

# Feasibility and Alternatives for Receipt, Storage, and Processing of HTGR Pebble Fuel at SRS

## *Appendix A: High Level Objectives, Functions and Requirements (WFO Task 1)*

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OPERATED BY SAVANNAH RIVER NUCLEAR SOLUTIONS

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## LIST OF ABBREVIATIONS

AVR	<i>Arbeitsgemeinschaft Versuchreaktor</i>
CY	Calendar Year
DOE	Department of Energy
DU	Depleted Uranium
EA	Environmental Assessment
EIS	Environmental Impact Statement
HEU	Highly Enrichment Uranium
HLW	High Level Waste
HTGR	High Temperature Gas Reactor
Jülich	Forschungszentrum Jülich GmbH
LEU	Low Enrichment Uranium
LLW	Low Level Waste
M&O	Management and Operations
MC&A	Material Control and Accountability
NEPA	National Environmental Policy Act
S&S	Safeguards and Security
SSCs	Systems, Structures, and Components
SNM	Spent Nuclear Material
SOW	Statement of Work
SRNL	Savannah River National Laboratory
SRNS,LLC	Savannah River Nuclear Solutions, LLC and its duly authorized representatives
SRS	Savannah River Site
TBD	To Be Determined
TBV	To Be Verified
TH	Thorium
THTR	<i>Thorium Hochtemperaturreaktor</i>
TRL	Technology Readiness Level
U. S.	United States
U	Uranium
WFO	Work for Others

## 1. INTRODUCTION

The U. S. Department of Energy Contractor, Savannah River Nuclear Solutions (SRNS), LLC and Forschungszentrum Jülich GmbH (Jülich) are partnering to develop a digestion technology to process graphite-based high temperature gas-cooled reactor (HTGR) nuclear fuel. The fuel consists of small kernels of uranium /thorium (U/Th) embedded in a graphite sphere (“pebbles”).

The fuel was fabricated using DOE-owned enriched uranium and irradiated in two reactors, AVR (*Arbeitsgemeinschaft Versuchreaktor*) and THTR (*Thorium Hochtemperaturreaktor*) in Germany. The used fuel, consisting of approximately 920,000 pebbles, is stored at two locations in casks that are suitable for both storage and transportation. Fuel from the THTR reactor is stored in 303 casks at a cask Storage Facility in the city of Ahaus, and fuel from the AVR reactor is stored in 152 casks at the Jülich Research Center. The total uranium content of the used fuel is approximately one metric ton.

The development of a digestion technology to process the fuel will be performed under the Work for Others Agreement WFO 13-021, “Research and Development on Graphite Destruction for the Pebble Bed Fuel Elements” (Reference 1). The single Step 1 deliverable is a “Report on Feasibility and Alternatives for Receipt, Storage and Processing of HTGR Pebble Fuel as SRS” (Reference 2). The report will contain an update on technology maturation of the graphite digestion process, a discussion of alternative technologies and facility locations, and a risk assessment of the alternatives.

This report satisfies Reference 1, Statement of Work: Task Identification Number 1. This task states that the SRS team will initiate the development of High Level Objectives and Functions of the project to ensure the following are addressed: 1. Receipt and storage facilities, 2. Security infrastructure for storage of casks, 3. Security infrastructure for processing and recovery of U kernels, 4. Graphite Removal and Kernel recovery processing, 5. Kernel packaging and interim storage, 6. Kernel dissolution and down blending, 7. Storage, Transport and Disposition of waste and resulting Low Enriched Uranium.

The information in this report will be summarized and/or referenced in the appropriate sections of Reference 2 described above. The functions and performance requirements documented in this report are based on subject matter experts’ judgments, expertise, and insight at the time the report was written. As the unknowns associated with the Project’s objectives and requirements are better defined, additional functions and requirements will be documented.

## 2. HIGH LEVEL OBJECTIVES

### 2.1 Program Objectives/Requirements

As stated in Reference 1, Statement of Work: Section 1.1 (Background), the objective of the program is to perform studies that scale the research data/results up to a target of 1000 pebble/day production rate. In addition, the work scope would produce a conceptual design for both the receipt/storage and would progress conceptual design toward the processing phases of the production scale operation based on documented safety analysis, criticality reviews, safeguards analysis, and facility/process assumptions and constraints.

As stated in Reference 1, Statement of Work: Section 3.0 (Task Requirements), the WFO is divided into two steps. The first step provides information for development of the analysis information for NEPA as well as continued process scale up work on the technology and preliminary conceptual design activities. This information will help inform the Sponsor on the potential outcome of the entire project. The Sponsor (Jülich) will make a decision during Step 1 on whether or not to proceed with the Step 2 activities. It is envisioned that Step 1 will complete by October 31, 2014. The Step 2 activities provide for finalization of NEPA activities (already funded as part of Step 1), continuation of process scale up and preliminary conceptual design activities.

### 2.2 Project Objectives

The Savannah River M&O Contract No. DE-AC09-08SR22470; Deliverables of Work For Others Agreement (WFO)-WFO-13-021 (Reference 3) states that the WFO 13-021 (Reference 1) was authorized to start work on May 22, 2014 and initiated several activities aimed at furthering the work on the feasibility of processing the High Temperature Gas Reactor (HTGR) fuel ("Pebble Bed Fuel") at SRS.

Since authorization was received, SRS has been working to ensure the planned activities meet the first objective (WFO Step1) which is to support a decision on the initial receipt of the Pebble Bed Fuel by the end of October 2014. Additionally, if the decision is made to move forward with preparations to receive and store the Pebble Bed Fuel, the second objective (WFO Step2) is to be ready to receive the first shipment by the end of June 2015.

### 2.3 HTGR Technology Maturation Objectives

***NOTE: Text in this was extracted from WFO-13-021 (Reference 1) and may be outdated. The outdated information needs to be identified and corrected in the next revision of this functions and requirements document.***

As stated in Reference 1, Attachment 1: Objectives Section, SRNL will demonstrate a first-of-a-kind technology to process production-scale quantities of HTGR pebble bed reactor fuel. This effort will transition from small-scale chemistry and feasibility testing to the demonstration of a facility-viable process with a throughput of 1/10 to 1/5 of production scale. Testing will be almost exclusively with graphite-only pebbles. Graphite represents 97-98% of the overall fuel and is the only fuel component digested in the process. SRNL performed a technical review of the technology in August 2013. The review team recognized that the technical basis for the chemistry has been established but that many

other technical issues must be addressed for the technology to mature for acceptance as viable for irradiated fuel digestion in a remote-handled facility.

SRNL will conduct several significant efforts in CY2014 (*Note: CY2014 scope has changed. The new scope has been documented in Reference 5*) to support the maturation of the HTGR fuel processing technology. The activities correspond to three principal areas: 1) supplemental sub-system definition, 2) small-scale system validation, and 3) pilot-scale engineering demonstration. A significant aspect of the test program involves the collection and analysis of off-gas samples to evaluate the presence and/or potential for corrosive and flammable gases as well as the migration of fission-product metals. These data will support important production facility design and safety basis considerations. At the conclusion of these efforts, SRNL intends to demonstrate a process that has a good probability for acceptance and deployment in a remote-handled process facility.

### **3. SOW REQUIREMENTS AND ASSUMPTIONS**

The SOW requirements and assumptions provided in Reference 1, Statement of Work: Sections 2.1 and 3.1 are documented below:

#### **3.1 Applicable Standards/Codes/Orders/Regulations**

U.S. Department of Labor Relations (<http://www.gpoaccess.gov/cfr/index.html>) including, but not limited to, 29 CFR Part 1910 Occupational Safety and Health Standards  
U.S. Department Of Energy Directives ([www.directives.doe.gov](http://www.directives.doe.gov)) including but not limited to,  
DOE O 460.2, *Departmental Materials Transportation and Packaging Management*  
DOE O 5400.5, *Radiation Protection of the Public and the Environment*  
DOE O 5480.19, *Conduct of Operations Requirements for DOE Facilities*  
DOE O 5480.20A, *Personnel Selection, Qualification, and Training Requirements for DOE Nuclear Facilities*  
DOE O 414.1C, *Quality Assurance*  
DOE O 451.1B Chg 3, *National Environmental Policy Act Compliance Program*  
DOE O 460.1C, *Packaging and Transportation Safety*  
DOE O 474.2, Admin Chg 2, *Nuclear Material Control and Accountability*  
DOE O 410.2, *Management of Nuclear Materials*  
DOE O 551.1C, *Official Travel*  
ISO 17025 Standard, *General Requirements for the Competence of Calibration and Testing Laboratories.*  
United States Code of Federal Regulations  
10 CFR Part 830, *Nuclear Safety Management*  
10 CFR Part 71, *and supporting guides*  
10 CFR Part 1021, *National Environmental Policy Act Implementing Procedures*  
10 CFR Part 73, *Physical Protection of Plants and Materials*  
10 CFR Part 110, *Export and Import of Nuclear Equipment and Material*  
49 CFR, *Transportation*  
International Atomic Energy Agency (IAEA) Safety Requirements  
TS-R-1, *Regulations for Safe Transport of Radiological Material and supporting guides*

## 3.2 Quality Requirements

1. Sponsor
  - a. No Quality Assurance requirements apply for the Sponsor.
2. SRNS Laboratories/Operations (General)
  - a. SRNS shall comply with the Quality Assurance requirements as specified in DOE Order 414.1C for:
    - i. Procedure development, review, approval, and task execution;
    - ii. Use approved industry methods for analyses;
    - iii. Have an approved calibration program/process for analytical equipment;
    - iv. Training of personnel for laboratory-scale and engineering-scale testing
    - v. Performance of scoping and baseline experimental studies;
    - vi. Documentation of experimental results;
    - vii. Third party analytical services;
    - viii. Procurement of process equipment;
    - ix. Research and Development,
    - x. Sample analysis and sample control; and
    - xi. QA records (surveys, completed procedures/forms, shipping documents, etc.).

### 3.3 Technology Maturation Requirements

**NOTE:** Text in this was extracted from WFO-13-021 (Reference 1) Attachment and may be outdated. The outdated information needs to be identified and corrected in the next revision of this functions and requirements document.

The customer technology maturation requirements provided in this section were extracted from Reference 1, Attachment 1. The specific section of the SOW is provided in the last column.

Table 1: Scope of Work Requirements

No.	SOW Requirement	Section
1.0	Although graphite digestion is a critical component of the overall technology, its successful deployment will depend upon the availability of methods for recovering the U/Th fuel kernels and for handling the process off gas. Preliminary studies were conducted as part of WFO-13-002. In particular, testing with unirradiated fuel pebbles and irradiated fuel kernels provided valuable data about fuel performance during graphite digestion. However, more-detailed information is necessary to successfully design the off-gas system and fuel-retention baskets. The quickest and most cost-effective approach entails small-scale studies while larger-scale systems are being designed.	Task Description: <i>Supplemental Sub-System Definition</i>
2.0	Four particular aspects of system design will be evaluated. The first is basket design. Earlier studies identified kernel degradation after graphite removal to be a potential technical issue. Fuel kernels appear to degrade because of agitation in the basket caused by graphite digestion. Retention of fuel kernels after graphite digestion will greatly impact the overall process in numerous ways including fuel recovery, accountability, nuclear material disposition, waste categorization, and waste handling. With residual pieces of unirradiated fuel, SRNL will evaluate alternate basket designs and configurations to determine if one can be identified that minimizes or eliminates kernel degradation. Success could have a significant impact on waste disposal.	Task Description: <i>Supplemental Sub-System Definition</i>
3.0	Four particular aspects of system design will be evaluated. A second design area will address the evaporation and capture behavior of Cs, Sr, I, and Tc during graphite digestion. Historically, these four fission products dominate off-gas and waste-handling strategies at Savannah River. Scoping studies with irradiated fuel kernels (<10 mg fuel per test) provided an initial assessment of their behavior. Additional work is necessary to evaluate their behavior with larger scale tests and with an off-gas scrubber design that is similar to the current proposed design. The ability to properly account for and manage these radionuclides is critical for success of the overall project.	Task Description: <i>Supplemental Sub-System Definition</i>

No.	SOW Requirement	Section
4.0	Four particular aspects of system design will be evaluated. A third design area relates to the off-gas system itself. While the graphite digestion aspect of the technology has some maturity due to extensive testing up to full-pebble digestion, the proposed off-gas system has received minimal evaluation thus far. The concept was developed after full-pebble digestion was complete and has only been evaluated with the digestion of 15-30 g of graphite. Consequently, it is not yet known whether the concept will prove to be viable. Therefore, continued identification of other possible off-gas handling approaches is warranted.	Task Description: <i>Supplemental Sub-System Definition</i>
5.0	Four particular aspects of system design will be evaluated. The fourth design area involves completion of a computer model for the digestion reaction. A COMSOL computer model will be completed that can be used to propose a production thermal profile and refine insulation requirements for pilot-scale testing. It will also predict thermal gradients and potentially predict if there might be mixing issues at larger-scale operations.	Task Description: <i>Supplemental Sub-System Definition</i>
6.0	Prior testing has digested an individual pebble and has evaluated an off-gas concept with fractions of a pebble. The two technical approaches have not been operated as an integrated unit. To effectively design a pilot-scale facility, small-scale multiple-pebble testing of an integrated system is necessary to validate the design concepts of the integrated pilot-scale facility.	Task Description: <i>Small Scale System Validation</i>
7.0	SRNL has constructed and will operate a system that uses heating of the reaction vessel from the bottom with a heating plate rather than placing the reaction vessel inside an insulated furnace. The side walls of the reaction vessel will radiate heat to the environment. Initial plans are to operate the system for the concurrent digestion of six graphite pebbles. If successful, SRNL will extend use of the heating device to the concurrent digestion of 10-15 pebbles. Although the heating equipment has a large enough footprint to accommodate the digestion of 10-15 pebbles, it is not known whether it can be properly configured to provide and retain enough heat to support the digestion. A total of 10-12 experiments are expected at this magnitude of demonstration.	Task Description: <i>Small Scale System Validation</i>
8.0	Based on engineering calculations, this system will be operated at the thermal cycle currently proposed for production-scale digestion. These tests will be the first to evaluate digestion of more than one pebble at a time. The results from the digestion tests can then be used to refine the digestion strategy. Digestion of 6-15 pebbles concurrently will also be used to validate the off-gas treatment concept, evaluate its throughput, and refine the off-gas design parameters to be compatible with the pilot-scale engineering demonstration.	Task Description: <i>Small Scale System Validation</i>

No.	SOW Requirement	Section
9.0	The process equipment will support a video camera to make observations inside the reaction vessel. These data will support equipment design and a more detailed understanding of the reaction chemistry. The ability to observe the reaction dynamics also provides necessary data regarding reaction transients that seem to occur at the surface of the salt melt.	Task Description: <i>Small Scale System Validation</i>
10.0	The off-gas system will support attempts at a quality mass balance, although the appropriate method of accounting for continuous (b)(3)(4) and carbon dioxide gas release in an air environment has not yet been determined. Also, the test program will collect and analyze off-gas samples to evaluate the presence and/or potential for corrosive and flammable gases. These data will support important production facility design considerations.	Task Description: <i>Small Scale System Validation</i>
11.0	(b)(3)(4)	Task Description: <i>Small Scale System Validation</i>
12.0	An additional benefit of the small-scale validation system is that it appears to be well-suited for multi-pebble testing with unirradiated fuel pebbles.	Task Description: <i>Small Scale System Validation</i>
13.0	Subsequent maturation of the technology will occur using a larger-scale system. A pilot-scale engineering system will be designed, fabricated, and operated using hardware capable of a nominal processing charge of 60 graphite pebbles. Demonstration of the process at this scale will enable SRNL to prove the technology at one-fifth to one-tenth of the expected production capacity.	Task Description: <i>Pilot- Scale Demonstration</i>

No.	SOW Requirement	Section
14.0	<p>The planned method for heating the pilot-scale system is induction heating. Based on SRNL’s extensive experience with melting both glass and metals at production scale, induction heating appears to be the best approach for both pilot-scale and production-scale operations. However, a thorough evaluation will be performed to select the best approach to heating. The digestion system will be attached to the best-available technology for off-gas handling. SRNL has the experience and equipment for analyzing the system off gas. Sampling of the off gas will continue to assess the presence or potential for corrosive or flammable gases. The off-gas system will be attached to available FTIR and GC/MS instruments previously used to analyze off gas from SRNL waste vitrification programs. Efforts will continue to optimize the off-gas exhaust system; fission product simulants (Cs and Sr) will be introduced in some tests to evaluate their proportionation to the off gas and salt.</p>	<p>Task Description: <i>Pilot- Scale Demonstration</i></p>
15.0	<p>As with the small-scale validation system, the process will be operated using the proposed production-scale thermal profile to continue verifying that the digestion cycle is appropriate and can be completed safely. These tests will use bulk-available chemicals instead of analytical-grade chemicals. It is not yet known what impact the change in chemical sources will cause. Particular care will be taken to collect temperature data from multiple locations in the digestion process to facilitate thermal modeling that accounts for inter-pebble behavior. To the extent possible, the behavior of the reaction inside the basket will be modeled prior to this stage of testing based on data and observations from the small-scale validation system. A programmable controller with operator interface will be demonstrated for satisfactory control of the digestion process.</p>	<p>Task Description: <i>Pilot- Scale Demonstration</i></p>
16.0	<p>Behavior of the materials of construction will be assessed as the induction field will be designed to couple to the reaction vessel. <b>(b)(3)(4)</b> [Redacted] Although there will be no actual fuel kernels associated with this stage of testing, the proposed production basket design will be incorporated into the design to insure its mechanical integrity throughout the stages of testing.</p>	<p>Task Description: <i>Pilot- Scale Demonstration</i></p>
17.0	<p>As necessary, the spent process salt will be dissolved from the reaction vessel. Attempts will be made to identify a particulate form of metal or ceramic to simulate the presence of fuel kernels. Consequently, testing can demonstrate basket handling and unloading of the fuel from the basket. A total of 8-10 pilot-scale demonstration tests is anticipated.</p>	<p>Task Description: <i>Pilot- Scale Demonstration</i></p>
18.0	<p>The above tasks will advance the maturity of HTGR processing from its current feasibility level to pilot-scale engineering demonstration. At completion of the pilot-scale testing, there should be sufficient data for a production-scale design.</p>	<p>Customer Conclusions</p>

No.	SOW Requirement	Section
19.0	<p>The task ahead is complex because the task involves a first-of-a-kind development and deployment in a remote-handled facility. However, maturation of the process is greatly simplified by three factors. First, the process digests discrete HTGR pebbles that are the same size as the ones SRNL has already tested and will be testing throughout the program. The only change will be the quantity of pebbles digested concurrently. Second, from a chemical perspective, all of the pebbles are fundamentally identical, in fact about 2/3 of the pebbles are even physically identical.</p>	Customer Conclusions
20.0	<p>The process does not have to plan for any significant variability. (b)(3)(4)</p> <p>[REDACTED]</p> <p>[REDACTED]. SRNL will not need an extensive program of optimization. The project will be closer to one of flowsheet validation.</p>	Customer Conclusions
21.0	<p>Equally important for success are SRNL's expertise and technical capabilities. As a result of supporting nuclear material production and waste disposition operations for many years, SRNL researchers have the capabilities and skill sets to address the technical issues of the project. In particular, when facing a first-of-a-kind development like this, the probability of success is enhanced by the availability of melter experts, radioactive off-gas experts, nuclear material processing experts, experienced computer modelers, those familiar with remote-handled operations and pilot-scale facilities.</p>	Customer Conclusions

### 3.4 Technology Maturation – SOW Requirements

*NOTE: Text in this was extracted from WFO-13-021 (Reference 1) Statement of Work: Assumptions Section and may be outdated. The outdated information needs to be identified and corrected in the next revision of this document.*

The customer assumptions in this section were extracted from Reference 1, Statement of Work: Assumption section. These assumptions were captured and assessed as risks during the project high level risk assessment.

Table 2: Technology Maturation – Customer Assumptions

No	SOW Assumptions
1.0	Jülich to provide 750 graphite spheres to support small-scale and pilot-scale demonstrations.
2.0	Jülich will procure a melter system (currently assumed to be induction heating system) to SRNL specifications to accelerate the time needed to receive the equipment.[TBV]
3.0	Jülich will provide additional unirradiated fuel spheres, if necessary.
4.0	The inability to work extensively with irradiated fuel will always represent a significant risk to the project. Essential data for demonstrating process feasibility will be obtained using fission product simulants, as described in the “Supplemental Sub-System Definition” section above. However, additional work with irradiated fuel kernel will likely be necessary during the transition from pilot-scale design to full-scale production facility

## 4. PROJECT MAJOR ASSUMPTIONS

The following assumptions were developed in order to bridge the gap between the baseline document (Reference 1) requirements stated Section 3 of the this report, and the project performance requirements listed in Section 6. These assumptions were captured and assessed as risks during the project high level risk assessment.

- A. (b)(5) [Redacted]
- (b)(5) [Redacted].
- (b)(5) [Redacted]

- B. Regulators will not consider project activities as "significant" and will allow facilities to obtain new permits or modify existing permits per the project schedule. Assumption includes but is not limited to: (b)(3)(4) [Redacted]

**Basis:** Subject Matter Experts process knowledge.

**Verification Method:** Completion of the Permitting Process.

- C. SRS will dispose of the HLW without impacting the receipt facility waste acceptance criteria (WAC) , mission, or closure schedule.

**Basis:** Examples of ways the WAC could be impacted 1) If required, funding is not provided for the expanding the HLW mission or extending the Tank Farm life; 2) Thorium in HLW poses a processing problem due to thixotropic tendency (peanut butter consistency) of thorium; 3) If fission products cannot be separated from the salt, the salt would be considered HLW with no path for disposal; 4) (b)(5)

4) The amount of salt that can be sent to the HLW is defined in the WAC. The amount of salt that will be generated by the process is unknown at this time.

**Verification Method:** Implementing Decision.

- D. SRS will dispose of the HLW without generating significantly (100s) more glass canisters than originally estimated.

**Basis:** SRS- HLW Systems Waste Acceptance Criteria [Reference **TBD**]

**Verification Method:** Implementing Decision.

- E. E-Area Performance Assessment (PA) can be modified to allow disposal of LLW grout or the LLW can be shipped off-site. Note: Involves the Uranium to Grout process.

**Basis:** SRS- LLW systems Waste Acceptance Criteria

**Verification Method:** Implementing Decision

- F. Technology Readiness Levels (TRL) can be reached per the Technology Maturation Plan and project schedule.

**Basis:** Project expectation

**Verification Method:** Small-scale system validation and pilot-scale engineering demonstration.

- G. (b)(5)

(b)(5)

(b)(5)

**Verification Method:** Small-scale system validation and pilot-scale engineering demonstration.

- H. The process can be designed to work in a remote cell operation. Example: Remote operating and maintenance equipment can be designed or operated as required.

**Basis:** Fuel radiation rates are expected to be [TBD]. Remote operation is required to protect the worker.

**Verification Method:** Small-scale system validation, pilot-scale engineering demonstration and mockup of remote process equipment.

- I. The processing equipment can be designed to meet requirements in support of the mission. Example include but are not limited to: equipment size and scale, dissolving time for high Th oxide, digestion operating cycle, vessel size, off-gas systems characterization and treatment, amount of fission product allowed in the salt, and support facilities nozzle connections.

**Basis:** Project Requirement

**Verification Method:** Small-scale system validation, pilot-scale engineering demonstration., and mockup of remote process equipment.

- J. DOE-SR or DOE- HQ will agree with SRS categorization (i.e., Safeguard and Security (S&S) and Material Control and Accountability (MC&A) ) of the material in storage and in process.

**Basis:** Project Requirement

**Verification Method:** Approval of SRS S&S and MC&A plan.

## 5. FUNCTIONAL ANALYSIS

Functional analysis is the process of systematically examining the mission and objectives to identify what the solution to the problem *must do*. Based on the program objectives described in Section 2.0 and the project major assumptions described in Section 4.0, functions were developed and documented in the functional hierarchy diagram illustrated in Figure 1.0 and the functional flow diagram illustrated in Figure 2.0.

### 5.1 Functional Hierarchy Diagram

The functional hierarchy diagram (Figure 1.0) provides the hierarchical relationship between the functions to be performed. The top-level function was broken down into sub-functions. The sub-functions are the actions or capabilities necessary to perform the top-level function. In order to ensure consistency and promote clear communications during the functional analyses processes, the functions were allocated as follows:

- A. The top level function F 0.0 was allocated to the HTGR Program scope.
- B. Sub-functions F 1.1 and F 1.2 were allocated to the US Government/DOE receipt scope.
- C. Sub-function F 1.3 was allocated to SRS receipt scope.
- D. Sub-function F 1.4 was allocated to the Storage Location scope.
- E. Sub-functions F 1.5 through F 1.8 were allocated to the Process Facility scope.
- F. Sub-function F 1.9 was allocated to the on-site Disposal Facilities scope.
- G. Sub-function F 1.10 was allocated to the HTGR Program scope.

## 5.2 Functional Flow Diagram

The functional flow diagram is provided in Figure 2. It shows a logical interrelationship between the functions (Level 1 functions) to be performed.

## 5.3 External and Internal Interfaces

In order to ensure consistency and promote clear communications during the functional analyses process, the project scope and interfaces (external and internal) were defined below and illustrated in Figure 2.

- A. (b)(5)
- B. DOE scope starts with functions 1.1 and 1.2 and includes authorizations (e.g. shipping papers, cask certification, etc.) to accept the fuel.
- C. SRS responsibility for the fuel starts at SRS site boundaries. DOE still owns the fuel.
- D. SRS scope starts with function F 1.3 when the fuel arrives at SRS site boundaries. Train locomotives will be switched. DOE owns the fuel.
- E. The Storage Location scope starts with F 1.4 when the fuel is transferred to a Storage Location(s) and stored.
- F. The Process Facility scope starts with F 1.5 when the fuel casks are transferred to a processing facility and pebbles are unloaded. It stops with F 1.8 with activities needed to prepare process outputs for disposal at SRS or offsite.
- G. The on-site Disposal Facility scope starts with F 1.9.

- H. DOE ownership of the fuel also includes F. 10 because they will be responsible for transferring the fuel off-site for disposal.

### HTGR Functional Hierarchy Diagram

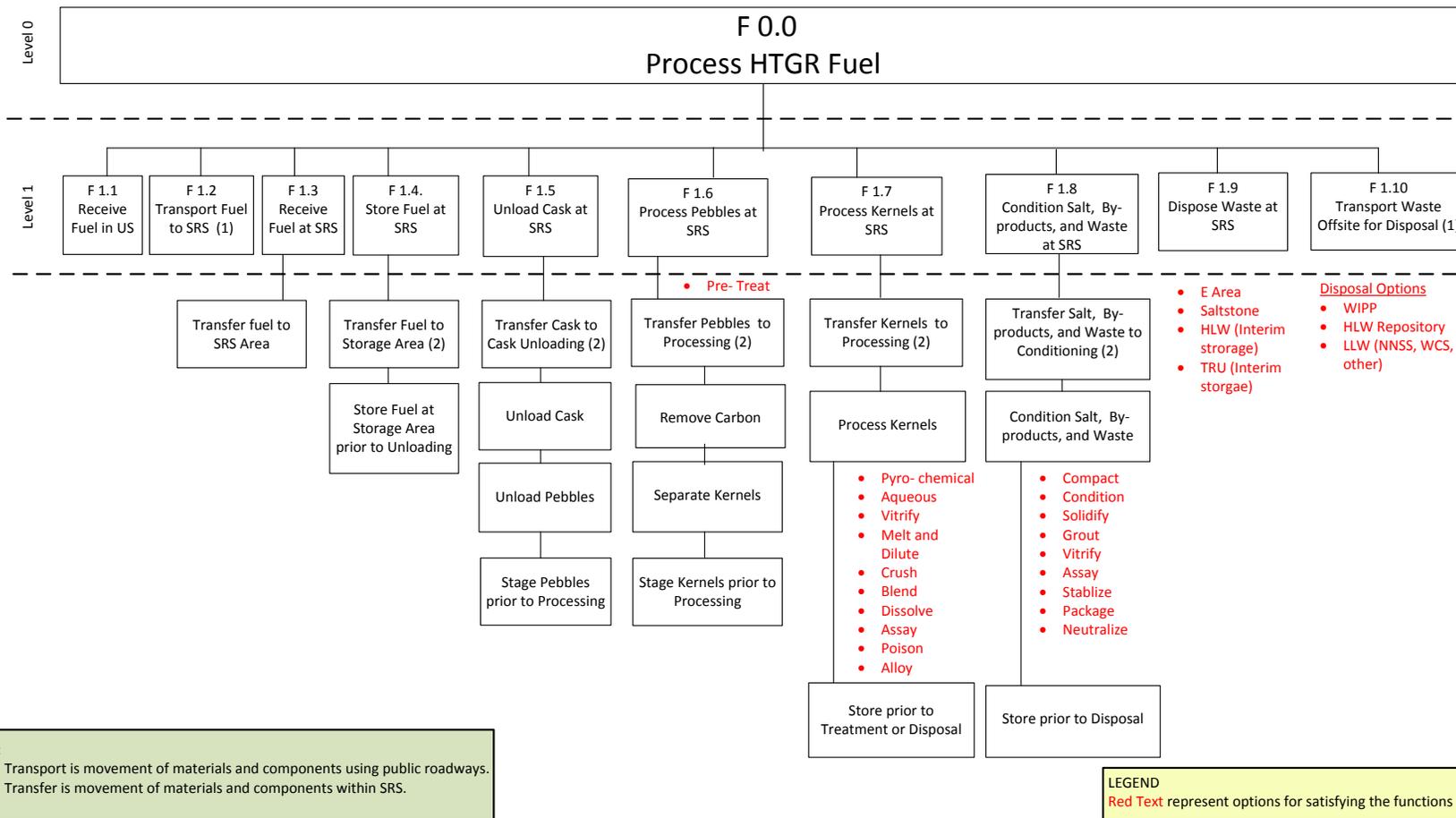


Figure 1: HTGR Functional Hierarchy Diagram

### HTGR Functional Flow Diagram (Level 1 Functions)

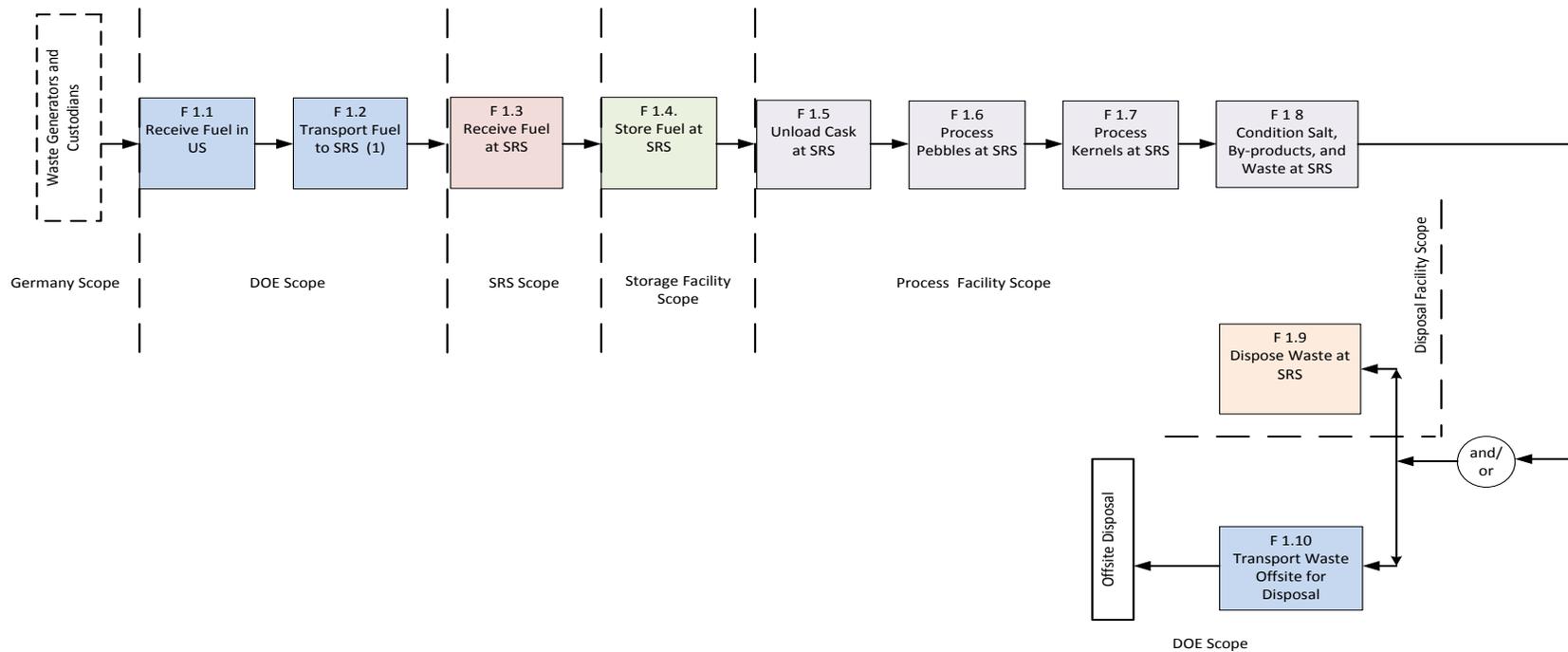


Figure 2: HTGR Functional Flow Diagram (Level 1 Functions)

## 6. FUNCTIONS AND PERFORMANCE REQUIREMENTS

This section provides the functions and performance requirements for the project. The functional hierarchy (Figure 1.) provides the hierarchical relationship between the functions to be performed. The functional flow diagram (Figure 2.) shows a logical interrelationship and interfaces (external and internal) between the functions (Level 1) to be performed. The hierarchical relationship and interrelationship between the functions are described in Section 5. These figures and text should be reviewed prior to reading this section. In this section:

- Functions are indicated by an “F” in front of the numbers.
- A performance requirement is a qualitative or quantitative statement that describes a characteristic or constraint that must be met. Requirements define how well a function must perform. The requirements are indicate by an “R” in front of the numbers.
- In support of the requirements, bases are provided to describe the reason and/or source for the performance requirement. The bases are indicated by the word “**Basis**”.

### F 0.0 Process HTGR Fuel

R 0.1 (b)(5) [REDACTED]

[REDACTED]

R 0.2 SRS shall receive approximately 920,000 fuel pebbles which represent the following:

A. Fuel from the AVR reactor stored in 152 casks at the Jülich Research Center.

**Basis:** Work for Others Agreement WFO 13-021 (Reference 1) [TBV].

B. Fuel from the THTR reactor stored in 303 casks at a cask Storage Facility in the city of Ahaus.

**Basis:** Work for Others Agreement WFO 13-021 (Reference 1) [TBV].

R 0.3 (b)(5) [REDACTED]

(b)(5) [REDACTED]

R 0.3.1 Each shipment of AVR fuel from the seaport (Charleston, SC) to SRS shall include:

A. A maximum of 8 rail cars.

- B.** Each rail car is ~ 90 ft long.
- C.** Each rail car can carry a maximum of 2 CASTOR casks<sup>a</sup>, therefore, each shipment shall include a maximum of 16 CASTOR casks.
- D.** Each loaded CASTOR cask is estimated to weigh ~30 Metric tons. This does not include the weight of the impact limiters or ISO containers.
- E.** The dimensions of each CASTOR cask (without the impact limiters) are 9.13 ft. tall with a diameter of 4.53ft. **[TBV]**

**Basis:** The shipping rate and railcar consist reflects a reasonable schedule to meet the start date and completion dates described in R 0.3. The CASTOR cask dimensions and weight are derived from available CASTOR cask specifications.

R 0.4 SRS shall provide a Storage Location for the fuel (i.e., CASTOR casks) until it is ready for processing.

**Basis:** (b)(5)  The fuel requires storage until it is ready for processing.

R 0.5 The pebble processing rate (AVR and THTR fuel) shall be a minimum of ~ 1,000 pebbles/day **[TBV]**.

**Basis:** Work for Others Agreement WFO 13-021 (Reference 1).

**Basis:** (b)(5) 

R 0.6 The output (Salt, By-products and Waste) from the processing operations shall be conditioned to meet **[TBD]** Disposal Facilities requirements.

**Basis:** Applicable Disposal Facilities WACs {References TBD}.

## **F 1.1 Receive Fuel in U.S.**

R 1.1.1 Same as R 0.2 and R 0.3.

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<sup>a</sup> 'CASTOR Cask' and 'Cask' will be used interchangeable thought-out this document.

*NOTE: Additional requirements for receiving the fuel in the U.S. will be provided by DOE in Document [TBD].*

## **F 1.2 Transport Fuel to SRS**

R 1.2.1 Germany shall provide the capabilities needed to transport the casks by rail.

**Basis:** Project Requirement.

R 1.2.2 DOE shall ensure the railcars (individual cars and consists) will be certified [TBV].

**Basis:** Project Requirement.

## **F 1.3 Receive Fuel at SRS**

R 1.3.1 SRS shall provide the capability needed to receive the casks at SRS site boundaries.

**Basis:** Requisite Step.

R 1.3.2 Germany shall provide the Systems, Structures and Components (SSCs) needed to receive the casks at SRS site boundaries.

**Basis:** SSCs such as lifting yokes, cradles, up-ending/down-blending frames, etc. are unique to the CASTOR casks.

R 1.3.3 SRS shall switch the train locomotives at SRS site boundary. The fuel casks will be transported within SRS boundaries by SRS locomotives.

**Basis:** [TBD]

## **F 1.4 Store Fuel at SRS**

R 1.4.1 Same as R 0.4.

**Basis:** Same as R 0.4.

R 1.4.2 SRS shall provide the capability needed to transport the casks from the site boundaries to the Storage Location and Process Facility (after start-up).

**Basis:** Requisite Step.

R 1.4.3 Germany shall provide the SSCs needed to transport the casks from the site boundaries to the Storage Location and Process Facility (after start-up).

**Basis:** Requisite Step.

R 1.4.4 SRS shall provide the capability needed to unload the casks from the rail car at the Storage Location or Process Facility (after start-up).

**Basis:** Requisite Step.

R 1.4.5 Germany shall provide the SSCs needed to unload the casks at the Storage Location and Process Facility (after start-up).

**Basis:** Requisite Step.

R 1.4.6 SRS shall provide the capability needed to store the fuel at the Storage Location.

**Basis:** Requisite Step.

*NOTE: Additional requirements for storing the fuel at SRS are provided" in Reference 4.*

## **F 1.5 Unload Casks at SRS**

R 1.5.1 SRS shall provide the capability and the SSCs needed to transfer the casks from the Storage Facility to the process facility unloading location. Examples of capabilities and SSCs include but are not limited to: cranes and cask transporters.

**Basis:** Requisite Step.

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R 1.5.2 SRS shall provide the capability and the SSC needed to unload the fuel cans (AVR and THTR) from the casks at the process facility's unloading location. Examples of capabilities and SSCs include but are not limited to: cranes and can transporters.

**Basis:** Requisite Step.

Each cask shall contain 2 AVR fuel cans or 1 THTR fuel can.

- A. Each AVR fuel can weighs [TBD]
- B. The dimensions of each AVR fuel can are [TBD]
- C. Each THTR fuel can weighs [TBD]
- D. The dimensions of each THTR fuel can [TBD]

R 1.5.3 SRS shall provide the capability and SSCs needed to unload the pebbles from the fuel cans in a processing area designed to minimize worker radiation exposure.

**Basis:** Requisite Step.

R 1.5.4 SRS shall provide the capability and SSCs needed to repack the pebbles in a fuel can or basket; transfer the pebbles to a hopper for direct feeding; transfer the pebbles to a temporary staging area and/or meet the material control and accountability requirements.

**Basis:** Requisite Step

R 1.5.5 SRS shall provide the capability and SSCs needed to stage the pebbles until they are ready for processing.

**Basis:** Requisite Step.

R 1.5.6 SRS shall provide the capability and SSCs needed to stage the empty cans until they can be removed from the processing area. The empty fuel cans are assumed to be disposed of as LLW.

**Basis:** Requisite Step.

## **F 1.6 Process Pebbles at SRS**

R 1.6.1 SRS shall provide the capability and the SSCs needed to transfer the pebbles from the pebble repackaging area to the processing area.

**Basis:** Requisite Step.

- R 1.6.2 SRS shall provide the capability and the SSCs needed to process the pebbles. Examples of capabilities and SSCs include but are not limited to: cranes, control room, process equipment, processing areas, support facilities, personnel radiation protection, off-gas system, safeguards and security, MC&A, H&V, fire protection, maintenance, etc.

**Basis:** Requisite Step.

- A. SRS shall provide the processing technology, capability, and SSCs needed to process the pebbles by removing the carbon (i.e., 5mm outer graphite pebble layer and graphite matrix) surrounding the kernels.

**Basis:** Requisite Step.

*NOTE: Additional requirements for processing the pebbles will be provided in "Technology Maturation Plan" (Reference [TBV]), and a HTGR Processing Requirements Document [TBV].*

- B. SRS shall provide the capability and the SSCs needed to treat the off-gases produced by the carbon removal process as well as cooling of the stream prior to discharge to the process facility ventilation stack.

**Basis:** The selected process for removing the carbon will produce off-gases. In addition to volatile radionuclides (isotopes of krypton, iodine, tritium, and carbon), the off gas will contain significant quantities of cesium and strontium, as well as uranium and entrained salt. An off gas system must provide the capability to capture these materials, as well as cooling of the stream prior to discharge to the stack.

- R 1.6.3 SRS shall provide the capability and SSCs needed to collect and package the kernels for processing.

**Basis:** Requisite Step.

- R 1.6.4 SRS shall provide the capability and SSCs needed to stage the kernels until they are ready for processing.

**Basis:** Requisite Step.

## **F 1.7 Process Kernels at SRS**

- R 1.7.1 SRS shall provide the capability and the SSCs needed to transfer the kernels to a kernel processing area.

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**Basis:** Requisite Step.

R 1.7.2 SRS shall provide the capability and the SSCs needed to process the kernels. Examples are the same as the examples provided in R 1.6.2.

**Basis:** [TBD]

## **F 1.8 Condition Salt, By-products, and Waste at SRS**

R 1.8.1 SRS shall provide the capability and the SSCs needed to transfer the salt, by-products and waste to conditioning processes.

**Basis:** Requisite Step.

R 1.8.2 SRS shall provide the capability and the SSCs needed to condition the salt, by-products and waste. Examples are the same as the examples provided in R 1.6.2.

**Basis:** (b)(3)(4)

**Basis:** Liquid wastes from graphite digestion and kernel processing will be processed through the existing high level waste infrastructure to produce saltstone and HLW glass. Liquid wastes of appropriately low radioactivity (e.g. recovered uranium or uranium/thorium) may be grouted for disposal as low level waste. Although transuranic wastes are not expected from processing of HTGR used fuel, any processes producing transuranic waste must ensure that the waste forms meet acceptance criteria for disposal at the Waste Isolation Pilot Plant (WIPP). The casks and canisters are to be disposed as low level waste. The casks may be repurposed as disposal containers for the grouted waste forms of uranium disposed of as low level waste.

*NOTE: Additional requirements for conditioning the salt, by-products and waste will be provided after the process, process facility location, and disposal strategy has been better defined.*

## **F 1.9 Dispose Waste at SRS**

R 1.9.1 SRS shall provide the capability and the SSCs needed to dispose of the waste on site.

**Basis:** Requisite Step.

*NOTE: Additional requirements for disposing of the waste on-site will be provided after the process, process facility location, and on-site disposal requirements have been better defined.*

## **F 1.10 Transport Waste Off-site for Disposal**

R 1.10.1 If needed, DOE shall provide the capability and the SSCs needed to transport the waste off-site for disposal:

**Basis:** Requisite Step.

*NOTE: Additional requirements transporting the waste off-site will provided after the process, process for facility location, and off-site disposal requirements have been better defined.*

## **7. REFERENCES**

1. Work for Others Agreement No.-WFO-13-021, “*Research and Development on Graphite Destruction for the Pebble Bed Fuel Elements*”, April 23, 2014
2. “*Report on Feasibility and Alternatives for Receipt, Storage and Processing of HTGR Pebble Fuel as SRS*” , Revision 0
3. SRNS-U1000-2014-00156, “*The Savannah River M&O Contract No. DE-AC09-08SR22470; Deliverables of Work For Others Agreement (WFO)-WFO-13-021*”, August 6, 2014.
4. Email from Surrinder Chahal to George Sewell “*HTGR Fuel Receipt L-Area Cask Storage*”, September 9, 2014.
5. SRNL-RP=2014-00464,”*Scale-up Maturation Plan for Digestion of Graphite Fuel Pebbles*”, R. A. Pierce, K. M. Fox, June 2014, Revision 0.

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## 8. Appendix A: DEFINITIONS

This section provides definitions of key terms used in this document. These definitions are not requirements but are provided to ensure consistency when describing the project and its requirements.

Assumptions	In order to bridge the gap between the SOW (Reference 2) requirements and the performance requirements provided in this document, several assumptions were developed. If applicable, these assumptions were written as performance requirements. If the assumptions are validated, they will be deleted from the assumptions sections. If they are found to be invalid, they will be removed from the assumptions section and the performance requirements will be rewritten.
Bases	In support of the requirements, bases are provided to describe the reason and/or source for the performance requirement.
Can	A can is the structure surrounding the waste form (e.g., Pebbles) that facilitates handling, storage, transportation, and/or disposal. A can is a metal receptacle with the following purpose: (1) for solidified HLW, its purpose is a pour mold and (2) for UNF, it may provide structural support for intact UNF, loose rods, nonfuel components, or containment of radionuclides.
Cask	A cask is a container for shipping and/or storing UNF (bare or canistered) and/or canistered HLW that is certified by the NRC.
Damaged and Failed Fuel	<p>These terms are used interchangeably by the Utilities. In this document, “damaged and failed fuel” is referred to as “damaged/failed fuel”</p> <p>Below are failed fuel categories defined 10 CFR 961</p> <p>Failed Fuel: Class F-1: Visual Failure or Damaged Class F-2: Radioactive “Leakage” Class F-3: Encapsulated</p>
Function	A function is a primary statement of purpose; it defines what a system or subsystem must accomplish to meet the system mission.
Functional Hierarchy Diagram	A functional hierarchy diagram provides the hierarchical relationship between the functions to be performed. The top-level function was broken down into sub-functions. The sub-

functions are the actions or capabilities necessary to perform the top-level function.

Government Owned  
High Level Waste (HLW)

Government owned HLW is HLW that is currently managed by the government.

Government Owned  
Used Nuclear Fuel (UNF)

Government owned UNF is fuel that is currently managed by the government, and includes fuel that has been withdrawn from a nuclear reactor following irradiation, the constituent elements of which have not been separated.

Great than Class C (GTCC) -  
Low Level Waste (LLW)

In this document Low Level Radioactive Waste (LLRW) is referred to as Low Level Waste (LLW).

GTCC - LLRW is defined by the NRC as LLRW that has radionuclide concentrations exceeding the limits for Class C LLRW in 10 CFR 61.55. The NRC identifies four classes of LLRW in 10 CFR 61.55 for disposal purposes based on the concentrations of specific long- and short-lived radionuclides: Classes A, B, C, and GTCC. Classes A, B, and C LLRW can be disposed of in near-surface disposal facilities licensed by the NRC or an Agreement State.

High Level Waste (HLW)

In this document High Level Radioactive Waste (HLRW) is referred to as High Level Waste HLW).

High Level Radioactive Waste (HLRW) is (1) the highly radioactive material resulting from the reprocessing of spent nuclear fuel, including liquid waste produced directly in reprocessing and any solid material derived from such liquid waste that contains fission products in sufficient concentrations; and (2) other highly radioactive material that the Nuclear Regulatory Commission, consistent with existing law, determines by rule requires permanent isolation.

Requirement

A requirement is a qualitative or quantitative statement that describes a characteristic or constraint that must be met for a system, product or process to be acceptable. Requirements define how well a function must perform. The following types of requirements were used in this document.

Regulatory

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Requirement	A requirement that is established by, or derived from, key Federal laws and regulations
Performance Requirement	A requirement that defines the capability the system or one of its elements must have to accomplish its allocated function.
External and Internal Interface Requirement	A requirement that applies to the inputs to, or outputs from, the functions; or the physical connection or dependence between architectural items.
To Be Determined (TBDs)	A <b>TBD</b> indicates places where descriptive information or quantitative values are not yet available.
To Be Verified (TBVs)	A <b>TBV</b> is used when descriptive or quantitative information is provided but requires further development because it: <ul style="list-style-type: none"><li>➤ Is preliminary and unapproved;</li><li>➤ Involves an uncertain design feature;</li><li>➤ Has insufficient technical justification;</li><li>➤ Needs verification; or</li><li>➤ Creates a discrepancy or inconsistency.</li></ul>
Transfer	Movement of materials and components within SRS boundaries.
Transport	Movement of materials and components using public roadways.