued)

Key personnel identifier	Highest degree earned	Academic major	Position[a]	Direct ^{233}U experience in years					
				Handling	Remote handling	Processing	Process support	Safety	Materials management
ORNL-13	B.S.	Physics	Facility safety staff					3	
ORNL-14	Ph.D.	Physical chemistry	Senior scientist			2		2	2
ORNL-15[b]	Ph.D.	Chemical engineering	Research engineer		5		10	5	10
ORNL-16	M.S.	Chemical engineering	Development engineer	10	10	10	10	10	10
ORNL-17	Ph.D.	Chemical engineering	Engineering project coordinator					13	13
ORNL-18	B.S.	Physics	Criticality safety					15	
ORNL-19	M.S.	Nuclear engineering	Staff member	1	1	1	1	7	7
ORNL-20[b]	M.S.	Chemical engineering	Assistant chief/operator	10	10	5	10	10	10
ORNL-21	B.S.	Business/ engineering	Manager/field engineer			2		2	4
ORNL-22	M.S.	Chemistry	*c*	15	29	30	30	20	10
ORNL-23	M.S.	Chemical engineering	Repository manager	23	23	23	23	23	23
ORNL-24[b]	B.S.	Chemical engineering	Chief/ Technology group	20	10	15	15	20	15
ORNL-25	B.S.	Nuclear engineering	Criticality safety					2	

Table 2.7 (continued)

Key personnel identifier	Highest degree earned	Academic major	Position[a]	Direct ^{233}U experience in years					
				Handling	Remote handling	Processing	Process support	Safety	Materials management
ORNL-26	B.S.	Electrical engineering	Safety analyst					4	
ORNL-27	M.S.	Chemical engineering	Facility manager	17	17	10		17	17
ORNL-28	M.A.	Nuclear engineering	Development staff					2	
ORNL-29	A.S.	Nuclear technology	Radiation control technician					19	
ORNL-30	Ph.D.	Nuclear engineering	Program manager	2	1	6		3	2
ORNL-31	B.S.	Engineering science	Development engineer	3	15		3	10	10
ORNL-32	B.S.	Biology	Radiation control technician	3				3	
ORNL-33	*c*	*c*	Senior health physics technician	6				6	
ORNL-34	Ph.D.	Chemical engineering	Engineer	1		4	1	1	1
ORNL-35[b]	M.S.	Chemical engineering	Task leader	22	10	22	22	10	22
ORNL-36	Ph.D.	Physics/analytical chemistry	Development chemist			2		2	2
ORNL-37	c	*c*	Operator/ maintenance supervisor	24		13			4

Table 2.7 (continued)

Key personnel identifier	Highest degree earned	Academic major	Position[a]	Direct ^{233}U experience in years					
				Handling	Remote handling	Processing	Process support	Safety	Materials management
ORNL-38	M.S.	Nuclear engineering	Staff engineer						2
ORNL-39	A.S.	Health physics	Radiation control technician	10		10	10	10	10
ORNL-40	Ph.D.	Chemical physics	Senior staff member			2		2	
ORNL-41	B.S.	Chemical engineering	Engineer		4	6	4		1
ORNL-42	M.S.	Nuclear engineering	Project engineer						1
ORNL-43[b]	M.S.	Chemical engineering	Development engineer	2		2			

[a] Position is intended to reflect each person's role at time of involvement with ^{233}U.

[b] Retired.

[c] Not available.

Table 2.8 Key personnel at Pacific Northwest National Laboratory (PNNL)-Hanford

Key personnel identifier	Highest degree earned	Academic major	Position[a]	Direct ^{233}U experience in years					
				Handling	Remote handling	Processing	Process support	Safety	Materials management
PNNL-1	Ph.D.	Chemistry	Lead scientist	8	8		5	2	2
PNNL-2[b]	B.A.	Chemistry	Staff scientist	30			30		
PNNL-3[b]	M.S.	Chemistry	Senior scientist				40		
PNNL-4	[c]	[c]	Technician	30	5		30		30
PNNL-5	[c]	[c]	Technician				5		
PNNL-6	B.S.	Chemical engineering	Senior engineer			1		3	

[a] Position is intended to reflect each person's role at time of involvement with ^{233}U.

[b] Retired.

[c] Not available.

Table 2.9 Key personnel at Savannah River Site (SRS)

				Direct ^{233}U experience in years					
Key personnel identifier	Highest degree earned	Academic major	Position[a]	Handling	Remote handling	Processing	Process support	Safety	Materials management
SRS-1	B.S.	Chemical engineering	Senior engineer			10			

[a] Position is intended to reflect each person's role at time of involvement with ^{233}U.

2.4 Uranium-233 AND RELATED ACTINIDE PROGRAMS WITHIN THE DOE COMPLEX

Information on ^{233}U and related actinide programs is provided in Tables 2.10–2.15 for the DOE sites with major ^{233}U holdings.

Table 2.10. Uranium-233 and related actinide programs at Idaho National Engineering and Environmental Laboratory (INEEL)

					Scale of material handled					
Program title	Sponsor[a]	Status[b]	FTEs[c]	Funding ($K)	^{233}U	Np	Pu	Am	Cm	Trans-curium
Spent fuel reprocessing	DOE, ERDA, AEC	h	1000	>100,000		kg	kg			
Recovery of Np, Pu	ERDA	h	3	300		kg	kg			
^{233}U Storage	DOE	c	7	1,000	MT					

[a] DOE = Department of Energy; ERDA = Energy Research and Development Administration; AEC = Atomic Energy Commission.

[b] Status: c = current (small related projects may be grouped together); r = recent (past 5 years); h = historic [more than 5 years ago — major programs only (e.g., those involving more than 10 person-years).

[c] Estimated number of personnel in full-time equivalents (FTEs).

Table 2.11. Uranium-233 and related actinide programs at Los Alamos National Laboratory (LANL)

					Scale of material handled					
Program title	Sponsor	Status[a]	FTEs[b]	Funding[c] ($K)	^{233}U	Np	Pu	Am	Cm	Trans-curium
Np	DOE	h	*d*	*d*		kg				
Am	DOE	h	*d*	*d*				kg		
Nuclear test program assemblies	DOE	r	*d*	*d*			kg			
Special isotopes production	DOE	c	*d*	*d*						mg – g
Uranium programs	DOE	c	20	2,300	kg	kg				
Pu processing, storage, and handling	DOE	c	500	80,000			MT			

[a] Status: c = current (small related projects may be grouped together); r = recent (past 5 years); h = historic [more than 5 years ago — major programs only (e.g., those involving more than 10 person-years)].

[b] Estimated number of personnel in full-time equivalents (FTEs).

[c] These numbers are only estimates of LANL funding levels.

[d] Not available.

Table 2.12. Uranium-233 and related actinide programs at Lawrence Livermore National Laboratory (LLNL)

					Scale of material handled					
Program title	Sponsor	Status[a]	FTEs[b]	Funding ($K)	^{233}U	Np	Pu	Am	Cm	Trans-curium
Nuclear test	DOE	r	200	800,000	kg	kg	kg	g	g	
Heavy elements	DOE	c	3	300		mg	mg	mg	g	mg
Nuclear forensics	DOE	c	4	1,000	g	g	g	mg	mg	
Pu facility	DOE	c	20	*c*		g	kg	g		

[a] Status: c = current (small related projects may be grouped together); r = recent (past 5 years); h = historic [more than 5 years ago — major programs only, (e.g., those involving more than 10 person years)].

[b] Estimated number of personnel in full-time equivalents (FTEs).

[c] Not available.

Table 2.13. Uranium-233 and related actinide programs at Oak Ridge National Laboratory (ORNL)

					Scale of material handled					
Program title[a]	Sponsor	Status[b]	FTEs[c]	Funding ($K)	^{233}U	Np	Pu	Am	Cm	Trans-curium
Bismuth phosphate	U.S. Army	h	>100	>10,000			MT			
Redox-25, Purex, SCRUP-2, SRPE, BNL-1/2, SNAP-A, H-240, S-240, MTR-1	U.S. Army, AEC	h	>100	>10,000			kg			
Thorex, high-isotopic-purity ^{233}U, Kilorod, LWBR, ZPR, CEUSP	AEC	h	>100	>10,000	kg					
MSRE remediation[d]	DOE	c	80	20000	kg					
Californium source fabrication	DOE	c	15	2000						mg
Mark-42 processing	DOE	c	30	4500			g			
Trans-Pu processing	DOE	c	40	6000				mg		mg
^{229}Th	DOE	c	7	1000	kg					
^{233}U storage	DOE	c	30	4500	kg					

[a] LWBR = light-water breeder reactor; ZPR = Zero Power Reactor; CEUSP = Consolidated Edison Uranium Solidification Program; MSRE = Molten Salt Reactor Experiment.

[b] Status: c = current (small related projects may be grouped together); r = recent (past 5 years); h = historic [more than 5 years ago — major programs only (e.g., those involving more than 10 person-years)].

[c] Estimated number of personnel in Full-Time Equivalents (FTEs).

[d] Recent activities involve removal and stabilization of fuel.

Table 2.14. Uranium-233 and related actinide programs at Pacific Northwest National Laboratory (PNNL)-Hanford

					Scale of material handled					
Program title[a]	Sponsor	Status[b]	FTEs[c]	Funding ($K)	^{233}U	Np	Pu	Am	Cm	Trans-curium
WG/FG Pu scrap recovery & stabilization	DOE	c,r,h	*d*	*d*			kg	kg		
^{233}U production	AEC	h	*d*	*d*	kg					
WG-Pu production	DOE	h	*d*	*d*		kg	MT			
Thorium oxide fuel processing	DOE	h	*d*	*d*	MT					
^{213}Bi generator	DOE	*d*	1	200	g					
Pu immobilization	DOE	*d*	4	650			g			

[a] WG/FG = Weapons Grade/Fuel Grade.

[b] Status: c = current (small related projects may be grouped together); r = recent (past 5 years); h = historic [more than 5 years ago — major programs only [e.g., those involving more than 10 person-years)].

[c] Estimated number of personnel in full-time equivalents (FTEs).

[d] Not available.

Table 2.15. Uranium-233 and related actinide programs at Savannah River Site

			Scale of material handled					
Program title	Sponsor	Status[a]	^{233}U	Np	Pu	Am	Cm	Trans-curium
^{233}U production	DOE	h	kg					
Np production	DOE	h		kg				
^{239}Pu metal production	DOE	r			kg			
Am/Cm	DOE	h				g	g	
^{238}Pu program	DOE	r			kg			
Californium	DOE	h						g
^{235}U	DOE	h						

[a] Status: c = current (small related projects may be grouped together); r = recent (past 5 years); h = historic [more than 5 years ago — major programs only (e.g., those involving more than 10 person-years)].

2.5 SUMMARY OF ^{233}U TECHNICAL KNOWLEDGE AND COMPETENCE

2.5.1 Key Personnel

The availability of direct ^{233}U expertise at all the DOE sites responding to the survey is summarized in Table 2.16.

Table 2.16. Availability of ^{233}U expertise at DOE sites

Site[a]	Handling	Remote handling	Processing	Process support	Safety	Materials management
ANL-West	X	X			X	X
DOE	X		X		X	X
INEEL	X	X	X	X	X	X
LLNL	X	X	X	X	X	X
ORNL	X	X	X	X	X	X
PNNL-Hanford	X	X	X	X	X	X
SRS			X			

[a] ANL = Argonne National Laboratory; DOE = Department of Energy; INEEL = Idaho National Engineering and Environmental Laboratory; LLNL = Lawrence Livermore National Laboratory; ORNL = Oak Ridge National Laboratory; PNNL = Pacific Northwest National Laboratory; SRS = Savannah River Site.

The number of key personnel identified at each of the DOE sites (based on the responses to the survey on direct ^{233}U experience), listed by academic backgrounds, are shown in Table 2.17. The number of key personnel identified at each of the DOE sites, listed by years of direct ^{233}U experience, are shown in Table 2.18.

Table 2.17. Number of key personnel identified

Site[a]	Chemical engineering			Chemistry			Nuclear engineering			Mechanical engineering			Technicians	Other	Total	
	B.S.	M.S.	Ph.D.	B.S.	M.S.	Ph.D.	B.S.	M.S.	Ph.D.	B.S.	M.S.	Ph.D.			Active	Retired
ANL-West														2	2	
DOE					1	1		1	1	3				1	8	
INEEL					1	2	1	2			1			1	8	
LANL						2								3	5	
LLNL						2		1					1	5	6	3
ORNL	4	6	5		1	4	1	5	2	1			9	5	36	7
PNNL-Hanford	1			1	1	1							2		4	2
SRS	1														1	

[a] ANL = Argonne National Laboratory; DOE = Department of Energy; INEEL = Idaho National Engineering and Environmental Laboratory; LANL = Los Alamos National Laboratory; LLNL = Lawrence Livermore National Laboratory; ORNL = Oak Ridge National Laboratory; PNNL = Pacific Northwest National Laboratory; SRS = Savannah River Site.

Table 2.18. Number of active key personnel identified by years of direct ^{233}U experience[a]

Site	<5 years	5 to 10 years	11 to 20 years	21 to 40 years	Retired
ANL-West	1		1		
DOE	4	2		2	
INEEL	1	1	4	2	
LANL		2	3		
LLNL	2	3	1		3
ORNL	17	9	6	4	7
PNNL-Hanford	1	2		1	2
SRS		1			

[a]Inferred from the highest number of years of ^{233}U experience as listed in the key personnel tables.

[b]ANL = Argonne National Laboratory, DOE = Department of Energy; INEEL = Idaho National Engineering and Environmental Laboratory; LANL = Los Alamos National Laboratory; LLNL = Lawrence Livermore National Laboratory; ORNL = Oak Ridge National Laboratory; PNNL = Pacific Northwest National Laboratory; SRS = Savannah River Site.

2.5.2 Involvement of Retired Key Personnel

The results of the survey for key personnel across the DOE complex indicate that many technically active retirees represent a large portion of the ^{233}U expertise. Many of these retirees are involved with current ^{233}U programs. (SRS does not have any retirees serving as consultants, nor are there any plans to include them.) At ORNL, highly qualified and experienced retirees are working as consultants and serving as mentors in ongoing ^{233}U-related activities. The activities that retirees are involved with include MSRE remediation, facility upgrades and maintenance activities, thorium recovery from ^{233}U at Building 3019, and the DNFSB Recommendation 97-1 program. These experts are providing valuable knowledge in areas such as materials handling, facility design and operations, processing, ^{233}U storage, and safety. In working with the current generation of workers, the retirees are not only imparting their technical knowledge and experience but are also providing a historical perspective as well (e.g., the reason things were done a certain way).

2.5.3 Short-Term Needs To Maintain Technical Competency

Based on results of the survey for key personnel, there currently exists an adequate level of technical knowledge and competency to ensure safe storage of ^{233}U-bearing material in the short term. The critical needs are to maintain the involvement of highly qualified and experienced retirees over the next few years and to make sure that technology related to practices involving high-^{232}U-content batches of ^{233}U is transferred to the next generation of workers. Presently, this technology transfer is occurring effectively at a relatively high rate, resulting in an increase in the level of ^{233}U expertise. This is due to activities related to the MSRE remediation project at ORNL, the new emphasis on ^{233}U storage at ORNL, thorium recovery from ^{233}U, and ^{233}U disposition planning (through the DOE Fissile Materials Disposition Program). As a result of these activities, young professionals are gaining ^{233}U expertise and experience through "hands-on" involvement with ^{233}U activities and interface with retirees. Since the current set of ^{233}U activities is scheduled to continue into the next few years, the transfer of knowledge and expertise from the retirees to the new workers is expected to continue as well.

3. CONCLUSIONS

Uranium-233 (with concomitant ^{232}U) is a man-made fissile isotope of uranium with unique nuclear characteristics which require high-integrity alpha containment, biological shielding, and remote handling. The special handling considerations and the fact that much of the ^{233}U processing and large-scale handling was performed over a decade ago underscore the importance of identifying the people within the DOE complex who are currently working with or have worked with ^{233}U. The availability of these key personnel is important in ensuring safe interim storage, management, and ultimate disposition of ^{233}U at DOE facilities. Significant programs are ongoing at several DOE sites with actinides. The properties of these actinide materials require many of the same types of facilities and handling expertise as does ^{233}U.

The survey for key personnel (defined as people with direct ^{233}U experience) identified a total of 82 people. These personnel are from DOE sites with either current ^{233}U holdings or significant past ^{233}U program involvement. The survey results indicate that ORNL, LLNL, and INEEL have the largest concentrations of key personnel with the broadest range of expertise. Sites other than ORNL and INEEL have some key personnel available, but the range of expertise is typically limited. The concentration of key personnel largely reflects the current status of ^{233}U and related actinide programs at the DOE sites. Both ORNL and INEEL currently maintain the largest inventories of ^{233}U, in the hundreds-of-kilograms range. The other sites have inventories of substantially less than 10 kg ^{233}U.

Slightly more than half of the key personnel have earned advanced (graduate) university degrees. Twenty-four of the key personnel hold Ph.D. degrees in engineering or chemistry. Twenty-two of the key personnel hold M.S. degrees in either engineering or a physical science. Ten technicians were identified as key personnel. Where academic backgrounds are concerned, 17 of the key personnel have their highest degrees in chemical engineering, and 17 have their highest degrees in chemistry. Thus, approximately 40% of all the key personnel have degrees in either chemistry or chemical engineering. The next largest representation in academic backgrounds is in nuclear engineering (14 key personnel).

Twelve of the key personnel, or 15% of the total, were identified as being retired. While most of these retirees are still active professionally, they represent a resource that will be unavailable in the future. Additionally, as gleaned from the number of expertise years, many of the key personnel with experience in ^{233}U processing are nearing retirement. Major processing programs for ^{233}U were conducted almost two to three decades ago and ended in the mid-1980s.

Of the programs listed by the six DOE sites that provided such information, only two sites, ORNL and INEEL, list current programs related to ^{233}U. The ^{233}U program at INEEL currently consists of storage, while ORNL programs include MSRE remediation, serving as the National ^{233}U Repository, fissile material disposition, and thorium recovery from ^{233}U for medical applications. LLNL had in the past used ^{233}U in support of nuclear testing experiments but currently has no program involving the material. This site is negotiating with ORNL to ship all of its ^{233}U inventory to ORNL. However, LLNL is also requesting that certain ^{233}U materials in their possession now be saved in their present form at ORNL for future use. Five of the sites responding to the survey reported having current programs in the related actinides; these sites are LANL, LLNL, ORNL, PNNL-Hanford, and SRS. Other ^{233}U activities at the remaining DOE sites include, to varying degrees, inspection, consolidation, and repackaging actions that are part of DOE's Implementation Plan for 97-1.

The core knowledge base needed for safe storage of ^{233}U is still available, and much of this expertise is involved in current ^{233}U programs (i.e., safe storage, MSRE remediation, fissile material disposition, and medical radioisotope research and development). Since many of these programs are relatively recent, the number of personnel with ^{233}U experience has been increasing. Many retirees are serving as consultants to current ^{233}U programs. These retirees are providing valuable experience, knowledge, and mentorship through their involvement with the ^{233}U projects. Some of these retirees will continue to be available for the next few years, providing a transition period for the transfer of skills, knowledge, and experience. Their participation in current ^{233}U work will result in the transfer of knowledge to a new generation of technical personnel and will help perpetuate the technical knowledge and competencies in this area. In addition, experience in processing other actinides, such as Am, Cm, Np, and ^{238}Pu, is applicable to the ^{233}U work. Through this or a similar strategy, an appropriate base of knowledge will continue to exist.

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