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SRNL HTGR Technology Maturation Activities

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OVERVIEW

Based on the state of the technology development of vapor-phase graphite digestion for the processing of HTGR fuel, the next goal for technology maturation is to demonstrate an optimized and integrated engineering-scale system. Technology maturation to a technology readiness level (TRL) of 6 constitutes Phase 1 of the overall project. Validations will be completed using non-radioactive simulants whose critical components are subsequently confirmed by tests conducted with unirradiated fuel pebbles and irradiated fuel kernels. Variations of the equipment downstream of the digestion system will be based on the end state of the fuel, but the development requirements for the digestion process remain relatively unchanged. Integration of technology elements upstream and downstream of graphite digestion must also be demonstrated. The technology development has been broken down into a preliminary task and seven major activities, each a significant development or support effort. The following sections describe the tasks and how they support the technology development using the DOE Technology Readiness Assessment process to guide the work scope. Appendix 1 correlates the task activities of this scope of work with the TRL 5 and 6 guidelines.

BACKGROUND

The Savannah River National Laboratory (SRNL) and Jülicher Entsorgungsgesellschaft für Nuklearanlagen mbH (JEN) are partnering in the demonstration of a digestion technology for the processing of graphite-based nuclear fuels. The purpose of this partnership is to identify, demonstrate, and mature a technology for processing high temperature gas-cooled reactor (HTGR) fuel currently stored at the Jülich and Ahaus facilities in Germany.

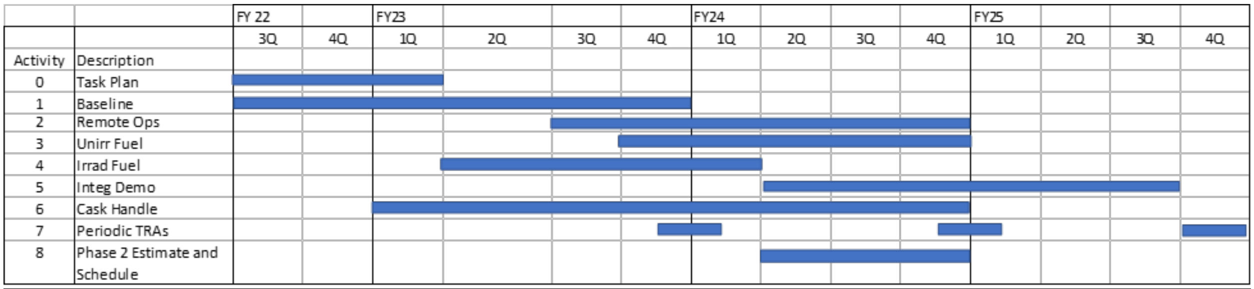
[redacted]

SRNL has a patented vapor-phase oxidation process for digestion of the graphite and recovery of the U and Th for disposition. Feasibility of the process and an improved understanding of the chemistry have been documented. Furthermore, small-scale testing of a multi-zone system has proven that the optimization of the process can result in process acid-use efficiencies in excess of 300%. Following-the multi-zone results, studies continued to the engineering-scale to mature the technology to a level sufficient for the U. S. Department of Energy (DOE) to take ownership of the fuel and have it transported to the Savannah River Site (SRS).

A technology readiness assessment (TRA) in December 2015 identified the critical technology elements (CTEs). The TRA determined the CTEs to all be at a TRL of 4 or higher and the integrated system to be at a TRL of 3. Additional technology maturation occurred in 2018-2019, but a follow-up TRA has not yet been completed.

ACTIVITY DESCRIPTIONS

A preliminary sequencing of activities is provided below. The actual timing will be contingent upon funding profiles, staff availability, and the progression of the technology maturation process.



Elements of the technology will be developed that support completing the design in compliance with DOE STD 1189-2016. The activities undertaken by SRNL and described below constitute the pre-conceptual and conceptual design phases for the aspects of technology being matured. Consequently, in consultation with the Phase 2 contractor, SRNL will develop data and documentation discussed in Sections 4.2 (Pre-Conceptual Design Phase) and 4.3 (Conceptual Design Phase) of STD-1189-2016. In general, these phases are described as follows:

- Pre-Conceptual – Develop the Mission Need Statement based on gap analysis.
- Conceptual – Evaluate alternatives for satisfying the Mission Need Statement to identify the preferred alternative for preliminary design.

Preliminary Task: Approved Test Plan for TRL 6

When project activities begin, a team will be convened to define all requirements that must be met to establish achieving TRL 6. The team should include representatives from SRNL, DOE, and other SRS Contractors, as required. SRNL will develop a comprehensive integrated system test plan to achieve development of the technology to TRL 6. The test plan will receive concurrence from a representative of DOE who attests that the TRL 6 requirements are adequately captured. Activities 1 and 6, outlined later in this document, can begin while the test plan is being developed. Similarly, efforts to transport materials from JEN can commence.

Considering the DOE-EM Technology Readiness Assessment (TRA) guide [Rev 1, August 2013], the appendices contain objectives that must be met to achieve TRL 5 and TRL 6. Two objectives related to TRL 5 are included in this activity. The item number from the TRA Appendix F is included in parentheses.

TRL 5 Objectives

- Requirements for technology verification established, to include testing and validation of safety functions (5)
- Test plan documents for engineering-scale tests completed (26)

Activity 1: Establish Baseline Process Conditions and System Design

This activity matures the technology at the engineering-scale (~140 pebbles/day) to finalize the engineering technical baseline. Engineering-scale reflects the baseline full-scale design in two dimensions – height and cross-sectional diameter. There are two approaches under consideration for the full-scale design. One approach uses a single digestion vessel, and the second approach uses several smaller, modular vessels. The modular full-scale design complicates material handling issues (pebble feeding and product removal) while simplifying the geometry of fundamental engineering components (top vent screen and bottom screen). A decision of which approach to pursue will be made early in Activity 1.

[redacted]

Minor modifications to the existing engineering-scale design are necessary to finalize the baseline design and process conditions. These changes include modifications to the oxidant feeding system and the bottom screen. The modification to the oxidant feeding will optimize the digester design and control. Modifications to the bottom screen are required to enable the system to adequately transition fuel from the bottom of the digester without transfer of excessive quantities of particulate graphite.

Other modifications include changes to the acid feed and more prototypic design of the off-gas system, especially the areas immediately downstream of the digestion vessel. It is necessary to demonstrate off gas management. It is also essential that good measurements of decontamination factors be obtained for each unit operation of the off-gas system. Prototypical heating will also be identified, designed, and installed, although testing may start without it.

Finalization of analysis and reporting from simulant fission product tests is needed to provide vital data to modeling efforts and the off-gas exhaust design. Laboratory-scale tests were completed, and samples analyzed. A report of the results has been drafted but not issued. Engineering-scale tests with simulant fission products were also completed, but the samples have not been analyzed. Those sample should be analyzed, and the results documented to further validate the design.

The data must be collected and analyzed to provide the baseline flowsheet and material balance for operation in the Canyon plus the baseline system design. Waste calculations should consider either acid neutralization for discard or acid recovery. A decision is needed for determining whether the digestion process will be run as a single reaction vessel or a series of smaller modular vessels.

Computer modeling will be performed to model the internal reactions of the digestion process. The model will aid in the evaluation of process data as well as serve as a tool for predicting optimum conditions. Other computer models to be developed will be one related to the behavior of particulate graphite in the digestion vessel and another assessing the possible conditioning of the acid feed to the digestion vessel. A baseline flowsheet will be developed which factors all requirements of the waste processing system downstream of the digestion process.

The objectives related to TRL 5 and TRL 6 that are addressed in Activity 1 are listed below. The item number from the Appendixes of the Guide are included in parentheses.

TRL 5 Objectives

- Preliminary design engineering has begun (4)

- Detailed 3D design drawing and P&IDs have been completed to support specification of an engineering-scale testing system (12)
- Requirements definition with performance thresholds and objectives established for final plant design (13)
- Simulants have been developed that cover the full range of feed properties (19)
- Laboratory bench-scale tests, at a minimum, on the full range of simulants using a prototypical system have been completed – results validate design (21)
- Test results for simulants and real materials are consistent (23)
- Laboratory/bench to engineering scale scale-up issues are understood, if applicable and resolved, to include testing and validation of safety functions (24)

TRL 6 Objectives

- The relationships between system and sub-system parameters are understood at engineering scale allowing process/design variations and tradeoffs to be evaluated (1)
- Operating environment for final system known (4)
- Analysis of project timing ensures technology will be available when required (12)
- Have established an interface control process (13)
- Most pre-production hardware is available to support fabrication of the system (16)
- Technology "system" design specification complete and ready for detailed design (19)
- Testing has verified that the properties/performance of the simulants match the properties / performance of actual materials (20)
- Engineering-scale tests, at a minimum, on the full range of simulants using a prototypical system have been completed – results validate design (24)
- Finalization of hazardous materials forms and inventories, completion of process hazards analysis, and identification of system/components level controls at the appropriate preliminary / final design phase (29)

Activity 2: Demonstrate Process Rates and Design for Remote Operation and Maintenance

Using the engineering-scale design and process conditions established in Activity 1, this activity begins to simulate production and maintenance activities. Modifications to the engineering-scale system will be made to periodically add fresh feed pebbles, remove particulate graphite and fuel kernel simulants, and regenerate the top screen. Testing will address extended-duration operations and off-normal process conditions. The need and means for conducting system maintenance will be evaluated, including strategies for periodic clean-out of digester residues.

[redacted] Although the engineering system has been successfully designed and operated, it lacks the features and capabilities to be operated in a sustainable manner. The system must be modified for material addition and removal, screen regeneration, and periodic maintenance. Of particular importance, the process activities must be done in a manner that involves no hands-on activities that would likely be in the heavily shielded areas of the operating process. With those capabilities in place, it will be possible to perform extended-duration operations and establish a more-representative throughput rate, demonstrating the adequacy and robustness of the top and bottom screens of the digester. Testing with fission product simulants will be included in these tests.

As part of this activity, the process data will be used to model the reaction vessel to aid in predicting the system response during normal and off-normal operations. In addition to the chemical model, there will be a time-motion study performed for operations in the Canyon to establish how limiting the Canyon resources may be on process throughput. A third model to be developed is a heat transfer model to determine the maximum possible process throughput based on the removal of heat from the system.

The objectives related to TRL 5 and TRL 6 that are addressed in Activity 2 are listed below.

TRL 5 Objectives
- System interface requirements known (How would system be integrated into the plant?) (3)
- Preliminary design engineering has begun (4)
- Requirements definition with performance thresholds and objectives established for final plant design (13)
- The range of all relevant chemical and physical properties has been determined (to the extent possible) (18)
- Risk management plan documented, to include compliance with STD 1189-2016 (27)

TRL 6 Objectives
- The relationships between system and sub-system parameters are understood at engineering scale allowing process/design variations and tradeoffs to be evaluated (1)
- Availability and reliability (RAMI) levels established (2)
- Collection of actual maintainability, reliability, and supportability data has been started (5)
- Operating limits for components determined (design, safety, and environmental compliance) (7)
- Off-normal operating responses determined for engineering-scale system (9)
- Have established an interface control process (13)
- Engineering feasibility fully demonstrated (17)
- Engineering to full-scale scale-up issues are understood and resolved (25)
- Test results are consistent for laboratory/bench and engineering-scale experiments, and/or prototype testing as applicable (26)

Activity 3: Unirradiated Fuel Demonstrations

Using the engineering-scale design and process conditions established in Activity 1, this activity simulates process conditions during the digestion of unirradiated fuel. [redacted]. Therefore, additional demonstrations will be conducted with bounding types of full-size unirradiated fuel pebbles exposed to process conditions closer to those of the current baseline process. The results will provide baseline U-Th partitioning data and compare actual fuel behavior with the behavior of simulants.

Tests with representative fuel simulants require comparisons with actual fuel. The amount of relevant vapor digestion data for unirradiated fuel in baseline system designs is limited. Previous data is helpful, but not enough to confirm technical maturity. Although the availability of irradiated fuel is limited, some unirradiated fuel pebbles are available. Of interest are those pebble types which represent best-case and worst-case conditions. Successful testing with pebbles of best-case and worst-case fuel types is needed to validate critical design features of the engineering-scale system and provide data comparisons for other simulant studies. JEN must provide unirradiated pebbles to support this activity. A set of 33 pebbles has been identified. An alternate approach, pending concurrence from JEN, involves purchasing unirradiated pebbles from a U.S. vendor.

Included in this activity are demonstrations to prove conversion of dissolved solution to waste, including analyses of the waste characteristics. This will include establishing the details for the Canyon to neutralize and batch the dissolved solution for disposal. As part of these studies, the nuclear poison will be identified, neutralized, and its behavior characterized to ensure that it continues to provide protection against criticality throughout the disposition process. The framework for the process exists from prior SRS campaigns, but the details must be defined and demonstrated.

The objectives related to TRL 5 and TRL 6 that are addressed in Activity 3 are listed below.

TRL 5 Objectives
- Laboratory/bench-scale tests, at a minimum, on a limited range of real materials using a prototypical system have been completed – results validate design (22)
- Test results for simulants and real materials are consistent (23)
- Laboratory/bench to engineering scale scale-up issues are understood, if applicable and resolved, to include testing and validation of safety functions (24)

TRL 6 Objectives
- Test results are consistent for laboratory/bench and engineering-scale experiments, and/or prototype testing as applicable (26)

Activity 4: Irradiated Fuel Kernel Demonstrations

All work to date with vapor-phase digestion to establish fission product behavior is based on simulant studies, unirradiated fuel, or irradiated fuel digestion with different chemical systems. Thus far, the simulant studies with vapor digestion have significant overlap with the irradiated fuel digestion studies of other chemical systems. However, there is a high risk associated with designing the off-gas system based on simulant studies without any irradiated fuel digestion studies to validate the simulant data.

It is essential that data be obtained with irradiated fuel to support the validity of decisions based on studies with simulants and unirradiated fuel. Critical data will be obtained using irradiated fuel kernels that greatly reduce the technical risk if the simulant data and the irradiated fuel data agree. These studies will be bench-scale tests with at least two different fuel kernel types. JEN must provide irradiated fuel kernels to support the completion of this activity. Preliminary discussions between SRNL and JEN have identified that meet the programmatic need.

Using computer modeling, vapor digestion of irradiated fuel kernels will correlate simulant data and validate fuel residue and fission product assumptions. The behaviors of actual and simulated fission products will be correlated to satisfy critical design and modeling inputs. Of particular concern will be the absence of data obtained using irradiated fuel pebbles. Therefore, additional calculations are required to apply the data from the digestion of irradiated fuel kernels to the variety of fuel types and irradiation levels to obtain confidence that release fractions can be adequately estimated.

The objectives related to TRL 5 and TRL 6 that are addressed in Activity 4 are listed below.

TRL 5 Objectives
- Laboratory/bench-scale tests, at a minimum, on a limited range of real materials using a prototypical system have been completed – results validate design (22)
- Test results for simulants and real materials are consistent (23)

TRL 6 Objectives
- Test results are consistent for laboratory/bench and engineering-scale experiments, and/or prototype testing as applicable (26)

Activity 5: Integrated Engineering-Scale Demonstrations

[redacted]

At the end of Activities 1, 2, and 6, which will mature the engineering interfaces, the unit operations must be shown to work together at least at the engineering scale to evaluate the interfaces. This effort will require semi-continuous pebble feeding must be incorporated into the system upstream of the digester. Additionally, milling and secondary digestion capability downstream of the digester.

The objectives related to TRL 5 and TRL 6 that are addressed in Activity 5 are listed below.

TRL 5 Objectives
- Plant size components available for testing (2)
- Preliminary design engineering has begun (4)
- Requirements definition with performance thresholds and objectives established for final plant design (13)
- Formal control of all components to be used in final prototypical test system (16)
- Risk management plan documented, to include compliance with STD 1189-2016 (27)

TRL 6 Objectives
- Availability and reliability (RAMI) levels established (2)
- Collection of actual maintainability, reliability, and supportability data has been started (5)
- Operating limits for components determined (design, safety, and environmental compliance) (7)
- System technical interfaces defined (10)
- Component integration demonstrated at an engineering-scale, at a minimum (11)
- Have established an interface control process (13)
- Materials, process, design, and integration methods have been employed (e.g., can design be produced?) (18)
- Engineering-scale system is high-fidelity functional prototype of operational system (20)
- Final technical report on technology completed, to include compliance with STD 1189-2016; report is a summary of technology development activities (22)
- Production demonstrations are complete (at least one time) (27)
- Integration demonstrations of the CTE have been completed (e.g., constructing of test system); to include testing and validation of safety functions (28)

Activity 6 – Remote Cask Handling and Pebble Transfer

An essential technology development activity is the remote mechanical opening and unloading of irradiated pebbles from the transport casks and their inner containers. The casks have defined procedures for their opening, but the goal will be to open them with little or no contamination so that the casks can be discarded as low-level waste. The inner container, although it has a removeable plug, will probably have to be cut open because the narrow opening will not permit the free flow of pebbles from the container.

This activity will demonstrate the ability to remotely unload the pebbles from the casks and inner containers. Allowances will be made from normal and upset conditions. The pebbles will be transferred to a feed hopper, providing methods to detect and mitigate the impact of potentially broken pebbles. Last, the activity will demonstrate the ability to feed intact and broken pebbles to the digesters in a manner that does not break containment in the digesters. The digesters operate under a slight negative pressure.

The objectives related to TRL 5 and TRL 6 that are addressed in Activity 6 are listed below.

TRL 5 Objectives

- Preliminary design engineering has begun (4)
- Manufacturing techniques have been defined to the point where largest problems are defined (8)
- Component integration issues and requirements identified. (11)
- Requirements definition with performance thresholds and objectives established for final plant design. (13)

TRL 6 Objectives

- Critical manufacturing processes prototyped (15)
- Engineering feasibility fully demonstrated (17)
- Process and tooling are mature to support fabrication of components/system (23)

Activity 7 –Periodic Technology Readiness Assessments

This activity will provide for interim and final TRAs. It will also provide for other performance assessments, such as monthly updates and periodic reviews. Monthly expenditures and activity progress updates will be provided to JEN. The final TRA occurring at the conclusion of Activity 5 will judge SRNL performance against the TRL 5 and 6 requirements. A final technical report will be provided which describes the technology maturation level against the TRL 6 requirements. This report will establish whether the technology achieved TRL 6 for the initiation of Phase 2 of the project.

TRL 6 Objectives

- Final technical report on technology completed, to include compliance with STD 1189-2016; report is a summary of technology development activities (22)

Activity 8 – Phase 2 Cost Estimate

This activity provides for a detailed total cost, scope, and schedule estimate for Phase 2 execution. The estimate will be a joint effort of the Savannah River Site M&O contractor (currently Savannah River Nuclear Solutions), the Savannah River Site liquid waste processing contractor (currently Savannah River Mission Completion), DOE-Savannah River, and SRNL. The written, formal cost estimate with suitable detail will be provided to JEN and DOE for negotiation of a Phase 2 contract.

The objective related to TRL 6 is as follows.

TRL 6 Objectives

- Performance Baseline (including total project cost, schedule, and scope) has been completed (TRL 6, 6)

Activity 9 – Support Functions

This activity provides funding for those project functions that support many or all other activities. These functions include research management, project management, project budget controls, scheduling, environmental compliance, quality assurance, procurement, contracts, safety, industrial health, facility support, radiation protection, transportation, and travel.

TRL Activities Post Phase I

At the conclusion of Phase I of the project, the technology will be at a state of maturation ready for full-scale system design. Because SRNL is not the design agency for the Phase 2 operating contractor, certain aspects of achieving TRL 6 will be deferred until Phase 2. Specific elements of the TRA guide which will not be completed in Phase I include the following.

- Preliminary design drawings for final plant system are complete, to include compliance with DOE STD 1189-2016 (TRL 6, 3)
- Operational requirements document available, includes compliance with STD 1189-2016 (TRL 6, 8)
- Acquisition program milestones established for start of final design (CD-2) (TRL 6, 14)
- Formal configuration management program defined to control change process (TRL 6, 21)

KEY ASSUMPTIONS

- SRNL will share with JEN, to the full extent allowed by export control, technical reports and other information related to this technology development.
- [redacted]
- The fuel will be received into and processed through the remote-handle H-Canyon facility, and the consequences of that handling require significant remote mechanical development.
- All materials received from JEN and equipment associated with its processing will be dispositioned by SRNL. All costs associated with material and equipment disposition are included in the cost estimate.
- Dissolved fuel for the Phase 2 project will go to the SRS HLW system for disposal primarily in DWPF. No process will be designed or constructed to decouple from the SRS HLW system.
- Activity 8 (cost estimate for Phase 2) will not begin until Activities 1 and 4 are complete, and Activity 2 has advanced to providing reliability and maintainability (RAMI) data and extended-duration operation information for the Phase 2 cost estimate.
- Preparations for receipt and storage of Castor Casks and interface with Joint Base Charleston is not included in the Phase 1 SPP.
- JEN will provide the necessary unirradiated fuel pebbles and irradiated fuel kernels in a timely manner to support the project scope, or alternatives will be identified. The attainment of alternative unirradiated pebbles from a U.S. vendor is included in the estimate. Obtaining an alternate source of irradiated fuel kernels is not included in the cost estimate.
- [redacted]

SUMMARY

The maturation of the HTGR technology will require the completion of an array of laboratory-, engineering-, and plant-scale activities with non-radioactive, unirradiated, and irradiated material. Consequently, successful maturation of the technology is facilitated by a laboratory organization with a wide range of capabilities.

APPENDIX 1. Correlation of Activities with TRL 5 and 6 Guidelines

Appendix F, TRL 5 Guidelines			**Appendix F, TRL 6 Guidelines**	
Item	Activity to Complete		Item	Activity to Complete
1	[TRL 6, Item 1]		1	1,2
2	5		2	2,5
3	2		3	Phase 2
4	1,2,5,6		4	1
5	0		5	2,5
6	[TRL 6, Item 11]		6	8
7	[TRL 6, Item 17]		7	2,5
8	6		8	1,2 -> Phase 2
9	[TRL 6, Items 2&5]		9	2
10	[TRL 6, Items 7&9]		10	5
11	6		11	5
12	1		12	1
13	1,2,5,6		13	1,2,5
14	[TRL 6, Item 22]		14	Phase 2
15	[TRL 6, Item 28]		15	6
16	5		16	1
17	[TRL 6, Item 21]		17	2,6
18	2		18	5
19	1		19	1
20	[TRL 6, Items 24&26]		20	1,5
21	1		21	Phase 2
22	3		22	5,7
23	1,3,4		23	6
24	1,3,4		24	1
25	[TRL 6, Items 9&28]		25	2
26	0		26	2,3,4
27	2,5		27	5
28	[TRL 6, Items 20&28]		28	5
29	[TRL 6, Item 29]		29	1