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

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EXECUTIVE SUMMARY

The U.S. Department of Energy contractor, Savannah River Nuclear Solutions (SRNS) and Forschungszentrum Jülich GmbH (Jülich) are partnering to develop a digestion technology to process graphite-based high temperature gas-cooled reactor (HGTR) 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 uranium and irradiated in one of two reactors: AVR (*Arbeitsgemeinschaft Versuchreaktor*) and THTR (*Thorium Hochtemperaturreacktor*) 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. The total uranium content of the used fuel is approximately one metric ton.

Fuel from the THTR reactor is stored in 303 casks at a cask storage facility in the city of Ahaus; fuel from the AVR reactor is stored in 152 casks at the Jülich Research Center. This project has developed data to support National Environmental Policy Act (NEPA) activities to expedite the transport of the fuel for receipt and storage at SRS. In conjunction, processing options have been developed for the HTGR fuel, based on the technology under development at the Savannah River National Laboratory. Receipt and processing of the fuel will provide for return of the HEU material to the United States, increase the stability of the material by conversion of the constituents to more robust waste forms, and potentially allow down blending of the uranium for reuse in commercial applications.

The immediate objective is to provide storage for the 152 casks at the Jülich facility. To meet the required deinventory schedule, shipments will arrive at SRS monthly. Each shipment will consist of a maximum of eight railcars, with two casks per railcar, packaged in a standardized container (ISO container). The cask tie downs and impact limiters will be removed, and the cask will be lifted horizontally, upended to the vertical position, and transferred to a gravel storage pad. The form of the material (Attractiveness Level E) requires only a Property Protection Area for security. This will be provided by fencing, locks, lighting, and other infrastructure upgrades. The preferred designated storage location is a prepared area adjacent to the Building 105-L Protected Area; preliminary review and a Consolidated Hazard Assessment have determined that L Area is preferred due to the existing infrastructure and experience with fuel cask handling operations. The area required for the storage of the initial 152 casks is approximately 14,000 ft^2. Analyses of potential hazards and material-at-risk will be performed to develop safety basis modifications required for cask storage.

Options for processing of the HTGR fuel have been identified and evaluated for implementation in site facilities. In addition to the salt digestion currently under development other established technologies, including electrochemical processing and thermal decomposition of carbon were considered. From the full spectrum of alternatives nine were selected for evaluation. Four were deemed the most feasible, and worthy of further definition, when measured against established screening and evaluation criteria. Three are deployed in the H Canyon facility, and one utilizes reconditioned areas of the Purification Wing in the L Area Material Storage facility (Building 105-L). An alternative location to H Canyon was included in the list of preferred options because the evaluation team recognized that advantages such as cost, schedule, and risk reductions could potentially be realized from process implementation in a relatively clean facility without co-occupancy. All of the preferred options rely on the salt digestion of the graphite pebbles for recovery of the fuel kernels. The four options include:

- <u>Option 1</u> - Pebble digestion followed by dissolution of the kernels in H Canyon with direct disposal of the dissolver solution to the existing liquid waste treatment system.
- <u>Option 2</u> - Pebble digestion followed by dissolution of the kernels in H Canyon, and operation of solvent extraction for separation and recovery of the uranium. The uranium solution is down-blended and grouted to meet acceptance criteria for disposal as low level

waste. Fission products, thorium, and minor actinides are processed via liquid waste treatment.

- Option 2T - Pebble digestion followed by dissolution of the kernels in H Canyon and operation of solvent extraction for separation and recovery of the uranium and thorium. The uranium/thorium solution is down-blended and grouted to meet acceptance criteria for disposal as low level waste. Fission products and minor actinides are processed via liquid waste treatment.
- Option 6 - Pebble digestion followed by separation of the kernels in L Area, followed by down-blending and conversion of the uranium to an alloy in a casting furnace. The product ingots are loaded into canisters and transferred to pad-mounted dry storage. The salt waste stream is treated for fission product and actinide removal to meet acceptance criteria for transfer and disposal as saltstone.

Options that were rejected included the following:

- Option 3, which recovered the uranium as in Option 2, but converted the down blended solution to oxide for storage and potential reuse. This option was rejected due to the cost of conversion and packaging, as well as the programmatic impacts of long-term storage.
- Option 4 also provided uranium recovery for disposal as low level waste as in Option 2, but performed the digestion and kernel recovery in L Area. This option required modifications in two facilities, and resulted in interarea transport of uranium and liquid wastes.
- Option 5 provided for vitrification of the recovered kernels, and placement of small cans of the glass within a DWPF canister for immobilization using high level waste glass. This option required a large number of additional unit operations, significant lag storage space for kernels, cans, and loaded DWPF canisters, and close-coupling of operations with DWPF. The acceptability of the resulting waste form would have to be demonstrated.
- Option 7 included thermal decomposition of the carbon in a fluidized bed. Historical experience with fission product volatilization and ash residue disposition present significant challenges for this option.
- Option 8 provided an electrochemical process for carbon separation and actinide recovery in a molten chloride salt matrix. Although completely non-aqueous, the metallic TRU and glass wastes produced make disposal problematic.

Material balances and conceptual equipment arrangements were developed for each of the preferred options assuming a processing rate of ~1,000 pebbles per day, or a 3.5 year campaign. Pebble digestion can be performed independently with accumulation of kernels for a separate campaign. The pebble processing is assumed to be rate-limiting. Data from the material balances and equipment arrangements were provided as a basis for estimate development for the options.

A primary contributor to cost, environmental sensitivity, and stakeholder concern are the forms and quantities of wastes produced from fuel processing. Waste volumes from each option are summarized in Table ES-1.

Table ES-1 Waste Volume Summary

Waste Form	Option 1	Option 2	Option 2T	Option 6
HLW solution from Dissolving (gallons)	2.02E+05	2.08E+05	2.08E+05	None
HLW solution from Salt Processing (gallons)	4.03E+05	4.79E+05	4.79E+05	4.03E+05
Saltstone Grout (gallons)	1.45E+06	1.65E+06	1.65E+06	9.68E+05
HLW canisters	101	32	15	None
SNF canisters				82
LLW equipment waste (cubic feet)	6.69E+04	7.89E+03	7.89E+03	6.69E+04
LLW grout in CASTOR (cubic feet)		6.69E+04	6.69E+04	
Tons NO_2/year (post scrubber)	25.9	25.9	25.9	11.8

The material balances were based on available data from process development. Equipment arrangements were developed from preliminary data on reaction rates and efficiencies, off gas flow rates and compositions, criticality limits, and material handling constraints. Conservative assumptions were made where technology details were unavailable. More detailed process definition may provide reductions in waste generation, equipment size, and project cost. While process development activities continue, the current level of technology readiness is not sufficiently mature to begin a conceptual design. A technology maturation plan has been developed to address the risks inherent in process scale up to full remote operations. Completion of the plan, which includes pilot plant construction and operation, can be achieved within five years. Process start up can then be achieved after an additional five years.

A risk assessment was performed to identify technical and programmatic risks that could impact the project. In addition to the technology maturity risk, a total of five major program risks and seven major project risks were identified. Handling strategies were developed to address or mitigate each risk to acceptable levels.

Preliminary cost estimates for both Total Project Cost and Life Cycle Cost were prepared for each option, as shown in Table ES-2. TPC provides cost for design, construction, and startup of the new process. The TPC estimate includes site overheads and escalation, as well as management reserve for uncertainty in cost and schedule, and technical and programmatic risk. LCC includes costs for facility operations for the duration of the campaign, waste processing and disposal, and process chemicals, utilities, spare parts and other consumables required to support processing. The pilot plant facilities and operation are also included in LCC.

Table ES-2 Summary Cost Data (AVR and THTR Fuel)

(b)(3)(4)

Cost data has also been developed (Table ES-3) for the case where only the 152 casks containing AVR fuel are processed. Although representing approximately one-third of the casks, this fuel contains 56% of the uranium, almost 90% of the transuranics, and all of the TRISO (SiC-coated) kernels in the HTGR fuel. TPC estimates for the four options with only AVR fuel are the same as those for the full complement of 455 casks. There is no reduction in TPC because the equipment required is the same; the lower throughput requirement is offset by the longer cycle time required for pebble processing and kernel dissolution. The reduction in LCC results from a shorter operating period (~ two years) and smaller volumes of liquid and solid waste requiring treatment and disposal.

Table ES-3 Summary Cost Data (AVR Fuel Only)

[redacted]

(b)(3)(4)

technology, cost, and schedule. Further evaluation, based on continuing technology development, may reveal cost, waste, or footprint reductions that could identify one of the four as the preferred alternative for implementation.

CONTENTS

FIGURES

TABLES

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ACRONYMS

AACE	American Association of Cost Engineering
AHP	Analytic Hierarchy Process
AVR	*Arbeitsgemeinschaft Versuchreaktor*
BISO	Bi-isotropic
CASTOR	Cask for Storage and Transportation of Radioactive Material
CST	Crystalline silicotitanate
DBA	Design Basis Accident
DF	Decontamination Factor
DU	Depleted Uranium
EA	Environmental Assessment
EPA	Environmental Protection Agency
HLW	High Level Waste
HTGR	High Temperature Gas-Cooled Reactor
HEU	High Enriched Uranium
IAEA	International Atomic Energy Agency
ISO	International Shipping Organization
kg	Kilogram
LEU	Low Enriched Uranium
LLW	Low Level Waste
LWR	Light Water Reactor
MC&A	Material Control and Accountability
MST	Monosodium titanate
MT	Metric Ton
MTU	Metric Ton Uranium
NEPA	National Environmental Policy Act
NU	Natural Uranium
PDSA	Preliminary Documented Safety Analysis
PPA	Property Protection Area
SDS	Safety Design Strategy
SNM	Special Nuclear Material
SRNL	Savannah River National Laboratory
SRNS	Savannah River Nuclear Solutions
SSCs	Structures, Systems, and Components
Th	Thorium
THTR	*Thorium Hochtemperaturreacktor*
TRISO	Tri-isotropic
TRL	Technology Readiness Level
TRU	Transuranic
U	Uranium
WIPP	Waste Isolation Pilot Plant
WIR	Waste Incidental to Reprocessing

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1.0 PROJECT SCOPE/MISSION

The U.S. Department of Energy contractor, Savannah River Nuclear Solutions (SRNS) 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 uranium, and irradiated in one of two reactors, AVR (*Arbeitsgemeinschaft Versuchreaktor*) and THTR (*Thorium Hochtemperaturreacktor*) 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. The total uranium content of the used fuel is approximately one metric ton.

Fuel from the THTR reactor is stored in 303 casks at a cask storage facility in the city of Ahaus; fuel from the AVR reactor is stored in 152 casks at the Jülich Research Center. This project will provide analysis to support National Environmental Policy Act (NEPA) activities to expedite the transport of the fuel for receipt and storage at SRS. It will also continue the technology development and maturation for fuel processing, and evaluate concepts for processing of the fuel in existing site facilities. Receipt and processing of the fuel will provide for return of the HEU material to the United States, increase the stability of the material by conversion of the constituents to more robust waste forms, and potentially allow down blending of the uranium for reuse in commercial applications.

Major scope areas of the project include:

- Receipt and storage of fuel casks, including design and construction of a storage pad, identification of safeguards and/or cask surveillance requirements while in storage, and procurement of the necessary equipment for transfer of casks to storage and from storage to fuel processing.
- Development, testing, and scale up of equipment for graphite removal from fuel, including kernel recovery and off gas treatment.
- Identification of alternatives for fuel processing, including conceptual equipment arrangements in existing facilities, for graphite removal and kernel processing. Processes will consider options for uranium separation, for recovery or disposal, and include treatment and identification of disposal paths for all waste streams generated.
- Development of data to support completion of NEPA activities that quantify radioactive and hazardous material releases, and document environmental impacts and permit modifications required for project implementation.
- Completion of the Safety Basis Modification packages to identify process hazards, required engineered controls, and criticality safety limits for receipt, storage, handling, and processing.
- Development of an MC&A plan, and identification of equipment to be provided to satisfy nuclear material accountability requirements for fuel processing.

Due to regulatory commitments, receipt of fuel from the Jülich facility must be completed by September 2016. Fuel processing can be deferred until existing facilities are available, or modifications can be made without impact to existing missions.

2.0 PROJECT OBJECTIVE

An immediate objective of this project is to provide analysis and a conceptual strategy to allow receipt and storage of the HTGR used fuel beginning in June 2015. The strategy will provide storage of up to 455 casks from both the Jülich and Ahaus sites, and include all required infrastructure and support for railcar unloading, storage pad construction, cask placement, physical security, and operational surveillance in accordance with DOE order requirements.

A second objective is to provide scale-up of the prototypical digestion process to a target of 1,000 pebbles per day, and develop and evaluate alternatives, in conjunction with existing site capabilities, to disposition the fuel. Alternatives will consider existing and emerging technologies to be deployed in existing facilities. Evaluation of each alternative must consider the technical and project risks, environmental releases, quantities and types of wastes generated, and facility or program impacts from implementation.

A third objective is to provide estimates for the cost and schedule for implementation of preferred alternatives. These will provide the basis for determining whether to proceed.

3.0 ASSUMPTIONS

Assumptions were developed by subject matter experts following a review of existing facility missions and capabilities, safety, security, and regulatory constraints, and the maturity of process technology at the time of the review. Additions or modifications may be made to the assumptions list as the objectives, requirements, and technology become better defined.

- Approval of environmental permit modifications for receipt, storage, and processing of fuel will be completed without impact to the program schedule.
- Receipt, storage, and processing of HTGR fuel will not adversely impact existing facility missions.
- Receipt rates:

  Initially, up to 16 CASTOR casks to be received every month beginning June 2015 through September 2016. The remainder will be received per shipper/receiver agreement.
- The HTGR fuel will be Attractiveness Level E. Receipt and storage of all the fuel will remain a Category IV quantity, requiring a Property Protection Area (PPA).
- Fuel processing will maintain the SNM at Attractiveness Level D.
- Processing rates:
  - Pebble processing for kernel recovery: 3 years (1,000 pebbles/day)
  - Kernel processing: 1 year (one metric ton U)
- All handling and processing of fuel must be performed in shielded, remotely operated cells due to intense radiation of the used fuel.
- All remote operations can be automated or performed from a shielded overhead crane
- Fuel canisters containing pebbles are welded, and will require cutting to open.
- Kernel processing in H Canyon will occur after completion of all other programmatic missions.
- Pebble digestion in H Canyon can occur coincidentally with other missions, but will require interim in-cell storage of recovered kernels.
- Site infrastructure and safety analysis will allow interarea shipments of radioactive materials (fuel, products, and wastes) for disposition.
- All wastes generated will have a defined disposition path.
- Jülich will continue to support the technology maturation by providing equipment and feed materials for testing and evaluation.
- Facility process design will require a minimum TRL of 6, requiring pilot facility operations and process demonstration with irradiated materials.

4.0 FUNCTIONS and REQUIREMENTS

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 and the project assumptions, functions were developed and documented in the functional hierarchy diagram illustrated in Figure 4.1 and the functional flow diagram illustrated in Figure 4.2. Additional discussion of Functions and Requirements is provided in Appendix A.

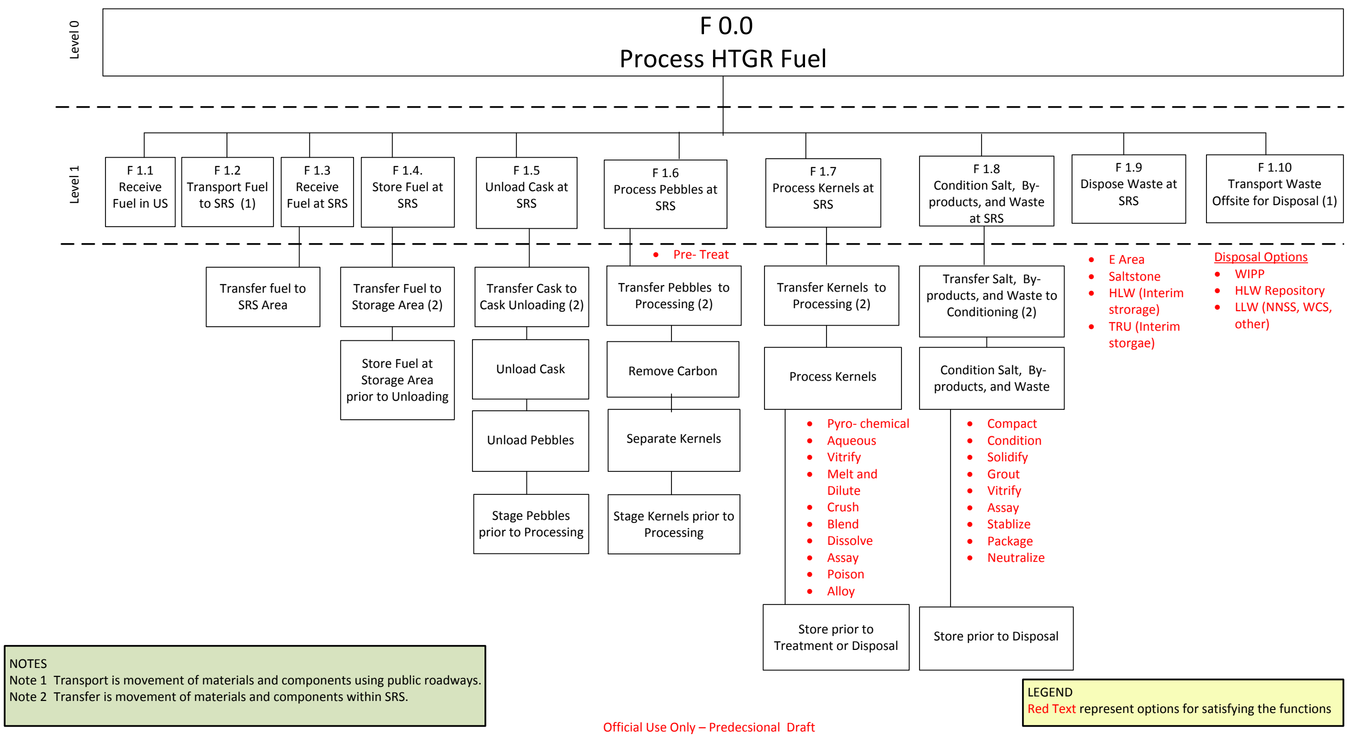

Figure 4-1 HTGR Functional Hierarchy Diagram

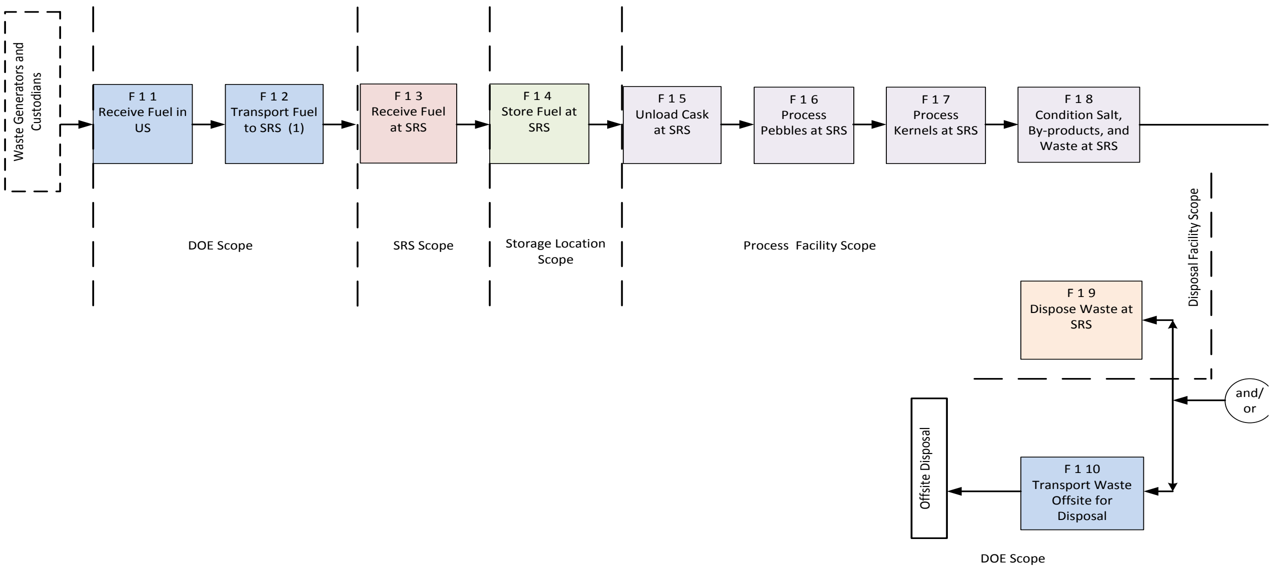

Figure 4-2 Level 1 Functional Flow Diagram

The key goal of requirements analysis is to specify the attributes, characteristics and performance of a system without specifying a specific design for the system. Not specifying a specific system design or facility location enables decision makers to evaluate and compare multiple optional system configurations (and technologies) and select a preferred design solution from a set of solutions.

While the recent focus of technology development has focused on the use of (b)(3)(4) salt for carbon digestion, both historical processes and promising new process alternatives were considered, and evaluated based on their respective ability to meet the program requirements. A summary of major requirements for the functional areas include:

<u>Fuel Receipt</u>

- Ready to receive fuel by June 2015
- Receive a total of 455 casks, each shipment of up to 16 casks arriving monthly
- Isocontainers and impact limiters used for cask shipments must be returned for reuse

<u>Fuel Storage</u>

- Casks must be stored in a Property Protection Area (PPA)
- Cask spacing must allow for placement and access for inspection and/or monitoring
- Casks must be covered to prevent deterioration of carbon steel
- Storage area must have adequate lighting and access control

Processing

- Fuel processing operations must be located in a PPA
- Fuel digestion (carbon removal) to be completed in ~ three years
- Kernel processing to be completed in ~ one year
- Cask unloading, fuel handling, and kernel processing must be done remotely due to high radiation
- All waste generated must be treated and disposed in accordance with established waste acceptance criteria for onsite or offsite disposal facilities

In addition to these functional and performance requirements, the program is also subject to the following constraints:

- Use of existing facilities is encouraged to minimize cost, schedule, and regulatory impacts to the program.
- Fuel receipt, storage, and processing must minimize impacts to existing programs at other site facilities, including H Canyon, L Area Material Storage Facility, Tank Farm Operations, and DWPF.
- Environmental releases must be authorized by the appropriate regulatory agency (e.g. EPA, SCDHEC)
- Generation of waste with no identified path to disposal is discouraged.

Using metrics developed for performance measurement, the process options will be evaluated (Section 6.0) to determine how well the individual options satisfy these requirements. This will provide a basis for prioritizing and screening out of unattractive, less promising options, and allow the program to focus resources to develop technologies associated with the options that provide a “best fit” with the requirements. Requirements are also used to indicate where technology gaps (Section 8.0) may exist.

5.0 ALTERNATIVES DESCRIPTION

Alternatives for fuel processing were developed that provided graphite removal in preparation for kernel processing. In addition to the salt dissolution process currently under development, other existing technologies previously explored for HTGR fuel processing were reviewed. Conceptual flow sheets were developed that could be implemented in existing facilities, using existing waste infrastructure for treatment and disposal of high level, low level, and transuranic (TRU) wastes generated from process operations.

5.1 Fuel Description

The HGTR fuel consists of two types of U-Th fuel elements: bi-isotropic (BISO) and tri-isotropic (TRISO). The designation refers to the number of isotropic carbon layers (Figure 5-1) surrounding the individual fuel kernels. In addition to a third layer of carbon, the TRISO fuel kernels include a thin coating of silicon carbide, which together provided greater fission product retention during reactor operation. Composition of AVR and THTR used fuel is shown in Table 5-1. The TRISO fuel elements are found only in the AVR fuel. Typically 10,000 to 35,000 fuel kernels (diameter: 200 – 600 µm) are dispersed into a 60 mm graphite matrix (Figure 5-2) in the form of pebbles. The average composition of a fuel pebble contains one gram of uranium, 8 grams of thorium, and 190 grams of carbon. The TRISO fuel pebbles also contain about 2 grams of silicon as SiC.

Irradiation of the fuel resulted in the production of significant quantities of ^{233}U, a fissile isotope. ^{233}U decays to ^{232}U which produces a radioactive decay daughter (^{208}Tl) that presents a significant radiation exposure hazard (SRS 2014a) due to the emission of a high energy gamma ray. Remote operation behind heavy shielding will be required for all processing and handling operations. ^{14}C is also produced from activation of the elemental carbon present in the fuel pebble.

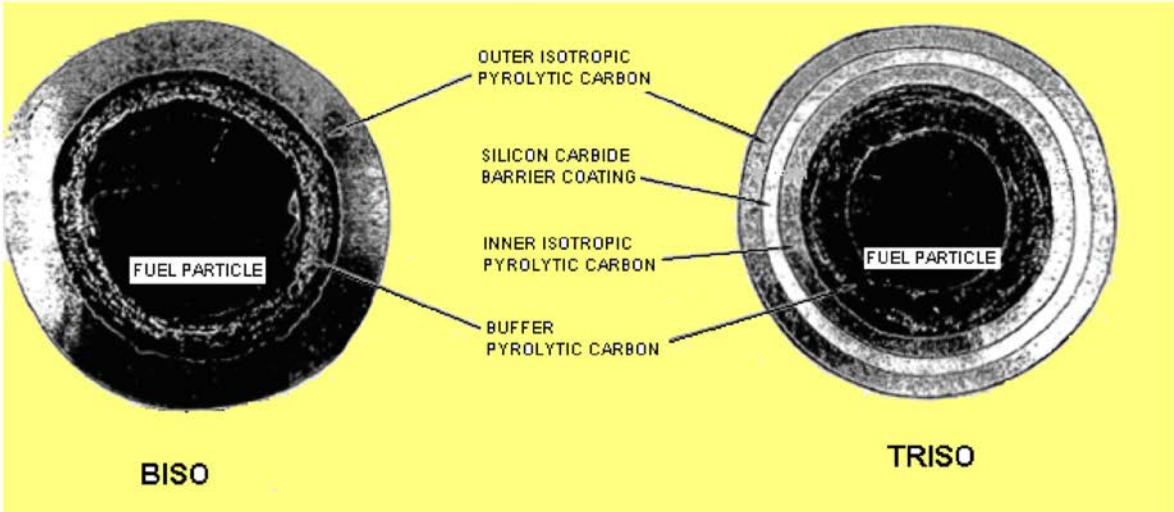

Figure 5-1 BISO and TRISO Fuel Kernels

Table 5-1 HGTR Fuel Characterization

Fuel Type	AVR "A"	AVR "B"	AVR "C"	Total AVR	THTR	Total
# Casks	55	47	50	152	303	455
Pebbles	97,200	90,000	101,000	288,200	628,053	916,253
Fuel Type	TRISO	BISO	BISO/TRISO	-	BISO	-
Total U	458,603	45,078	44,138	547,819	420,317	968,136
^{235}U	35,005	15,228	9,210	59,443	233,706	293,149
^{233}U	3,738	9,093	12,341	25,173	78,886	104,058
^{235}U + ^{233}U, %	8.4	54.0	48.8	15.4	74.4	41.0
Thorium	284,355	428,232	575,922	1,288,508	6,172,679	7,461,188
Plutonium	4,769	454	824	6,047	1,034	7,081

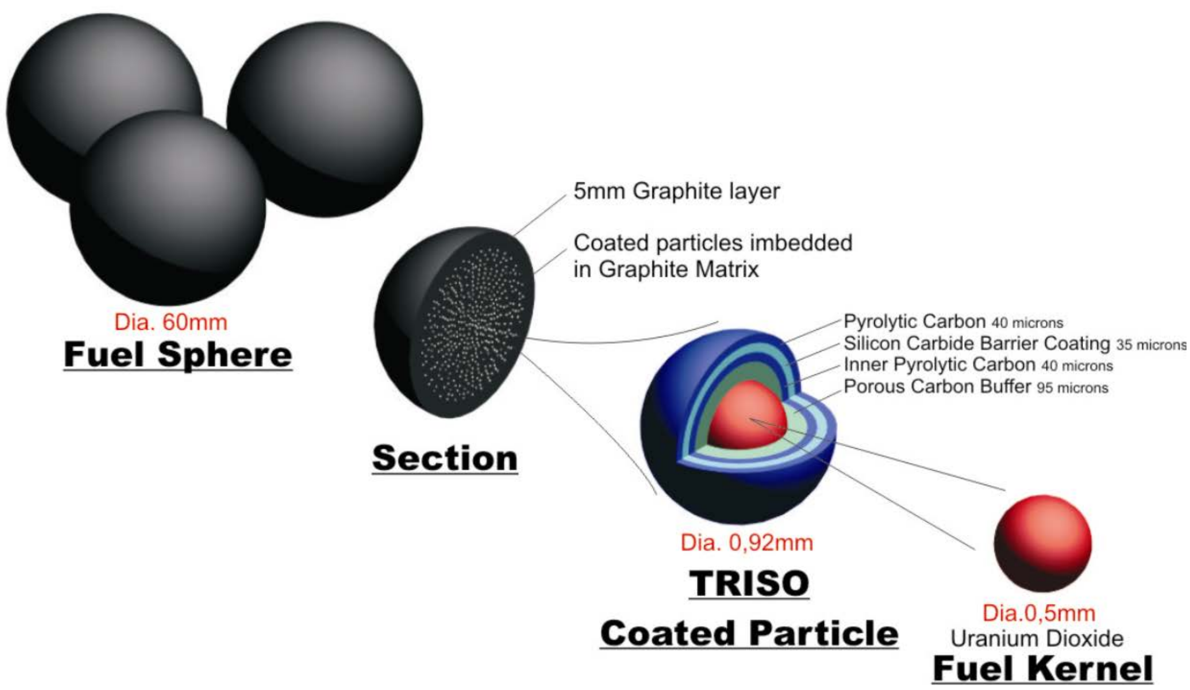

Figure 5-2 Fuel Pebble Composition

The fuel pebbles have been loaded into TLK (*trockenlagerkanne*) canisters (Figure 5-3) containing up to 1,000 pebbles. After loading, the canisters were fitted with a plug that is assumed to have a welded closure. Two canisters have been loaded into a CASTOR cask (Figure 5.4) for storage and transportation. (Some casks contain a single, larger canister with 2,000 pebbles.) Up to 455 casks in this configuration will be received at SRS for storage and subsequent processing. A loaded CASTOR cask is estimated to weigh about 30 tons.

Figure 5-3 TLK Pebble Canister

Figure 5-4 TLK Pebble Canisters in CASTOR Cask

5.2 Storage Options

Based on security requirements (Section 11.0), storage of the casks will be provided within a PPA. Space is available in both H and L Areas to accommodate storage of all 455 CASTOR casks; preliminary review and a Consolidated Hazard Assessment have determined that L Area is preferred due to the existing infrastructure and experience with fuel cask handling operations.

5.3 Range of Possible Process Options

A generic block flow diagram that captures all potentially available process options is shown in Figure 5-5. Major process functions common to all options include:

- Receipt of cask from storage

This completes transfer of the CASTOR cask into the process facility for fuel unloading.

- Unloading of fuel cans from casks

This includes opening of the CASTOR cask, removal of the fuel cans, and transfer to the can opening work station. A shielded transfer cask may be required if can movement is required to be made through accessible areas.

- Opening and unloading of fuel cans

The TLK canisters must be cut open to allow removal of the pebbles for collection and transfer to the process cell. The pebbles can be repackaged in a can or basket, or transferred to a hopper for direct feeding. The opened cans will be discarded as low level waste.

- Removal of graphite with separation/storage of kernels

Direct dissolution of the carbon is not a feasible alternative. The baseline process under development (SRNL 2013) oxidizes graphite in the HGTR fuel to carbon dioxide(b)(3)(4) [redacted]

(b)(3)(4) [redacted]

For the TRISO fuel kernels, a second reaction is required for removal of the SiC coating:

$$SiC + 4NaOH + 2O_2 \rightarrow Na_2SiO_3 + Na_2CO_3 + 2H_2O$$

Other processes for carbon removal include oxidation in a fluidized bed, mechanical removal via crushing and grinding of the pellets, and cathodic reduction of carbon electrochemically.

- Treatment of off gas

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. The off-gas system must provide capture of these materials, as well as cooling of the stream prior to discharge to the stack.

- Processing of kernels

The kernels consist of a mixture of uranium and thorium oxides, and are suitable for chemical dissolution in the H Canyon dissolver, or electrochemical reduction to metals. Processing options include direct disposal of dissolver solution, or separation and purification of uranium for reuse as fuel or for disposal (with or without thorium) as low level waste. Direct disposal of kernels as a high level waste via can-in-canister in a vitrified form or an ingot in a metallic spent fuel form are also candidates for consideration.

- Blend down of uranium

  All of the uranium disposition options require isotopic dilution with either depleted uranium (DU) natural uranium (NU) or low enriched uranium (LEU) to meet criticality safety, material safeguards, or fuel feed specifications for the high level waste, low level waste, and fuel fabrication facilities.

- Treatment and/or packaging of wastes for disposal

  Most options assume 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. Processes producing transuranic waste must ensure that the waste forms meet acceptance criteria for disposal at the Waste Isolation Pilot Plant (WIPP). CASTOR casks and TLK canisters are to be disposed at low level waste.

The two candidate facilities considered for processing include the H Canyon facility (Building 221-H) and areas of L-Area Material Storage Facility (Building 105-L). These facilities have robust architectural features, established perimeter security zones (Limited Area and Protected Area, respectively), sufficient available area for cask staging, and ongoing missions providing trained staff and maintenance of equipment.

(b)(3)(4)

Figure 5-5 Range of Possible Process Options

- 1- Pretreat? Germans developed fractionation technologies to remove graphite not integral to kernel. The option would not look at grinding the kernels. Possible impact of up to 90% C reduction to process.
- 2- Digestion approach: The default assumption is the (b)(3)(4) [redacted] digestion approach. One option would be electrolytic C removal. At least look at feasibility.
- 3- Is it feasible to concentrate kernels by gravity in digester and drain out kernel rich fraction on a batch basis?
- 4- One approach is to process kernels in canyon. An option is to look at various dry approaches or options that do not use canyon.
- 5. There are two bounding scenarios pending demonstration. One is to assume no in-situ regeneration of the salt. The other is to assume 10/1 regeneration.
- 6. Some options need H area while other can be done in H or elsewhere. Decision 4 and 6 are not identical.
- 7. Waste solution from filter can be dumped to HLW via tank farm is processing is in canyon. Other options would need provisions for dealing with liquid.
- 8. Canyon options must decide between dumping the solution to the tank farm (with very high waste outcome) or separating the Th, U, and FP streams. One approach is to use existing SE equipment at end of canyon life. The other is to install frame to use anion resins to separate our Th. We are looking at degree of separation possible for other elements.
- 9. The separated U stream would be either blended down and dropped to the tank farm for conversion to glass. The removal of Th makes this more feasible but still lots of waste. The other option is to install some stabilization process and send LEU to LLW or possible, but unlikely reuse.
- 10. One option is to completely recycle the salt by cleanup, evaporation, and crystallization.
- 11. Dry options include direct down blend with NU oxide or pellets, conversion to glass and disposal via can-in-canister, use of melt and dilute technology to produce a form equivalent chemical and physically to SNF, or pyrochemical processing and down blend.
- 12. If LLW criteria does not require separation, then bypass electrorefining.
- 13. Assumptions on salt recycle cleanup levels impact outcomes.
- 14. Assumptions on need to remove Np, Pu, MA, Th, etc. and processing approach could impact outcomes.
- 15. It may be possible to send a small stream of aluminum alloyed metals to HLW glass using something like can-in-canister.
- 16. Offgas issues may drive decision? Carbon capture? Release limits?
- 17. LLW criteria to ship to LLW sites like NSS and WCS could severely impact process and waste volume. A related issue is safeguard termination. Default assumption is blenddown to <10% U-233&235 in total U. Actual limits based on LLW site could require 10X more U dilution.
- 18. Uranium reuse is unlikely but option needs exploration.
- 19. HLW glass limits could impact decision. If low 898g/m3 limit in effect, volume may be prohibitive.
- 20. Can-in canister was once a viable option . It is not clear if new 898g/m3 limit would impact PIP logic that put a couple dozen kg fissile per canister.
- 21. Are there viable options for HLW streams other that are not already in existence?
- 22. Design approach on basic digestion could significantly impact cost and complexity of options and waste outputs.
- 23. Option to use fluidized bed to burn graphite
- 24. Disposal of Th to HLW is assumed pathway
- 25. It may be beneficial in non-canyon options to include the stabilized Cs and Sr in with the kernels to simplify disposal
- Note;: This is a preliminary list and does not include engineering approach and performance variables. The intent is merely to stimulate development of a better picture. Definition of end state LLW paths is critical to selection of metrics.

5.4 Process Alternatives Selected for Evaluation

The list of possible processing alternatives presented by Figure 5-5 was condensed in nine credible options for development and evaluation. Bases for their selection included historical experience, assumptions on salt regeneration or reuse, off gas treatment requirements, chemical compatibility, treatment requirements for waste streams, and volume of waste produced. As options were developed, minor modifications were identified and incorporated to improve material recovery, reduce cycle time, or minimize waste. A description of the selected alternatives is provided below.

<u>Option 1. Disposition of All Constituents via High Level Waste System (Figure 5-6)</u>

This option transfers the CASTOR cask from storage to H Canyon, where the inner cans are removed and transferred to an unloading station. The cans are opened, and the pebbles are transferred to the digester for carbon and (where necessary) SiC removal (b)(3)(4)
(b)(3)(4) . Off gas from the digester is treated to remove Cs, Sr, and entrained salt.

After digestion is complete, the salt is decanted and the kernels, containing a small amount of salt, are drained into a can designed for storage or insertion in the 10-well canyon dissolver insert for dissolution. The salt is regenerated (b)(3)(4) , allowing the salt to be reused. The decant step includes filtration of the salt, with the collected solids flushed back into the digester with the salt. (Spent salt that can no longer be regenerated is drained into a can designed for immersion into a washing vessel for salt dissolution.) The filtrate, containing up to 12% of the U and residual quantities of minor actinides, is combined with the dissolver solution and blended with sufficient quantities of poisons (or depleted uranium) to meet liquid waste acceptance criteria. The down blended solution is neutralized and transferred to the waste tanks, using existing waste transfer infrastructure, for processing into HLW glass and saltstone.

Process areas utilized to support this option include the Hot Shop or Swimming Pool (section 3H, 4H) for can opening and fuel unloading, and a major portion of at least one process cell (5H) for carbon digestion equipment. Existing canyon equipment (dissolvers, waste evaporators) will be used for kernel processing. Kernel processing could be concurrent with kernel recovery, or deferred to a separate campaign by providing interim storage (in a canyon cell) for the separated kernels.

<u>Option 2. Dissolve and Separate Uranium for Disposition as Low Level Waste</u>

This option receives and processes the fuel pebbles for dissolution as described for option 1. In this option, the dissolver solution is adjusted and fed to solvent extraction for separation and purification of the uranium to meet low level waste acceptance criteria. The product uranium solution is down blended to < 10% fissile (^{233}U + ^{235}U) with DU solution, and poisons (e.g. Gd) are added to increase the allowable package loading. The resultant solution is then mixed with grout in a stainless steel vessel. After curing, the vessel is placed in a CASTOR cask for onsite or offsite disposal.

This option requires a supply of DU solution for blending, using existing equipment provided for the LEU blend down program using natural uranium. It also requires a new facility and equipment for uranium solution grouting.

<u>Option 2T. Dissolve and Separate Uranium and Thorium for Disposition as Low Level Waste</u>

This option is similar to option 2, but recovers both the uranium and the thorium for grouting and disposal as low level waste.

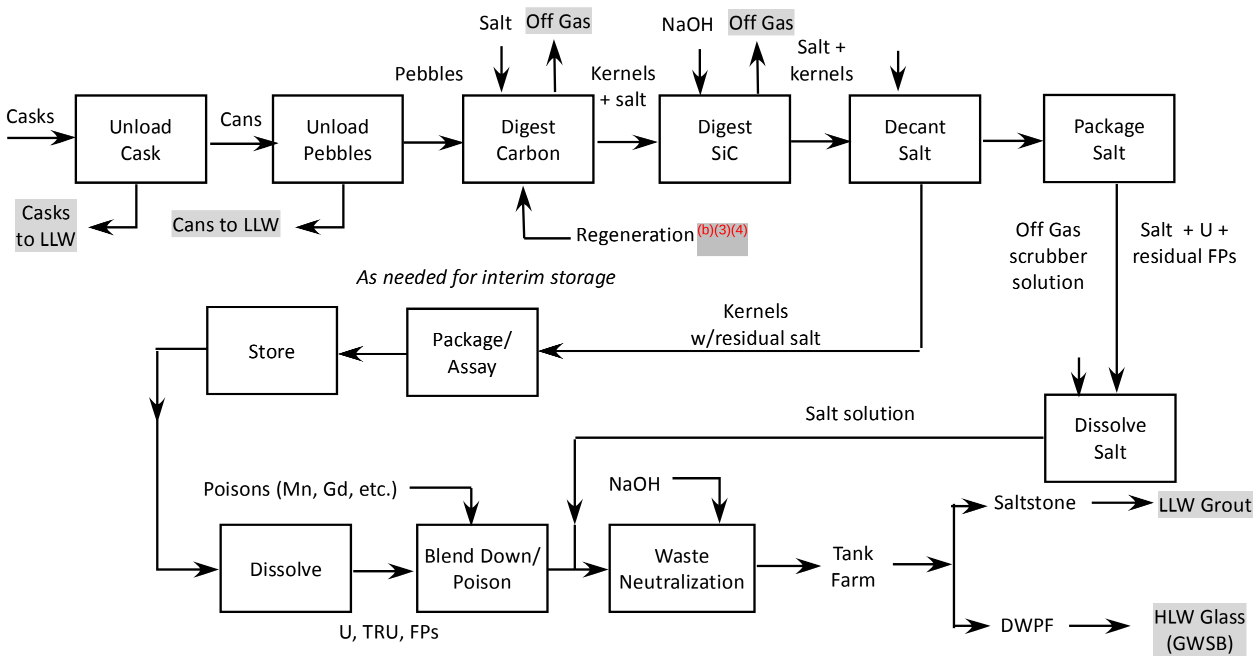

Figure 5-6 Option 1 Block Flow Diagram

Option 3. Dissolve and Separate Uranium for Reuse

This option is the same as Option #2, with the exception that the recovered uranium is down blended to LEU, converted to an oxide, and packaged for storage pending reuse. New equipment will be required for conversion of the uranium solution to oxide and packaging of the oxide product. Pad storage within a Limited Area boundary is adequate for this material (Attractiveness Level E).

Option 4. Dissolve and Separate Uranium for Disposition as Low Level Waste

This option uses the same process functions as option 2; however, the front end activities, up through kernel packaging, are performed in L-Area to allow for accelerated construction and startup. This option requires packaging and transfer of the kernels, spent salt, and liquid waste to H Area for disposition. Because of the cost and complexity of interarea liquid waste shipments, the volume of liquid waste must be minimized. Implementation of this option requires a minimum salt regeneration ratio of 10:1.

Areas of Building 105-L used to implement this option include the stack area for cask unloading, and the Purification Wing for installation of process equipment. This area contains process cells serviced by an overhead crane, with equipment operated and maintained remotely. The cells are configured for standard jumper connections using Hanford connectors.

Option 5. Recover Kernels for Disposal via Can-in-Canister (Figure 5-7)

Receipt, unloading, and front-end processing of the fuel in this option is the same as for Option #1, again using L Area as a basis for implementation. In this option, the separated kernels will be size-reduced and combined with frit to produce a glass form. Because of the low tolerance for sodium, the kernel separation is achieved by dissolution of the salt after digestion. The kernels are dried and packaged for storage to de-couple the front-end from vitrification; the salt solution is combined with off-gas scrubber solution, filtered, and transferred via trailer to H Area for disposition as high level waste. Alternatively, the salt filtrate could be treated (similar to the Salt Waste Processing Facility process) for removal of fission products and actinides, and transferred via trailer for disposal as saltstone. The same restrictions imposed on option 4 for liquid waste generation are applicable for this option.

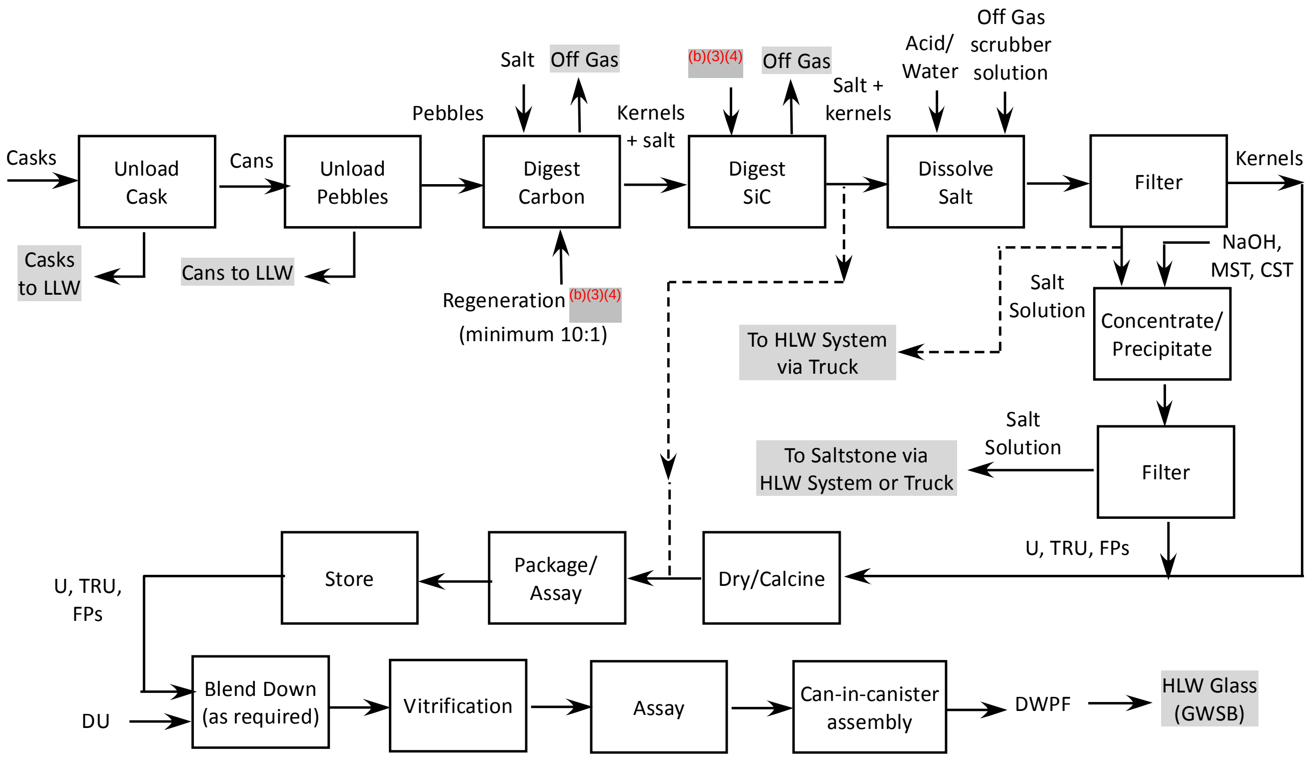

Figure 5-7 Option 5 Block Flow Diagram

Option 6. Recover Kernels for Disposal via Melt and Dilute

This option provides a cask unloading and digestion system similar to Option 1, but installed in L-Area with one-half the capacity. The kernels, with some salt, produced in digestion are processed though the melt and dilute process (WSRC 2000), where the dried kernels are blended with LEU or DU (if required to satisfy safeguards requirements), then combined with aluminum and magnesium metal to produce an alloy that is cast into an ingot. The ingots (4.2” diameter x 47” high) can be loaded into canisters that can be processed (dried, inerted, welded) and placed in a pad-mounted dry storage cask as previously proposed for L-Basin fuel (SRNL 2012). The salt waste is treated using a process demonstrated in the SRS tank farms for sufficient removal of radionuclides to meet low-level waste requirements. Because of the reliance on inter-area shipments for liquid waste disposition, this option requires a high salt reuse factor of at least ten to one.

Option 7. Pretreat Pebbles and Dissolve/Separate U for Disposition as Low Level Waste (Figure 5-8)

This option provides gross removal of the carbon matrix via thermal decomposition in a fluidized bed ORNL 2002, ORNL 2005). The kernels, containing small amounts of carbon, are transferred to the H Canyon dissolver, and processed in a manner described in option #2 The solution from kernel dissolution is adjusted for feeding to solvent extraction, where the uranium is separated, and the thorium, transuranics, and fission products are rejected to waste. The uranium is blended with sufficient poisons or depleted uranium to meet low level waste acceptance criteria, then stabilized by mixing with grout. The waste stream from solvent extraction is processed through the existing liquid waste treatment infrastructure for disposition as HLW glass and saltstone.

This option uses H Canyon for implementation due to need for dissolution and uranium separation. Uranium blend down and grouting equipment will be required.

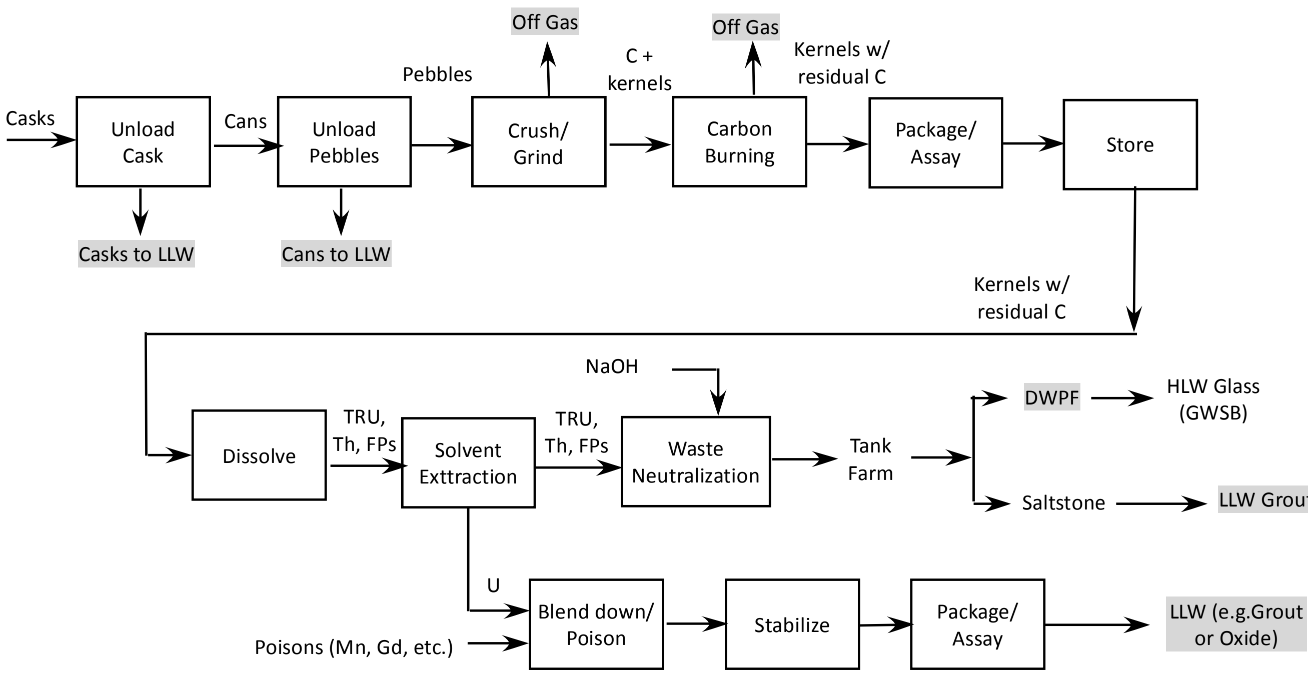

Figure 5-8 Option 7 Block Flow Diagram

Option 8. Carbon Digestion with Electrochemical Processing of Kernels (Figure 5-9)

This option uses a chloride-based salt for all the operations, even for carbon digestion. Initially, the pebbles are charged to a basket, where the carbon is oxidized in a lithium oxide/lithium chloride salt to form lithium carbonate. The carbon is removed from the salt by electroreduction to elemental carbon, and deposited on a cathode.

The basket containing the kernels is then transferred to an electroreducer, where the oxides are converted to metallic form. Finally, the impure metal undergoes electrorefining, in which the uranium and thorium, along with transuranic minor actinides are sequentially oxidized and reduced to metal at the cathode. After distillation of the salt, the uranium mixture is down blended to meet safeguards termination limits, and packaged for disposal as transuranic waste. The fission products and noble metals remain in the salt phase. Salt cleanup is achieved by absorption on zeolite, which is then converted to a glass-bonded sodalite ceramic high level waste form.

This option is more amenable to implementation in L Area because the electrochemical process is chloride-based, and requires an inert atmosphere due to the presence of the molten chloride salts and metallic waste forms.

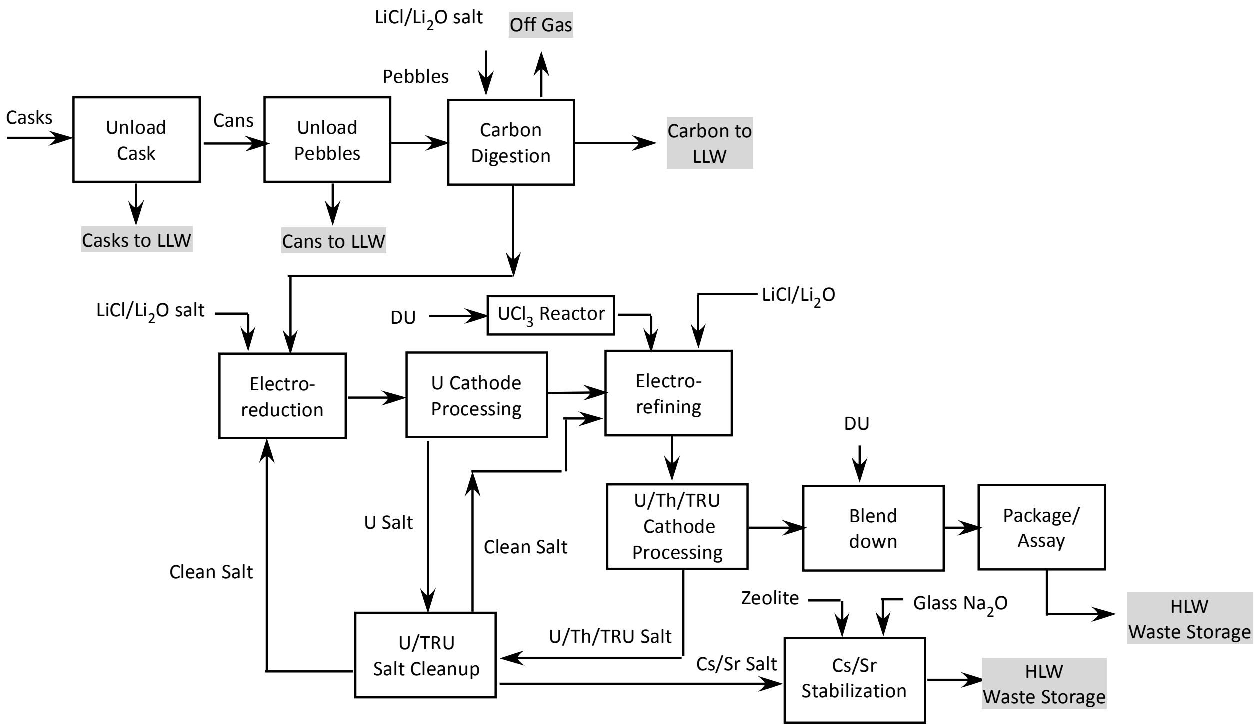

Figure 5-9 Option 8 Block Flow Diagram

6.0 PROCESS ALTERNATIVES EVALUATION

Applicable Criteria

Screening criteria represent non-negotiable performance requirements for alternatives that, if not met, would eliminate that alternative from further consideration. In addition to screening criteria, evaluation criteria were identified to provide qualitative and quantitative measurement of an alternative's ability to meet the program requirements. A complete discussion of the evaluation process, including the methodology used in determining the relative weighting of evaluation criteria and performance metrics, is discussed in Appendix F.

Screening Criteria

Three screening criteria were established for the HTGR process:

- Alternative doesn't discard or down blend the uranium to appropriate standards.

Much of the HTGR fuel was originally fabricated using HEU. Down blending of the uranium to LEU (or lower enrichment) to increase the potential for reuse, and reduce the proliferation potential are important objectives of the program.

- Alternative can't meet the HLW WAC.

Waste forms that do not meet established acceptance criteria become "waste with no path to disposition", and will require further treatment prior to removal from the site. The resultant increase in the volume and radioactivity of the site's waste inventory are unacceptable to stakeholders.

- Alternative whose method of shipment can't be received by rail by June, 2015

The permit authorizing storage at the Jülich facility expires in September 2016. Based on the number of casks and the projected shipping schedule, shipments must begin by June 2015 to complete the site deinventory by the regulatory deadline.

All of the nine alternatives satisfied the screening criteria.

Evaluation Criteria

Nine evaluation criteria were identified with the following relative weighting (Figure 6-1):

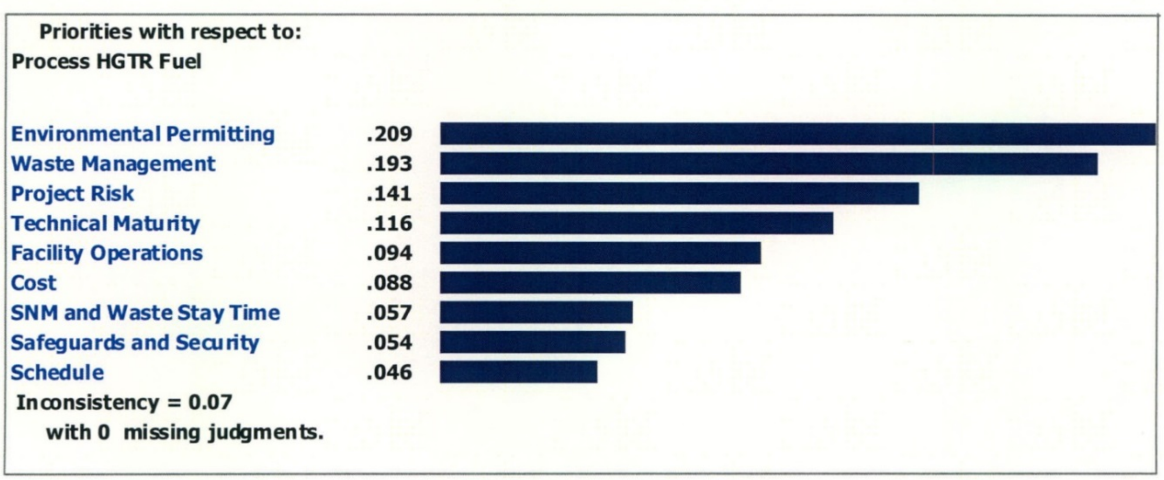

Figure 6-1 Criteria Weighting

Environmental permitting was rated the most important criterion because regulatory delay could jeopardize the milestone for deinventory of the Jülich facility. Waste management was also a significant criterion because of the range of forms and quantities of waste produced by the various options, and the relative impacts to the Waste Management facilities. In general, options producing lower volumes of liquid waste, smaller incremental numbers of HLW canisters, and established waste forms with accepted paths to disposition were rated more favorably.

Project risk, reflecting the ability to meet milestones within budget and schedule baselines, was the third most important criterion.

Process technical maturity received considerable weight, in recognition of the effort required to achieve a minimum Technology Readiness Level (TRL) of 6 for the completion of pilot plant studies and facility design.

The relative weight or importance of each alternative with respect to each of the above criteria was assessed using the Analytic Hierarchy Process (AHP) decision-making methodology. The summary of results for the evaluation of the nine alternatives is shown in Figure 6-2.

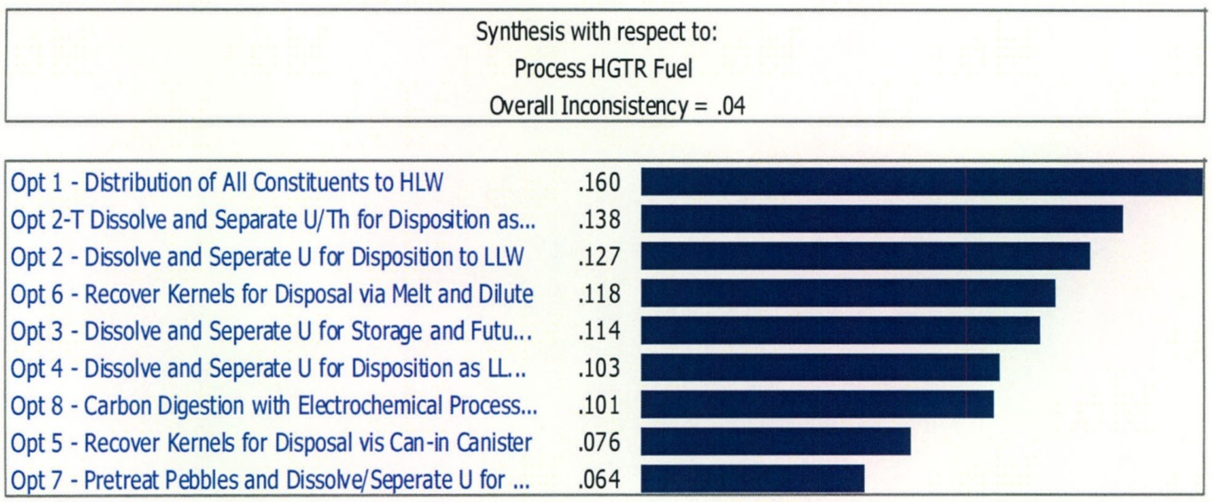

Figure 6-2 Alternative Evaluation Using AHP

Discussion of Results

The data used for evaluation were developed based on the Alternative Evaluation Team subject matter experts' judgments, expertise, and insight at the time of the evaluation. As the unknowns associated with the Project's objectives and requirements are better defined, the data may be modified to incorporate new or updated information.

The data shows a minor break between the top three most preferred options (1, 2T, and 2) and the 4th most preferred option (6). Option 6, the only one of the top four options with the proposed process located in an L-Area Facility, was included with options 1, 2T and 2 as the most preferred options for completion. Option 6 was the highest-ranked non-H Canyon option, and the evaluation team recognized potential cost, schedule, and risk reductions that could be realized from process implementation in a relatively clean facility without co-occupancy. A complete process description and preliminary material balance for these four options is provided in Appendix G.

Options 1, 2T, and 2 scored the highest because they all involve implementation in an existing, operating facility (H Canyon) with supporting infrastructure (utilities, ventilation, environmental monitoring). For option 1, an assumption was made that the high level waste stream could be managed in the Tank Farm to allow blending with existing waste to minimize the incremental number of HLW canisters produced. The production and disposal of HLW canisters resulting from direct conversion of the HTGR liquid waste, containing substantial quantities of thorium and down blended uranium, without blending, could be cost prohibitive.

Options 2T and 2 eliminate the major actinides from the high level waste, reducing the impact of HTGR process. Implementation of these options assumes that the performance assessment of the proposed solidified waste form can confirm the feasibility of disposal as low level waste.

Options 6 ranked relatively high because of the synergy with earlier engineering development work completed for the melt and dilute process for used fuel disposition. Implementation in L Area also eliminates co-occupancy issues with construction and operations in an existing facility. Preparation and placement of the ingots in dry storage adds to the cost and complexity of this option.

Option 3 has advantages similar to options 1,2, and 2T, but was less attractive because it requires (1) a new LEU conversion process, (2) uranium packaging, and (3) storage. The isotopic distribution and resultant radiation exposure present in this material make handling and storage difficult. The lack of a commercial entity with the ability to handle the material and no identified end-use is also detrimental.

Option 4 provides the uranium separation for waste disposal benefits as described in option 2, but utilizes L Area for the front-end kernels. Accelerated processing schedule and elimination of co-occupancy issues are offset, however, by the interarea shipments of kernels, salt, and liquid waste required to support process operations. This also requires operational and support staffing for two facilities.

Option 5, proposing a “can-in-canister” disposition for the kernels, is implemented exclusively in L Area because the vitrification and can handling operations were deemed more compatible with the proposed facility layout. However, the large number of unit operations, and lag storage requirements for kernels, glass cans, and loaded DWPF canisters make this option difficult to construct and operate in the available space.

The seven options discussed above all share the graphite digestion and kernel recovery process currently under development. The other two options are based on alternative technologies, and were considered to balance the technology risk inherent in a new process.

Option 8 uses electrochemical technology to sequentially separate carbon and then actinides from fission products in a salt matrix; the process is completely dry. However, this option scored poorly because of the metallic TRU waste form produced by actinide recovery, and the glass waste produced from spent salt processing.

Option 7 revisited thermal decomposition of the carbon using a fluidized bed. Although the technology is mature, disposition of ash residues and volatilization of fission products present significant engineering and regulatory challenges not present in other options.

7.0 RISK ASSESSMENT

A team of subject matter experts identified and assessed the HTGR risks by the assessable elements (i.e. functions) illustrated in Figure 4-1. The scope of the Risk Assessment follows the function flow diagram (Figure 4-2) from sub-function F 1.1 “Receive Fuel at SRS” through the sub-function F 1.10 “Transport Waste at SRS”. In most cases, risks associated with Functions F 1.1, F 1.2 and F 1.10 were categorized as Program Risks, and risks associated with Functions F 1.3 through F 1.9 were categorized as Project or Technical risks.

A total of (28) risks were identified including (8) “High”, (14) “Moderate”, and (6) “Low”. Risk handling strategies (avoid, transfer, mitigate or accept) were identified for managing the risk. Because the project is in the pre-conceptual design phase, actual cost data and schedule dates were not developed for each risk or for the associated handling strategy. A complete discussion of the risk assessment methodology and handling strategies is provided in Appendix B.

The following list of major risks include all eight of the “high” level risks and a few “moderate” level risks that were judge by subject matter experts to be significant to the success of the project. The “moderate” level risks are indicated by an asterisk (*) after the risk number.

The major Program Risks are:

- The NEPA Process determines that an EIS is required.
- Project cost estimates exceed expectations.
- SRS cannot receive all of the AVR Fuel by September, 2016.
- A Waste Incidental to Reprocessing (WIR) is required.
- Security requirements for shipment of fuel to SRS cannot be met per the project schedule*.

The major Project Risks are:

- Processing Facilities cannot obtain new or modify existing permits*.
- SRS cannot dispose of the HLW without impacting the receipt facility waste acceptance criteria, mission, or closure schedule.
- E-Area Performance Assessment (PA) cannot be modified to allow disposal of LLW grout or the LLW cannot be shipped off-site.
- LLW cannot be trucked to a new unloading station in Tank Farm or Salt Waste Processing Facility (SWPF).
- If H-Canyon is the selected Processing Facility, SRS does not finish processing the fuel in a timely manner and the project has to pay the full cost of operating the Canyon*.
- The process cannot be designed to meet requirements (e.g., equipment size, operational scale, etc.) in support of the mission.
- DOE-SR or DOE- HQ does not approve SRS Deviation Request to protect the material in compliance with Category IV requirements rather than Category II requirements*.

The major Technical Risks is:

- Technology Readiness Levels (TRL) cannot be reached per the Technology Maturation Plan and project schedule*.

Several opportunities were identified during the assessment, including three related to improved digester performance, one for the alloy melt and dilute alternative, and an innovative waste treatment technology:

- Optimization of salt recycle – one-time salt use results in unacceptably large volumes of liquid waste requiring treatment and disposal. In-situ regeneration (b)(3)(4) [redacted] would minimize waste, and potentially increase throughput by eliminating digester downtime resulting from salt removal and recharging.
- Improved digestion process – (b)(3)(4) [redacted] This has the potential for substantial reduction of waste generated from salt processing.
- Optimization of scrubber design – the conceptual layouts developed for pebble processing assumed a conservative approach to off-gas design, based on the DWPF system. More detailed material balances and off-gas stream characterization will allow for reduced volumetric flows (b)(3)(4) [redacted] from off-gas scrubber streams, resulting in lower waste volume and a smaller equipment footprint in the facility.
- Utilize existing spent fuel for alloy crucible charge – Alternative 6 requires addition of LEU, DU, or NU for isotopic dilution of the alloy to less than 10% by weight. In addition, a minimum of 4:1 aluminum to actinide (U, Th) ratio is needed to meet alloy composition requirements. Use of existing L Basin fuels with a high Al:U ratio could be used in the melt and dilute process to disposition these materials without the use of H Canyon. The process could also use available stocks of DU or NU to meet these requirements.
- Modular vitrification systems – Kurion technologies has developed a modular vitrification system that utilizes an induction melter for in-can vitrification of wastes. This technology has potential waste and equipment footprint reduction potential for the process.

An opportunity assessment will be completed as part of the preconceptual design activities. Handling strategies and cost estimates for implementation of opportunities will be developed when a final alternative has been selected.

8.0 TECHNOLOGY MATURATION

Process technology development for the HTGR fuel is ongoing to address the technical risks associated with implementation of the process in a hot facility. The process technology readiness level (TRL) is estimated to be 2, on a scale of 1 ("basic principles observed") through 9 ("total system used successfully in project operations"). A maturation plan has been developed (SRNL 2014a) and is being executed to provide bench-scale demonstrations of individual unit operations, focusing primarily on graphite digestion and SiC removal. Additional work is being planned and executed to address ancillary functions such as kernel separation, salt regeneration, and off gas treatment.

The goal of the technology maturation process is to demonstrate integrated operation of the process at an engineering scale. Completion of these pilot plant operations will establish a TRL of 6, and provide enough confidence to proceed with facility design activities at an acceptable risk. A proposed schedule for the technology maturation program is shown in Figure 8-1. A complete discussion of the technology maturation scope is provided in Appendix H. Major areas of focus are discussed below.

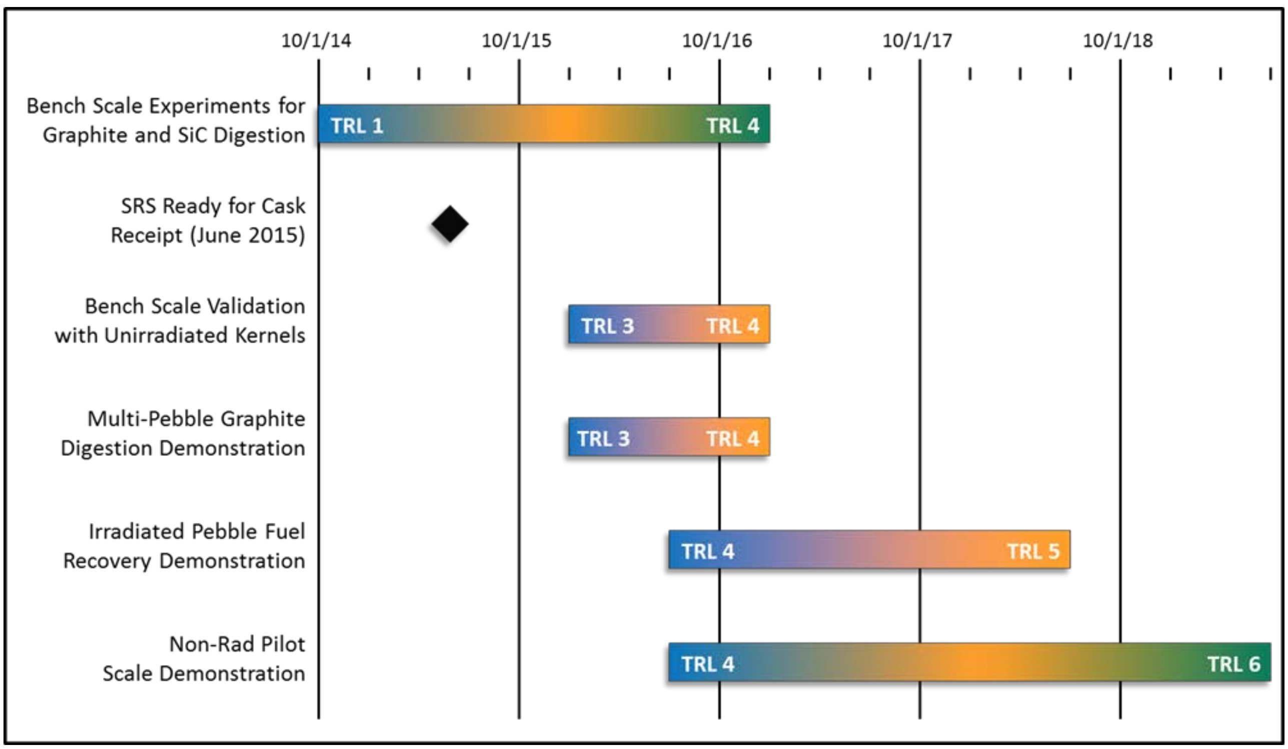

Figure 8-1 Technology Maturation Schedule

8.1 Pebble Digestion

Preliminary studies have been completed assessing the feasibility of (b)(3)(4) [redacted] These studies validate the type and rates of chemical reactions, quantify reaction kinetics and thermodynamics, and identify the chemical composition of product and waste streams. Limitations of these studies include:

- The studies were conducted at "bench-scale" only
- Irradiated fuel pebbles were not tested, only irradiated kernels (SRNL 2014b)

- The studies didn't address factors affecting radionuclide distribution to product, waste, off gas
- Limited work was done to determine reaction rates and control requirements for digestion
- Analysis of salt rheology and kernel separation was very preliminary
- SiC digestion from TRISO fuels has not been addressed as an integrated process.

A Technology Maturation Plan (SRNL 2014a) has been prepared to address the technology needs for process definition. This work is required to:

- Demonstrate the integrated operation of carbon and SiC digestion, kernel separation, and salt regeneration.
- Provide complete characterization of salt and off-gas streams, and provide demonstration of recommended treatment technologies providing acceptable removal of particulates and fission products without plugging of piping or equipment.
- Specify operating parameters and conditions, including potential hazards, for development of safety basis documentation
- Identify equipment development needs

These items are required to advance the technology readiness of the process to support pilot plant design and construction for an engineering-scale demonstration, which will provide integrated end-to-end operation of the process equipment at a minimum of $1/10^{th}$ of full scale. This will ensure that material compatibility issues are addressed, and material handling, equipment operation and equipment maintenance can be performed remotely.

8.2 Salt Treatment

Once the carbon digestion is complete, the salt will require processing to recover the fuel kernels, (b)(3)(4) [redacted] Subsequent treatment of the salt solution with crystalline silicotitanate (CST) and monosodium titanate (MST), followed by filtration, can provide effective removal of cesium and strontium/actinides, respectively. The resultant salt solution would be a candidate for disposal in saltstone.

A demonstration (SRNL 2014c) has been completed that confirms the chemical reactions, and confirms the removal of carbonate and recovery of both fuel kernels and precipitated actinides and fission products. Additional testing is required to demonstrate acceptable scale up of equipment, reaction kinetics, and acceptable decontamination factors (DFs) for the process.

An alternative process (b)(3)(4) [redacted], has also been investigated (SRNL2014d). (b)(3)(4) [redacted] Additional work is required to establish operating parameters that will provide improved reaction kinetics, reduced cycle times, (b)(3)(4) [redacted]

8.3 Alternative Digestion Process

A promising technology for carbon digestion (b)(3)(4) [redacted] Preliminary investigation (SRNL 2014d) of the process indicates acceptable digestion performance with low particulate levels, and strong temperature dependence. While some salt would still be needed for SiC and residual carbon removal, development of a salt-less digestion process has throughput, waste reduction, and material handling advantages. Additional work is required to better understand reaction kinetics, off-gas composition and treatment requirements, and potential hazards.

8.4 Other Technology Challenges

In addition to the pebble digestion process issues, there are technology development issues associated with specific disposition alternatives:

- Equipment engineering (all alternatives)

  A significant development effort is needed to transition the process chemistry from laboratory to process facility. Major issues include: materials of construction, material handling (pebbles, kernels, various containers), remotability (installation, operation, and maintenance), and radiation resistance.

- SNM measurement (all alternatives)

  Material accountability and criticality safety may require SNM measurement of pebbles, kernels, and salt prior to processing. Instrumentation that can be remotely operated and maintained in a high radiation environment will be required.

- Can opening (all alternatives)

  The pebble cans have been fitted with a mechanical plug that was possible to remove with specialized tooling. However, due to the anticipated long term storage, the plugs were welded in place. Due to the welded closure and its unique shape, the can must be cut to allow removal of the pebbles.

- Kernel dissolution (Alternatives 1, 2, 2T)

  The fuel was high-fired up to 1950 °C (IAEA 2010) during fabrication, and some has received very high exposure during irradiation. This, along with the high thorium content, may require process development to achieve acceptable dissolution rates

- Thorium separation (Alternative 2T)

  Thorium separation in H Canyon requires modification of the process flow sheet, including feed adjustment and cold stream compositions and temperatures (Du Pont 1966).

- Uranium, thorium grouting (Alternatives 2, 2T)

  Specific grouting formulations for the stabilization of uranium and uranium/thorium mixtures to meet low level waste acceptance criteria must be identified and developed (if necessary).

- Melt and dilute process (Alternative 6)

  Although this process underwent extensive development and testing (WSRC 2000), additional work is needed to evaluate oxide reduction and the impact of residual salt inclusion in the melt. Off gas characterization and isotope capture will also require investigation.

- Salt solution treatment (Alternative 6)

  Salt waste produced in Alternative 6 must be clean enough for disposition as LLW. Additional development work is needed to identify treatment technologies that provide acceptable actinide and fission product removal.

- Ingot packaging (Alternative 6)

  The preliminary process layout requires removal of product ingots to a clean area for canister loading for dry storage. Historically, removal of products and wastes from contaminated process lines uses a bagout technique, or a "bagless" transfer system to maintain the confinement barrier. A new system must be developed to handle the oversized (~ 47" long) ingots from the alloy melter.

9.0 RECEIPT and STORAGE STRATEGY

Each shipment of HTGR fuel will include up to eight railcars containing a maximum of sixteen casks. The casks, weighing approximately 30 tons, are contained in ISO-standardized shipping packages loaded on railcars. The railcars will be transported by commercial carrier to the site boundary, where an SRS locomotive will be used for movement of the casks to the unloading site outside the L Area Protected Area fence.

Upon receipt, the shipment will be subject to a visual inspection, radiological survey, and data verification to ensure the casks meet all requirements for acceptance. When receipt inspections have been successfully completed, the casks are unloaded in the following sequence:

- dismantle and remove the package cover
- remove restraints and retract impact limiters
- affix lifting apparatus (rigging) for horizontal movement of cask
- transfer cask from railcar to engineered upender
- remove horizontal cask lifting apparatus and affix vertical lifting apparatus
- rotate cask to vertical orientation and place on transport carrier
- remove lifting device
- transport cask from unloading area to storage pad
- install vertical lifting apparatus
- transfer cask from transport carrier to designated storage location
- remove rigging
- reassemble the railcar shipping package for return trip

Major equipment required for these operations include a mobile crane, cask upending carriage, the cask transporter, and the necessary yokes and rigging equipment for both horizontal and vertical lifting of the casks. The CASTOR casks are authorized for both transportation and storage, and have been in indoor storage service for many years. Because cask storage at SRS will be outside, they will be fitted (either individually or collectively) with an engineered cover to protect the casks from the elements. The storage pad will be provided with the necessary infrastructure (lighting, fencing, locks) to meet security requirements (Section 11.0). The initial pad will be designed for storage of the 152 AVR fuel casks, with expansion to be completed, if necessary, to accommodate the additional 303 THTR fuel casks.

The casks are fabricated with a cast iron outer shell, and equipped with an inner and outer lid, each provided with a mechanical seal. Analyses will be performed to establish the surveillance and maintenance requirements to ensure the integrity of the casks in storage. The interstitial space between the two lids was pressurized with helium after loading to provide a mechanism for monitoring of the seal integrity during storage. Aging effects, failure modes, and accident consequences will be reviewed to determine the appropriate scope and frequency of inspection and monitoring activities. These will be documented in the Safety Basis modification to be developed for the L Area Material Storage Facility.

10.0 ENVIRONMENTAL PERMITTING STRATEGY

Receipt, storage, and processing of HTGR fuel must be in compliance with regulations and permits for hazardous and radioactive emissions to streams and the atmosphere. (Compliance for disposal of solid wastes is discussed in Section 13.0.) Requirements are derived from EPA, SCDHEC, DOE, and site directives for prevention and control of releases which may adversely impact the public and the environment. A complete discussion of the environmental permitting process is provided in Appendix C.

10.1 NEPA

The HTGR project will require new facility construction, modification of existing facilities, and the implementation of new chemical processes which invokes the need for a NEPA evaluation. A preliminary review of the project scope has initiated an environmental assessment (EA) to characterize and quantify the impacts of project activities; The EA includes a brief discussion of need, alternatives, environmental impacts, and other pertinent information for the proposed action. The initiation of the EA will be formalized by completion of an environmental evaluation checklist (SRS 2014b). Technical data has been compiled for the four preferred options (Section 6.0) documenting form and quantity of all raw materials, process chemicals, hazardous and radioactive releases from construction and operational activities. A final determination will be made, with a finding of no significant impact (FONSI) or recommendation for completion of an environmental impact statement (EIS).

10.2 Permitting

Permitting programs at SRS are related to the Resource Conservation and Recovery Act (RCRA), the Clean Water Act (CWA), and the Clean Air Act (CAA). RCRA and CWA will have negligible impact to the HTGR project. Permitting requirements are applied to the design, construction, and operational phases of the project. Requirements of the CAA are implemented through a permit program by the State of South Carolina, referred to as a Title V permit. Evaluation of the HTGR project will be performed to determine if a Prevention of Significant Deterioration (PSD) permit is required for the release of site-specified pollutants. A preliminary review of the four options has determined that releases of (b)(3)(4) [redacted] the only relevant species of interest, are below the significant emission rate for permit requirements. This will be revisited as the technology development progresses.

Because the project will require new facilities, modification of existing facilities, and the deployment of new chemical processes, a construction permit must be obtained from SCDHEC prior to the start of construction activities. Because of the potential for radionuclide emissions, an evaluation must be performed in accordance with 40 CFR Part 61, National Emission Standard for Hazardous Air Pollutants (NESHAPs), to assess compliance with the Title V permit for potential and calculated effective dose equivalent to a maximally exposed offsite individual. A preliminary review has determined that carbon-14, the only relevant species for HTGR processing, is within regulatory limits. Technology changes and process option selection will incorporate assessments of NESHAPs requirements for the form and quantity of the radioactive releases that may be expected, also determine design requirements for emission monitoring.

Table 10-1 provides a list of permits and plans that require consideration for the HTGR program.

Table 10-1 Potential Permit/Plan Requirements

SITE UTILIZATION PERMITS AND PLANS • Environmental Evaluation Checklist • Site Utilization Permit • Site Clearance Permit
SURFACE WATER PROTECTION PERMITS AND PLANS • NPDES Industrial Wastewater Discharge Permit • NPDES Storm Water Discharge Permit • Grading Permit • Storm Water Pollution Prevention Plan • Storm Water Notice of Intent • Storm Water Notice of Termination • Storm Water Pollution Prevention Plan • NPDES Permit Minor Modification
AIR QUALITY PROTECTION PERMITS AND PLANS • NESHAP Alternate Calculation/Exemption • BAQ Construction Permit/Exemption • Construction Emissions Control Plan • PSD Review (assure PSD not required) • Title V Permit Modification
WASTE MANAGEMENT PERMITS AND PLANS • Pollution Prevention and Waste Minimization Plan

11.0 SECURITY and MC&A STRATEGY

The Security/MC&A strategy for HTGR fuel is described in Appendix D. Security and MC&A requirements are derived from the quantity and attractiveness of the material, as shown in Table 11-1.

Table 11-1 Nuclear Material Safeguards Categories

	Attractiveness Level	Pu/U-233 Category (kg)				Contained U-235/Separated Np-237/Separated Am-241 and -243 Category (kg)				All E Materials Category IV
		I	II	III	IV[1]	I	II	III	IV[1]	
WEAPONS Assembled weapons and test devices	A	All	N/A	N/A	N/A	All	N/A	N/A	N/A	N/A
PURE PRODUCTS Pits, major components, button ingots, recastable metal, directly convertible materials	B	≥2	≥0.4<2	≥0.2<0.4	<0.2	≥5	≥1<5	≥0.4<1	<0.4	N/A
HIGH-GRADE MATERIALS Carbides, oxides, nitrates, solutions (≥25 g/L) etc.; fuel elements and assemblies; alloys and mixtures; UF_4 or UF_6 (≥ 50% enriched)	C	≥6	≥2<6	≥0.4<2	<0.4	≥20	≥6<20	≥2<6	<2	N/A
LOW-GRADE MATERIALS Solutions (1 to 25 g/L), process residues requiring extensive reprocessing; moderately irradiated material; Pu-238 (except waste); UF_4 or UF_6 (≥ 20% < 50% enriched)	D	N/A	≥16	≥3<16	<3	N/A	≥50	≥8<50	<8	N/A
ALL OTHER MATERIALS Highly irradiated forms, solutions (<1 g/L), uranium containing <20% U-235 or <10% U-233[2] (any form, any quantity)	E	N/A	N/A	N/A	Reportable Quantities	N/A	N/A	N/A	Reportable Quantities	Reportable Quantities

[1]The lower limit for Category IV is equal to reportable quantities in this Manual.
[2]The total quantity of U-233 = [Contained U-233 + Contained U-235]. The category is determined by using the Pu/U-233 side of this table.

11.1 Receipt and Storage

Each cask of both AVR and THTR fuel holds pebbles that contain Special Nuclear Material (SNM) bound in a matrix of sintered refractory material. The SNM concentration is less than 0.5 weight % for all casks; as determined from Table 11-2, each cask is Attractiveness Level E. Therefore, because all 455 casks *in toto* cannot roll up to a higher Category, they will constitute a Category IV quantity of SNM and will be protected as such in the L-Area Property Protection Area (PPA) as per DOE Order 473.3, *Protection Program Operations*, as follows:

- Storage requirements Category IV Quantities of SNM:

Category IV quantities of SNM must be stored in a locked area within at least a PPA, and procedures must be documented in an approved site security plan (SSP). The cask storage pad will be located within a locked fenced area for access control.

- Intrusion Detection System for Category IV quantities of SNM.

Intrusion detection and assessment systems and/or visual observations by protective force (PF) personnel must be used to protect SNM and classified matter to ensure breaches of security barriers or boundaries are detected and alarms annunciate. Protective force patrols will be conducted on a routing basis.

- Lock and Keys

Level III. Buildings, gates in fences, cargo containers, and storage areas protecting Category IV SNM, and government property whose loss would adversely impact security and/or site/facility operations require Level III security locks and keys.

Table 11-2 Additional Attractiveness Level E Criteria

Description/Form	Maximum SNM concentration (wt%) for MC&A and physical protection termination	Maximum SNM concentration (wt%) for only physical protection equivalent to Category IV
SNM solutions and oxides: (b)(3)(4), caustic or chloride solutions, contaminated/impure oxides, metal fines and turnings, glove box sweepings	0.1	N/A
SNM amenable to dissolution and subsequent separation: (b)(3)(4), chloride melt, hydroxide cake, floor sweepings, alumina, condensates reduction residues, sand, slag, and crucible, magnesium oxide crucibles spent fuel and spent fuel residues	0.1	0.2
SNM in organic matrixes or requiring mechanical separation disassembly and subsequent multiple recovery operations: HEPA filters, organic solutions, oils and sludges, graphite or carbon scrap, surface contaminated plastics, metal components, combustible rubber	0.2	1.0
SNM bound in matrix of solid, sintered, or agglomerated refractory materials: SNM embedded in glass or plastic, high-fired incinerator ash, spent resins, salt sludges, raffinates, and sulfides	0.5	2.0
SNM microencapsulated in refractory compounds or in solid-dilution: vitrified, bituminized, cemented, or polymer-encapsulated materials, SNM alloyed with refractory elements (tungsten, platinum, chromium, stainless steel); ceramic/glass salvage	1.0	5.0

11.2 Processing

The security objective for fuel processing is to maintain the SNM at Attractiveness Level D. This can be accomplished by:

- Ensuring solution concentrations are < 25 g/l SNM
- Ensuring solids are < 10 weight % SNM (achieved in most cases by not separating thorium from uranium)
- Down blending HEU to Attractiveness Level E with NU or DU
- Avoiding the production of SNM in metal form
- Avoiding the production of HEU oxide

The separated kernels recovered from the carbon digestion are Attractiveness Level D, and cannot roll up to a Category I quantity. If an L Area option is selected, the process equipment will be located inside the 105-L Building, which is inside a Protected Area. For an H Canyon option, an assessment will be required to ensure the adequacy of kernel storage within the process cell area.

All waste streams will be Attractiveness Level E prior to discharge from the process facility for final treatment.

12.0 SAFETY in DESIGN TAILORING STRATEGY

Safety basis development for the HTGR fuel program will be in accordance with DOE-STD-1189-2008, *Integration of Safety into the Design Process* (DOE 2008). The overall goal of the HTGR Disposition safety design is to provide robust protection to members of the public, co-located workers, and the facility workers by identifying all hazardous scenarios with the potential for significant consequences and selecting controls to either prevent accident events from occurring or mitigate the resulting consequences of the event. In general, passive controls are preferred over active controls, preventers are preferred over mitigators, and engineered controls are preferred over administrative controls or operator actions, although all of these may be used where deemed appropriate either independently or in combination with one another. The safety in design tailoring strategy for HTGR fuel at SRS is described in Appendix E.

Selection of safety controls will be performed in accordance with the Consolidated Hazards Analysis Process methodology. Functional classification of structures, systems and components (SSCs) shall be performed in accordance with Manual E7, Procedure 2.25, *Functional Classifications*.

The facilities being evaluated for the disposition of the HTGR fuel include the L area Complex and H Canyon. Both facilities are Hazard Category (HC)-2 facilities in accordance with DOE-STD-1027, Change Notice 1, *Hazard Categorization and Accident Analysis Techniques for Compliance with DOE Order 5480.23, Nuclear Safety Analysis Reports*.

The HTGR radiological inventory will be similar to other materials historically stored and processed in these facilities. Use of these facilities will require evaluation to determine if the required changes constitute a "major modification" that substantially changes the existing facility safety basis. Designation of a change as a major modification invokes the development of a Safety Design Strategy (SDS), and requires the preparation and approval of a Preliminary Documented Safety Analysis (PDSA) prior to procurement or construction of facility modifications.

Receipt and Storage

Preliminary review of the activities associated with receipt and storage of up to 455 casks of HTGR fuel in L or H Area indicates that this scope is not expected to meet the criteria for a major modification. An evaluation of the modification per manual 11Q (SRS 2010) will confirm this assumption. A separate Safety Basis Strategy document will be prepared for the receipt and storage scope of the project.

Fuel Processing

Implementation of any of the four likely fuel processing alternatives will likely require a major modification to an existing facility, resulting in the development of an SDS during the conceptual phase. The SDS provides a single source for the safety policies, philosophies, major safety requirements, and safety goals for the project. The strategy describes the major hazards anticipated in the facility, how those hazards will be addressed using safety SSCs considering natural phenomena, confinement ventilation, and other significant safety needs. The SDS will be updated throughout the design process; either for each phase of the project (e.g. pre-conceptual, conceptual, etc.), or when significant changes in the project occur. The SDS will guide design on applicable design criteria, establish major safety SSCs, and identify significant project risks associated with the project. Major activities/deliverables include:

- Hazard identification
- Unmitigated hazard analysis (includes development of hazardous events, identification of causes, estimation of frequencies and consequences, and risk binning).
- Control selection and mitigated hazard analysis (includes control selection, functional classification, control evaluation, risk acceptance)

- Candidate Design Basis Accident (DBA) selection.

These activities will be provided at the facility, system, and, if necessary, the component level. Coordination analyses and implementation of the SDS will be performed by a Safety Design Integration Team formally organized during the conceptual design phase of the project.

The process under development for carbon digestion of the fuel pebbles is currently at a relatively low level of technical maturity (Section 8.0), conducted on a small scale. Development of alternatives for fuel processing, requiring integration of the new technology with existing facility systems and operational constraints, invoke areas of consideration for Safety-in-Design to be addressed in the SDS:

- Reaction kinetics, material balances, and energy balances not fully defined
- Material handling and SNM measurement not demonstrated in a remote environment
- Hazards and upset conditions may not be well understood
- Material form may be one not previously studied for Airborne Release Fraction (ARF)
- Potential for additional or exacerbated accident scenarios
- Scale-up of bench scale technology or process or technology application maturity
- Production quantities could introduce unknowns in hazard behavior or material interactions

In addition, facility design interfaces related to capacity, material compatibility, operating conditions, and infrastructure support will also be considered.

The development of alternatives also provided preliminary identification of potential hazards posed by the required unit operations, requiring further analysis and providing a basis for CHAP development:

- Electrical
    - In-cell power feed for digester
- Thermal
    - (b)(3)(4) [redacted]
    - Uncontrolled exothermic reactio[redacted]
- Explosives/Pyrophorics
    - (b)(3)(4) [redacted]
- Radiological
    - Fuel cans > 100R/hour at contact
    - Radionuclide releases to stack
- Fissile Material
    - HEU in pebble form
    - HEU in kernel form
- Kinetic Energy
    - Can opening device (cutting wheel)
- Potential Energy
    - Cask unloading, can handling operations

13.0 WASTE MANAGEMENT STRATEGY

The process and secondary waste streams resulting from processing the HTGR used fuel will be characterized as either high level waste (HLW), low level waste (LLW) or transuranic (TRU) waste. DOE Manual 435.1-1, *Radioactive Waste Management Manual*, defines the requirements for managing these wastes.

Major goals of the Waste Management Strategy include:

- Minimize the volume of high level waste (HLW) requiring geologic disposal
- Minimize the volume of liquid waste requiring treatment in SRS Tank Farm facilities
- Minimize the volume of low level waste (LLW) requiring disposal in onsite or off site facilities
- Prevent the generation of waste with no identified path to disposal

A complete discussion of waste characterization and regulatory requirements for disposal are provided in Appendix I.

13.1 Waste Sources

Waste streams resulting from the processing of High Temperature Gas Reactor (HTGR) used fuel can be broadly categorized as process wastes and secondary wastes. Process wastes are those waste streams that result directly from process operations and often contain major constituents of the used fuel being processed. Examples of process waste include:

- The solid waste resulting from the vitrification of the dissolved HTGR fuel (Option 1) or the vitrification of actinides and fission products separated from the dissolved HTGR used fuel (Options 2 and 2T).
- The solid waste resulting from the solidification of the liquid waste separated from the sludge containing the dissolved fuel constituents, e.g. saltstone (Options 1, 2 and 2T).
- The solid waste resulting from the solidification of the uranium stream (Option 2) or the uranium/thorium stream (Option 2T) separated from the dissolved HTGR used fuel.
- The solid waste (metal alloy) containing the uranium, actinides and fission products resulting from processing the used fuel kernels using the melt and dilute process (Option 6).
- The solid waste (metal alloy) containing the uranium, actinides and fission products resulting from processing the used fuel kernels using the melt and dilute process (Option 6).
- The solid wastes resulting from the solidification of the salt solution generated from carbon digestion for kernel disposition using the melt and dilute process, e.g. saltstone (Option 6).
- The CASTOR® THTR/AVR casks (all options).
- The opened and empty TLK canisters and separated lids (all options).

Secondary wastes are those waste streams that result indirectly from process operations and maintenance activities. Secondary waste streams do not generally contain a significant portion of the HTGR used fuel constituents; although, the minor amount of radioactive contamination present in the secondary waste streams is representative of the radionuclides contained in the HTGR used fuel or a subset thereof. Examples of secondary waste include:

- Job control waste such as gloves, shoe covers, plastic suits, step-off pads, etc. resulting from normal operational activities or from maintenance activities.
- Used equipment and debris routinely generated from normal operations such as filters, cutting wheels or tools, sample vials, etc.
- Failed equipment such as pumps, valves, motors, instruments, etc.

13.2 Disposal Strategy

Liquid HLW streams from processing HTGR used fuel will be processed through the existing liquid HLW system at the Savannah River Site. Planning for liquid HLW processing is documented in the report *Liquid Waste System Plan* [SRR-LWP-2009-00001]. The plan documents the activities required to disposition the existing and future liquid HLW streams and to ultimately remove radioactive liquid waste tanks from service. The *Liquid Waste System Plan* will require modification to incorporate the waste streams resulting from the processing of HTGR used fuel.

LLW streams from processing HTGR used fuel will be processed through or disposed at the existing solid radioactive waste management facilities at the Savannah River Site where feasible. Planning for disposal of TRU waste and LLW is documented in the report *System Plan for Solid Waste Management* [SRNS-RP-2011-01321]. The plan provides a comparative analysis of options to determine a preferred treatment and disposal for all identified waste groups handled by Solid Waste Management and provides the scoping information necessary to support future solid waste budgetary requirements. The *System Plan for Solid Waste Management* may require modification to incorporate the impact of disposal of waste streams generated by the processing of HTGR used fuel. No TRU waste streams are anticipated to be generated from processing HTGR used fuel; however, if any are generated and they are considered defense related waste then they also would be processed through the SRS solid radioactive waste management facilities for final disposal at WIPP.

No mixed waste streams are anticipated to be generated; however, if they are, they would be collected, handled and treated in accordance with the SRS 1S Manual, *SRS Radioactive Waste Requirements* and the *System Plan for Solid Waste Management.*

The potential process waste streams and volumes associated with the four options evaluated in this report for processing HTGR used fuel are identified in Appendix G. Tables 13-1 and 13-2 summarize the process HLW and LLW streams generated by the four options respectively.

The tables also include some of the major anticipated secondary waste streams. These lists of secondary waste should not be regarded as comprehensive. For HLW, the secondary waste streams with the potential for requiring a WIR determination are identified. Although listed as having the potential for requiring a WIR determination, these waste streams are assumed to be handled as LLW. For LLW, the primary disposal path is identified and where applicable or available, alternate disposal path(s) are identified. All waste streams anticipated to be generated by processing HTGR used fuel are expected to have an identified path to disposal.

Table 13-1 Summary of HLW Streams

HLW Stream	Waste Volume				WIR? [1]
	Option 1	Option 2	Option 2T	Option 6	
Process Waste					
Vitrified HLW DWPF canisters (2'D x 10'H)	101	32	15	NA	HLW
Metal alloy waste form MCO[2] canisters (2'D x 13'-4"H)	NA	NA	NA	82	HLW
Secondary Waste					
Failed equipment from solvent extraction	Waste Volumes Undetermined				E
Job control waste associated with solvent extraction					C
Maintenance waste associated with solvent extraction					C
Laboratory equipment associated with analysis from of samples solvent extraction					C

[1] Is a WIR determination potentially required? If so, does the Citation (C) or Evaluation (E) process apply? HLW indicates that a WIR determination is not needed because the waste stream is inherently HLW. See Appendix I for additional explanation of WIR issues.

[2] Multi-Canister Overpack

Table 13-2 Summary of LLW Streams

LLW Stream	Waste Volume				Primary Disposal Path
	Option 1	Option 2	Option 2T	Option 6	
Process Waste					
Solidified salt solution, gallons	1.45x10^{6}	1.65x10^{6}	1.65x10^{6}	9.68x10^{5}	SRS Z-Area Saltstone Facilities
Grouted uranium, ft^{3}	NA	6.69x10^{4}	NA	NA	SRS E-Area Components-In-Grout (CIG) Trench with grouted waste placed in CASTOR® casks
Grouted uranium/thorium, ft^{3}	NA	NA	6.69x10^{4}	NA	
CASTOR® THTR/AVR casks [1], ft^{3}	6.69x10^{4}	Included in grouted uranium above	Included in grouted uranium/ thorium above	6.69x10^{4}	SRS E-Area Engineered Trench (ET) or CIG Trench
TLK canisters and lids [2], ft^{3}	Included in CASTOR® THTR/AVR casks above	7.89x10^{3}	7.89x10^{3}	Included in CASTOR® THTR/AVR casks above	
Secondary Waste					
Failed equipment	Waste Volumes Undetermined				SRS E-Area ET or CIG Trench
Job control waste					SRS E-Area ET
Maintenance equipment					SRS E-Area ET unless overly large, then CIG Trench
Laboratory equipment					SRS E-Area ET
Used equipment and debris					SRS E-Area Slit Trench (ST) for debris and SRS E-Area ET or CIG Trench

[2]Some or possibly all of the CASTOR® THTR/AVR casks may be used (repurposed) to contain the grouted uranium or grouted uranium/thorium waste streams. If so the quantities listed would be reduced accordingly.

[3]The quantity of TLK canisters listed assumes that all 303 CASTOR® THTR casks contain one tall TLK canister each and that all 152 CASTOR® AVR casks contain two short TLK canisters each.

14.0 SCHEDULE

The startup schedule for processing of the HTGR fuel (Figure 14-1) is highly dependent on the completion of the technology maturation program activities (Section 8.0). Approximately two years of development work are required to achieve a TRL sufficient for design of the pilot scale process. Pilot plant operations are expected to continue well into the design phase for the full process; several degrees of scale up are expected to be required to provide an integrated demonstration. A three year period is provided for construction activities, but this could be affected by the alternative selected: co-occupancy issues in H Canyon, larger scope in L Area. For H Canyon alternatives, facility startup is assumed to commence after H Canyon programmatic missions are complete.

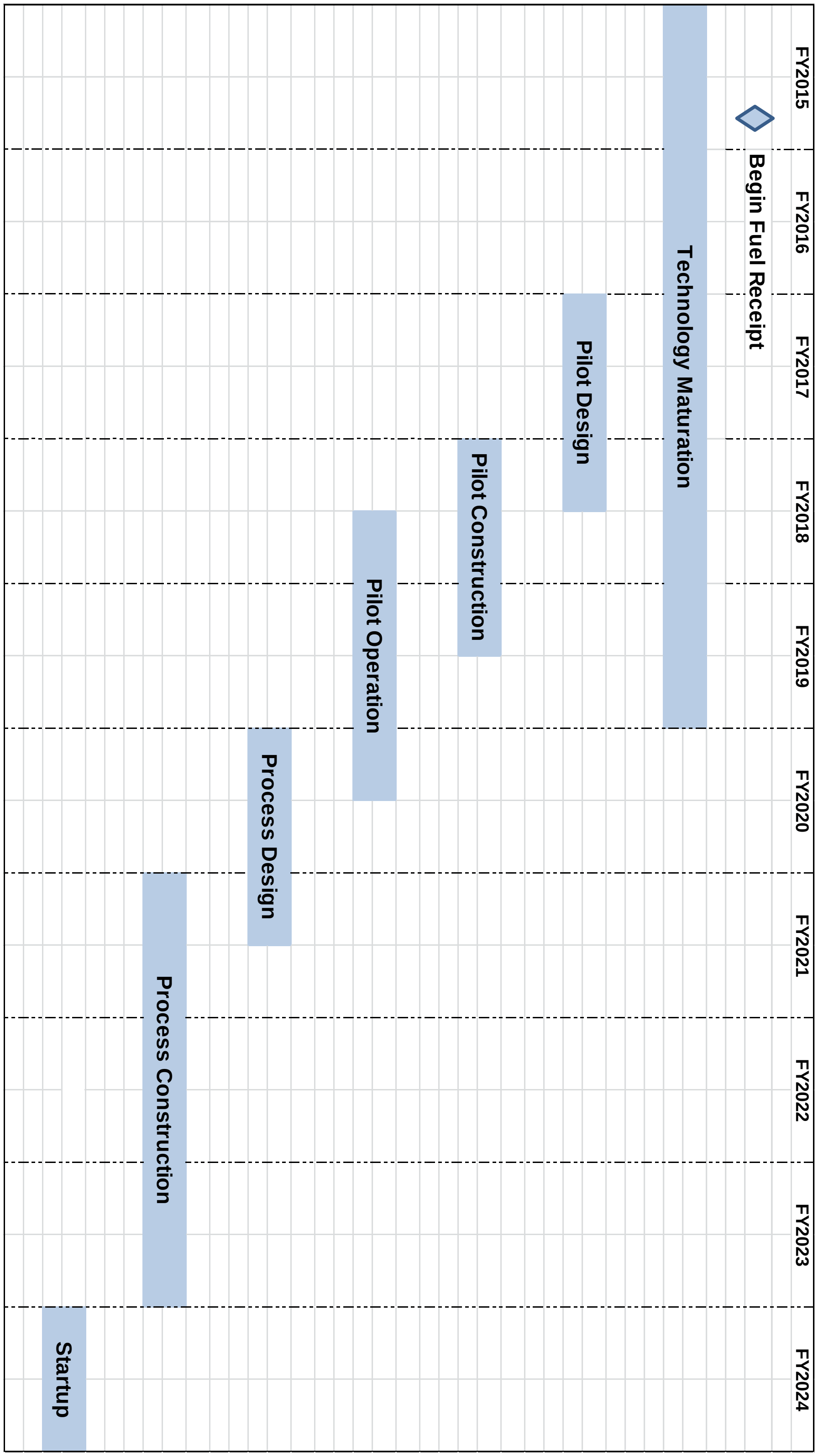

Figure 14-1 Project Schedule for Process Implementation

15.0 LIFE CYCLE COST ANALYSIS

Total Project Cost (TPC) and Life Cycle Costs (LCC) have been developed for the four preferred options (Section 6.0). Results are provided in Table 15-1. A stochastic estimating methodology was used requiring the utilization of judgment, analogy, and parametric estimating methods (e.g. use of estimating models, scale of operations factors, equipment factors, gross unit cost / ratios) to help develop the costs required for the various HTGR fuel options.

TPC provides cost for design, construction, and startup of the new process. The TPC estimate includes site overheads and escalation (based on the project schedule, Section 14.0), as well as management reserve for uncertainty in cost and schedule. Initial values for the minimum and maximum of the percentages for the four options were developed from American Association of Cost Engineering (AACE) recommendations for this stage of project definition. These ranges were modified subsequently to reflect project maturity and assumed condition differences for the individual options. Technical and programmatic risks (identified in Section 7.0) were not taken into account at this stage, but will be evaluated in subsequent phases of program definition.

LCC includes costs for facility operations for the duration of the campaign, waste processing and disposal, and process chemicals, utilities, spare parts and other consumables required to support processing. The pilot plant facilities and operation are also included in LCC.

Table 15-1 Summary Cost Data (AVR and THTR Fuel)

(b)(3)(4)

A brief discussion of the results is provided below. Complete details of the estimates, compiled by work breakdown structure for each option, are provided in Appendix K. The basis for direct material costs are provided in Appendix J.

15.1 Option 1

Option 1 provides pebble digestion followed by dissolution of the kernels, and direct disposal of the dissolver solution via the existing liquid waste treatment system. The estimate includes construction, mockup, and testing of equipment prior to installation in H Canyon. Management reserve for TPC is 60% and 100% for the low and high estimates, respectively.

The LCC for this option assumes a 3.5 year operating period. The low estimate assumes an initial two years of concurrent operations with other H Canyon missions, with processing completed in the final 1.5 years with no other concurrent missions. The high estimate assumes that the canyon operations are dedicated to HTGR processing for the full operating period. Waste processing includes the full cost of liquid waste processing in the H Tank Farm facilities, and the production of the requisite saltstone and

HLW canisters. A repository disposal cost of $1M is also included for each canister. Management reserve for LCC is provided at 25% and 50% for the low and high estimates, respectively.

15.2 Option 2

Option 2 provides for pebble digestion and kernel dissolution, and operates H Canyon solvent extraction processes to recover uranium. The uranium solution is down-blended and grouted to produce a low level waste form for disposal at the E Area Solid Waste Disposal facilities. TPC is slightly higher for this option (relative to Option 1) because of the design and construction of the grouting equipment. Overheads, escalation, and management reserve are the same as those for Option 1.

LCC for this option makes the same assumptions for H Canyon utilization, and includes operational cost for solvent extraction and uranium grouting, as well as disposal of the grout to LLW. The pilot plant cost is increased slightly to demonstrate the grouting process. Although this option includes disposal of the grouted uranium as LLW, the overall waste cost for this option is significantly lower due to the lower HLW canister production resulting from removal of the uranium from the liquid waste stream.

15.3 Option 2T

Option 2T is essentially the same as Option 2, but separates and recovers both the uranium and thorium for grouting as a low level waste form. H Canyon utilization and management reserve assumptions are the same as for Options 1 and 2. As in Option 2, the pilot plant cost is higher to provide (1) demonstration of the U/Th grouted waste form, and (2) development and demonstration of the modified solvent extraction process for thorium separation and recovery. The waste cost reflects the reduced number of HLW canisters, with the corresponding additional cost for disposal of the grouted U/Th waste.

15.4 Option 6

Option 6 is implemented in L Area. The TPC provides equipment for pebble digestion and kernel recovery, and treatment to allow disposal of waste salt solution as saltstone. Kernel processing includes down-blending and conversion to an alloy form in a melter, and packaging of the resultant ingots in sealed canisters transferred to pad-mounted dry storage. The facility size constraints require an operating period of seven years. The TPC for this option reflects higher costs for facility preparation (more D&D required), and additional infrastructure (e.g. ventilation, stack upgrades, cold chemical supply, utilities) that must be provided to support operations. In addition, the TPC includes the cost of the storage pad and dry storage canisters. TPC management reserve for this option (75% and 125% for the low and high estimates, respectively) reflects the larger scope and complexity of design, construction, and installation.

LCC for this option is comparable to the other options. The operating cost is the same for both the low and high ranges because there is no discount for operating costs shared with concurrent missions, as assumed for the H Canyon low estimate. Despite the longer operating period, the operating cost is similar to the H Canyon low estimate because the L Area facility is more compact and less complex than H Canyon. However, the low operating cost is offset by higher waste cost due to the inclusion of the $1M canister disposal cost, and the interarea transport of the liquid salt waste. The pilot plant cost is also higher, reflecting equipment development for both the melter and ingot packaging system. Management reserve for LCC in this option has been increased to 40% and 70% for low and high estimates, respectively, reflecting the longer operating period and increased complexity of the total process.

15.5 AVR Fuel Processing

Cost data has also been developed (Table 15-2) for the case where only the 152 casks containing AVR fuel are processed. Although representing approximately one-third of the casks, this fuel contains

56% of the uranium, almost 90% of the transuranics, and all of the TRISO (SiC-coated) kernels in the HTGR fuel. TPC estimates for the four options with only AVR fuel are the same as those for the full complement of 455 casks. There is no reduction in TPC because the equipment required is the same; the lower throughput requirement is offset by the longer cycle time required for pebble processing and kernel dissolution. The reduction in LCC results from a shorter operating period (~ two years) and smaller volumes of liquid and solid waste requiring treatment and disposal.

Table 15-2 Summary Cost Data (AVR Fuel Only)

(b)(3)(4)

16.0 REFERENCES

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SRS 2014b — Manual 3B, Procedure 5.1, "*National Environmental Policy Act (NEPA) Implementation and the Environmental Evaluation Checklist*", Revision 12 (March 29, 2014)

WSRC 2000 — Adams, T.M., H.B. Peacock. and R.L. Sindelar, "*The Melt-Dilute Disposition Option for* ^{233}U", WSRC-MS-2000-00199 (December 1999)

17.0 APPENDICES

A. **High Level Objectives and Functions**

B. **Risk Assessment**

C. **Environmental Permitting & Handling Strategy**

D. **Security/MC&A Strategy**

E. **Safety in Design Tailoring Strategy**

F. **Alternative Evaluation Process and Results**

G. **Process Descriptions and Material Balances**

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J. **Basis for Estimating of Direct Materials Cost**

K. **Cost Estimate**