Preliminary Technology Maturation Plan for Immobilization of High-Level Waste in Glass-Ceramics

Fuel Cycle Research & Development

Prepared for

U.S. Department of Energy

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SUMMARY

A technology maturation plan (TMP) was developed for immobilization of high-level waste (HLW) raffinate in a glass-ceramic waste form using a cold-crucible induction melter (CCIM). The TMP was prepared by the following process: 1) define the reference process and boundaries of the technology being matured, 2) evaluate the technology elements and identify the critical technology elements (CTE), 3) identify the technology readiness level (TRL) of each of the CTE's using the DOE G 413.3-4, 4) describe the development and demonstration activities required to advance the TRLs to 4 and 6 in order, and 5) prepare a preliminary plan to conduct the development and demonstration. Results of the technology readiness assessment identified five CTE's and found relatively low TRL's for each of them:

- Mixing, sampling, and analysis of waste slurry and melter feed: TRL-1
- Feeding, melting, and pouring: TRL-1
- Glass ceramic formulation: TRL-1
- Canister cooling and crystallization: TRL-1
- Canister decontamination: TRL-4.

Although the TRL's are low for most of these CTE's (TRL-1) primarily because the specific waste stream is not known or tested, the effort required to advance them to higher values is relatively low. A TRL of 2 would be obtained by completing an initial waste composition/property estimate, a preliminary engineering study, some additional laboratory scale tests of the glass-ceramic, and a mixing and sampling test. Relatively little additional effort is required to advance the technology to TRL-3.

The activities required to advance the TRL's through level 6 include:

- Complete this TMP
- Perform a preliminary engineering study
- Complete paper study, characterize, estimate volumes and ranges, and simulate waste to be treated
- Laboratory scale glass ceramic testing
- Melter and off-gas testing with simulants
- Test the mixing, sampling, and analyses
- Canister testing
- Decontamination system testing
- Issue a requirements document
- Issue a risk management document
- Complete preliminary design
- Integrated pilot testing
- Issue a waste compliance plan.

A preliminary schedule and budget were developed to complete these activities as summarized in the following table (assuming 2012 dollars).

	TRL						Budget
Year	MSA	FMP	GCF	CCC	CD	Overall	$M
2012	1	1	1	1	4	1	0.3
2013	2	2	1	1	4	1	1.3
2014	2	3	1	1	4	1	1.8
2015	2	3	2	2	4	2	2.6
2016	2	3	2	2	4	2	4.9
2017	2	3	3	2	4	2	9.8
2018	3	3	3	3	4	3	7.9
2019	3	3	3	3	4	3	5.1
2020	3	3	3	3	4	3	14.6
2021	3	3	3	3	4	3	7.3
2022	3	3	3	3	4	3	8.8
2023	4	4	4	4	4	4	9.1
2024	5	5	5	5	5	5	6.9
2025	6	6	6	6	6	6	6.9

CCC = canister cooling and crystallization; CD = canister decontamination; FMP = feeding, melting, and pouring; GCF = glass ceramic formulation; MSA = mixing, sampling, and analyses.

This TMP is intended to guide the development of the glass-ceramic waste form and process to the point where it is ready for industrialization.

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ABBREVIATIONS

AgZ	silver mordenite
ASX	autosampler
BSG	borosilicate waste glass
BWR	boiling water reactor
CCC	canister cooling and crystallization
CCIM	cold crucible induction melter
CD	canister decontamination
CEA	Commissariat à l'énergie atomique
CTE	critical technology element
CUA	Catholic University of America
DOE	U.S. Department of Energy
DWPF	Defense Waste Processing Facility
EVS	ejector venturi scrubber
FP	fission products
FMP	feeding, melting, and pouring
FRG	Federal Republic of Germany
GAC	granular activated carbon
GC	glass ceramic (waste form)
GCF	glass ceramic formulation
GFC	glass forming chemical
GWd/t	gigawatt-day per metric tonne (of initial heavy metal)
HEME	high-efficiency mist eliminator
HEPA	high-efficiency particulate air
HLW	high-level radioactive wastes
HWIM	hot-walled induction melter
INL	Idaho National Laboratory
JHCM	Joule-heated ceramic melter
KHNP	Korean Hydro-Nuclear Power
KRI	Khlopin Radium Institute
LANL	Los Alamos National Laboratory

LAW	low-activity waste
LETI	Leningrad Electrotechnical Institute (now Electrotechnical University of St. Petersburg)
M	manufacturing
MOF	metal-organic-framework
MSA	mixing, sampling, and analyses
ORR	operation readiness review
P	programmatic
PIC	products of incomplete combustion
PNNL	Pacific Northwest National Laboratory
Q	qualification
RAMI	reliability, availability, maintainability, and inspectability
R&D	research and development
RF	radio frequency
SBS	submerged-bed scrubber
SCO	selective catalytic oxidizer
SCR	selective catalytic reducer
SIA	Scientific and Industrial Association
SMF	sintered-metal filter
SRNL	Savannah River National Laboratory
SS	stainless-steel
SWF	Separations and Waste Forms (Campaign)
S&T	science and technology
T	technical
Tg	glass transition point
TMP	technology maturation plan
TRA	technology readiness assessment
TRL	technology readiness level
TRU	transuranic
UDS	undissolved-solids
VF	vitrification facility (sampler)
WESP	wet electrostatic-precipitator
WBS	work-breakdown structure

WCP	waste compliance plan
WTP	Hanford Tank Waste Treatment and Immobilization Plant
WVDP	West Valley Demonstration Project

1. INTRODUCTION

1.1 Project Description

The Fuel Cycle Research and Development Program is developing technologies for next-generation sustainable nuclear fuel cycles. Sustainable fuel cycles are those that improve uranium resource availability and utilization, minimize waste generation, and provide adequate capability and capacity to manage all wastes produced by the fuel cycle. The key challenge for the U.S. Department of Energy (DOE) in this objective is to develop a suite of options that will enable future decision-makers to make informed choices about how best to manage used fuel from reactors. The overall goal is to demonstrate the technologies necessary to allow commercial deployment of solution(s) for the sustainable management of used nuclear fuel that is safe, economical, secure, and widely acceptable to society. The proposed schedule for the next-generation fuel cycle is to begin operation of an engineering scale facility by 2040.

The Separations and Waste Forms (SWF) Campaign is developing the next generation of fuel cycle separation and waste management technologies that will enable a sustainable fuel cycle with minimal processing, waste generation, and potential for material diversion. This scope includes waste management approaches for advanced separation technologies.

Vitrification is a mature technology that is used worldwide for the immobilization of high-level radioactive wastes (HLW). However, shortcomings in existing vitrification technologies and the reference borosilicate waste glass (BSG) have prompted the investigation of a glass ceramic (GC) waste form (as summarized in Table 1).

Table 1. Comparison of borosilicate glass and glass-ceramic for high-level radioactive waste immobilization.

Issue	Reference Borosilicate Glass	Proposed Glass-ceramic
Chemical durability	Borosilicate glass has good chemical durability but conservatisms in current models indicate that it may not be sufficiently protective of the environment to avoid other engineered barriers.	Glass ceramic formulations aim to immobilize radionuclides of concern in host ceramic phases with durabilities that are orders of magnitude greater than the reference BSG.
Chemical compatibility	Several components of HLW inherent to advanced fuel cycles are not very soluble in BSG. For example, Mo, Ru, Pd, and Rh are sparsely soluble and limit the loading of waste in glass.	The aim of glass ceramic formulations is to incorporate those elements that are not soluble in BSG into durable crystalline phases, thereby increasing the loading of waste in glass by ~50%.
Decay heat tolerance	There is a strict limit of heat that can be handled in BSG. If canister centerline temperatures are allowed to rise above the glass transition temperature (Tg≈450°C), phase changes may degrade the waste form.	In glass-ceramic, the glass phase targeted will have relatively high Tg and high melting point crystalline phases. Combined, the waste form is likely to handle roughly twice the decay heat without significant chemical changes.
Process	The reference process for vitrification is well established and efficient for BSG production.	Glass ceramic formulations will use a process very similar to that used for BSG to take advantage of the operating experience, equipment design, and remote operation.
BSG = Borosilicate waste glass.		

1.2 Technology Readiness Assessment Process

Technology readiness assessment (TRA) is a process for evaluating the readiness of a technology for deployment that was developed by the National Aeronautics and Space Administration (NASA) and later adopted by the U.S. Department of Defense and DOE (DOE 2009). The process works in three parts:

1. Identifying critical technology elements (CTEs). CTEs are the at-risk technologies that are essential to the successful operation of the facility, and are new or are being applied in new or novel ways to the environment.

2. Assessing the technology readiness level (TRL). The TRL scale indicates the maturity level of a given technology ranging from 1 (basic principle observed) through 9 (total system used successfully in project operations). TRL is not an indication of the quality of technology implementation in the design or the relative challenge of obtaining a higher TRL.

3. Developing a technology maturation plan (TMP). The TMP is a plan to increase the TRL of all CTEs to a predetermined level at a target date. This plan defines the major functions to be performed and the relationship of those functions to technical maturity.

Table 2 summarizes the TRLs and compares the stages of development. TRLs are determined by answering an extensive list of questions (Appendix A) for each CTE. To attain a specific TRL, the CTE should receive a “yes” or “not applicable” response to all questions at the TRL level from which the questions are found. Thus, the TRL for a specific CTE is defined by the level from which all questions are answered affirmatively. The TRL for the technology is then defined as the lowest of the TRLs of all the CTEs.

Table 2. Summary of technology readiness levels (from DOE 2009).

Technology Development Stage	TRL	TRL Definition	Description
System Operations	9	Actual system operated over the full range of expected conditions	The technology is in its final form and operated under the full range of operating conditions. Examples include using the actual system with the full range of wastes in hot operations.
System Commissioning	8	Actual system completed and qualified through tests and demonstrations	The technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental testing and evaluation of the system with actual waste in hot commissioning. Supporting information includes operational procedures that are virtually complete. An operational readiness review has been successfully completed prior to the start of hot testing.
	7	Full-scale, similar (prototypical) system demonstrated in relevant environment	This represents a major step up from TRL 6, requiring demonstration of an actual system prototype in a relevant environment. Examples include testing full-scale prototype in the field with a range of simulants in cold commissioning. Supporting information includes results from the full-scale testing and analysis of the differences between the test environment, and analysis of what the experimental results mean for the eventual operating system/environment. The final design is virtually complete.
Technology Demonstration	6	Engineering/pilot-scale, similar (prototypical) system validation in relevant environment	Engineering-scale models or prototypes are tested in a relevant environment. This represents a major step in a technology's demonstrated readiness. Examples include testing an engineering scale prototypical system with a range of simulants. Supporting information includes results from the engineering scale testing and analysis of the differences between the engineering scale, prototypical system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. TRL 6 begins true engineering development of the technology as an operational system. The major difference between TRL 5 and TRL 6 is the advancement from laboratory scale to the engineering scale, and the determination of scaling factors that will enable design of the operating system. The prototype should be capable of performing all the functions that will be required of the operational system. The operating environment for the testing should closely represent the actual operating environment.

Technology Development Stage	TRL	TRL Definition	Description
Technology Development	5	Laboratory scale, similar system validation in relevant environment	The basic technological components are integrated so that the system configuration is similar to (matches) the final application in almost all respects. Examples include testing a high-fidelity, laboratory scale system in a simulated environment with a range of simulants and actual waste. Supporting information includes results from the laboratory scale testing, analysis of the differences between the laboratory and eventual operating system/environment, and analysis of what the experimental results mean for the eventual operating system/environment. The major difference between TRL 4 and TRL 5 is the increase in the fidelity of the system and environment to the actual application. The system tested is almost prototypical.
	4	Component and/or system validation in laboratory environment	The basic technological components are integrated to establish the pieces will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of ad hoc hardware in a laboratory and testing with a range of simulants and small-scale tests on actual waste. Supporting information includes the results of the integrated experiments and estimates of how the experimental components and experimental test results differ from the expected system performance goals. TRL 4-6 represent the bridge from scientific research to engineering. TRL 4 is the first step in determining whether the individual components will work together as a system. The laboratory system will probably be a mix of on-hand equipment and a few special purpose components that may require special handling, calibration, or alignment to get them to function.
Research to Prove Feasibility	3	Analytical and experimental critical function and/or characteristic proof of concept	Active R&D is initiated. This includes analytical studies and laboratory-scale studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or are representatively tested with simulants. Supporting information includes results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. At TRL 3, the work has moved beyond the paper phase to experimental work that verifies the concept works as expected on simulants. Pieces of the technology are validated, but there is no attempt to integrate the components into a complete system. Modeling and simulation may be used to complement physical experiments.

Technology Development Stage	TRL	TRL Definition	Description
Basic Technology Research	2	Technology concept and/or application formulated	Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are still limited to analytical studies. Supporting information includes publications or other references that outline the application being considered and that provide analysis to support the concept. The advancement from TRL 1 to TRL 2 moves the ideas from pure to applied research. Most of the work is analytical or paper studies with the emphasis on understanding the science better. Experimental work is designed to corroborate the basic scientific observations made during TRL 1 work.
Basic Technology Research	1	Basic principles observed and reported	This is the lowest level of technology readiness. Scientific research begins to be translated into applied R&D. Examples might include paper studies of a technology’s basic properties or experimental work that consists mainly of observations of the physical world. Supporting information includes published research or other references that identify the principles that underlie the technology.
TRL = Technology Readiness Level; R&D = research and development.			

According to DOE guidance (DOE 2009), a TRL = 4 is targeted for critical decision-1 and a TRL = 6 is targeted for critical decision-2/3. Therefore, TMPs are generally written to achieve TRLs of 4 and/or 6. A technology will generally exit the technology development and demonstration phase at a TRL of 6 and if a U.S. congressional line item project, the technology will be “projectized” at TRL 4.

2. TECHNOLOGY DESCRIPTION

The first step in developing the TMP is to define the technology or "system" to be evaluated. In general, the technology is a GC containing 50% more HLW than in the BSG waste forms produced in current European reprocessing facilities and the process required to make it. The process inputs are HLW and various services; the process outputs are secondary effluents and GC waste forms as summarized in Figure 1.

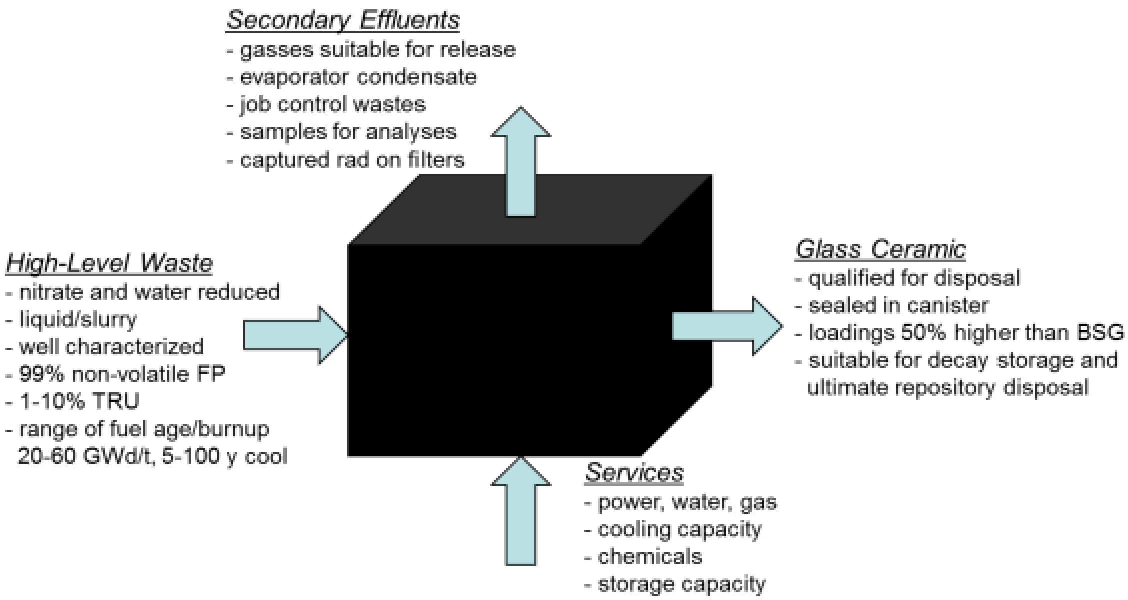

Figure 1. Schematic of major components entering and exiting the glass ceramic waste form fabrication process.

A set of reference and alternative waste process technologies were selected based on experience with previous projects aimed at vitrification of similar wastes. The options considered for each function, the selected reference technology, and comments on the selection of the reference technology are summarized in Table 3. Figure 2 shows a schematic of this chosen reference process.

Table 3. Summary of reference process components.

Function	Reference Option	Reason for Selection	Other Options Considered
Feed and sampling	• Mechanical agitator • Coil cooled vessel • VF sampler	• Impellers have performed better than any other mixing system. The challenge of maintaining a well-mixed waste feed for consistent transfer and representative sampling is worth the added maintenance. • With the possibility of high-heat waste, and impeller agitation, cooling is deemed essential. • VF sampler performed very well at WVDP; the ASX autosampler had some significant challenges at the WTP.	• Pulse-jet mixers • No cooling • ASX sampler
Feed adjustment	• Dry addition of additives • Mechanical agitator, coil cooled vessel • VF sampler	• Dry addition of additives reduces the need for excess water removal and handling. • Vessel mixing—rather than calcination—reduces maintenance, and if a CCIM is chosen, the processing rate per unit hot cell volume is likely to be higher without a calciner.	• Slurry addition of additives with feed evaporator • Rotary calciner for feed mixing and drying • ASX sampler
Melting and pouring	• CCIM • Slurry fed	• High-specific throughput, high temperature, high technical maturity, and crystal tolerance of the CCIM are attractive for this application. • Slurry feed will reduce the process rate but also reduce the maintenance requirements and downtime of the vitrification operation.	• HWIM, JHCM, and in-can melters • Calciner head-end to the melter
Heat treatment	• Controlled cooling with insulation	• With very little extra equipment, a slow cooling can be controlled; the team believes researchers can predictably and reliably form the correct phases and microstructure.	• Natural cooling • Controlled cooling with furnace • Cooling, then controlled heating with furnace
Canister	• 2’φ × 14.8’, ${}^{3}/_{8}$” walled 304L SS can	• Standard WTP HLW canister, already qualified for use, large volume per canister, with height consistent with current BWR assembly lengths.	• WVDP canister (2’φ × 10’) • LaHague canister (1.4’φ × 4.4’)
Canister handling	• Arc-welded lid • CO_2 blasting decontamination	• Demonstrated at WVDP and WTP. • Too hot for chemical and water blasting.	• DWPF welder • Crimp lid • Outer can • Chemical decontamination • Sand/frit blasting decontamination
Cooling and preventing	• Film cooler	• Simple solution shown to reduce gas line buildups.	• No gas cooling

Function	Reference Option	Reason for Selection	Other Options Considered
deposit buildup at melter gas outlet		• Demonstrated at WVDP, DWPF, and WTP.	• Feed calciner • Close-coupled NOxIDIZER
Particulate and semivolatile removal	• EVS • HEME • Recycle-evaporator	• EVS worked well at DWPF; avoided some problems associated with SBS or packed-plate columns. • HEME and evaporator are required if wet scrub is used. Dry processing not considered because high maintenance is expected based on plugging potential observed in previous testing on spray calciners and test melters.	• SBS, WESP, and HEME • SMF and HEPA • Packed-plate column, HEME • All with recycle
Gas reheater	• Electric resistance heater	• Simple, inexpensive, and proven technology.	• Electric or burner preheated dilution air
Organic removal	• None required	• Assume that hazardous organics and PICs are not sufficient to require organics removal.	• NOxIDIZER • SCO.
Nitrate mitigation	• SCR	• A proven technology well suited for a broad range of nitrate concentration with little secondary waste.	• Burner • Trap • Caustic scrub • NOxIDIZER • None
Iodine capture	• AgZ	• Proven technology (Rokkasho, Tokai, WTP).	• Ag/aerogel • Caustic scrub • MOF • GAC

AgZ = silver mordenite; ASX = ASX autosampler; BWR = boiling water reactor; CCIM = cold crucible induction melter; DWPF = Defense Waste Processing Facility; EVS = ejector venturi scrubber; GAC = granular activated carbon; HEME = high-efficiency mist eliminator; HEPA = high-efficiency particulate air; HWIM = hot-walled induction melter; JHCM = Joule-heated ceramic melter; MOF = metal-organic-framework; PIC = products of incomplete combustion; SBS = submerged bed-scrubber; SCO = selective catalytic oxidizer; SCR = selective catalytic reducer; SMF = sintered-metal filter; VF = Vitrification facility; WESP = wet electrostatic-precipitator; WTP = Waste Treatment and Immobilization Plant; WVDP = West Valley Demonstration Project.

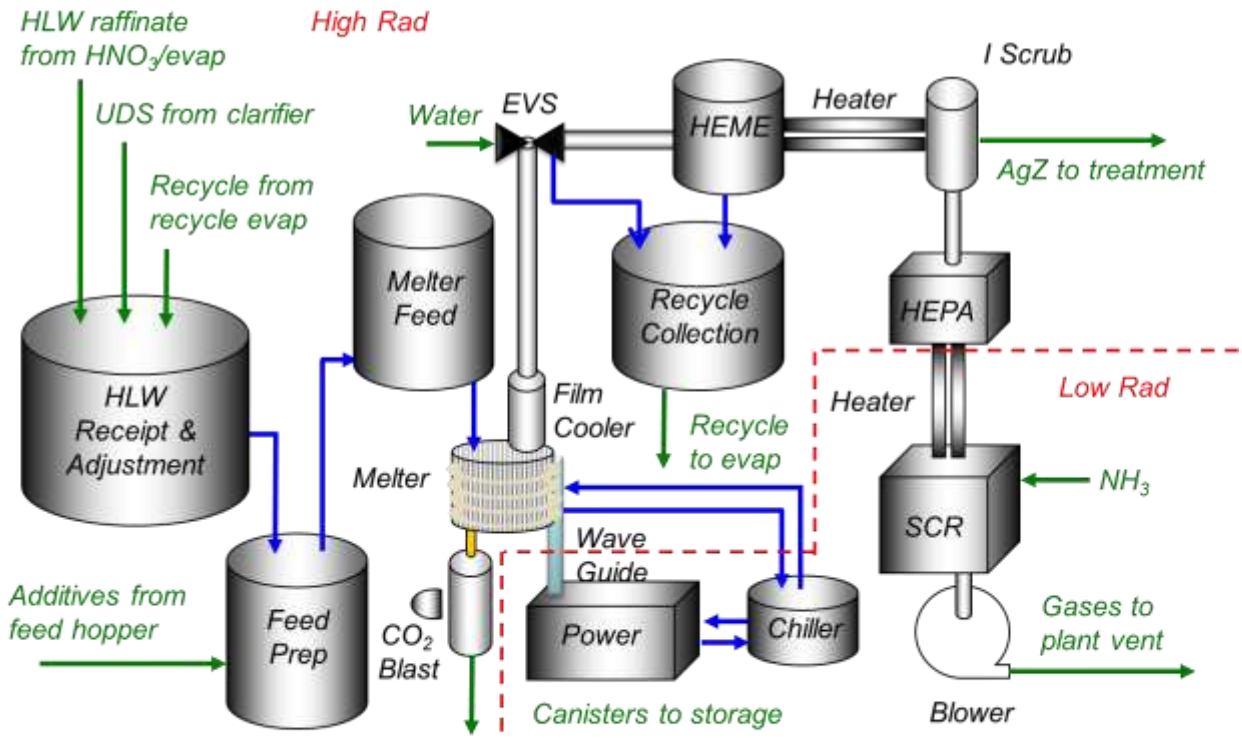

Figure 2. Schematic of reference flowsheet (the inputs and outputs shown in green are not analyzed as part of this study).

3. TECHNOLOGY READINESS ASSESSMENT

3.1 Panel and Assessment Method

The selected process is then evaluated for technology readiness using the process described in DOE (2009) with the key exception that an independent panel of experts was not used to perform the assessment. Instead, a group of technical experts with backgrounds sufficient to evaluate this set of technologies performed the assessment:

- **Jarrod V. Crum**: Mr. Crum is a staff scientist at Pacific Northwest National Laboratory (PNNL) with 14 years of experience in borosilicate glass and ceramics waste form characterization and development. He earned a B.S. in Geology from the University of Idaho. Mr. Crum has focused on measuring the liquidus temperature and crystallization behavior of borosilicate glasses, and applying microscopy and X-ray diffraction technologies. He was the lead author for the baseline borosilicate glass report for the combined fission products waste form for secondary waste streams generated by aqueous reprocessing (Crum et al. 2009). He has lead formulation aspects of the glass ceramic waste form development. Other areas of research are oxide synthesis (such as sodalite, oxyapatite, olivine, and spinel) and phase diagram measurement of MnO_x-FeO_x binary phase diagram in air. Mr. Crum is also involved in the development and characterization of the epsilon-metal waste form for treatment of the noble metals fraction of the fission products generated from aqueous reprocessing.
- **Gary J. Sevigny**: Mr. Sevigny has worked for PNNL for 32 years and earned a B.S. in Chemical Engineering from Washington State University. His experience has focused on the research and development of processes for treatment of hazardous and radioactive material including vitrification, liquid waste treatment, tritium extraction, spent fuel stabilization, plutonium stabilization, and waste separation. He has worked on several vitrification projects, including the Defense Waste Processing Facility at the Savannah River Site; the West Valley Vitrification System; several Hanford Site vitrification projects; the vitrification of over 30 canisters of waste containing approximately 10 million curies of cesium and strontium for the Republic of Germany; and supported the bulk vitrification test program. He was responsible for a vacuum drying system design and start-up for treating stainless-steel reactor fuel from the BN350 reactor in Kazakhstan in 1997 and 1998. He was the principal engineer for treatment of the high-activity mixed waste containing large quantities of cesium and strontium. This activity recovered strontium for the medical isotope program in 1996. Mr. Sevigny worked on the K-Basin reactor fuel pool stabilization, and provided engineering support for the Plutonium Finishing Plant Stabilization Environmental Impact Statement. He has recently performed engineering evaluations and technology maturity assessments for the Pit Disassembly and Conversion Facility at the Savannah River Site.
- **Gary L. Smith**: Dr. Smith earned a Ph.D. in Materials Science & Engineering from the University of Arizona. He is a staff scientist at PNNL and is currently on assignment to the DOE Office of Environmental Management (EM) - Office of Tank Waste Management, Tank Waste & Nuclear Materials. In this assignment, Dr. Smith is the Immobilization Lead who supports implementation of the EM roadmap, including work breakdown structure element planning and multi-year program planning to more effectively integrate national and international capabilities into the Tank Waste & Nuclear Materials Management Program. Dr. Smith has been involved with all aspects of the nuclear waste flowsheet for approximately 20 years, taking on roles of

increasing responsibility in both a technical capacity and in management. He has extensive program management experience, most recently serving as PNNL's Deputy Program Manager for the DOE Office of River Protection's Waste Treatment Plant Project Support Program. This program contributes significantly to the characterization, retrieval, pretreatment, and vitrification of Hanford Site tank waste for the Hanford Tank Waste Treatment and Immobilization Plant (WTP). Prior to this role, Dr. Smith served as a technical advisor, directly supporting the WTP contractor. He has managed and acted as principal investigator on projects ranging from vitrification and glass product testing to examining the processability of slurry feeds as a function of batch chemistry for laboratory-, bench- and pilot-scales. Dr. Smith has published more than 70 refereed journal articles, technical reports, and conference papers as well as numerous classified documents. He has co-edited three volumes of *Ceramic Transactions* on the topic of "Environmental and Waste Management Issues in the Ceramic Industry." He is a fellow of the American Ceramic Society and the ASTM International. Dr. Smith is past chair of the ASTM International Committee C-26 on the Nuclear Fuel Cycle, and chair of the Subcommittee C26.13 on Spent Fuel and High Level Waste that develops consensus standards for the international nuclear community. He is also vice chair of the U.S. Nuclear Technical Advisory Group and past chair of the American Ceramic Society Nuclear and Environmental Technology Division.

- **John D. Vienna**: Dr. Vienna earned a Ph.D. in Materials Science from Washington State University. In 1993, he joined the Glass Development Laboratory at PNNL as a research scientist and currently serves as Chief Scientist in the Radiological and Nuclear Science and Technology Division. He conducts research in waste processing and waste form testing. He leads waste form technology development projects for DOE's Office of Environmental Management and the Office of Nuclear Energy. Dr. Vienna has published over 200 journal articles, conference papers, and technical reports in materials science and its applications to waste management. He has performed independent research in basic waste form materials chemistry, nucleation and growth kinetics, waste form processing, and thermodynamics of multi-component, multi-phased waste forms. Dr. Vienna spent 7 years as a vitrification subject matter expert for the Hanford Tank Waste Treatment and Immobilization Plant. He served on a Technology Readiness Assessment Panel for the DOE Calcine Disposition Project. Dr. Vienna is a Fellow of the American Ceramic Society, a founding member of the Nuclear Waste Vitrification technical committee of the International Commission on Glass, and is an Associate Editor of the International Journal of Applied Glass Science.

The assessment was conducted according to the following process:

1. A subset of the panel (Vienna and Crum) prepared the assessment.
    a. The reference process description (Section 2) was developed
    b. An initial selection of CTEs was made
    c. Literature was reviewed to determine what testing, modeling, demonstration, equipment fabrication, and operating experience was published for each CTE
    d. The available data were used to answer questions related to TRL for each CTE using the question list given in Appendix A.
2. The full panel was brought together to review the preliminary process description, CTE selection, and question list.
3. The full panel independently completed the question lists for the CTEs for which they were technically proficient.

4. The panel again met and the final consensus responses to the list questions for each CTE were collected, thereby defining the TRL of each CTE.
5. The panel again met and developed a list of activities needed to advance each CTE to TRL-4 and TRL-6.
6. A draft of this TMP was written to summarize the process, panel findings, and the tasks to be completed.
7. The full panel reviewed the draft TMP, comments were discussed and addressed, and a final TMP was issued.

Note that several scores, including the CTE list, have changed through the process by the full panel. The final results are provided in Section 3.2.

3.2 Critical Technology Elements

From the process description (Section 2), the research team obtained the following distinct technology elements:

- High-level waste receipt and adjustment
- HLW mixing, sampling, analyses
- Glass forming chemical (GFC) addition
- Feed mixing, sampling, analyses
- Melter feeding, melting, and pouring
- Glass ceramic formulation
- Canister cooling and crystallization
- Film cooler
- Ejector venturi scrubber (EVS)
- Recycle collection
- High efficiency mist eliminator (HEME)
- Selective catalytic reducer (SCR)
- Off-gas heater
- Iodine scrubber
- High-efficiency particulate air (HEPA)
- Blower
- Melter power supply and wave guide
- Canister handling
- Canister lid welding
- Canister decontamination

Each of these technology elements are compared to the CTE determination questions in Table 4. For a technology to be considered critical, it must have a positive response to at least one criteria set 1 question (criticality to program) and to at least one criteria set 2 question (new or novel). The method used to select technology elements in this study ensures that each of the technology elements are critical to the program (at least on question of the criteria set one is positive). Table 5 shows the selection of CTEs.

Although six CTEs result from this process, two are highly related: the mixing, sampling, and analyses (MSA) of the HLW input material and the melter feed. Thus, these two are combined into a single CTE for MSA. The resulting CTEs, along with a brief description, are in Section 3.2.1. Note: the off-gas treatment system was not identified as a CTE as each of the components of the system have been individually been demonstrated to work with similar off-gas streams. However, if the melter operating temperature required to make the glass-ceramic waste form turns out to be significantly above the range of temperatures over-which off-gas equipment have been demonstrated, then, certain off-gas components may become CTEs. For now we assume moderate temperatures and allow the preliminary engineering study and integrated testing to identify any potential issues.

Table 4. Critical technology element decision questions (after DOE 2009).

Set 1 - Criteria
Does the technology directly impact a functional requirement of the process or facility?
Do limitations in the understanding of the technology result in a potential schedule risk; i.e., the technology may not be ready for insertion when required?
Do limitations in the understanding of the technology result in a potential cost risk; i.e., the technology may cause significant cost overruns?
Do limitations in the understanding of the technology impact the safety of the design?
Are there uncertainties in the definition of the end state requirements for this technology?
Set 2 - Criteria
Is the technology new or novel?
Is the technology modified?
Have the potential hazards of the technology been assessed?
Has the technology been repackaged so a new relevant environment is realized?
Is the technology expected to operate in an environment and/or achieve performance beyond its original design intention or demonstrated capability?

3.2.1 Mixing, Sampling, and Analyses

The process requires that undissolved solids from dissolution, single-phase HLW raffinate, and multiphase recycle streams will be mixed. One of the critical factors for successful operation is to maintain the noble metals (Pd, Ru, Rh) in proper concentrations in the melter feed. This requires the mixing of fast settling solids into a low viscosity liquid, representative sampling, and thorough analyses of the sample. These three aspects have proven difficult for U.S. HLW treatment plants: the West Valley Demonstration Project (WVDP), the Defense Waste Processing Facility (DWPF), and the WTP. Each of these three plants was forced to redesign their mixing and sampling systems even though they had full access to the lessons learned from the previous plants. Additionally, the solutions being generated in this process are distinctly different from those processed at any of the three U.S. plants in that they will not be neutralized for storage in carbon-steel tanks and they will contain significantly lower concentrations of nonradioactive chemical additions.

Mixing will be performed in water cooled, impeller agitated vessels. The sampling system will be modeled after the WVDP vitrification facility (VF) sampler, which was the most successful of the three sampling systems employed in the U.S. and functioned in the only plant that processed exclusively commercial power reactor fuel (with higher noble metals fractions). Chemical analyses will be performed by fusion of the sample in a series of melts (Na_2O_2, $LiBO_2$, and KOH), and the fused material will be dissolved in nitric acid solution in volumetric flasks according to ASTM C-1463 (ASTM 2007). Solution analysis will be performed using inductively coupled plasma-optical emission spectroscopy according to

ASTM C-1109 (ASTM 2010). Analyses by inductively coupled plasma-mass spectrometry may also be necessary for some analytes.

3.2.2 Melter Feeding, Melting, and Pouring

The cold-crucible induction melter (CCIM) was selected for this process because of the relatively high operating temperatures and tolerance to crystals that it affords. CCIMs have been deployed for many decades to process metal, ceramic, and glass melts, including radioactive glasses (Sobolev et al. 1996; Song 2003; Bonnetier et al. 2003). The only CCIM currently deployed to treat HLW is at the AREVA LaHague site in France, plant number R7. In the R7 plant, the CCIM is fed by a rotary calciner that takes liquid HLW and some additives and converts the mixture to a granular dry feed for the melter. The GFCs, in the form of a frit, are simultaneously added to the melt with the calcined waste.[1] In LaHague process the calciner both dries the feed and is the first component of the off-gas treatment system. In the proposed process, the research team conducting this study differed from this approach for several reasons. 1) The calciner requires rotation and a beater bar to operate which increases the maintenance requirements. 2) The calciner must be located at the top of the cell with allowance for easy removal and maintenance access reducing the design options. 3) The primary benefit of the calciner is to reduce melting rate can be more easily accomplished by a larger melter surface area. 4) The secondary benefit of the calciner is as an initial component of the off-gas treatment system is not as efficient, requires more maintenance, and is larger than our proposed EVS.

The operating philosophy adopted here is one of minimal down time for maintenance. The liquid-fed melting rates have been demonstrated for the CCIM to be as high as 6000 kg/($m^2 \cdot d$) for slurries with ~500 g of glass per liter of feed with no mechanical stirrer (Kobelev et al. 2006). Although the slurry feeding process was demonstrated on a number of occasions, no long-term processing experience is available for every simulant and not for actual HLW feeds.

The crystal tolerance of the CCIM is part of the decision to select this melter as a reference technology. However, it has not yet been demonstrated if the exact crystals being generated for the proposed glass-ceramic can be successfully processed in a CCIM. In addition, the allowable concentration of noble metals is a key uncertainty. AREVA officials have reported a noble metal limit for processing in the R7 CCIM of 3 wt% (combined RuO_2, PdO, and Rh_2O_3) (Ladirat et al. 2004). However, the tests that led to this limit are not well described nor is it clear if higher concentrations can be tolerated. The primary concern with high noble metal concentrations is the formation of macroscopic metal particles (through agglomeration and settling) that will preferentially couple to the induction field and heat to sufficient temperatures that they melt through the frozen glass scull of the melter (Demin and Matyunin 1995).

Pouring from the melter is more of a technical challenge for glass-ceramic than for simple glasses because the glass-ceramic are designed to crystallize relatively quickly upon cooling, causing dramatic viscosity increase, effectively freezing the melt. After a portion of the melt is poured from the melter bottom, the pour is stopped by moving a cold gate valve across the opening. The cooling of the melt near the valve will almost certainly cause the melt to crystallize. It has yet to be demonstrated if these crystals will dissolve sufficiently fast to reinitiate pouring.

[1] *A frit is assumed sufficient for this process because the range of waste compositions is not likely to require changes in additive concentrations on a regular basis.*

Table 5. Critical technology element selection.

Technology Elements	HLW receipt and adjustment	HLW mixing, sampling, analyses	GFC addition	Feed mixing, sampling, analyses	Melter feeding, melting, and pouring	Glass ceramic formulation	Canister cooling and crystallization	Film cooler	EVS	Recycle collection	HEME	SCR	Off-gas heater	Iodine scrubber	HEPA	Blower	Melter power supply, waveguide	Canister handling	Canister decontamination	Lid welding
Set 1 – Criteria																				
Does the technology directly impact a functional requirement of the process or facility?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Do limitations in the understanding of the technology result in a potential schedule risk; i.e., the technology may not be ready for insertion when required?	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Do limitations in the understanding of the technology result in a potential cost risk; i.e., the technology may cause significant cost overruns?	Y	Y	Y	Y	Y	Y	Y	N	N	N	N	Y	N	Y	N	N	Y	N	Y	N
Do limitations in the understanding of the technology impact the safety of the design?	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Are there uncertainties in the definition of the end state requirements for this technology?	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Set 2 – Criteria																				
Is the technology new or novel?	N	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Is the technology modified?	N	N	N	N	N	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N
Have the potential hazards of the technology been assessed?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Has the technology been repackaged so a new relevant environment is realized?	N	Y	N	Y	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	Y	N
Is the technology expected to operate in an environment and/or achieve performance beyond its original design intention or demonstrated capability?	N	N	N	N	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Critical Technology Elements	N	Y	N	Y	Y	Y	Y	N	N	N	N	N	N	N	N	N	N	N	Y	N

3.2.3 Glass Ceramic Formulation

Borosilicate-based glass is the waste form of choice for HLW immobilization worldwide (Vienna 2010; Donald et al. 1997; Ojovan and Lee 2005). Scientists have long recognized that allowing insoluble components to precipitate from the borosilicate melt would increase the loading of waste in glass and may increase waste forms performance (Hrma 2010; Juoi and Ojovan 2007; Juoi et al. 2008). However, to date no HLW glass-ceramic formulations have been produced at scale for HLW immobilization. The challenges are partly with the processability of the glass ceramic as discussed in the preceding and following sections, but also with the ability to predict and control the phases that form in an industrial process. In the United States, it is not sufficient to produce a good durable waste form. The waste form must have both good and predictable performance. To predict performance, the research team will need to predict the amounts, types, and compositions of phases formed in the final, canistered waste form. This prediction is problematic because of a difficulty in controlling the exact composition of melt and the wide range of cooling schedules in the canister. Alternatively, the performance may be bounded by a "worst-case" waste form and cooling schedule. If this worst-case is shown to meet all the waste form requirements, then any waste form bounded by it would meet the requirements.

A glass ceramic composition must be formulated so that a predictable phase assemblage is formed for the full range of anticipated composition space and temperature history variations. In addition, the melt must be processable with minimal risk of process upsets. Finally, the impacts of off-normal processing events (e.g., loss of power, etc.) must be accounted for in glass formulation to ensure a recovery method is compatible with the final formulation.

Finally, the glass ceramic must tolerate a wide range of decay heat. Typical commercial HLW glasses are decay heat limited. Putting key radionuclides into crystalline phases that do not melt until high temperature helps to relax decay heat limits. However, the range of resulting phase assemblages must tolerate the decay heat without significant chemical or physical changes that might impact performance.

3.2.4 Canister Cooling and Crystallization

The phases formed during canister cooling must be predictable and lead to a sufficiently high performing waste form as described in Section 3.2.3. The assumed process for allowing these phases to form is direct cooling from the melt without any reheating. This adds to the problems during the formulation process because the melt must crystallize fast enough to form the correct phase assemblage during natural cooling while remaining fluid enough to fill the entire canister. The crystallization cannot harden the glass before it flows to the canister edges.

Two alternative processes will be considered while developing this waste form: 1) slowing the cooling process by insulating the canister, and 2) employing a secondary heat treatment to the canister during and after filling using an electric heater.

In evaluating the technical maturity of the CTEs, it was often difficult to separate the characteristics of the GCF from the canister cooling and crystallization. The distinction used in this study is somewhat arbitrary. However, this does not impact the final product, which is a TMP. This is because the TMP is designed to cover the needs from all of the CTEs and where there is overlap, testing is combined.

3.2.5 Canister Decontamination

Canister decontamination is performed regularly around the world. However, the target of the GCFs is to increase the loading of HLW in the waste form by 50%. With this increase comes a higher temperature canister that adds significant challenges to decontamination processes. Carbon-dioxide (CO_2) pellet blasting was selected for canister decontamination because it is the proven decontamination process that is the least impacted by canister wall temperature. It was chosen as the WTP low-activity waste (LAW) glass canister decontamination method for the same reason.[2] A complete technology readiness assessment was performed for the Hanford Site LAW vitrification process resulting in a TMP (Holton et al. 2007). Rather than repeat the process in this study, the research team adopted the results for CO_2 pellet blasting directly from the WTP TMP.

3.3 Technology Readiness Level

According to the DOE (2009) guidance:

> *To attain a specific TRL, the CTE should receive a "yes" response to all questions at the TRL level from which the questions are found.*

It is not clear what TRL to assign a CTE if some of the TRL level 1 questions are answered "no." The research team will assume a TRL level of 1 in such cases. The question list was answered for each of the CTEs and responses are provided in Appendix A. These responses resulted in a TRL 1 for all CTEs, except for canister decontamination as summarized in Table 6.

The low TRL for this technology may be misleading; it suggests that only a general notion exists without significant development. However, a review of the criteria missed shows the TRL can be advanced for most CTEs to level 2 by completing an initial waste composition/property estimate, a preliminary engineering study, and some additional laboratory scale tests of the glass-ceramic. The one exception is the mixing, sampling, and analysis CTE which would also require some mixing and sampling tests.

The TRL's of most CTE's would also advance to level 3 with a relatively small additional effort including:

- Laboratory scale glass ceramic testing
- Melter and off-gas testing with simulants
- Test the mixing, sampling, and analyses
- Canister testing
- Issue a requirements document
- Issue a risk management document
- Issue a waste compliance plan.

The canister decontamination question list was answered only for TRL 5 and TRL 6 level questions, using a previous version of the guidance (Holton et al. 2007). Although the application reviewed by Holton et al. (2007) was different from the current proposed application, it was deemed by the panel to be similar enough to assume the maturity level is equivalent.

[2] *The Hanford Site WTP LAW glass canister is roughly 4 ft diameter and therefore has significant thermal mass. This thermal mass leads to a high surface temperature at the time of decontamination.*

Table 6. Criteria answered no by technology readiness level (no/ total).

Critical Technology Element	TRL-1	TRL-2	TRL-3	TRL-4	TRL-5	TRL-6
Mixing, sampling, and analysis	1/9	6/25	16/33	29/37	34/39	28/35
Feeding, melting, and pouring	0/9	2/25	16/33	30/37	34/39	28/35
Glass ceramic formulation	0/9	7/25	15/33	23/37	29/39	24/35
Canister cooling and crystallization	0/9	10/25	15/33	29/37	37/39	28/35
Canister decontamination *	--	--	--	--	7/23	10/28

TRL = Technology readiness levels.

*Note that a previous question list was used for the canister decontamination TRA that had significantly fewer questions, and only questions for TRL-5 and TRL-6 were answered.

4. TECHNOLOGY MATURATION PLAN

A TMP is provided in this report to guide testing of the glass-ceramic waste form and process to the point where it is ready to be turned over to an industrial partner to implement the process in a reprocessing plant design project. The turnover point will be in the TRL-4 to TRL-6 range depending on negotiations. In the case of the early turnover, the industrial partner will likely follow a similar plan to achieve TRL-6 prior to construction.

4.1 Summary

The method to develop this plan is to group similar activities needed to answer questions within and between CTEs. A base set of activities was found to cover the work required to obtain a TRL of 4 and then to obtain a TRL of 6 for all CTEs. Table 7 summarizes the questions answered by each of these activities for each CTE.

Table 7. Summary of questions answered by each technology maturation activity.

Activity	MSA	FMP	GCF	CCC	CD
Complete this TMP	2.18, 4.13	2.18, 4.13	2.18, 4.13	2.18, 4.13	--
Preliminary engineering study	2.07, 2.09, 3.06, 3.07, 3.16, 3.18, 3.19, 3.26, 4.05, 4.19	3.06, 3.07, 3.16, 3.18, 3.19, 3.26, 4.05, 4.19	3.16, 3.18, 3.19, 3.26, 4.19	2.07, 2.09, 2.12, 2.14, 3.06, 3.07, 3.16, 3.18, 3.19, 3.26, 4.05, 4.19	--
Characterize, estimate, and simulate waste to be treated	1.08, 3.27, 3.28, 4.28, 5.24, 5.25, 5.26	2.20, 3.28, 4.28, 5.24, 5.25, 5.26	2.20, 2.23, 5.25, 5.26	2.20, 2.23, 5.25, 5.26	--
Laboratory scale glass ceramic testing	--	--	2.09, 2.12, 2.13, 2.24, 3.03, 3.07, 3.10, 3.22, 3.27, 4.04, 4.11, 4.12, 4.18, 4.26, 4.28, 4.29, 4.30, 4.32, 4.37, 5.11, 5.24, 5.29, 5.32, 5.36, 5.39, 6.09	2.13, 2.24, 3.03, 4.18, 4.28, 4.29, 4.30, 4.37, 5.24, 5.29, 5.36, 5.39, 6.09	--
Melter and off-gas testing with simulants	--	3.03, 3.10, 3.22, 3.27, 3.29, 4.02, 4.04, 4.17, 4.18, 4.29, 4.32, 4.37, 5.02, 5.07, 5.14	5.14	2.15	--

Activity	MSA	FMP	GCF	CCC	CD
Test the mixing, sampling, and analyses	2.14, 2.15, 3.03, 3.10, 3.22, 3.29, 4.02, 4.04, 4.17, 4.18, 4.29, 4.30, 4.32, 4.37, 5.02, 5.07, 5.14, 5.27	--	--	--	--
Canister testing	--	--	--	3.10, 3.22, 4.02, 4.04, 4.26, 4.32, 5.02, 5.07, 5.14	
Decontamination system testing	--	--	--	--	5.09, 5.14
Requirements document	3.12, 3.13, 4.06, 4.08, 4.09, 5.19, 6.08	3.12, 3.13, 3.18, 4.06, 4.07, 4.08, 4.09, 5.19, 6.08	3.12, 3.13, 3.18, 4.06, 4.07, 4.08, 4.09, 5.19, 6.08	3.12, 3.13, 3.18, 4.06, 4.07, 4.08, 4.09, 5.19, 6.08	5.19
Risk management document	3.25, 4.21, 5.34	3.25, 4.21, 5.34	3.25, 4.21, 5.34	3.25, 4.21, 5.34	--
Preliminary design	4.01, 4.07, 4.16, 4.23, 4.25, 4.31, 5.03, 5.04, 5.05, 5.13, 5.15, 5.18, 5.20, 5.23, 5.31, 6.02, 6.03, 6.05, 6.06, 6.09, 6.12, 6.13, 6.14, 6.15, 6.20, 6.23, 6.25	4.01, 4.16, 4.23, 4.25, 4.27, 4.31, 5.03, 5.04, 5.05, 5.13, 5.15, 5.18, 5.20, 5.23, 5.31, 6.02, 6.03, 6.05, 6.06, 6.09, 6.12, 6.13, 6.14, 6.15, 6.20, 6.23, 6.25	4.01, 4.25, 4.31, 5.03, 5.05, 5.04, 5.20, 5.23, 5.31, 6.06, 6.12, 6.13, 6.14, 6.15, 6.20, 6.23, 6.25	4.01, 4.16, 4.17, 4.23, 4.25, 4.31, 5.03, 5.04, 5.05, 5.13, 5.15, 5.18, 5.20, 5.23, 5.31, 5.38, 6.02, 6.03, 6.05, 6.06, 6.12, 6.13, 6.14, 6.15, 6.20, 6.23, 6.25	5.05, 6.25
Integrated pilot testing	4.10, 4.11, 4.12, 4.14, 4.20, 4.26, 5.01, 5.06, 5.09, 5.11, 5.12, 5.16, 5.17, 5.21, 5.22, 5.30, 5.32, 5.33, 5.36, 5.37, 6.01, 6.04,	4.10, 4.11, 4.12, 4.14, 4.20, 4.26, 5.01, 5.06, 5.09, 5.11, 5.12, 5.16, 5.17, 5.21, 5.22, 5.27, 5.30, 5.32, 5.33, 5.36, 5.37, 6.01,	4.14, 4.20, 5.06, 5.12, 5.16, 5.17, 5.21, 5.22, 5.27, 5.30, 5.33, 5.37, 6.01, 6.04, 6.07, 6.10, 6.11, 6.18, 6.22, 6.24, 6.27, 6.28,	4.10, 4.11, 4.12, 4.14, 4.20, 5.01, 5.06, 5.09, 5.11, 5.12, 5.16, 5.17, 5.21, 5.22, 5.27, 5.30, 5.32, 5.33, 5.37, 6.01, 6.04, 6.07,	5.12, 5.17, 5.21, 6.01, 6.11, 6.18, 6.21, 6.22, 6.24, 6.27, 6.31, 6.32

Activity	MSA	FMP	GCF	CCC	CD
	6.07, 6.10, 6.11, 6.18, 6.21, 6.22, 6.24, 6.27, 6.28, 6.29, 6.30, 6.31, 6.32	6.04, 6.07, 6.10, 6.11, 6.18, 6.21, 6.22, 6.24, 6.27, 6.28, 6.29, 6.30, 6.31, 6.32	6.29, 6.30, 6.31, 6.32	6.10, 6.11, 6.18, 6.21, 6.22, 6.24, 6.27, 6.28, 6.29, 6.30, 6.31, 6.32	
Waste compliance plan	3.33, 4.36 5.35	3.33, 4.36 5.35	3.33, 4.36 5.35	3.33, 4.36 5.35	--
CCC = canister cooling and crystallization; CD = canister decontamination; GCF = glass ceramic formulation; FMP = feeding, melting, and pouring; MSA = mixing, sampling, and analyses.					

4.2 Technology Maturation Plan

Two criteria are satisfied by the completion of this TMP for each CTE:

- 2.18 - Preliminary strategy to obtain TRL 6 developed (e.g., scope, schedule, and cost)?
- 4.13 - Science and Technology Demonstration exit criteria established (S&T targets understood, documented, and agreed to by sponsor)?

To meet these criteria, the research team established the strategy to obtain TRL 6 including scope, schedule, and cost; and described the exit criteria from technology development.

4.3 Preliminary Engineering Study

A preliminary engineering study is needed to meet many of the lower TRL criteria. This study is generally aimed at estimating the performance of each function or unit operation in the process, scale the equipment, estimate mass and energy balances, and determine interfaces that allow all the components to work together based on current estimates of their capacity. The study will also estimate the capital and operating costs of the process; the criteria met by this study are listed in Table 8.

The results of this preliminary engineering study will be documented in a project report that establishes the basis for further glass-ceramic technology development. As technology development progresses and assumptions in the preliminary engineering study are confirmed or updated, the results will be incorporated into preliminary design efforts and planning for integrated pilot facility testing.

Table 8. Criteria satisfied by preliminary engineering study.

#	Criteria	MSA	FMP	GCF	CCC
2.07	Desktop environment (paper studies)?	✓			✓
2.09	Performance predictions made for each element?	✓			✓
2.12	Modeling & Simulation only used to verify physical principles?				✓
2.14	Rigorous analytical studies confirm basic principles?				✓
3.06	Preliminary system performance characteristics and measures have been identified and estimated?	✓	✓		✓
3.07	Predictions of elements of technology capability validated by modeling and simulation (M&S)?	✓	✓		✓

#	Criteria	MSA	FMP	GCF	CCC
3.16	Paper studies indicate that system components ought to work together?	✓	✓	✓	✓
3.18	Performance metrics for the system are established (what must it do)?	✓			
3.19	Scaling studies have been started?	✓	✓	✓	✓
3.26	Rudimentary best value analysis performed for operations?	✓	✓	✓	✓
4.05	Modeling & Simulation used to simulate some components and interfaces between components?	✓	✓		✓
4.19	Initial cost drivers identified?	✓	✓	✓	✓
CCC = canister cooling and crystallization; FMP = feeding, melting, and pouring; GCF = glass ceramic formulation; MSA = mixing, sampling, and analyses.					

4.4 Characterize, Estimate, and Simulate Waste to be Treated

One fundamental aspect of developing and demonstrating the technology is to understand the waste to be treated. This activity is aimed at characterizing, estimating, and simulating the wastes to be treated. It will continue through most of the development process. Early activities include the estimation of the composition and bounding physical properties (density, rheology, solids fraction, particle size distribution, etc.) of the waste (ASTM 2011a, 2011b). Simulants will be designed and prepared to match the key physical and chemical aspects of the waste for testing. In later stages, the wastes generated from laboratory scale experiments, engineering scale experiments, and pilot testing (if applicable) will be characterized. Their physical and chemical properties will be compared to the simulants used in testing. Actual waste testing results will be compared to simulant testing results to confirm that the simulants used were appropriate or to design improved simulants for further testing. The criteria met by this study are listed in Table 9.

Table 9. Criteria satisfied with characterize, estimate, and simulate waste to be treated.

#	Criteria	MSA	FMP	GCF	CCC
1.08	Basic characterization data exists?	✓			
2.20	The scope and scale of the waste problem has been determined?	✓	✓	✓	✓
2.23	Have the range of waste species and waste loading for the waste form been identified?			✓	✓
3.27	Key physical and chemical properties have been characterized for a number of waste samples?	✓			
3.28	A simulant has been developed that approximates key waste properties?	✓	✓		
4.28	Key physical and chemical properties have been characterized for a range of wastes?	✓	✓		
5.24	The range of all relevant physical and chemical properties has been determined (to the extent possible)?	✓	✓		
5.25	Simulants have been developed that cover the full range of waste properties?	✓	✓	✓	✓
5.26	Testing has verified that the properties/performance of the simulants match the properties/performance of the actual wastes?	✓	✓	✓	✓
CCC = canister cooling and crystallization; FMP = feeding, melting, and pouring; GCF = glass ceramic formulation; MSA = mixing, sampling, and analyses.					

4.5 Laboratory-Scale Glass Ceramic Testing

Laboratory testing of glass-ceramic serves many functions and will continue through most of the technology development program. The focus of glass ceramic testing includes the following:

- Development of reference formulations that meet all the processing and product quality requirements.
- Measure the impacts of composition, temperature, and other process parameter variability on waste form properties.
- Generate models to predict the properties of the waste form as functions of controllable parameters. These models will be applied for process control and to evaluate the impact of off-normal events.
- Evaluate the performance of the waste form over long time-scales in anticipated disposal environments using accelerated laboratory tests and ancient analogs. (Ryan et al. 2011, for example)
- Compare the performance of glass-ceramic produced by simulants with those produced by actual wastes. Also compare the performance of glass-ceramic produced in laboratory-scale experiments with those produced in scaled process tests.

These activities will be performed in stages that generally follow the order of activities listed above and the list of criteria met. Each stage of testing will be documented in project reports and peer-reviewed journal articles.

Table 10. Criteria satisfied with laboratory-scale glass ceramic testing.

#	Criteria	GCF	CCC
2.09	Performance predictions made for each element?	✓	
2.12	Modeling & Simulation only used to verify physical principles?	✓	
2.13	System architecture defined in terms of major functions to be performed?	✓	✓
2.24	Are the general properties of the waste form well understood and published in peer review journals?	✓	✓
3.03	Predictions of elements of technology capability validated by analytical studies?	✓	✓
3.07	Predictions of elements of technology capability validated by Modeling and Simulation (M&S)?	✓	
3.10	Predictions of elements of technology capability validated by laboratory experiments?	✓	
3.22	Scientific feasibility fully demonstrated?	✓	
3.27	Key physical and chemical properties have been characterized for a number of waste samples?	✓	
4.04	Subsystems composed of multiple components tested at lab scale using simulants?	✓	
4.11	Laboratory experiments with available components show that they work together?	✓	
4.12	Analysis completed to establish component compatibility (do components work together)?	✓	
4.18	Controlled laboratory environment used in testing?	✓	✓
4.26	Low fidelity technology "system" integration and engineering completed in a lab environment?	✓	

#	Criteria	GCF	CCC
4.28	Key physical and chemical properties have been characterized for a range of wastes?	✓	✓
4.29	A limited number of simulants have been developed that approximate the range of waste properties?	✓	✓
4.30	Laboratory-scale tests on a limited range of simulants and real waste have been completed?	✓	✓
4.32	Test plan documents for prototypical lab- scale tests completed?	✓	
4.37	Have the range of chemistry and processing parameters for acceptable waste form been identified and documented?	✓	✓
5.11	Lab-scale, similar system tested with range of simulants?	✓	
5.24	The range of all relevant physical and chemical properties has been determined (to the extent possible)?	✓	✓
5.29	Test results for simulants and real waste are consistent?	✓	✓
5.32	Test plan for prototypical lab-scale tests executed - results validate design?	✓	
5.36	Have all relevant physical and chemical properties been sufficiently well determined and bounded to meet proposed disposal criteria?	✓	✓
5.39	Have release rate law models been established (for relevant environment(s))?	✓	✓
6.09	Off-normal operating responses determined for engineering scale system?	✓	✓
CCC = Canister cooling and crystallization; GCF = glass ceramic formulation; M&S = modeling and simulation.			

4.6 Melter and Off-Gas Testing with Simulants

Melter operation is paramount to successful glass ceramic fabrication. Melter tests will be performed primarily to demonstrate the process and its boundaries, and to generate data needed for process design. Operation is necessarily broader than the melter as a unit because the effectiveness of the melter is largely driven by the ancillary systems such as the feed and off-gas system. For CCIMs, the cooling and radio frequency (RF) systems are also critical to melter operation. Portions of all these systems are required to perform even the most focused melter tests. Scaling of melter and off-gas systems has often been a source of uncertainty that will be solved by a combination of melter tests at increasing scales and modeling. Table 11 lists the criteria that will be satisfied by melter and off-gas system testing. Melter operation at near prototypical rates will also be required to fill canisters for canister cooling and crystallization testing as described in Section 3.2.4.

There is a significant overlap between the data that can be generated on a melter system and the integrated pilot system. For the purposes of this plan, the research team assumed that melter tests will be used to the extent practical and if the pilot system is available before all objectives are met, decisions will be made at that time if it is more effective to meet the remaining needs using the integrated pilot.

The research team assumes that a full melter and off-gas system will not be built for actual waste testing. This will leave a certain amount of residual project risk as a plant is built and commissioned for full radioactive operations. The decision will be revisited when the official risk management process begins.

Table 11. Criteria satisfied with melter and off-gas testing with simulants.

#	Criteria	FMP	GCF
2.15	Analytical studies reported in scientific journals/conference proceedings/technical reports?		✓
3.03	Predictions of elements of technology capability validated by analytical studies?	✓	
3.10	Predictions of elements of technology capability validated by laboratory experiments?	✓	
3.22	Scientific feasibility fully demonstrated?	✓	
3.27	Key physical and chemical properties have been characterized for a number of waste samples?	✓	
3.29	Laboratory scale tests on a simulant have been completed?	✓	
4.02	Laboratory components tested are surrogates for system components?	✓	
4.04	Subsystems composed of multiple components tested at lab scale using simulants?	✓	
4.17	Equipment scale-up relationships are understood/accounted for in technology development program?	✓	
4.18	Controlled laboratory environment used in testing?	✓	
4.29	A limited number of simulants have been developed that approximate the range of waste properties?	✓	
4.32	Test plan documents for prototypical lab- scale tests completed?	✓	
4.37	Have the range of chemistry and processing parameters for acceptable waste form been identified and documented?	✓	
5.02	Plant size components available for testing?	✓	
5.07	Prototypes of equipment system components have been created (know how to make equipment)?	✓	
5.14	Some special purpose components combined with available laboratory components for testing?	✓	✓
FMP = feeding, melting, and pouring; GCF = glass ceramic formulation.			

4.7 Test the Mixing, Sampling, and Analyses

Mixing, sampling, and analyses tests will be performed to ensure that the multiphase (slurry) waste and melter feed can be effectively processed using a feed-forward qualification strategy such as that employed at DWPF and WTP. The most critical aspect of this testing is to ensure the results from chemical analyses of a sample are representative of the composition of an entire batch being transferred for processing. The challenges are as follows: 1) mix fast settling undissolved solids (UDS) in low viscosity liquid, 2) obtaining a representative sample (e.g., correct solids to liquids ratio), and 3) analyses that give an accurate concentration for metals that are notoriously difficult to fuse and dissolve (Pd, Ru, Rh). Testing will be initially performed in an engineering scale unit and will be repeated in pilot scale integrated tests (Section 4.13). The criteria satisfied by this testing are listed in Table 12.

Table 12. Criteria satisfied with mixing, sampling, and analyses testing.

#	Criteria	MSA
2.14	Rigorous analytical studies confirm basic principles?	✓
2.15	Analytical studies reported in scientific journals/conference proceedings/technical reports?	✓
3.03	Predictions of elements of technology capability validated by analytical studies?	✓
3.10	Predictions of elements of technology capability validated by laboratory experiments?	✓
3.22	Scientific feasibility fully demonstrated?	✓
3.29	Laboratory scale tests on a simulant have been completed?	✓
4.02	Laboratory components tested are surrogates for system components?	✓
4.04	Subsystems composed of multiple components tested at lab scale using simulants?	✓
4.17	Equipment scale-up relationships are understood/accounted for in technology development program?	✓
4.18	Controlled laboratory environment used in testing?	✓
4.29	A limited number of simulants have been developed that approximate the range of waste properties?	✓
4.30	Laboratory-scale tests on a limited range of simulants and real waste have been completed?	✓
4.32	Test plan documents for prototypical lab- scale tests completed?	✓
4.37	Have the range of chemistry and processing parameters for acceptable waste form been identified and documented?	✓
5.02	Plant size components available for testing?	✓
5.07	Prototypes of equipment system components have been created (know how to make equipment)?	✓
5.14	Some special purpose components combined with available laboratory components for testing?	✓
5.27	Laboratory-scale tests on the full range of simulants using a prototypical system have been completed?	✓

4.8 Canister Testing

The canister function is distinctly different in a glass ceramic process when compared to a borosilicate glass process. The key differences include the following: 1) glass-ceramic is processed at a higher temperature, 2) the canister is insulated (or potentially heated) to slow the cooling process and thereby crystallize the appropriate phases, and 3) the radiation field and temperature of the canistered waste form will be as much as twice the standard.[3]

Prototypical canisters need to be filled and cooled according to predictable temperature histories. The mechanical properties of the canister will be tested to ensure the differences in thermal history between the borosilicate glass process and the glass-ceramic process do not degrade the canister material(s) properties. The canister will also be sectioned and glass-ceramic samples representing the range of thermal histories will be evaluated to confirm the predicted phase assemblages were achieved. Additionally, prototypically filled canisters will be required to demonstrate thermal history and canister decontamination process. Finally, canister drop testing and analyses will be required for waste form qualification activities. Table 13 lists the criteria satisfied by this testing.

[3] *The research team assumes the standard would be the universal canister as produced in France, Japan, and the United Kingdom with their reference commercial fuel reprocessing waste heat levels.*

Table 13. Criteria satisfied with canister testing.

#	Criteria	CCC
3.10	Predictions of elements of technology capability validated by laboratory experiments?	✓
3.22	Scientific feasibility fully demonstrated?	✓
4.02	Laboratory components tested are surrogates for system components?	✓
4.04	Subsystems composed of multiple components tested at lab scale using simulants?	✓
4.26	Low fidelity technology "system" integration and engineering completed in a lab environment?	✓
4.32	Test plan documents for prototypical lab- scale tests completed?	✓
5.02	Plant size components available for testing?	✓
5.07	Prototypes of equipment system components have been created (know how to make equipment)?	✓
5.14	Some special purpose components combined with available laboratory components for testing?	✓

4.9 Decontamination System Testing

The decontamination system is a generally mature technology. However, it has not been demonstrated for the current application. The challenges are associated with the canister temperature and dose, in particular when high heat wastes (high burn up and/or short cooled fuel). To complete the maturation, complete decontamination system demonstrations are required. Demonstrations should include tests with heated full-size canisters. The following criteria will be satisfied by this testing:

- 5.09 - High fidelity lab integration of system completed, ready for test in relevant environments?
- 5.14 - Some special purpose components combined with available laboratory components for testing?

4.10 Requirements Document

To mature the technology as a whole to TRL-3 and higher, a systems requirements document should be approved by the client and issued. This document will describe, in progressing detail with revisions, the requirements for the system as a whole and each of the subsystems. Design and testing activities will be planned according to these documented requirements. The criteria satisfied by the various revisions of the requirements document are listed in Table 14.

Table 14. Criteria satisfied with requirements document.

#	Criteria	MSA	FMP	GCF	CCC	CD
3.12	Customer participates in requirements generation?	✓	✓	✓	✓	
3.13	Requirements tracking system defined to manage requirements creep?	✓	✓	✓	✓	
3.18	Performance metrics for the system are established (What must it do)?	✓	✓	✓	✓	
4.06	Overall system requirements for end user's application are known?	✓	✓	✓	✓	
4.07	Overall system requirements for end user's application are documented?	✓	✓	✓	✓	
4.08	System performance metrics measuring requirements have been established?	✓	✓	✓	✓	

#	Criteria	MSA	FMP	GCF	CCC	CD
4.09	Laboratory testing requirements derived from system requirements are established?	✓	✓	✓	✓	
5.19	Requirements definition with performance thresholds and objectives established for final plant design?	✓	✓	✓	✓	✓
6.08	Operational requirements document available?	✓	✓	✓	✓	
CCC = canister cooling and crystallization; CD = canister decontamination; FMP = feeding, melting, and pouring; GCF = glass ceramic formulation; MSA = mixing, sampling, and analyses.						

4.11 Risk Management Document

As part of the technology maturation process, risks associated with successful completion of the desired mission are assessed, evaluated, documented, and managed. The following three criteria are satisfied by the risk management documents:

3.25 - Risk mitigation strategies identified?

4.21 - Formal risk management program initiated?

5.34 - Risk management plan documented?

4.12 Preliminary Design

A preliminary design is required to obtain TRL-4 and higher. This design will address criteria listed in Table 15. It will include the following:

- Equipment sizing calculations
- General arrangement drawings
- Heat and mass balances
- Piping and interface drawings
- Functional process descriptions
- Hazard evaluations.

In later revisions of the preliminary design, additional requirements will be included:

- Design, construction, and operating cost estimates
- Project schedule
- Reliability, availability, maintainability, and inspectability (RAMI) data collection and plant efficiency modeling
- Identification of off-normal events and their mitigation strategies
- Design drawings
- Interface control documents
- Configuration management process.

The two design revisions are the conceptual design and preliminary design. However, for the purposes of this plan, the research team assumes the first set of functions will be completed to achieve TRL-4 and the second will be completed to achieve TRL-6.

Table 15. Criteria satisfied with preliminary design.

#	Criteria	MSA	FMP	GCF	CCC	CD
4.01	Key process variables/parameters been fully identified and preliminary hazard evaluations have been performed?	✓	✓	✓	✓	
4.07	Overall system requirements for end user's application are documented?	✓				
4.16	Draft conceptual designs have been documented (system description, process flow diagrams, general arrangement drawings, and material balance)?	✓	✓		✓	
4.17	Equipment scale-up relationships are understood/accounted for in technology development program?				✓	
4.23	Scaling documents and designs of technology have been completed?	✓	✓		✓	
4.25	Functional process description developed. (Systems/subsystems identified)?	✓	✓	✓	✓	
4.27	Mitigation strategies identified to address manufacturability/producibility shortfalls?		✓			
4.31	Process/parameter limits and safety control strategies are being explored?	✓	✓	✓	✓	
5.03	System interface requirements known (how would system be integrated into the plant?)	✓	✓	✓	✓	
5.04	Preliminary design engineering begins?	✓	✓	✓	✓	
5.05	Requirements for technology verification established?	✓	✓	✓	✓	✓
5.13	Availability and reliability (RAMI) target levels identified?	✓	✓		✓	
5.15	Three dimensional drawings and P&IDs for the prototypical engineering-scale test facility have been prepared?	✓	✓		✓	
5.18	Detailed design drawings have been completed to support specification of engineering-scale testing system?	✓	✓		✓	
5.20	Preliminary technology feasibility engineering report completed?	✓	✓	✓	✓	
5.23	Configuration management plan in place?	✓	✓	✓	✓	
5.31	Limits for all process variables/parameters and safety controls are being refined?	✓	✓	✓	✓	
5.38	Was the transportation and storage package designed?				✓	
6.02	Availability and reliability (RAMI) levels established?	✓	✓		✓	
6.03	Preliminary design drawings for final plant system are complete?	✓	✓		✓	
6.05	Collection of actual maintainability, reliability, and supportability data has been started?	✓	✓		✓	
6.06	Performance Baseline (including total project cost, schedule, and scope) has been completed?	✓	✓	✓	✓	
6.09	Off-normal operating responses determined for engineering	✓	✓			

#	Criteria	MSA	FMP	GCF	CCC	CD
	scale system?					
6.12	Scaling issues that remain are identified and understood. Supporting analysis is complete?	✓	✓	✓	✓	
6.13	Analysis of project timing ensures technology will be available when required?	✓	✓	✓	✓	
6.14	Have established an interface control process?	✓	✓	✓	✓	
6.15	Acquisition program milestones established for start of final design (CD-2)?	✓	✓	✓	✓	
6.20	Technology "system" design specification complete and ready for detailed design?	✓	✓	✓	✓	
6.23	Formal configuration management program defined to control change process?	✓	✓	✓	✓	
6.25	Final technical report on technology completed?	✓	✓	✓	✓	✓

CCC = canister cooling and crystallization; CD = canister decontamination; FMP = feeding, melting, and pouring; GCF = glass ceramic formulation; MSA = mixing, sampling, and analyses.

4.13 Integrated Pilot Testing

The work-horse of technology maturation is an integrated pilot system. The pilot system will be used to evaluate the functionality of each major system component (including those not determined to be CTEs in this demonstrated evaluation, e.g. off-gas treatment system), the interfaces between major system components, and as the primary source of design data. The success of implementing any new technology in nuclear environments depends on a robust integrated pilot facility testing program. The design and operation of this system is the *most important aspect* of developing technologies to the point of success in nuclear applications. Table 16 lists the criteria satisfied by integrated pilot testing.

The trade-off in pilot facility design in testing is between 1) the scale and representativeness, and 2) the cost of construction and operation. This may lead to the development of two facilities: 1) a small-scale, non-nuclearized, incomplete integrated process for the early stages of testing, and 2) a nearly full-scale, nuclearized, complete pilot for the later stages of technology maturation. The research team assumed for the purposes of this plan that a two-system approach will be used. In this case, a laboratory-scale system will be developed around a melter and off-gas system and pieces of the entire system will be added to complete the integrated system as testing progresses. This will reduce both the cost of the system and the rate of spending.

The pilot-scale system will then be constructed at the later stages of development (TRL-5) and will include a relatively mature design that includes hazard mitigation strategies, nuclearized equipment, and a well-developed operating and maintenance approach.

Table 16. Criteria satisfied with integrated pilot testing.

#	Criteria	MSA	FMP	GCF	CCC	CD
4.10	Available components assembled into laboratory scale system?	✓	✓		✓	
4.11	Laboratory experiments with available components show that they work together?	✓	✓		✓	
4.12	Analysis completed to establish component compatibility (Do components work together)?	✓	✓		✓	

#	Criteria	MSA	FMP	GCF	CCC	CD
4.14	Technology demonstrates basic functionality in simulated environment?	✓	✓	✓	✓	
4.20	Integration studies have been started?	✓	✓	✓	✓	
4.26	Low fidelity technology "system" integration and engineering completed in a lab environment?	✓	✓			
5.01	The relationships between major system and sub-system parameters are understood on a laboratory scale?	✓	✓		✓	
5.06	Interfaces between components/subsystems in testing are realistic (bench top with realistic interfaces)?	✓	✓	✓	✓	
5.09	High fidelity lab integration of system completed, ready for test in relevant environments?	✓	✓		✓	
5.11	Lab-scale, similar system tested with range of simulants?	✓	✓		✓	
5.12	Fidelity of system mock-up improves from laboratory to bench-scale testing?	✓	✓	✓	✓	✓
5.16	Laboratory environment for testing modified to approximate operational environment?	✓	✓	✓	✓	
5.17	Component integration issues and requirements identified?	✓	✓	✓	✓	✓
5.21	Integration of modules/functions demonstrated in a laboratory/bench-scale environment?	✓	✓	✓	✓	✓
5.22	Formal control of all components to be used in final prototypical test system?	✓	✓	✓	✓	
5.27	Laboratory-scale tests on the full range of simulants using a prototypical system have been completed?		✓	✓	✓	
5.30	Laboratory to engineering scale scale-up issues are understood and resolved?	✓	✓	✓	✓	
5.32	Test plan for prototypical lab-scale tests executed - results validate design?	✓	✓		✓	
5.33	Test plan documents for prototypical engineering-scale tests completed?	✓	✓	✓	✓	
5.36	Have all relevant physical and chemical properties been sufficiently well determined and bounded to meet proposed disposal criteria?	✓	✓			
5.37	Have the waste impacting process steps been demonstrated to function within acceptable range?	✓	✓	✓	✓	
6.01	The relationships between system and sub-system parameters are understood at engineering scale allowing process/design variations and tradeoffs to be evaluated?	✓	✓	✓	✓	✓
6.04	Operating environment for final system known?	✓	✓	✓	✓	
6.07	Operating limits for components determined (from design, safety and environmental compliance)?	✓	✓	✓	✓	
6.10	System technical interfaces defined?	✓	✓	✓	✓	
6.11	Component integration demonstrated at an engineering scale?	✓	✓	✓	✓	✓
6.18	Engineering feasibility fully demonstrated (e.g. would it work)?	✓	✓	✓	✓	✓
6.21	Components are functionally compatible with operational system?	✓	✓		✓	✓
6.22	Engineering-scale system is high-fidelity functional prototype of operational system?	✓	✓	✓	✓	✓

#	Criteria	MSA	FMP	GCF	CCC	CD
6.24	Integration demonstrations have been completed (e.g. construction of testing system)?	✓	✓	✓	✓	✓
6.27	Engineering-scale tests on the full range of simulants using a prototypical system have been completed?	✓	✓	✓	✓	✓
6.28	Engineering to full-scale scale-up issues are understood and resolved?	✓	✓	✓	✓	
6.29	Laboratory and engineering-scale experiments are consistent?	✓	✓	✓	✓	
6.30	Limits for all process variables/parameters and safety controls are defined?	✓	✓	✓	✓	
6.31	Plan for engineering-scale testing executed - results validate design?	✓	✓	✓	✓	✓
6.32	Production demonstrations are complete (at least one time)?	✓	✓	✓	✓	✓
CCC = canister cooling and crystallization; CD = canister decontamination; FMP = feeding, melting, and pouring; GCF = glass ceramic formulation; MSA = mixing, sampling, and analyses.						

4.14 Waste Compliance Plan

A waste compliance plan (WCP) will be developed to meet TRL-3 criteria and will be updated with more detail at TRL-4 and -5. This plan highlights the methods for qualifying wastes for disposal. It includes the functions that will be performed prior to plant construction (qualification), during plant readiness testing (commissioning), and during plant operation (compliance). The activities will include analysis, demonstration, inspection, and testing activities. As the technology matures to TRL-5, a detailed, near-final version of the plan will be required. This version will identify precisely what analysis, demonstration, inspection, and testing activities will be performed during the project or facility operation, and how the data will be applied to qualifying wastes for disposal. The criteria satisfied by the WCP are listed below:

- *3.33 - Is a general strategy for waste form qualification developed?*
- *4.36 - Has a detailed waste qualification plan been documented?*
- *5.35 - Is a program in place to qualify the waste form and production process?*

5. SCHEDULE AND COST

5.1 Schedule

An initial schedule to meet TRL-4 and TRL-6 was generated (Figure 3) assuming a non-accelerated R&D effort. This schedule results in TRL values listed in Table 17. The schedule was not optimized to any specific spending schedule.

Figure 3. Initial schedule of research and technology development activities.

Item	2012				2013				2014				2015				2016				2017				2018				2019				2020				2021				2022				2023				2024				2025			
Subitem	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4
Technology maturation plan		x	x																																																					
Preliminary engineering study					x	x	x																																																	
Characterize, estimate, and simulate waste to be treated																																																								
Initial waste estimates and simulant recipies					x	x																																																		
Actual waste characterization															x	x							x	x							x	x																								
Simulant/actual waste comparisons																	x	x							x	x							x	x																						
Laboratory scale glass ceramic testing																																																								
Initial Reference formulation	x	x	x																																																					
Formulation and testing for initial compositions (incl. LSM)							x	x	x	x	x	x	x																																											
Preliminary model development (loading and heat models for cost benefit analyse													x	x	x	x	x																																							
Variability study																			x	x	x	x	x	x	x	x	x	x	x	x																										
Final model development																													x	x	x	x	x	x	x	x																				
Performance evaluation															x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x																
Compare actual and simulant																		x	x							x	x							x	x																					
Melter and off-gas testing with simulants																																																								
Initial proof of principle				x	x					x	x																																													
Scaling tests													x	x	x	x	x	x	x	x	x	x	x	x																																
Off-gas functionality													x	x	x	x	x	x	x	x	x	x	x	x																																
Variability tests													x	x	x	x	x	x	x	x	x	x	x	x																																
Long-term run-by-wire																					x	x	x	x	x	x																														
Design data needs																									x	x	x	x	x	x	x	x																								
Test the mixing, sampling, and analyses																																																								
Preliminary study based on literature search						x	x	x																																																
Laboratory scale tests of mixing, sampling, and analyses																					x	x	x	x	x	x																														
Canister testing																	x	x	x	x	x	x	x	x	x																															
Decontamination system testing																										x	x	x	x	x	x																									
Requirements document																																																								
Initial requirements document									x	x																																														
Final requirements management system																																	x	x	x																					
Risk management document																																																								
Initial risks identification									x	x																																														
Final risk management system																																	x	x	x																					
Preliminary design																																																								
Conceptual design																													x	x	x	x	x	x	x	x																				
Preliminary design																																					x	x	x	x	x	x	x	x	x	x	x	x								
Integrated pilot testing																																																								
Construct test bed																																	x	x	x	x																				
Shake-out testing (budget in construct)																																				x	x																			
Design data needs																																						x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Waste compliance plan																																																								
Develop waste qualification strategy								x	x																																															
Issue WCP																																												x	x	x	x									

Table 17. Technology readiness level achieved for each critical technology element by year.

Year	MSA	FMP	GCF	CCC	CD	Overall
2012	1	1	1	1	4	1
2013	2	2	1	1	4	1
2014	2	3	1	1	4	1
2015	2	3	2	2	4	2
2016	2	3	2	2	4	2
2017	2	3	3	2	4	2
2018	3	3	3	3	4	3
2019	3	3	3	3	4	3
2020	3	3	3	3	4	3
2021	3	3	3	3	4	3
2022	3	3	3	3	4	3
2023	4	4	4	4	4	4
2024	5	5	5	5	5	5
2025	6	6	6	6	6	6
CCC = canister cooling and crystallization; CD = canister decontamination; FMP = feeding, melting, and pouring; GCF = glass ceramic formulation; MSA = mixing, sampling, and analyses.						

5.2 Cost

The costs for technology development to TRL-6 were estimated using costs for performing similar research. The total cost is estimated at roughly \$90 million over a 14-year period. This estimate is subject to a relatively high uncertainty with an estimated range of \$45 million to \$180 million (-50%, +100%). The nominal cost estimate is shown as a function of time in Figure 4.

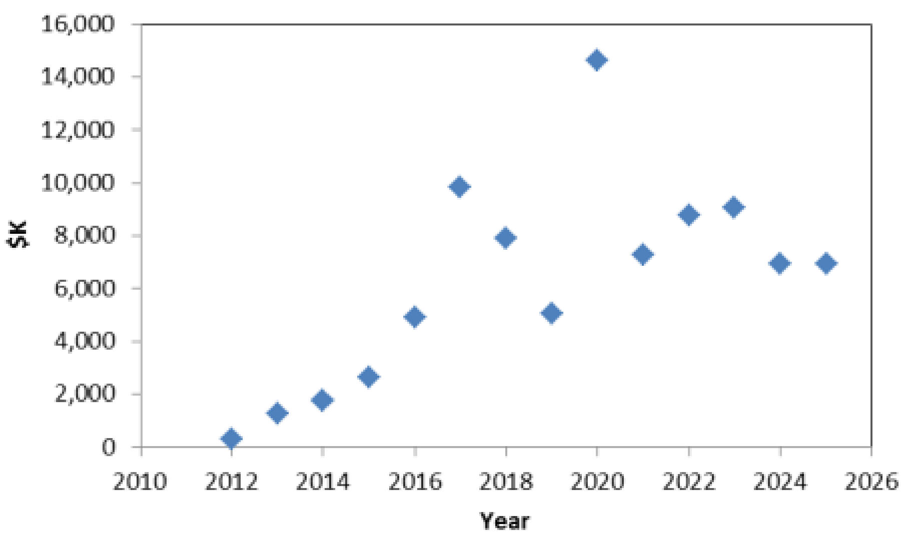

Figure 4. Cost by year for non-optimized project plan.

6. REFERENCES

ASTM. 2007. *Standard Practices for Dissolving Glass Containing Radioactive and Mixed Waste for Chemical and Radiochemical Analysis*. ASTM C1463, ASTM International, West Conshohocken, PA.

ASTM. 2010. *Standard Practice for Analysis of Aqueous Leachates from Nuclear Waste Materials Using Inductively Coupled Plasma-Atomic Emission Spectrometry*. ASTM C1109, ASTM International, West Conshohocken, PA.

ASTM. 2011a. *Standard Guide for Measuring Physical and Rheological Properties of Radioactive Solutions, Slurries, and Sludges*. ASTM C1752, ASTM International, West Conshohocken, PA.

ASTM. 2011b. *Standard Guide for Development, Verification, Validation, and Documentation of Simulated High-Level Tank Waste*. ASTM C1750, ASTM International: West Conshohocken, PA.

Bonnetier, A., J. F. Hollebecque, J. Lacombe, R. D. Quang, and P. Rivat. 2003. "Development of an Advanced Cold Crucible for Direct Induction Melting of Glass." *Proceedings of the 4th International Conference on Electromagnetic Processing of Materials*, Lyon, France.

Crum, J.V., A.Y. Billings, J.B. Lang, J.C. Marra, C.P. Rodriguez, J.V. Ryan, and J.D. Vienna. 2009. *Baseline Glass Development for Combined Cs/Sr, LN, and TM Fission Products Waste Streams*, AFCI-WAST-WAST-MI-DV-2009-000075, Advanced Fuel Cycle Initiative, U.S. Department of Energy, Office of Nuclear Energy, Washington, D.C.

Demin, A.V. and Y.I. Matyunin. 1995. "Investigation of the Behavior of Platinum-Group Elements During Vitrification of Model High-Level Wastes in Application to an Induction Melter with a Cold Crucible." *Atomic Energy* **79**(1): p. 443-446.

DOE. 2009. *U.S. Department of Energy Technology Readiness Assessment Guide*. DOE G 413.3-4, U.S. Department of Energy, Washington, D.C.

Donald, I.W., B.L. Metcalfe, and R.N.J. Taylor. 1997. "Review: The Immobilization of High Level Radioactive Wastes Using Ceramics and Glasses." *Journal of Materials Science* **32**: p. 5851-5887.

Holton, L., D. Alexander, C. Babel, H. Sutter, J. Young. 2007. *Technology Readiness Assessment for the Waste Treatment and Immobilization Plant (WTP) Analytical Laboratory, Balance of Facilities and LAW Waste Vitrification Facilities*. 07-DESIGN-042, U.S. Department of Energy, Office of River Protection, Richland, WA.

Hrma, P. 2010. *Crystallization During Processing of Nuclear Waste Glass. Journal of Non-Crystalline Solids* **356**: p. 3019-3025.

Juoi, J.M. and M.I. Ojovan. 2007. "The Effect of Waste Loading on the Microstructure of Glass Composite Waste Forms for the Immobilisation of Spent Clinoptilolite." *Glass Technology-European Journal of Glass Science and Technology Part A* **48**(3): p. 124-129.

Juoi, J.M., M.I. Ojovan, and W.E. Lee. 2008. "Microstructure and Leaching Durability of Glass Composite Wasteforms for Spent Clinoptilolite Immobilisation." *Journal of Nuclear Materials* **372**(2-3): p. 358-366.

Kobelev, A.P. et al. 2006. *Maximizing Waste Loading for Application to Savannah River High Level Waste - 2006 & 2007 Scope: CCIM Testing to Demonstrate Maximized Waste Loading with SB2*. SIA Radon, Moscow, Russia.

Ladirat, C., et al. 2004. *Advanced Cold Crucible Melter Pilot Plant Characteristics and First Results on HLLW Surrogates*, in *Waste Management 2004*, Tucson, AZ. pp. 4223.

Ojovan, M.I. and W.E. Lee. 2005. *An Introduction to Nuclear Waste Immobilization*. ISBN: 978-0-08-044462-8, Elsevier Ltd. Oxford, United Kingdom.

Ryan, JV, WL Ebert, JP Icenhower, DM Strachan, CI Steefel, LJ Criscenti, IC Bourg, RE Williford, KA Murphy, CG Pantano, EM Pierce, DK Shuh, GA Waychunas, JC Marra, JD Vienna, P Zapol, and CM Jantzen. 2011. *Technical Program Plan for the International Technical Evaluation of Alteration Mechanisms (I-Team)*, PNNL-21031, Pacific Northwest National Laboratory, Richland, WA.

Sobolev IA, SA Dmitriev, FA Lifanov, SV Stefanovsky, AP Kobelev, VN Kornev, and MI Ojovan. 1996. "Experience of SIA "Radon" in Radioactive Waste Vitrification." In: *Topseal '96 -International Topical Meeting: Demonstrating the Practical Achievements of Nuclear Waste Management and Disposal*, Vol. II, p. 21-24.

Song, M.J. 2003. "The Vitrified Solution." *Nuclear Engineering International* **48**(583): p. 22.

Vienna, J.D. 2010. "Nuclear Waste Vitrification in the United States: Recent Developments and Future Options." *International Journal of Applied Glass Science* **1**(3): p. 309-321.

Appendix

Criteria Lists

Table A.1. Technology readiness assessment criteria list (T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus, documentation; and Q-Qualification, waste form qualification and compliance).

C#	T/M/P/Q	Criteria
1.01	T	Back of envelope environment?
1.02	T	Physical laws and assumptions used in new technologies defined?
1.03	T	Paper studies confirm basic principles?
1.04	P	Initial scientific observations reported in journals/conference proceedings/technical reports?
1.05	T	Basic scientific principles observed and understood?
1.06	P	Know who cares about the technology, e.g., sponsor, funding source, etc.?
1.07	T	Research hypothesis formulated?
1.08	T	Basic characterization data exists?
1.09	P	Know who would perform research and where it would be done?
2.01	P	Customer identified?
2.02	T	Potential system or components have been identified?
2.03	T	Paper studies show that application is feasible?
2.04	P	Know what program the technology would support?
2.05	T	An apparent theoretical or empirical design solution identified?
2.06	T	Basic elements of technology have been identified?
2.07	T	Desktop environment (paper studies)?
2.08	T	Components of technology have been partially characterized?
2.09	T	Performance predictions made for each element?
2.10	P	Customer expresses interest in the application?
2.11	T	Initial analysis shows what major functions need to be done?
2.12	T	Modeling & Simulation only used to verify physical principles?
2.13	P	System architecture defined in terms of major functions to be performed?
2.14	T	Rigorous analytical studies confirm basic principles?
2.15	P	Analytical studies reported in scientific journals/conference proceedings/technical reports?
2.16	T	Individual parts of the technology work (No real attempt at integration)?
2.17	T	Know what output devices are available?
2.18	P	Preliminary strategy to obtain TRL Level 6 developed (e.g., scope, schedule, cost)?
2.19	P	Know capabilities and limitations of researchers and research facilities?
2.20	T	The scope and scale of the waste problem has been determined?
2.21	T	Know what experiments are required (research approach)?
2.22	P	Qualitative idea of risk areas (cost, schedule, performance)?
2.23	Q	Have the range of waste species and waste loading for the waste form been identified?
2.24	Q	Are the general properties of the waste form well understood and published in peer review journals?

Table A.1. Technology readiness assessment criteria list (T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus, documentation; and Q-Qualification, waste form qualification and compliance).

C#	T/M/P/Q	Criteria
2.25	Q	Have experiments started with the goal of determining the mechanism for the release of radionuclides?
3.01	T	Academic (basic science) environment?
3.02	P	Some key process and safety requirements are identified?
3.03	T	Predictions of elements of technology capability validated by analytical studies?
3.04	P	The basic science has been validated at the laboratory scale?
3.05	T	Science known to extent that mathematical and/or computer models and simulations are possible?
3.06	P	Preliminary system performance characteristics and measures have been identified and estimated?
3.07	T	Predictions of elements of technology capability validated by Modeling and Simulation (M&S)?
3.08	M	No system components, just basic laboratory research equipment to verify physical principles?
3.09	T	Laboratory experiments verify feasibility of application?
3.10	T	Predictions of elements of technology capability validated by laboratory experiments?
3.11	P	Customer representative identified to work with development team?
3.12	P	Customer participates in requirements generation?
3.13	P	Requirements tracking system defined to manage requirements creep?
3.14	T	Key process parameters/variables and associated hazards have begun to be identified?
3.15	M	Design techniques have been identified/developed?
3.16	T	Paper studies indicate that system components ought to work together?
3.17	P	Customer identifies technology need date?
3.18	T	Performance metrics for the system are established (What must it do)?
3.19	P	Scaling studies have been started?
3.20	M	Current manufacturability concepts assessed?
3.21	M	Sources of key components for laboratory testing identified?
3.22	T	Scientific feasibility fully demonstrated?
3.23	T	Analysis of present state of the art shows that technology fills a need?
3.24	P	Risk areas identified in general terms?
3.25	P	Risk mitigation strategies identified?
3.26	P	Rudimentary best value analysis performed for operations?
3.27	T	Key physical and chemical properties have been characterized for a number of waste samples?
3.28	T	A simulant has been developed that approximates key waste properties?
3.29	T	Laboratory scale tests on a simulant have been completed?
3.30	T	Specific waste(s) and waste site(s) has (have) been defined?
3.31	T	The individual system components have been tested at the laboratory scale?
3.32	Q	Has the type of disposal environment(s) been defined?

Table A.1. Technology readiness assessment criteria list (T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus, documentation; and Q-Qualification, waste form qualification and compliance).

C#	T/M/P/Q	Criteria
3.33	Q	Is a general strategy for waste form qualification been developed?
4.01	T	Key process variables/parameters been fully identified and preliminary hazard evaluations have been performed?
4.02	M	Laboratory components tested are surrogates for system components?
4.03	T	Individual components tested in laboratory or by supplier?
4.04	T	Subsystems composed of multiple components tested at lab scale using simulants?
4.05	T	Modeling & Simulation used to simulate some components and interfaces between components?
4.06	P	Overall system requirements for end user’s application are known?
4.07	T	Overall system requirements for end user’s application are documented?
4.08	P	System performance metrics measuring requirements have been established?
4.09	P	Laboratory testing requirements derived from system requirements are established?
4.10	M	Available components assembled into laboratory scale system?
4.11	T	Laboratory experiments with available components show that they work together?
4.12	T	Analysis completed to establish component compatibility (Do components work together)?
4.13	P	Science and Technology Demonstration exit criteria established (S&T targets understood, documented, and agreed to by sponsor)?
4.14	T	Technology demonstrates basic functionality in simulated environment?
4.15	M	Scalable technology prototypes have been produced (Can components be made bigger than lab scale)?
4.16	P	Draft conceptual designs have been documented (system description, process flow diagrams, general arrangement drawings, and material balance)?
4.17	M	Equipment scale-up relationships are understood/accounted for in technology development program?
4.18	T	Controlled laboratory environment used in testing?
4.19	P	Initial cost drivers identified?
4.20	M	Integration studies have been started?
4.21	P	Formal risk management program initiated?
4.22	M	Key manufacturing processes for equipment systems identified?
4.23	P	Scaling documents and designs of technology have been completed?
4.24	M	Key manufacturing processes assessed in laboratory?
4.25	P/T	Functional process description developed. (Systems/subsystems identified)?
4.26	T	Low fidelity technology “system” integration and engineering completed in a lab environment?
4.27	M	Mitigation strategies identified to address manufacturability/producibility shortfalls?
4.28	T	Key physical and chemical properties have been characterized for a range of wastes?
4.29	T	A limited number of simulants have been developed that approximate the range of waste properties?
4.30	T	Laboratory-scale tests on a limited range of simulants and real waste have been completed?
4.31	T	Process/parameter limits and safety control strategies are being explored?

Table A.1. Technology readiness assessment criteria list (T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus, documentation; and Q-Qualification, waste form qualification and compliance).

C#	T/M/P/Q	Criteria
4.32	T	Test plan documents for prototypical lab- scale tests completed?
4.33	P	Technology availability dates established?
4.34	Q	Are current regulations and policy established for disposal of the form?
4.35	Q	Have waste form affecting process steps been identified?
4.36	Q	Has a detailed waste qualification plan been documented?
4.37	Q	Have the range of chemistry and processing parameters for acceptable waste form been identified and documented?
5.01	T	The relationships between major system and sub-system parameters are understood on a laboratory scale?
5.02	T	Plant size components available for testing?
5.03	T	System interface requirements known (How would system be integrated into the plant?)
5.04	P	Preliminary design engineering begins?
5.05	T	Requirements for technology verification established?
5.06	T	Interfaces between components/subsystems in testing are realistic (bench top with realistic interfaces)?
5.07	M	Prototypes of equipment system components have been created (know how to make equipment)?
5.08	M	Tooling and machines demonstrated in lab for new manufacturing processes to make component?
5.09	T	High fidelity lab integration of system completed, ready for test in relevant environments?
5.10	M	Manufacturing techniques have been defined to the point where largest problems defined?
5.11	T	Lab-scale, similar system tested with range of simulants?
5.12	T	Fidelity of system mock-up improves from laboratory to bench-scale testing?
5.13	M	Availability and reliability (RAMI) target levels identified?
5.14	M	Some special purpose components combined with available laboratory components for testing?
5.15	P	Three dimensional drawings and P&IDs for the prototypical engineering-scale test facility have been prepared?
5.16	T	Laboratory environment for testing modified to approximate operational environment?
5.17	T	Component integration issues and requirements identified?
5.18	P	Detailed design drawings have been completed to support specification of engineering-scale testing system?
5.19	T	Requirements definition with performance thresholds and objectives established for final plant design?
5.20	P	Preliminary technology feasibility engineering report completed?
5.21	T	Integration of modules/functions demonstrated in a laboratory/bench-scale environment?
5.22	T	Formal control of all components to be used in final prototypical test system?
5.23	P	Configuration management plan in place?
5.24	T	The range of all relevant physical and chemical properties has been determined (to the extent possible)?
5.25	T	Simulants have been developed that cover the full range of waste properties?
5.26	T	Testing has verified that the properties/performance of the simulants match the properties/performance of the actual wastes?
5.27	T	Laboratory-scale tests on the full range of simulants using a prototypical system have been completed?

Table A.1. Technology readiness assessment criteria list (T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus, documentation; and Q-Qualification, waste form qualification and compliance).

C#	T/M/P/Q	Criteria
5.28	T	Laboratory-scale tests on a limited range of real wastes using a prototypical system have been completed?
5.29	T	Test results for simulants and real waste are consistent?
5.30	T	Laboratory to engineering scale scale-up issues are understood and resolved?
5.31	T	Limits for all process variables/parameters and safety controls are being refined?
5.32	P	Test plan for prototypical lab-scale tests executed - results validate design?
5.33	P	Test plan documents for prototypical engineering-scale tests completed?
5.34	P	Risk management plan documented?
5.35	Q	Is a program in place to qualify the waste form and production process?
5.36	Q	Have all relevant physical and chemical properties been sufficiently well determined and bounded to meet proposed disposal criteria?
5.37	Q	Have the waste impacting process steps been demonstrated to function within acceptable range?
5.38	Q	Was the transportation and storage package designed?
5.39	Q	Have release rate law models been established (for relevant environment(s))?
6.01	T	The relationships between system and sub-system parameters are understood at engineering scale allowing process/design variations and tradeoffs to be evaluated?
6.02	M	Availability and reliability (RAMI) levels established?
6.03	P	Preliminary design drawings for final plant system are complete?
6.04	T	Operating environment for final system known?
6.05	P	Collection of actual maintainability, reliability, and supportability data has been started?
6.06	P	Performance Baseline (including total project cost, schedule, and scope) has been completed?
6.07	T	Operating limits for components determined (from design, safety and environmental compliance)?
6.08	P	Operational requirements document available?
6.09	P	Off-normal operating responses determined for engineering scale system?
6.10	T	System technical interfaces defined?
6.11	T	Component integration demonstrated at an engineering scale?
6.12	P	Scaling issues that remain are identified and understood. Supporting analysis is complete?
6.13	P	Analysis of project timing ensures technology will be available when required?
6.14	P	Have established an interface control process?
6.15	P	Acquisition program milestones established for start of final design (CD-2)?
6.16	M	Critical manufacturing processes prototyped?
6.17	M	Most pre-production hardware is available to support fabrication of the system?
6.18	T	Engineering feasibility fully demonstrated (e.g., would it work)?
6.19	M	Materials, process, design, and integration methods have been employed (e.g., can design be produced?)
6.20	P	Technology “system” design specification complete and ready for detailed design?

Table A.1. Technology readiness assessment criteria list (T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus, documentation; and Q-Qualification, waste form qualification and compliance).

C#	T/M/P/Q	Criteria
6.21	M	Components are functionally compatible with operational system?
6.22	T	Engineering-scale system is high-fidelity functional prototype of operational system?
6.23	P	Formal configuration management program defined to control change process?
6.24	M	Integration demonstrations have been completed (e.g., construction of testing system)?
6.25	P	Final Technical Report on Technology completed?
6.26	M	Process and tooling are mature to support fabrication of components/system?
6.27	T	Engineering-scale tests on the full range of simulants using a prototypical system have been completed?
6.28	T	Engineering to full-scale scale-up issues are understood and resolved?
6.29	T	Laboratory and engineering-scale experiments are consistent?
6.30	T	Limits for all process variables/parameters and safety controls are defined?
6.31	T	Plan for engineering-scale testing executed - results validate design?
6.32	M	Production demonstrations are complete (at least one time)?
6.33	Q	Have the transportation and storage systems been identified?
6.34	Q	Are performance assessment models available for the form/disposal environment?
6.35	Q	Has a preliminary performance assessment been done to determine the acceptability of the waste form?

Table A.2. Mixing, sampling, and analyses criteria evaluation.

C#	Y/N	Criteria	Comments
1.01	Y	Back of envelope environment?	Back of the envelope calculations were performed to complete this report.
1.02	Y	Physical laws and assumptions used in new technologies defined?	Physical laws known and understood for multiphase flow with primarily Newtonian fluids and dense particles. The pro's and con's of different multiphase sampling methods are known.[1]
1.03	Y	Paper studies confirm basic principles?	No paper studies done for this specific application. However, many studies were performed to support WTP design and other applications.[2-6] It is assumed that both Newtonian fluids with dense particles (waste) and non-Newtonian slurries (melter feed) must be managed for this application.
1.04	Y	Initial scientific observations reported in journals/conference proceedings/technical reports?	Generally information on the mixing of Newtonian slurries is available from literature.[7-10] Less is known about non-Newtonian fluid flow, but, recent articles do exist.[11]
1.05	Y	Basic scientific principles observed and understood?	Basic settling and issues with sampling and analyses known and have been addressed in design of HLW mixing and sampling systems.[12, 13]
1.06	Y	Know who cares about the technology, e.g., sponsor, funding source, etc.?	DOE-NE is the sponsor.[14]
1.07	Y	Research hypothesis formulated?	Hypotheses are: 1) both Newtonian and non-Newtonian slurries are expected to be managed in the plant; 2) Paraflow or a similar model can be used to predict the slurry behavior sufficiently to design effective mixing and sampling systems.[2, 11]
1.08	N	**Basic characterization data exists?**	Basic data not available to the researchers for these slurries. However, they are likely available from international collaborators and efforts will be made to obtain that data.
1.09	Y	Know who would perform research and where it would be done?	Testing can be performed in a fashion similar to that performed for the WTP at the Catholic University of America [15], for the WVDP at PNNL[12], or for the DWPF at SRNL[13].
2.01	Y	Customer identified?	The customer is DOE-NE.[14]
2.02	Y	Potential system or components have been identified?	Mixing in vessels will be performed by mechanical rotating agitators, slurry sampling by "VF" sampler [16], and analyses by fusion and wet chemical analyses.[17]
2.03	Y	Paper studies show that application is feasible?	Assume the PUREX type studies are adequate for this application at TRL-2.[18]
2.04	Y	Know what program the technology would support?	A domestic reprocessing facility program that has not yet been initiated.[14]
2.05	Y	An apparent theoretical or empirical design solution identified?	The details of the design shown in this document are deemed sufficient for TRL-2. Additional studies are available in support of the Engineering Alternatives Study (EAS) and the Advanced Fuel Cycle Facility (AFCF).
2.06	Y	Basic elements of technology have been identified?	Mixing in vessels, sampling of slurries, pumping of slurries, fusion/dissolution of slurries and chemical analyses.
2.07	N	**Desktop environment (paper studies)?**	Information such as the number of samples, mass and volumes in vessels, or processing rates have been estimated.
2.08	Y	Components of technology have been partially characterized?	Several components were characterized for other applications (mixers, pumps, samplers, analysis equipment, etc.).
2.09	N	**Performance predictions made for each element?**	No performance predictions yet made for mixing and sampling.
2.10	Y	Customer expresses interest in the application?	Yes. Customer requested and funded the development of this TMP.
2.11	Y	Initial analysis shows what major functions need to be done?	The technology elements identified in TRA spreadsheet.
2.12	Y	Modeling & Simulation only used to verify physical principles?	We interpret this question to mean that modeling and simulation was applied to the problems of mixing.
2.13	Y	System architecture defined in terms of major functions to be performed?	System has been defined by the major functions within this document.
2.14	N	**Rigorous analytical studies confirm basic principles?**	No analytical studies have yet been performed. It is assumed to mean heat and mass balances, equipment scaling, etc.
2.15	N	**Analytical studies reported in scientific journals/conference proceedings/technical reports?**	No analytical studies yet reported.
2.16	Y	Individual parts of the technology work (No real attempt at integration)?	Parts of the technology tested within operating PUREX plants.
2.17	Y	Know what output devices are available?	It is assumed for this study that output devises include data from mixers, pumps, and analytical data which have been developed for WTP, WVDP, and DWPF in the U.S. and likely internationally also.
2.18	Y	Preliminary strategy to obtain TRL Level 6 developed (e.g., scope, schedule, cost)?	This TMP documents the strategy.
2.19	Y	Know capabilities and limitations of researchers and research facilities?	The researchers at qualified institutions are well known along with their strengths and weaknesses/limitations.
2.20	N	**The scope and scale of the waste problem has been determined?**	The wastes to be immobilized are ill defined. They all result from a separations process that is still in development.
2.21	Y	Know what experiments are required (research approach)?	A basic research approach was developed by WTP for mixing and sampling of their feeds this will be followed.[19]
2.22	Y	Qualitative idea of risk areas (cost, schedule, performance)?	This TMP describes risk areas to be addressed which are deemed sufficient for TRL-2. A formal risk management process will be used to identify and track risks for higher TRL levels.
2.23		Have the range of waste species and waste loading for the waste form been identified?	NA, waste species and loading are not applicable to MSA
2.24		Are the general properties of the waste form well understood and published in peer review journals?	NA, the waste form properties are not applicable to MSA
2.25		Have experiments started with the goal of determining the mechanism for the release of radionuclides?	NA, the mechanism for release from the waste form is not applicable to MSA
3.01	Y	Academic (basic science) environment?	By our interpretation, this question is answered yes by the academic study of mixing of multiphase slurries.[11]

Table A.2. Mixing, sampling, and analyses criteria evaluation.

C#	Y/N	Criteria	Comments
3.02	Y	Some key process and safety requirements are identified?	The ability to obtain a representative sample analyses and no tank holdup are the key process and safety requirements.
3.03	N	**Predictions of elements of technology capability validated by analytical studies?**	No analytical studies of technology capability have been performed for this application.
3.04	Y	The basic science has been validated at the laboratory scale?	The basic science of mixing Newtonian fluids with dense solids has been shown.[2, 20]
3.05	Y	Science known to extent that mathematical and/or computer models and simulations are possible?	There are computer simulations available for many problems in multi-phase flow. Paraflow is one example.[2]
3.06	N	**Preliminary system performance characteristics and measures have been identified and estimated?**	No estimates of performance have been made.
3.07	Y	Predictions of elements of technology capability validated by Modeling and Simulation (M&S)?	Modeling and simulation work on mixing and sampling was performed for WTP.[21] Modeling and simulation work on mechanical rotary agitators.[22]
3.08	N	**No system components, just basic laboratory research equipment to verify physical principles?**	Equipment has not yet been selected, assembled, nor tested for this application.
3.09	N	**Laboratory experiments verify feasibility of application?**	Equipment has not yet been selected, assembled, nor tested for this application.
3.10	N	**Predictions of elements of technology capability validated by laboratory experiments?**	Equipment has not yet been selected, assembled, nor tested for this application.
3.11	Y	Customer representative identified to work with development team?	The client has selected Kimberly Gray to work with the development team.
3.12	N	**Customer participates in requirements generation?**	Requirements have not yet been generated, but when they do, the customer will participate.
3.13	N	**Requirements tracking system defined to manage requirements creep?**	A requirements tracking has not yet been initiated.
3.14	Y	Key process parameters/variables and associated hazards have begun to be identified?	This TMP makes an initial attempt at identifying the key process parameters and variables.
3.15	Y	Design techniques have been identified/developed?	Standard design techniques will be used.
3.16	N	**Paper studies indicate that system components ought to work together?**	The paper study defining the capacity requirements and equipment scaling has not been performed.
3.17	Y	Customer identifies technology need date?	The implementation plan for research objective 3 shows a start date at 2040.[23]
3.18	N	**Performance metrics for the system are established (What must it do)?**	Performance metrics have not been established.
3.19	N	**Scaling studies have been started?**	No testing yet or even scaling calculations.
3.20	Y	Current manufacturability concepts assessed?	No manufacturing difficulties are foreseen.
3.21	Y	Sources of key components for laboratory testing identified?	Mixer, tank, sampler, and analyses equipment will be required for testing. Specific equipment will be identified and/or procured at the time needed for testing.
3.22	Y	Scientific feasibility fully demonstrated?	Mixing, sampling, and analyses have been demonstrated for other applications which verify the scientific assumptions.
3.23	Y	Analysis of present state of the art shows that technology fills a need?	The state of the art technologies are expected to suffice for this application.
3.24	Y	Risk areas identified in general terms?	Risks are in mixing, sampling, and analyses, plus transferring a representative batch each time.
3.25	N	**Risk mitigation strategies identified?**	Risk mitigation strategies have not been developed.
3.26	Y	Rudimentary best value analysis performed for operations?	In the context of AFCF and EAS, conceptual designs were completed. These designs do not exactly match the proposed application, but, are deemed similar enough for TRL-3.
3.27	N	**Key physical and chemical properties have been characterized for a number of waste samples?**	Very little analyses of the particle sizes and densities for solids and physical properties of the liquid phases to be mixed, sampled, and analyzed are available. Our international partners may have data and we will attempt to get that data.
3.28	N	**A simulant has been developed that approximates key waste properties?**	No simulant has been developed with the UDS in it. A simulant of the UDS free waste was developed.[24]
3.29	N	**Laboratory scale tests on a simulant have been completed?**	No mixing, sampling, and analyses tests were performed.
3.30	Y	Specific waste(s) and waste site(s) has (have) been defined?	A range of potential wastes have been identified.[25]
3.31	Y	The individual system components have been tested at the laboratory scale?	Individual systems described in this TMP have been tested for other applications.
3.32		Has the type of disposal environment(s) been defined?	NA, disposal environment is not applicable to MSA
3.33	Y	Is a general strategy for waste form qualification been developed?	A waste form qualification strategy similar to WTP will be used.[26]
4.01	N	**Key process variables/parameters been fully identified and preliminary hazard evaluations have been performed?**	Hazards evaluations have not been performed.
4.02	N	**Laboratory components tested are surrogates for system components?**	No testing with surrogates for the proposed system.
4.03	Y	Individual components tested in laboratory or by supplier?	Suppliers have fabricated and tested the components that make up this system. No unique equipment is expected, only a unique application.
4.04	N	**Subsystems composed of multiple components tested at lab scale using simulants?**	No.
4.05	N	**Modeling & Simulation used to simulate some components and interfaces between components?**	Not for this application.

Table A.2. Mixing, sampling, and analyses criteria evaluation.

C#	Y/N	Criteria	Comments
4.06	N	**Overall system requirements for end user's application are known?**	No system requirements yet documented.
4.07	N	**Overall system requirements for end user's application are documented?**	No system requirements yet documented.
4.08	N	**System performance metrics measuring requirements have been established?**	No performance metrics.
4.09	N	**Laboratory testing requirements derived from system requirements are established?**	No.
4.10	N	**Available components assembled into laboratory scale system?**	Not the exact system for this application.
4.11	N	**Laboratory experiments with available components show that they work together?**	No experiments yet with these components all together.
4.12	N	**Analysis completed to establish component compatibility (Do components work together)?**	No analyses yet.
4.13	N	**Science and Technology Demonstration exit criteria established (S&T targets understood, documented, and agreed to by sponsor)?**	This plan spells out the S&T targets, but, the exit criteria must still be developed.
4.14	N	**Technology demonstrates basic functionality in simulated environment?**	No system has been assembled for testing.
4.15	Y	Scalable technology prototypes have been produced (Can components be made bigger than lab scale)?	Scaled mixing systems have been made and tested in the past.
4.16	N	**Draft conceptual designs have been documented (system description, process flow diagrams, general arrangement drawings, and material balance)?**	Conceptual designs for EAS and AFCF are not sufficiently similar to this system to count at TRL-4.
4.17	N	**Equipment scale-up relationships are understood/accounted for in technology development program?**	No attempt has been made to calculate scale.
4.18	N	**Controlled laboratory environment used in testing?**	No laboratory testing yet.
4.19	N	**Initial cost drivers identified?**	They tend to be obvious, but not sure if critically safe configuration is required.
4.20	N	**Integration studies have been started?**	No integrated studies started.
4.21	N	**Formal risk management program initiated?**	No risk control document yet.
4.22	Y	Key manufacturing processes for equipment systems identified?	Manufacturability not in question for these systems.
4.23	N	**Scaling documents and designs of technology have been completed?**	No.
4.24		Key manufacturing processes assessed in laboratory?	NA, manufacturing processes don't need to be tested for MSA.
4.25	N	**Functional process description developed. (Systems/subsystems identified)?**	No.
4.26	N	**Low fidelity technology "system" integration and engineering completed in a lab environment?**	No.
4.27		Mitigation strategies identified to address manufacturability/producibility shortfalls?	NA, manufacturing issues don't required mitigation for MSA.
4.28	N	**Key physical and chemical properties have been characterized for a range of wastes?**	The range of chemistries has been assessed, but not complete and no physical data.[25]
4.29	N	**A limited number of simulants have been developed that approximate the range of waste properties?**	No.
4.30	N	**Laboratory-scale tests on a limited range of simulants and real waste have been completed?**	No.
4.31	N	**Process/parameter limits and safety control strategies are being explored?**	No.
4.32	N	**Test plan documents for prototypical lab- scale tests completed?**	No.
4.33	N	**Technology availability dates established?**	No.
4.34		Are current regulations and policy established for disposal of the form?	NA, waste form disposal policy is not applicable to MSA.
4.35	Y	Have waste form affecting process steps been identified?	Yes, they are described in this TMP.
4.36	N	**Has a detailed waste qualification plan been documented?**	No.
4.37	N	**Have the range of chemistry and processing parameters for acceptable waste form been identified and documented?**	No.
5.01	N	**The relationships between major system and sub-system parameters are understood on a laboratory scale?**	No.

Table A.2. Mixing, sampling, and analyses criteria evaluation.

C#	Y/N	Criteria	Comments
5.02	N	**Plant size components available for testing?**	No.
5.03	N	**System interface requirements known (How would system be integrated into the plant?)**	No.
5.04	N	**Preliminary design engineering begins?**	No.
5.05	N	**Requirements for technology verification established?**	No.
5.06	N	**Interfaces between components/subsystems in testing are realistic (bench top with realistic interfaces)?**	No.
5.07	N	**Prototypes of equipment system components have been created (know how to make equipment)?**	No.
5.08		Tooling and machines demonstrated in lab for new manufacturing processes to make component?	NA, tooling does not apply to MSA.
5.09	N	**High fidelity lab integration of system completed, ready for test in relevant environments?**	No.
5.1		Manufacturing techniques have been defined to the point where largest problems defined?	NA, MSA does not require new parts to be manufactured.
5.11	N	**Lab-scale, similar system tested with range of simulants?**	No.
5.12	N	**Fidelity of system mock-up improves from laboratory to bench-scale testing?**	No.
5.13	N	**Availability and reliability (RAMI) target levels identified?**	No.
5.14	N	**Some special purpose components combined with available laboratory components for testing?**	No.
5.15	N	**Three dimensional drawings and P&IDs for the prototypical engineering-scale test facility have been prepared?**	No.
5.16	N	**Laboratory environment for testing modified to approximate operational environment?**	No.
5.17	N	**Component integration issues and requirements identified?**	No.
5.18	N	**Detailed design drawings have been completed to support specification of engineering-scale testing system?**	No.
5.19	N	**Requirements definition with performance thresholds and objectives established for final plant design?**	No.
5.20	N	**Preliminary technology feasibility engineering report completed?**	No.
5.21	N	**Integration of modules/functions demonstrated in a laboratory/bench-scale environment?**	No.
5.22	N	**Formal control of all components to be used in final prototypical test system?**	No.
5.23	N	**Configuration management plan in place?**	No.
5.24	N	**The range of all relevant physical and chemical properties has been determined (to the extent possible)?**	No.
5.25	N	**Simulants have been developed that cover the full range of waste properties?**	No.
5.26	N	**Testing has verified that the properties/performance of the simulants match the properties/performance of the actual wastes?**	No.
5.27	N	**Laboratory-scale tests on the full range of simulants using a prototypical system have been completed?**	No.
5.28	N	**Laboratory-scale tests on a limited range of real wastes using a prototypical system have been completed?**	No.
5.29	N	**Test results for simulants and real waste are consistent?**	No.
5.30	N	**Laboratory to engineering scale scale-up issues are understood and resolved?**	No.

Table A.2. Mixing, sampling, and analyses criteria evaluation.

C#	Y/N	Criteria	Comments
5.31	N	**Limits for all process variables/parameters and safety controls are being refined?**	No.
5.32	N	**Test plan for prototypical lab-scale tests executed - results validate design?**	No.
5.33	N	**Test plan documents for prototypical engineering-scale tests completed?**	No.
5.34	N	**Risk management plan documented?**	No.
5.35	N	**Is a program in place to qualify the waste form and production process?**	No.
5.36	N	**Have all relevant physical and chemical properties been sufficiently well determined and bounded to meet proposed disposal criteria?**	No.
5.37	N	**Have the waste impacting process steps been demonstrated to function within acceptable range?**	No.
5.38		Was the transportation and storage package designed?	NA, transportation does not apply to MSA.
5.39		Have release rate law models been established (for relevant environment(s))?	NA, release rates do not apply to MSA.
6.01	N	**The relationships between system and sub-system parameters are understood at engineering scale allowing process/design variations and tradeoffs to be evaluated?**	No.
6.02	N	**Availability and reliability (RAMI) levels established?**	No.
6.03	N	**Preliminary design drawings for final plant system are complete?**	No
6.04	N	**Operating environment for final system known?**	No.
6.05	N	**Collection of actual maintainability, reliability, and supportability data has been started?**	No.
6.06	N	**Performance Baseline (including total project cost, schedule, and scope) has been completed?**	No.
6.07	N	**Operating limits for components determined (from design, safety and environmental compliance)?**	No.
6.08	N	**Operational requirements document available?**	No.
6.09	N	**Off-normal operating responses determined for engineering scale system?**	No.
6.10	N	**System technical interfaces defined?**	No.
6.11	N	**Component integration demonstrated at an engineering scale?**	No.
6.12	N	**Scaling issues that remain are identified and understood. Supporting analysis is complete?**	No.
6.13	N	**Analysis of project timing ensures technology will be available when required?**	No.
6.14	N	**Have established an interface control process?**	No.
6.15	N	**Acquisition program milestones established for start of final design (CD-2)?**	No.
6.16	Y	Critical manufacturing processes prototyped?	Standard equipment will be assembled to make the process. All sampling equipment has been procured and installed under full nuclear QA systems at WVDP, DWPF, and WTP.
6.17	Y	Most pre-production hardware is available to support fabrication of the system?	Mixing, sampling, and analyses hardware exist off the shelf.
6.18	N	**Engineering feasibility fully demonstrated (e.g., would it work)?**	No.
6.19	Y	Materials, process, design, and integration methods have been employed (e.g., can design be produced?)	These methods have been employed for similar activities at WTP and other DOE projects.
6.20	N	**Technology "system" design specification complete and ready for detailed design?**	No.
6.21	Y	Components are functionally compatible with operational system?	The components specified are the same as those used in current plants.
6.22	N	**Engineering-scale system is high-fidelity functional prototype of operational system?**	No.
6.23	N	**Formal configuration management program defined to control change process?**	No.
6.24	N	**Integration demonstrations have been completed (e.g., construction of testing system)?**	No.

Table A.2. Mixing, sampling, and analyses criteria evaluation.

C#	Y/N	Criteria	Comments
6.25	N	**Final Technical Report on Technology completed?**	No.
6.26	Y	Process and tooling are mature to support fabrication of components/system?	Standard equipment will be assembled to make the process. All sampling equipment has been procured and installed under full nuclear QA systems at WVDP, DWPF, and WTP.
6.27	N	**Engineering-scale tests on the full range of simulants using a prototypical system have been completed?**	No.
6.28	N	**Engineering to full-scale scale-up issues are understood and resolved?**	No.
6.29	N	**Laboratory and engineering-scale experiments are consistent?**	No.
6.30	N	**Limits for all process variables/parameters and safety controls are defined?**	No.
6.31	N	**Plan for engineering-scale testing executed - results validate design?**	No.
6.32	N	**Production demonstrations are complete (at least one time)?**	No.
6.33		Have the transportation and storage systems been identified?	NA, transportation isn't applicable to MSA.
6.34	N	**Are performance assessment models available for the form/disposal environment?**	No.
6.35	N	**Has a preliminary performance assessment been done to determine the acceptability of the waste form?**	No.

Table A.3. Melter feeding, melting, and pouring criteria evaluation.

C#	Y/N	Criteria	Comments
1.01	Y	Back of envelope environment?	Calculations were performed to support the melter test planning at INL.[27]
1.02	Y	Physical laws and assumptions used in new technologies defined?	Physical laws known and some heat/mass/charge transport models started.[28-33]
1.03	Y	Paper studies confirm basic principles?	An evaluation of melter technologies shows this to be the most promising (size, production rate, temperature capabilities, etc.).[31, 34-38]
1.04	Y	Initial scientific observations reported in journals/conference proceedings/technical reports?	Many papers on CCIM use for other wastes (France, Russia, Korea, etc.).[39-50]
1.05	Y	Basic scientific principles observed and understood?	The basic scientific principles have been observed and understood. Many citations attest to the observations as listed in the three previous questions.
1.06	Y	Know who cares about the technology, e.g., sponsor, funding source, etc.?	DOE-NE is the sponsor.
1.07	Y	Research hypothesis formulated?	Past basic research into technology development has resulted in working systems.[51]
1.08	Y	Basic characterization data exists?	Basic data on CCIM exists for processing other wastes and other materials. See citations for questions 1.02 through 1.04.
1.09	Y	Know who would perform research and where it would be done?	Melter testing would be done at INL, KRI, Radon, KHNP, and CEA; glass development and characterization at PNNL and SRNL.
2.01	Y	Customer identified?	DOE-NE is the customer.
2.02	Y	Potential system or components have been identified?	Several potential unit operations were identified in this plan these for a reference process that will be used until replaced.
2.03	Y	Paper studies show that application is feasible?	This TMP provides sufficient paper study to demonstrate that this application is feasible at TRL-2 level.
2.04	Y	Know what program the technology would support?	Programs would be domestic reprocessing facility that hasn't yet begun.
2.05	Y	An apparent theoretical or empirical design solution identified?	The design solution of a CCIM with unit operations specified in this document is currently envisioned.
2.06	Y	Basic elements of technology have been identified?	Technology elements are identified in this TMP.
2.07	Y	Desktop environment (paper studies)?	A mass balance was completed for AFCF and EAS for an application similar enough to meet TRL-2.
2.08	Y	Components of technology have been partially characterized?	Several components were characterized for other waste immobilization applications.
2.09	Y	Performance predictions made for each element?	The melter body performance predictions were made for the Baseline waste forms report [52] and also the AFCF design.
2.10	Y	Customer expresses interest in the application?	The customer requested and funded this TMP.
2.11	Y	Initial analysis shows what major functions need to be done?	This TMP lists the major functions that need to be performed by this CTE.
2.12	Y	Modeling & Simulation only used to verify physical principles?	Models for heat, mass, and charge transport in the CCIM were developed.[33, 53-55] Models for cold-cap melting are under development.[56-58]
2.13	Y	System architecture defined in terms of major functions to be performed?	The system is defined in Section 2.
2.14	Y	Rigorous analytical studies confirm basic principles?	The basic principles of the melter have been shown analytically.[28-33] Pouring and feeding systems have been demonstrated to be successful for slurry feed partly crystallized waste forms.[39, 44, 48, 59-64]
2.15	Y	Analytical studies reported in scientific journals/conference proceedings/technical reports?	The use of CCIM is well documented in journals and proceedings.[39-50]
2.16	Y	Individual parts of the technology work (No real attempt at integration)?	The CCIM was demonstrated to work for HLW and other materials including the feeding of slurries and pouring of partly crystallized melts.[45, 48, 65-68]
2.17	Y	Know what output devices are available?	With some trepidation, this was interpreted as pour-spout and off-gas treatment. There are a number of pour-spout designs tested and developed specifically for the melting of waste glass in CCIM.
2.18	N	**Preliminary strategy to obtain TRL Level 6 developed (e.g., scope, schedule, cost)?**	This TMP presents a strategy to achieve TRL-6.
2.19	Y	Know capabilities and limitations of researchers and research facilities?	The researchers at qualified institutions are well known along with their strengths and weaknesses/limitations. They primarily consist of PNNL, SRNL, and CEA Marcoule for waste form formulation and INL, CEA Marcoule, SIA Radon, KHNP, Bochvar, LETI, and KRI for melter system testing.
2.20	N	**The scope and scale of the waste problem has been determined?**	The wastes to be immobilized are ill defined. They all result from a separations process that is still in development.
2.21	Y	Know what experiments are required (research approach)?	A basic research approach was developed and documented in this TMP.
2.22	Y	Qualitative idea of risk areas (cost, schedule, performance)?	This TMP lists the high risk areas and approach to lowering that risk. No quantitative analysis has been done.
2.23	Y	Have the range of waste species and waste loading for the waste form been identified?	A preliminary evaluation of waste compositions, waste loading constraints, and glass formulations was performed.[69]
2.24		Are the general properties of the waste form well understood and published in peer review journals?	NA, waste form properties are not applicable to FMP
2.25		Have experiments started with the goal of determining the mechanism for the release of radionuclides?	NA, release mechanism does not apply to FMP.
3.01	Y	Academic (basic science) environment?	Feeding, melting (in a CCIM) and pouring of glass has long been industrialized and is well past the academic endeavor.
3.02	Y	Some key process and safety requirements are identified?	Some of the requirements identified for HLW are the same as for this process/form.
3.03	N	**Predictions of elements of technology capability validated by analytical studies?**	Capability predictions have not yet been made.
3.04	Y	The basic science has been validated at the laboratory scale?	The principles of CCIM have been demonstrated at full scale with similar materials.[51, 70]

Table A.3. Melter feeding, melting, and pouring criteria evaluation.

C#	Y/N	Criteria	Comments
3.05	Y	Science known to extent that mathematical and/or computer models and simulations are possible?	Modeling of heat, mass, and charge transport in the melter have started.[33, 53-55] Models for cold-cap melting are under development.[56-58]
3.06	N	**Preliminary system performance characteristics and measures have been identified and estimated?**	No.
3.07	N	**Predictions of elements of technology capability validated by Modeling and Simulation (M&S)?**	No.
3.08	Y	No system components, just basic laboratory research equipment to verify physical principles?	Physical principles were demonstrated at scales up to and including scales up to 650 mm for the CCIM with similar materials.
3.09	Y	Laboratory experiments verify feasibility of application?	Laboratory tests of the melting and cooling processes suggest that the glass ceramic will work in a CCIM.[71]
3.10	Y	Predictions of elements of technology capability validated by laboratory experiments?	Glass ceramic melting and pouring were tested at laboratory scale.[69, 71, 72]
3.11	Y	Customer representative identified to work with development team?	DOE representative, Kimberly Gray, is involved with development team.
3.12	Y	Customer participates in requirements generation?	DOE will participate in requirements generation (when it begins).
3.13	N	**Requirements tracking system defined to manage requirements creep?**	No requirements tracking system yet.
3.14	N	**Key process parameters/variables and associated hazards have begun to be identified?**	No.
3.15	N	**Design techniques have been identified/developed?**	Melters and off-gas components have been made. Cooling coil, pour-spout, and their coatings are not yet designed.
3.16	N	**Paper studies indicate that system components ought to work together?**	No.
3.17	Y	Customer identifies technology need date?	Objective 3 lists a pilot facility in 2040.[23]
3.18	N	**Performance metrics for the system are established (What must it do)?**	No.
3.19	N	**Scaling studies have been started?**	No scaling studies have started for this application. However, general equipment scaling tenants are fairly well known for all the equipment to be used.
3.20	Y	Current manufacturability concepts assessed?	No issues are expected with manufacturability of any components based on the number of melters currently in service.
3.21	Y	Sources of key components for laboratory testing identified?	Melters are available at INL, KHNP, CEA, KRI, and SIA Radon.
3.22	N	**Scientific feasibility fully demonstrated?**	No.
3.23	Y	Analysis of present state of the art shows that technology fills a need?	An evaluation of melter technologies shows this to be the most promising (size, production rate, temperature capabilities, etc.). method for treating HLW from commercial fuel reprocessing.[52, 73, 74]
3.24	Y	Risk areas identified in general terms?	The risks are generally identified in this TMP.
3.25	N	**Risk mitigation strategies identified?**	No.
3.26	N	**Rudimentary best value analysis performed for operations?**	No.
3.27	N	**Key physical and chemical properties have been characterized for a number of waste samples?**	No.
3.28	N	**A simulant has been developed that approximates key waste properties?**	No.
3.29	N	**Laboratory scale tests on a simulant have been completed?**	No.
3.30	N	**Specific waste(s) and waste site(s) has (have) been defined?**	No.
3.31	N	**The individual system components have been tested at the laboratory scale?**	No.
3.32		Has the type of disposal environment(s) been defined?	NA, type of disposal environment does not apply to TMP.
3.33	N	**Is a general strategy for waste form qualification been developed?**	No.
4.01	N	**Key process variables/parameters been fully identified and preliminary hazard evaluations have been performed?**	Not for this application. Hazard analysis was performed prior to installation of the CCIM in LaHague for their application.[70]
4.02	Y	Laboratory components tested are surrogates for system components?	Laboratory and engineering scale CCIM tests have been performed with liquid feed and crystals in the melt.[48, 65, 68, 75]
4.03	Y	Individual components tested in laboratory or by supplier?	The melter and feed systems have been tested (see question 4.02). Also, individual off-gas components have been tested, but, not as an integrated system.
4.04	N	**Subsystems composed of multiple components tested at lab scale using simulants?**	No.
4.05	N	**Modeling & Simulation used to simulate some components and interfaces between components?**	No.
4.06	N	**Overall system requirements for end user's application are known?**	No.
4.07	N	**Overall system requirements for end user's application are documented?**	No.
4.08	N	**System performance metrics measuring requirements have been established?**	No.

Table A.3. Melter feeding, melting, and pouring criteria evaluation.

C#	Y/N	Criteria	Comments
4.09	N	**Laboratory testing requirements derived from system requirements are established?**	No.
4.10	Y	Available components assembled into laboratory scale system?	INL melter is assembled with liquid feeding. Similar systems are assembled at CEA, KHNP, SIA Radon, Bochvar, LETI, and KRI. All of these systems have the option for liquid feeding and pouring. The off-gas treatment systems are different at each laboratory and none are exactly the same as specified here.
4.11	N	**Laboratory experiments with available components show that they work together?**	No.
4.12	N	**Analysis completed to establish component compatibility (Do components work together)?**	No.
4.13	N	**Science and Technology Demonstration exit criteria established (S&T targets understood, documented, and agreed to by sponsor)?**	This plan spells out the S&T targets, but, the exit criteria must still be developed.
4.14	N	**Technology demonstrates basic functionality in simulated environment?**	No.
4.15	Y	Scalable technology prototypes have been produced (Can components be made bigger than lab scale)?	Melters and off-gas treatment units of various scales have been fabricated for other applications.
4.16	N	**Draft conceptual designs have been documented (system description, process flow diagrams, general arrangement drawings, and material balance)?**	No.
4.17	N	**Equipment scale-up relationships are understood/accounted for in technology development program?**	No.
4.18	N	**Controlled laboratory environment used in testing?**	No.
4.19	N	**Initial cost drivers identified?**	Not fully.
4.20	N	**Integration studies have been started?**	No.
4.21	N	**Formal risk management program initiated?**	No.
4.22	Y	Key manufacturing processes for equipment systems identified?	No manufacturing issues identified unless flat tubes are used. In which case manufacturing is a challenge.
4.23	N	**Scaling documents and designs of technology have been completed?**	No.
4.24		Key manufacturing processes assessed in laboratory?	NA, manufacturing issues don't apply to FMP.
4.25	N	**Functional process description developed. (Systems/subsystems identified)?**	No.
4.26	N	**Low fidelity technology "system" integration and engineering completed in a lab environment?**	No.
4.27	N	**Mitigation strategies identified to address manufacturability/producibility shortfalls?**	No manufacturing issues identified unless flat tubes are used. In which case manufacturing is a challenge.
4.28	N	**Key physical and chemical properties have been characterized for a range of wastes?**	No.
4.29	N	**A limited number of simulants have been developed that approximate the range of waste properties?**	No.
4.30	N	**Laboratory-scale tests on a limited range of simulants and real waste have been completed?**	No.
4.31	N	**Process/parameter limits and safety control strategies are being explored?**	No
4.32	N	**Test plan documents for prototypical lab-scale tests completed?**	No.
4.33	Y	Technology availability dates established?	Objective 3 lists a pilot facility in 2040.[23]
4.34		Are current regulations and policy established for disposal of the form?	NA, disposal regulations do not apply to FMP.
4.35	Y	Have waste form affecting process steps been identified?	The waste affecting processes are the same, in general, as those for Hanford HLW.[26]
4.36	N	**Has a detailed waste qualification plan been documented?**	No.
4.37	N	**Have the range of chemistry and processing parameters for acceptable waste form been identified and documented?**	No.
5.01	N	**The relationships between major system and sub-system parameters are understood on a laboratory scale?**	No.
5.02	Y	Plant size components available for testing?	Full scale melters are available at CEA and KHNP.
5.03	N	**System interface requirements known (How would system be integrated into the plant?)**	No.
5.04	N	**Preliminary design engineering begins?**	No.

Table A.3. Melter feeding, melting, and pouring criteria evaluation.

C#	Y/N	Criteria	Comments
5.05	N	**Requirements for technology verification established?**	No.
5.06	N	**Interfaces between components/subsystems in testing are realistic (bench top with realistic interfaces)?**	No.
5.07	Y	Prototypes of equipment system components have been created (know how to make equipment)?	Prototypes of 650 mm diameter melters and larger were fabricated for CEA and KHNP.
5.08		Tooling and machines demonstrated in lab for new manufacturing processes to make component?	NA, tooling does not apply to FMP.
5.09	N	**High fidelity lab integration of system completed, ready for test in relevant environments?**	No.
5.10	Y	Manufacturing techniques have been defined to the point where largest problems defined?	No.
5.11	N	**Lab-scale, similar system tested with range of simulants?**	No.
5.12	N	**Fidelity of system mock-up improves from laboratory to bench-scale testing?**	No.
5.13	N	**Availability and reliability (RAMI) target levels identified?**	No.
5.14	N	**Some special purpose components combined with available laboratory components for testing?**	No.
5.15	N	**Three dimensional drawings and P&IDs for the prototypical engineering-scale test facility have been prepared?**	No.
5.16	N	**Laboratory environment for testing modified to approximate operational environment?**	No.
5.17	N	**Component integration issues and requirements identified?**	No.
5.18	N	**Detailed design drawings have been completed to support specification of engineering-scale testing system?**	No.
5.19	N	**Requirements definition with performance thresholds and objectives established for final plant design?**	No.
5.20	N	**Preliminary technology feasibility engineering report completed?**	No.
5.21	N	**Integration of modules/functions demonstrated in a laboratory/bench-scale environment?**	No.
5.22	N	**Formal control of all components to be used in final prototypical test system?**	No.
5.23	N	**Configuration management plan in place?**	No.
5.24	N	**The range of all relevant physical and chemical properties has been determined (to the extent possible)?**	No.
5.25	N	**Simulants have been developed that cover the full range of waste properties?**	No.
5.26	N	**Testing has verified that the properties/performance of the simulants match the properties/performance of the actual wastes?**	No.
5.27	N	**Laboratory-scale tests on the full range of simulants using a prototypical system have been completed?**	No.
5.28	N	**Laboratory-scale tests on a limited range of real wastes using a prototypical system have been completed?**	No.
5.29	N	**Test results for simulants and real waste are consistent?**	No.
5.30	N	**Laboratory to engineering scale scale-up issues are understood and resolved?**	No.
5.31	N	**Limits for all process variables/parameters and safety controls are being refined?**	No.
5.32	N	**Test plan for prototypical lab-scale tests executed - results validate design?**	No.
5.33	N	**Test plan documents for prototypical engineering-scale tests completed?**	No.
5.34	N	**Risk management plan documented?**	No.
5.35	N	**Is a program in place to qualify the waste form and production process?**	No.
5.36	N	**Have all relevant physical and chemical properties been sufficiently well determined and bounded to meet proposed disposal criteria?**	No.

Table A.3. Melter feeding, melting, and pouring criteria evaluation.

C#	Y/N	Criteria	Comments
5.37	N	**Have the waste impacting process steps been demonstrated to function within acceptable range?**	No.
5.38		Was the transportation and storage package been designed?	NA, transportation is not applicable to FMP
5.39		Have release rate law models been established (for relevant environment(s))?	NA, release rates do not apply to FMP
6.01	N	**The relationships between system and sub-system parameters are understood at engineering scale allowing process/design variations and tradeoffs to be evaluated?**	No.
6.02	N	**Availability and reliability (RAMI) levels established?**	No.
6.03	N	**Preliminary design drawings for final plant system are complete?**	No.
6.04	N	**Operating environment for final system known?**	No.
6.05	N	**Collection of actual maintainability, reliability, and supportability data has been started?**	No.
6.06	N	**Performance Baseline (including total project cost, schedule, and scope) has been completed?**	No.
6.07	N	**Operating limits for components determined (from design, safety and environmental compliance)?**	No.
6.08	N	**Operational requirements document available?**	No.
6.09	N	**Off-normal operating responses determined for engineering scale system?**	No.
6.10	N	**System technical interfaces defined?**	No.
6.11	N	**Component integration demonstrated at an engineering scale?**	No.
6.12	N	**Scaling issues that remain are identified and understood. Supporting analysis is complete?**	No.
6.13	N	**Analysis of project timing ensures technology will be available when required?**	No.
6.14	N	**Have established an interface control process?**	No.
6.15	N	**Acquisition program milestones established for start of final design (CD-2)?**	No.
6.16	Y	Critical manufacturing processes prototyped?	Manufacturing of the LaHague and Ulchin melters is complete and the melters are in service. Although, neither are liquid fed and nor do they produce glass-ceramic.
6.17	Y	Most pre-production hardware is available to support fabrication of the system?	Hardware is available off-the-shelf for most components. Exceptions are the melter and wave-guide. These have been constructed at full scale for other applications.
6.18	N	**Engineering feasibility fully demonstrated (e.g., would it work)?**	No.
6.19	Y	Materials, process, design, and integration methods have been employed (e.g., can design be produced?)	These methods were employed for the retrofit of LaHague to CCIM [51], and the installation at Ulchin [76].
6.20	N	**Technology "system" design specification complete and ready for detailed design?**	No.
6.21	Y	Components are functionally compatible with operational system?	Components have been tested for similar applications and CCIM is actively used for HLW vitrification.
6.22	N	**Engineering-scale system is high-fidelity functional prototype of operational system?**	No.
6.23	N	**Formal configuration management program defined to control change process?**	No.
6.24	N	**Integration demonstrations have been completed (e.g., construction of testing system)?**	No.
6.25	N	**Final Technical Report on Technology completed?**	No.
6.26	Y	Process and tooling are mature to support fabrication of components/system?	Equipment fabrication processes are mature and have been deployed for a number of melters.
6.27	N	**Engineering-scale tests on the full range of simulants using a prototypical system have been completed?**	No.
6.28	N	**Engineering to full-scale scale-up issues are understood and resolved?**	No.
6.29	N	**Laboratory and engineering-scale experiments are consistent?**	No.
6.30	N	**Limits for all process variables/parameters and safety controls are defined?**	No.
6.31	N	**Plan for engineering-scale testing executed - results validate design?**	No.
6.32	N	**Production demonstrations are complete (at least one time)?**	No.
6.33	N	**Have the transportation and storage systems been identified?**	No.

Table A.3. Melter feeding, melting, and pouring criteria evaluation.

C#	Y/N	Criteria	Comments
6.34	N	**Are performance assessment models available for the form/disposal environment?**	No.
6.35	N	**Has a preliminary performance assessment been done to determine the acceptability of the waste form?**	No.

Table A.4. Glass-ceramic formulation criteria evaluation.

C#	Y/N	Criteria	Comments
1.01	Y	Back of envelope environment?	Initial glass-ceramic formulations are complete.[69, 71, 72]
1.02	Y	Physical laws and assumptions used in new technologies defined?	Physical laws known and data already developed.[69, 71, 72, 77-82]
1.03	Y	Paper studies confirm basic principles?	An evaluation of glass-ceramic shows waste loadings, phases, heat tolerance, etc. [69, 71, 72]
1.04	Y	Initial scientific observations reported in journals/conference proceedings/technical reports?	Basic concepts were recently published.[72]
1.05	Y	Basic scientific principles observed and understood?	Extensive understanding in multiphase waste forms dating back to the 1960's.[83]
1.06	Y	Know who cares about the technology, e.g., sponsor, funding source, etc.?	DOE-NE is the sponsor.[14]
1.07	Y	Research hypothesis formulated?	The hypotheses are that glass-ceramic can be formulated for higher loading and temperature tolerance than borosilicate glass and thereby reduce waste management costs for U.S. domestic reprocessing.
1.08	Y	Basic characterization data exists?	Basic data on glass-ceramic exists for lab-scale fabricated materials.[69, 71, 72]
1.09	Y	Know who would perform research and where it would be done?	PNNL, LANL, SRNL are all well suited to study this form.
2.01	Y	Customer identified?	DOE-NE is the customer.[14]
2.02	Y	Potential system or components have been identified?	Several potential unit operations were identified and listed in Section 2.
2.03	Y	Paper studies show that application is feasible?	Paper study resulted in the selection of this technology for this stream.[25, 69]
2.04	Y	Know what program the technology would support?	Programs would be U.S. domestic reprocessing that hasn't yet started.
2.05	Y	An apparent theoretical or empirical design solution identified?	The glass formulation solution is envisioned with some theoretical basis.[72]
2.06	Y	Basic elements of technology have been identified?	The basic elements of this technology are the glass ceramic waste form that can be fabricated by existing methods with typical cooling schedules. The targeted phases are those that will immobilize key radionuclides to increase waste solubility, chemical durability, and thermal/radiation stability.
2.07	Y	Desktop environment (paper studies)?	Waste form formulation was evaluated in paper and laboratory-scale studies.[72]
2.08	Y	Components of technology have been partially characterized?	Several samples have been partially characterized.[69, 71, 72]
2.09	N	**Performance predictions made for each element?**	Predictions of loadings have been made. However, predictions of long-term performance, temperature and radiation stability have not been predicted.
2.10	Y	Customer expresses interest in the application?	Customer requested and funded this TMP.
2.11	Y	Initial analysis shows what major functions need to be done?	The technology elements are described in previous documents [69, 71, 72] and summarized in this TMP.
2.12	N	**Modeling & Simulation only used to verify physical principles?**	No modeling/simulation have been used other than cooling rates, but not how cooling rates and composition impact crystallinity, process efficiency, or long-term performance.
2.13	N	**System architecture defined in terms of major functions to be performed?**	The system is described in terms of unit operations rather than major functions. This was done for convenience. However, all major functions are represented.
2.14	Y	Rigorous analytical studies confirm basic principles?	Analytical studies of the waste form itself and the formation of the right phases have been done.[69, 71, 72]
2.15	Y	Analytical studies reported in scientific journals/conference proceedings/technical reports?	A paper on this application was published [72], the general concept is well known and reported.[77, 78, 83-87]
2.16	Y	Individual parts of the technology work (No real attempt at integration)?	The waste form works. It's not clear, yet, if it works in a CCIM.
2.17		Know what output devices are available?	NA, output devices do not apply to GCF.
2.18	Y	Preliminary strategy to obtain TRL Level 6 developed (e.g., scope, schedule, cost)?	This TMP highlights the strategy to obtain TRL-6.
2.19	Y	Know capabilities and limitations of researchers and research facilities?	The researchers at qualified institutions are well known along with their strengths and weaknesses/limitations.
2.20	Y	The scope and scale of the waste problem has been determined?	The range of wastes to be treated have been estimated.[25] However, the wastes generated will be from a yet to be determined process so they are only a place holder.
2.21	Y	Know what experiments are required (research approach)?	A basic research approach is being developed by this TMP.
2.22	Y	Qualitative idea of risk areas (cost, schedule, performance)?	This TMP lists the high risk areas. No quantitative analysis yet done.
2.23	N	**Have the range of waste species and waste loading for the waste form been identified?**	We don't know the range of waste compositions as the process has not yet been defined. However, we have a placeholder based on similar processes.
2.24	N	**Are the general properties of the waste form well understood and published in peer review journals?**	Some of the properties were published in a journal.[72] However, many properties are still not known.
2.25	Y	Have experiments started with the goal of determining the mechanism for the release of radionuclides?	Property consistency test data were measured for 3, 7, and 28 days at 90°C.
3.01	Y	Academic (basic science) environment?	Concept of the waste form is sufficiently understood from a fundamental (academic) standpoint.[72]
3.02	Y	Some key process and safety requirements are identified?	Some of the requirements identified for HLW glass are the same as for this stream.
3.03	N	**Predictions of elements of technology capability validated by analytical studies?**	Amounts and compositions of all the phases that form and their impact on waste form properties have not been predicted.
3.04	Y	The basic science has been validated at the laboratory scale?	The principles of a crystallizing glass have been demonstrated at full scale with other compositions. [85]

Table A.4. Glass-ceramic formulation criteria evaluation.

C#	Y/N	Criteria	Comments
3.05	Y	Science known to extent that mathematical and/or computer models and simulations are possible?	We know how to model the form and slow cooling, but the modeling hasn't started.
3.06	N	**Preliminary system performance characteristics and measures have been identified and estimated?**	The performance requirements of the waste form aren't yet know, such as loading, temperature tolerance (canister size), or long-term durability.
3.07	N	**Predictions of elements of technology capability validated by Modeling and Simulation (M&S)?**	Models have not been used to validate technology predictions.
3.08	Y	No system components, just basic laboratory research equipment to verify physical principles?	Physical principles were demonstrated at lab-scale.[72]
3.09	Y	Laboratory experiments verify feasibility of application?	Laboratory experiments with simulated wastes have verified the feasibility of glass-ceramic waste forms.[69, 71, 72]
3.10	N	**Predictions of elements of technology capability validated by laboratory experiments?**	Waste loading and crystalline phases after a single slow cooling were validated for a composition. Not all elements have been validated.
3.11	Y	Customer representative identified to work with development team?	DOE has identified a representative, Kimberly Gray, to work with development team.
3.12	Y	Customer participates in requirements generation?	DOE will participate in requirements generation (when it begins).
3.13	N	**Requirements tracking system defined to manage requirements creep?**	No.
3.14	N	**Key process parameters/variables and associated hazards have begun to be identified?**	No.
3.15	Y	Design techniques have been identified/developed?	Standard waste glass design techniques will be applied, variable cooling rates are being evaluated, additionally, thermodynamic models will be used to predict equilibrium phases as functions of composition and temperature.
3.16	N	**Paper studies indicate that system components ought to work together?**	No.
3.17	Y	Customer identifies technology need date?	Project documents need pilot facility by 2040.[23]
3.18	N	**Performance metrics for the system are established (What must it do)?**	No.
3.19	Y	Scaling studies have been started?	Initial scaling studies have begun.[27]
3.20	Y	Current manufacturability concepts assessed?	CCIM is the reference manufacturing method.
3.21	Y	Sources of key components for laboratory testing identified?	Melters are available at INL, KHNP, CEA, KRI, and SIA Radon. All other testing available at PNNL and LANL.
3.22	N	**Scientific feasibility fully demonstrated?**	No.
3.23	Y	Analysis of present state of the art shows that technology fills a need?	An evaluation of HLW glass limitations shows that both chemical and heat limitations can be overcome by glass-ceramic.[25, 69, 72]
3.24	Y	Risk areas identified in general terms?	The high risk areas are highlighted in this TMP.
3.25	N	**Risk mitigation strategies identified?**	Risk management plan has not yet been developed.
3.26	N	**Rudimentary best value analysis performed for operations?**	No.
3.27	N	**Key physical and chemical properties have been characterized for a number of waste samples?**	No.
3.28	Y	A simulant has been developed that approximates key waste properties?	A preliminary waste simulant was fabricated.[24]
3.29	Y	Laboratory scale tests on a simulant have been completed?	Lab tests on the waste forms were completed and reported.[69, 72] A single laboratory test was performed with the waste simulant.[24]
3.30	Y	Specific waste(s) and waste site(s) has (have) been defined?	A four corners study of potential HLW is being used to bound the wastes.[25] However, the final process and it's resulting waste have not yet been identified.
3.31	Y	The individual system components have been tested at the laboratory scale?	Each of the target phases have been formed and tested at laboratory scale.[69, 71]
3.32	N	**Has the type of disposal environment(s) been defined?**	No.
3.33	N	**Is a general strategy for waste form qualification been developed?**	No.
4.01	N	**Key process variables/parameters been fully identified and preliminary hazard evaluations have been performed?**	No hazard evaluations have been performed.
4.02		Laboratory components tested are surrogates for system components?	NA, component testing is not applicable to GCF
4.03	Y	Individual components tested in laboratory or by supplier?	A couple of waste forms with a single cooling schedule have been tested.[72]
4.04	N	**Subsystems composed of multiple components tested at lab scale using simulants?**	Not all waste compositions or heat treatment schedules have been tested.
4.05	Y	Modeling & Simulation used to simulate some components and interfaces between components?	Models of the melt target in the CCIM have been performed.[27]
4.06	N	**Overall system requirements for end user's application are known?**	No.
4.07	N	**Overall system requirements for end user's application are documented?**	No.
4.08	N	**System performance metrics measuring requirements have been established?**	No.

Table A.4. Glass-ceramic formulation criteria evaluation.

C#	Y/N	Criteria	Comments
4.09	N	**Laboratory testing requirements derived from system requirements are established?**	No.
4.10		Available components assembled into laboratory scale system?	NA, GCF does not have components to assemble.
4.11	N	**Laboratory experiments with available components show that they work together?**	No.
4.12	N	**Analysis completed to establish component compatibility (Do components work together)?**	No.
4.13	N	**Science and Technology Demonstration exit criteria established (S&T targets understood, documented, and agreed to by sponsor)?**	No.
4.14	N	**Technology demonstrates basic functionality in simulated environment?**	No.
4.15	Y	Scalable technology prototypes have been produced (Can components be made bigger than lab scale)?	No larger melts than 100s of grams, but glass compositions are scalable.
4.16		Draft conceptual designs have been documented (system description, process flow diagrams, general arrangement drawings, and material balance)?	NA, conceptual design is not applicable to GCF
4.17		Equipment scale-up relationships are understood/accounted for in technology development program?	NA, equipment scale-up has been binned in FMP for this plan.
4.18	Y	Controlled laboratory environment used in testing?	Laboratory experiments have been successful.[69, 71, 72]
4.19	N	**Initial cost drivers identified?**	No.
4.20		Integration studies have been started?	NA, integration studies do not apply to GCF.
4.21	N	**Formal risk management program initiated?**	No.
4.22		Key manufacturing processes for equipment systems identified?	NA, manufacturing of GCF is a combination of FMP and CCC.
4.23		Scaling documents and designs of technology have been completed?	NA, scaling is not applicable to GCF.
4.24		Key manufacturing processes assessed in laboratory?	NA, manufacturing of GCF is a combination of FMP and CCC.
4.25	N	**Functional process description developed. (Systems/subsystems identified)?**	No.
4.26	N	**Low fidelity technology "system" integration and engineering completed in a lab environment?**	No.
4.27	Y	Mitigation strategies identified to address manufacturability/producibility shortfalls?	Mitigation strategy is to change composition and/or melter process, and/or cooling methods as described in Section 2.
4.28	N	**Key physical and chemical properties have been characterized for a range of wastes?**	No.
4.29	N	**A limited number of simulants have been developed that approximate the range of waste properties?**	No.
4.30	N	**Laboratory-scale tests on a limited range of simulants and real waste have been completed?**	No real wastes tests.
4.31	N	**Process/parameter limits and safety control strategies are being explored?**	No.
4.32	N	**Test plan documents for prototypical lab- scale tests completed?**	No.
4.33	Y	Technology availability dates established?	Based on program documents pilot in 2040.[23]
4.34	Y	Are current regulations and policy established for disposal of the form?	10 CFR 60 allows for commercial HLW disposal at Yucca Mountain. However, the current Administration policy is not to pursue Yucca Mountain.
4.35	Y	Have waste form affecting process steps been identified?	These are the same as for HLW glass.[12, 13, 26]
4.36	N	**Has a detailed waste qualification plan been documented?**	No.
4.37	N	**Have the range of chemistry and processing parameters for acceptable waste form been identified and documented?**	No.
5.01		The relationships between major system and sub-system parameters are understood on a laboratory scale?	NA, systems are not applicable to GCF.
5.02		Plant size components available for testing?	NA, plant size is not applicable to GCF.
5.03	N	**System interface requirements known (How would system be integrated into the plant?)**	No.
5.04	N	**Preliminary design engineering begins?**	No.
5.05	N	**Requirements for technology verification established?**	No.

Table A.4. Glass-ceramic formulation criteria evaluation.

C#	Y/N	Criteria	Comments
5.06	N	**Interfaces between components/subsystems in testing are realistic (bench top with realistic interfaces)?**	No.
5.07		Prototypes of equipment system components have been created (know how to make equipment)?	NA, GCF does not have prototype equipment.
5.08		Tooling and machines demonstrated in lab for new manufacturing processes to make component?	NA, tooling does not apply to GCF.
5.09		High fidelity lab integration of system completed, ready for test in relevant environments?	NA, integration of system is covered by FMP and CCC.
5.10		Manufacturing techniques have been defined to the point where largest problems defined?	NA, manufacturing of glass-ceramic is FMP and CCC.
5.11	N	**Lab-scale, similar system tested with range of simulants?**	No.
5.12	N	**Fidelity of system mock-up improves from laboratory to bench-scale testing?**	No.
5.13		Availability and reliability (RAMI) target levels identified?	NA, RAMI is not applicable to GCF.
5.14		Some special purpose components combined with available laboratory components for testing?	No.
5.15		Three dimensional drawings and P&IDs for the prototypical engineering-scale test facility have been prepared?	NA, drawings and P&ID's do not apply to GCF.
5.16	N	**Laboratory environment for testing modified to approximate operational environment?**	No.
5.17	N	**Component integration issues and requirements identified?**	No.
5.18		Detailed design drawings have been completed to support specification of engineering-scale testing system?	NA, drawings do not apply to GCF.
5.19	N	**Requirements definition with performance thresholds and objectives established for final plant design?**	No.
5.20	N	**Preliminary technology feasibility engineering report completed?**	No.
5.21	N	**Integration of modules/functions demonstrated in a laboratory/bench-scale environment?**	No.
5.22	N	**Formal control of all components to be used in final prototypical test system?**	No.
5.23	N	**Configuration management plan in place?**	No.
5.24	N	**The range of all relevant physical and chemical properties has been determined (to the extent possible)?**	No.
5.25	N	**Simulants have been developed that cover the full range of waste properties?**	No.
5.26	N	**Testing has verified that the properties/performance of the simulants match the properties/performance of the actual wastes?**	No.
5.27	N	**Laboratory-scale tests on the full range of simulants using a prototypical system have been completed?**	No.
5.28	N	**Laboratory-scale tests on a limited range of real wastes using a prototypical system have been completed?**	No.
5.29	N	**Test results for simulants and real waste are consistent?**	No.
5.30	N	**Laboratory to engineering scale scale-up issues are understood and resolved?**	No.
5.31	N	**Limits for all process variables/parameters and safety controls are being refined?**	No.
5.32	N	**Test plan for prototypical lab-scale tests executed - results validate design?**	No.
5.33	N	**Test plan documents for prototypical engineering-scale tests completed?**	No.
5.34	N	**Risk management plan documented?**	No.
5.35	N	**Is a program in place to qualify the waste form and production process?**	No.
5.36	N	**Have all relevant physical and chemical properties been sufficiently well determined and bounded to meet proposed disposal criteria?**	No.

Table A.4. Glass-ceramic formulation criteria evaluation.

C#	Y/N	Criteria	Comments
5.37	N	**Have the waste impacting process steps been demonstrated to function within acceptable range?**	No.
5.38		Was the transportation and storage package been designed?	NA, transportation package does not apply to GCF.
5.39	N	**Have release rate law models been established (for relevant environment(s))?**	No.
6.01	N	**The relationships between system and sub-system parameters are understood at engineering scale allowing process/design variations and tradeoffs to be evaluated?**	No.
6.02		Availability and reliability (RAMI) levels established?	NA, RAMI does not apply to GCF.
6.03		Preliminary design drawings for final plant system are complete?	NA, drawings do not apply to GCF.
6.04	N	**Operating environment for final system known?**	No.
6.05		Collection of actual maintainability, reliability, and supportability data has been started?	NA, RAMI does not apply to GCF.
6.06	N	**Performance Baseline (including total project cost, schedule, and scope) has been completed?**	No.
6.07	N	**Operating limits for components determined (from design, safety and environmental compliance)?**	No.
6.08	N	**Operational requirements document available?**	No.
6.09	N	**Off-normal operating responses determined for engineering scale system?**	No.
6.10	N	**System technical interfaces defined?**	No.
6.11	N	**Component integration demonstrated at an engineering scale?**	No.
6.12		Scaling issues that remain are identified and understood. Supporting analysis is complete?	NA, scaling of GCF is covered under FMP and CCC.
6.13	N	**Analysis of project timing ensures technology will be available when required?**	No.
6.14	N	**Have established an interface control process?**	No.
6.15	N	**Acquisition program milestones established for start of final design (CD-2)?**	No.
6.16		Critical manufacturing processes prototyped?	NA, prototypes for manufacturing do not apply to GCF.
6.17		Most pre-production hardware is available to support fabrication of the system?	NA, GCF does not include hardware.
6.18	N	**Engineering feasibility fully demonstrated (e.g., would it work)?**	No.
6.19		Materials, process, design, and integration methods have been employed (e.g., can design be produced?)	NA, design methods do not apply to GCF.
6.20	N	**Technology "system" design specification complete and ready for detailed design?**	No.
6.21		Components are functionally compatible with operational system?	NA, GFC does not include system components in a traditional sense.
6.22	N	**Engineering-scale system is high-fidelity functional prototype of operational system?**	No.
6.23	N	**Formal configuration management program defined to control change process?**	No.
6.24	N	**Integration demonstrations have been completed (e.g., construction of testing system)?**	No.
6.25	N	**Final Technical Report on Technology completed?**	No.
6.26		Process and tooling are mature to support fabrication of components/system?	NA, tooling is not applicable to GFC.
6.27	N	**Engineering-scale tests on the full range of simulants using a prototypical system have been completed?**	No.
6.28	N	**Engineering to full-scale scale-up issues are understood and resolved?**	No.
6.29	N	**Laboratory and engineering-scale experiments are consistent?**	No.
6.30	N	**Limits for all process variables/parameters and safety controls are defined?**	No.
6.31	N	**Plan for engineering-scale testing executed - results validate design?**	No.
6.32	N	**Production demonstrations are complete (at least one time)?**	No.
6.33		Have the transportation and storage systems been identified?	NA, transportation systems is not applicable to GFC.

Table A.4. Glass-ceramic formulation criteria evaluation.

C#	Y/N	Criteria	Comments
6.34	N	**Are performance assessment models available for the form/disposal environment?**	No.
6.35	N	**Has a preliminary performance assessment been done to determine the acceptability of the waste form?**	No.

Table A.5. Canister cooling and crystallization criteria evaluation.

C#	Y/N	Criteria	Comments
1.01	Y	Back of envelope environment?	Back of envelope for extreme cooling rates completed.[88]
1.02	Y	Physical laws and assumptions used in new technologies defined?	Physical laws known and data already developed.[88]
1.03	Y	Paper studies confirm basic principles?	An evaluation of the range of potential cooling rates complete by adding decay heat to CCC estimates.[88]
1.04	Y	Initial scientific observations reported in journals/conference proceedings/technical reports?	Reports on CCC models and on FRG glass cooling have been issued.[89-92]
1.05	Y	Basic scientific principles observed and understood?	Extensive understanding in cooling and crystallization on cooling exists. [79-81]
1.06	Y	Know who cares about the technology, e.g., sponsor, funding source, etc.?	DOE-NE is the sponsor.[14]
1.07	Y	Research hypothesis formulated?	The hypotheses are that we can reliably obtain the correct phase assemblages with the range of potential cooling environments.
1.08	Y	Basic characterization data exists?	The closest is the instrumented HLW glass canister.[90, 91, 93, 94] None had sufficient decay heat to validate that aspect. The FRG cans have surface temperature after fully cooling.[89]
1.09	Y	Know who would perform research and where it would be done?	PNNL, INL, SRNL and LANL are all well suited to study this process.
2.01	Y	Customer identified?	DOE-NE is the customer and requested and funded this TMP.
2.02	Y	Potential system or components have been identified?	Several potential unit operations were identified in Section 2.
2.03	Y	Paper studies show that application is feasible?	Paper study resulted in the selection of this technology and cooling approach.[72]
2.04	Y	Know what program the technology would support?	The program supported is U.S. domestic reprocessing that hasn't yet started.[23]
2.05	Y	An apparent theoretical or empirical design solution identified?	The design solutions are the uninsulated "free fall cooling," the insulated "slow cooling," and the furnace "reheat." Canisters would be based on the standard Hanford, WVDP, or universal "LaHague" canister.
2.06	Y	Basic elements of technology have been identified?	The basic elements of the technology are the melter, the canister, the cooling system, and the waste form.
2.07	N	**Desktop environment (paper studies)?**	Only the most extreme condition paper study was performed (standard Hanford canister with 14 kW of waste). [88] Additional paper studies are required to meet TRL-2.
2.08	Y	Components of technology have been partially characterized?	The crystallinity on the slowest extreme has been measured for a couple waste form compositions.[69, 71, 72]
2.09	N	**Performance predictions made for each element?**	Calculations of the full range of cooling schedules haven't yet been performed.
2.10	Y	Customer expresses interest in the application?	The DOE-NE customer requested and funded this TMP.
2.11	Y	Initial analysis shows what major functions need to be done?	The technology elements identified in this TMP.
2.12	N	**Modeling & Simulation only used to verify physical principles?**	The minimum cooling rate was simulated, but not the full range of cooling rates nor how cooling rates and composition impact crystallinity.
2.13	Y	System architecture defined in terms of major functions to be performed?	The system is the canister, the internal heat from decay and melting, and the crystals that form.
2.14	N	**Rigorous analytical studies confirm basic principles?**	The initial testing has started, but rigorous analytical studies are not yet complete.
2.15	N	**Analytical studies reported in scientific journals/conference proceedings/technical reports?**	No.
2.16	Y	Individual parts of the technology work (No real attempt at integration)?	For a single formulation, the extreme cooling does work.[72] This has not been integrated into a system.
2.17	Y	Know what output devices are available?	Output is the temperature distribution in the canisters as functions of time and location.
2.18	Y	Preliminary strategy to obtain TRL Level 6 developed (e.g., scope, schedule, cost)?	This TMP lays out the general approach to achieve TRL-6.
2.19	Y	Know capabilities and limitations of researchers and research facilities?	The researchers at qualified institutions are well known along with their strengths and weaknesses/limitations.
2.20	Y	The scope and scale of the waste problem has been determined?	The range of wastes to be treated have been roughly estimated by the four-corners study.[25]
2.21	Y	Know what experiments are required (research approach)?	A basic research is developed in this TMP.
2.22	Y	Qualitative idea of risk areas (cost, schedule, performance)?	This TMP describes the high risk areas. No quantitative analysis done yet.
2.23	Y	Have the range of waste species and waste loading for the waste form been identified?	A paper study was completed to analyze the range of waste compositions. These are not final as the separations processes and their resulting wastes aren't yet known. However, decay heat is the key aspect for the purpose of this technology.
2.24	N	**Are the general properties of the waste form well understood and published in peer review journals?**	No.
2.25	Y	Have experiments started with the goal of determining the mechanism for the release of radionuclides?	Product consistency tests have been performed for 3, 7, 28 days for a waste form fabricated with one cooling curve.[69]
3.01	Y	Academic (basic science) environment?	Concept of the cooling and crystallization are sufficiently understood from a fundamental standpoint.[79-82]
3.02	Y	Some key process and safety requirements are identified?	Some of the requirements identified for HLW glass are the same as for this stream.
3.03	N	**Predictions of elements of technology capability validated by analytical studies?**	No analytical studies to validate element predictions.
3.04	Y	The basic science has been validated at the laboratory scale?	The principles of a crystallizing glass and canister cooling curves have been demonstrated at full scale with other compositions.[85]
3.05	Y	Science known to extent that mathematical and/or computer models and simulations are possible?	We know how to model the slow cooling and have started, but the modeling of crystal precipitation hasn't started.

Table A.5. Canister cooling and crystallization criteria evaluation.

C#	Y/N	Criteria	Comments
3.06	N	**Preliminary system performance characteristics and measures have been identified and estimated?**	No.
3.07	N	**Predictions of elements of technology capability validated by Modeling and Simulation (M&S)?**	No.
3.08	Y	No system components, just basic laboratory research equipment to verify physical principles?	Physical principles were demonstrated at lab scale. No canister system has been tested.
3.09	Y	Laboratory experiments verify feasibility of application?	Laboratory experiments verify the feasibility of slow cooling within the canister for waste simulants.[69, 71, 72]
3.10	N	**Predictions of elements of technology capability validated by laboratory experiments?**	Canister cooling measured only for low heat HLW glasses.[71, 91, 93, 94]
3.11	Y	Customer representative identified to work with development team?	DOE-NE representative, Kimberly Gray, is involved with development team.
3.12	Y	Customer participates in requirements generation?	DOE will participate in requirements generation (when it begins).
3.13	N	**Requirements tracking system defined to manage requirements creep?**	No.
3.14	N	**Key process parameters/variables and associated hazards have begun to be identified?**	No.
3.15	Y	Design techniques have been identified/developed?	Standard engineering packages will be used.
3.16	N	**Paper studies indicate that system components ought to work together?**	No.
3.17	Y	Customer identifies technology need date?	Project documents plan for pilot facility in 2040.[23]
3.18	N	**Performance metrics for the system are established (What must it do)?**	No.
3.19	Y	Scaling studies have been started?	Studies have started to pour glass-ceramic into progressively higher diameter canisters and simulate cool-down.[27]
3.20	Y	Current manufacturability concepts assessed?	Manufacturing methods are mature for HLW canisters (supplying to DWPF, WVDP, and now WTP).
3.21	Y	Sources of key components for laboratory testing identified?	Melters are available at INL, KHNP, CEA, KRI, CUA, and SIA Radon. All other testing available at PNNL.
3.22	N	**Scientific feasibility fully demonstrated?**	No.
3.23	Y	Analysis of present state of the art shows that technology fills a need?	An evaluation of HLW glass limitations suggest that both chemical and heat limitations can be overcome by glass-ceramic. Further, it's been shown at laboratory scale that a direct, natural, cooling is sufficient to make the target phases.[69, 71, 72]
3.24	Y	Risk areas identified in general terms?	This TMP lists the general risk areas. No formal risk assessment has been performed.
3.25	N	**Risk mitigation strategies identified?**	No formal risk assessment has been performed.
3.26	N	**Rudimentary best value analysis performed for operations?**	No.
3.27	N	**Key physical and chemical properties have been characterized for a number of waste samples?**	No.
3.28	Y	A simulant has been developed that approximates key waste properties?	A waste simulant and canister simulant have been developed.[24, 27]
3.29	Y	Laboratory scale tests on a simulant have been completed?	Lab tests on the waste forms were completed and reported.[69, 71, 72]
3.30	Y	Specific waste(s) and waste site(s) has (have) been defined?	A four-corners study is being used to bound the wastes compositions and is reliable for heat content.[25]
3.31	Y	The individual system components have been tested at the laboratory scale?	Canisters,[91] cooling of melt to form crystals,[72] and canister handling have all been tested.
3.32	N	**Has the type of disposal environment(s) been defined?**	No.
3.33	N	**Is a general strategy for waste form qualification been developed?**	No.
4.01	N	**Key process variables/parameters been fully identified and preliminary hazard evaluations have been performed?**	No.
4.02	N	**Laboratory components tested are surrogates for system components?**	No.
4.03	Y	Individual components tested in laboratory or by supplier?	One heat treatment schedule was tested with a few glass ceramic compositions.[69, 71, 72]
4.04	N	**Subsystems composed of multiple components tested at lab scale using simulants?**	No.
4.05	Y	Modeling & Simulation used to simulate some components and interfaces between components?	A model was developed to simulate the impact of decay heat on canister cooling.[88] Another model is being developed to evaluate glass cracking on cooling (with decay heat).[95]
4.06	N	**Overall system requirements for end user's application are known?**	No.
4.07	N	**Overall system requirements for end user's application are documented?**	No.
4.08	N	**System performance metrics measuring requirements have been established?**	No.
4.09	N	**Laboratory testing requirements derived from system requirements are established?**	No.
4.10	Y	Available components assembled into laboratory scale system?	Equipment has been fabricated to pour large canisters and slow cool them.[27]

Table A.5. Canister cooling and crystallization criteria evaluation.

C#	Y/N	Criteria	Comments
4.11	N	**Laboratory experiments with available components show that they work together?**	No.
4.12	N	**Analysis completed to establish component compatibility (Do components work together)?**	No.
4.13	N	**Science and Technology Demonstration exit criteria established (S&T targets understood, documented, and agreed to by sponsor)?**	The general technology program is described in this TMP. Specific research exit criteria have not yet been agreed upon.
4.14	Y	Technology demonstrates basic functionality in simulated environment?	For the initial cooling schedule, the glass ceramic can be made without reheating.[72]
4.15	N	**Scalable technology prototypes have been produced (Can components be made bigger than lab scale)?**	No.
4.16	N	**Draft conceptual designs have been documented (system description, process flow diagrams, general arrangement drawings, and material balance)?**	No.
4.17	N	**Equipment scale-up relationships are understood/accounted for in technology development program?**	No.
4.18	Y	Controlled laboratory environment used in testing?	Controlled cooling schedules to reproduce the high-heat canister centerline cooling has been performed at laboratory scale.[72]
4.19	Y	Initial cost drivers identified?	The options are generally known, (natural cooling, insulated cooling, controlled cooling, or reheating). Equipment size and cost along with operating costs (including maintenance) will likely drive the cost.
4.20	N	**Integration studies have been started?**	No.
4.21	N	**Formal risk management program initiated?**	No.
4.22	Y	Key manufacturing processes for equipment systems identified?	Canister manufacturing is a mature technology.
4.23	N	**Scaling documents and designs of technology have been completed?**	No.
4.24	Y	Key manufacturing processes assessed in laboratory?	Canister manufacturing is a mature technology.
4.25	N	**Functional process description developed. (Systems/subsystems identified)?**	No.
4.26	N	**Low fidelity technology "system" integration and engineering completed in a lab environment?**	No.
4.27	Y	Mitigation strategies identified to address manufacturability/producibility shortfalls?	Canister manufacturing is a mature technology.
4.28	N	**Key physical and chemical properties have been characterized for a range of wastes?**	No.
4.29		A limited number of simulants have been developed that approximate the range of waste properties?	NA, CCC does not use simulants, but, rather glass from FMP which use simulants.
4.30	N	**Laboratory-scale tests on a limited range of simulants and real waste have been completed?**	No real waste testing.
4.31	N	**Process/parameter limits and safety control strategies are being explored?**	No.
4.32	N	**Test plan documents for prototypical lab- scale tests completed?**	No.
4.33	Y	Technology availability dates established?	In program planning documents a 2040 pilot-scale operation is called for.[23]
4.34		Are current regulations and policy established for disposal of the form?	NA, disposal policies do not apply to CCC.
4.35	Y	Have waste form affecting process steps been identified?	Temperature schedule and the resulting phase assemblage and performance impacts.
4.36	N	**Has a detailed waste qualification plan been documented?**	No.
4.37	N	**Have the range of chemistry and processing parameters for acceptable waste form been identified and documented?**	No.
5.01	N	**The relationships between major system and sub-system parameters are understood on a laboratory scale?**	No.
5.02	N	**Plant size components available for testing?**	No.
5.03	N	**System interface requirements known (How would system be integrated into the plant?)**	No.
5.04	N	**Preliminary design engineering begins?**	No.
5.05	N	**Requirements for technology verification established?**	No.
5.06	N	**Interfaces between components/subsystems in testing are realistic (bench top with realistic interfaces)?**	No.

Table A.5. Canister cooling and crystallization criteria evaluation.

C#	Y/N	Criteria	Comments
5.07	N	**Prototypes of equipment system components have been created (know how to make equipment)?**	No prototypes made for the yet undefined system.
5.08		Tooling and machines demonstrated in lab for new manufacturing processes to make component?	NA, tooling and machines do not apply to CCC. Canister manufacturing does not require any new equipment.
5.09	N	**High fidelity lab integration of system completed, ready for test in relevant environments?**	No.
5.10		Manufacturing techniques have been defined to the point where largest problems defined?	NA, Manufacturing techniques do not apply to CCC. Canister manufacturing does not require any new equipment.
5.11	N	**Lab-scale, similar system tested with range of simulants?**	No.
5.12	N	**Fidelity of system mock-up improves from laboratory to bench-scale testing?**	No.
5.13	N	**Availability and reliability (RAMI) target levels identified?**	No.
5.14	N	**Some special purpose components combined with available laboratory components for testing?**	No.
5.15	N	**Three dimensional drawings and P&IDs for the prototypical engineering-scale test facility have been prepared?**	No.
5.16	N	**Laboratory environment for testing modified to approximate operational environment?**	No.
5.17	N	**Component integration issues and requirements identified?**	No.
5.18	N	**Detailed design drawings have been completed to support specification of engineering-scale testing system?**	No.
5.19	N	**Requirements definition with performance thresholds and objectives established for final plant design?**	No.
5.20	N	**Preliminary technology feasibility engineering report completed?**	No.
5.21	N	**Integration of modules/functions demonstrated in a laboratory/bench-scale environment?**	No.
5.22	N	**Formal control of all components to be used in final prototypical test system?**	No.
5.23	N	**Configuration management plan in place?**	No.
5.24	N	**The range of all relevant physical and chemical properties has been determined (to the extent possible)?**	No.
5.25	N	**Simulants have been developed that cover the full range of waste properties?**	No.
5.26		Testing has verified that the properties/performance of the simulants match the properties/performance of the actual wastes?	NA, canisters will not be simulated.
5.27	N	**Laboratory-scale tests on the full range of simulants using a prototypical system have been completed?**	No real waste tests.
5.28	N	**Laboratory-scale tests on a limited range of real wastes using a prototypical system have been completed?**	No real waste tests.
5.29		Test results for simulants and real waste are consistent?	NA, real or simulated wastes do not impact CCC.
5.30	N	**Laboratory to engineering scale scale-up issues are understood and resolved?**	No.
5.31	N	**Limits for all process variables/parameters and safety controls are being refined?**	No.
5.32	N	**Test plan for prototypical lab-scale tests executed - results validate design?**	No.
5.33	N	**Test plan documents for prototypical engineering-scale tests completed?**	No.
5.34	N	**Risk management plan documented?**	No.
5.35	N	**Is a program in place to qualify the waste form and production process?**	No.
5.36	N	**Have all relevant physical and chemical properties been sufficiently well determined and bounded to meet proposed disposal criteria?**	No.
5.37	N	**Have the waste impacting process steps been demonstrated to function within acceptable range?**	No.
5.38	N	**Was the transportation and storage package been designed?**	No

Table A.5. Canister cooling and crystallization criteria evaluation.

C#	Y/N	Criteria	Comments
5.39		Have release rate law models been established (for relevant environment(s))?	NA, release rate law does not apply to CCC.
6.01	N	**The relationships between system and sub-system parameters are understood at engineering scale allowing process/design variations and tradeoffs to be evaluated?**	No.
6.02	N	**Availability and reliability (RAMI) levels established?**	No.
6.03	N	**Preliminary design drawings for final plant system are complete?**	No.
6.04	N	**Operating environment for final system known?**	No.
6.05	N	**Collection of actual maintainability, reliability, and supportability data has been started?**	No.
6.06	N	**Performance Baseline (including total project cost, schedule, and scope) has been completed?**	No.
6.07	N	**Operating limits for components determined (from design, safety and environmental compliance)?**	No.
6.08	N	**Operational requirements document available?**	No.
6.09	N	**Off-normal operating responses determined for engineering scale system?**	No.
6.10	N	**System technical interfaces defined?**	No.
6.11	N	**Component integration demonstrated at an engineering scale?**	No.
6.12	N	**Scaling issues that remain are identified and understood. Supporting analysis is complete?**	No.
6.13	N	**Analysis of project timing ensures technology will be available when required?**	No.
6.14	N	**Have established an interface control process?**	No.
6.15	N	**Acquisition program milestones established for start of final design (CD-2)?**	No.
6.16	Y	Critical manufacturing processes prototyped?	Canister manufacturing is a mature technology.
6.17	Y	Most pre-production hardware is available to support fabrication of the system?	Canister manufacturing is a mature technology.
6.18	N	**Engineering feasibility fully demonstrated (e.g., would it work)?**	No.
6.19	Y	Materials, process, design, and integration methods have been employed (e.g., can design be produced?)	Canister manufacturing is a mature technology.
6.20	N	**Technology "system" design specification complete and ready for detailed design?**	No.
6.21	N	**Components are functionally compatible with operational system?**	No.
6.22	N	**Engineering-scale system is high-fidelity functional prototype of operational system?**	No.
6.23	N	**Formal configuration management program defined to control change process?**	No.
6.24	N	**Integration demonstrations have been completed (e.g., construction of testing system)?**	No.
6.25	N	**Final Technical Report on Technology completed?**	No.
6.26	Y	Process and tooling are mature to support fabrication of components/system?	Canister manufacturing is a mature technology.
6.27	N	**Engineering-scale tests on the full range of simulants using a prototypical system have been completed?**	No.
6.28	N	**Engineering to full-scale scale-up issues are understood and resolved?**	No.
6.29	N	**Laboratory and engineering-scale experiments are consistent?**	No.
6.30	N	**Limits for all process variables/parameters and safety controls are defined?**	No.
6.31	N	**Plan for engineering-scale testing executed - results validate design?**	No.
6.32	N	**Production demonstrations are complete (at least one time)?**	No.
6.33		Have the transportation and storage systems been identified?	NA, transportation and storage do not apply to CCC.
6.34	N	**Are performance assessment models available for the form/disposal environment?**	No.
6.35	N	**Has a preliminary performance assessment been done to determine the acceptability of the waste form?**	No.

Table A.6. Canister decon criteria evaluation.*

C#	Y/N	Criteria	Comments
1.01		Back of envelope environment?	
1.02		Physical laws and assumptions used in new technologies defined?	
1.03		Paper studies confirm basic principles?	
1.04		Initial scientific observations reported in journals/conference proceedings/technical reports?	
1.05		Basic scientific principles observed and understood?	
1.06		Know who cares about the technology, e.g., sponsor, funding source, etc.?	
1.07		Research hypothesis formulated?	
1.08		Basic characterization data exists?	
1.09		Know who would perform research and where it would be done?	
2.01		Customer identified?	
2.02		Potential system or components have been identified?	
2.03		Paper studies show that application is feasible?	
2.04		Know what program the technology would support?	
2.05		An apparent theoretical or empirical design solution identified?	
2.06		Basic elements of technology have been identified?	
2.07		Desktop environment (paper studies)?	
2.08		Components of technology have been partially characterized?	
2.09		Performance predictions made for each element?	
2.10		Customer expresses interest in the application?	
2.11		Initial analysis shows what major functions need to be done?	
2.12		Modeling & Simulation only used to verify physical principles?	
2.13		System architecture defined in terms of major functions to be performed?	
2.14		Rigorous analytical studies confirm basic principles?	
2.15		Analytical studies reported in scientific journals/conference proceedings/technical reports?	
2.16		Individual parts of the technology work (No real attempt at integration)?	
2.17		Know what output devices are available?	
2.18		Preliminary strategy to obtain TRL Level 6 developed (e.g., scope, schedule, cost)?	
2.19		Know capabilities and limitations of researchers and research facilities?	
2.20		The scope and scale of the waste problem has been determined?	
2.21		Know what experiments are required (research approach)?	
2.22		Qualitative idea of risk areas (cost, schedule, performance)?	
2.23		Have the range of waste species and waste loading for the waste form been identified?	
2.24		Are the general properties of the waste form well understood and published in peer review journals?	
2.25		Have experiments started with the goal of determining the mechanism for the release of radionuclides?	
3.01		Academic (basic science) environment?	
3.02		Some key process and safety requirements are identified?	
3.03		Predictions of elements of technology capability validated by analytical studies?	
3.04		The basic science has been validated at the laboratory scale?	
3.05		Science known to extent that mathematical and/or computer models and simulations are possible?	
3.06		Preliminary system performance characteristics and measures have been identified and estimated?	

Table A.5. Canister cooling and crystallization criteria evaluation.

C#	Y/N	Criteria	Comments
3.07		Predictions of elements of technology capability validated by Modeling and Simulation (M&S)?	
3.08		No system components, just basic laboratory research equipment to verify physical principles?	
3.09		Laboratory experiments verify feasibility of application?	
3.10		Predictions of elements of technology capability validated by laboratory experiments?	
3.11		Customer representative identified to work with development team?	
3.12		Customer participates in requirements generation?	
3.13		Requirements tracking system defined to manage requirements creep?	
3.14		Key process parameters/variables and associated hazards have begun to be identified?	
3.15		Design techniques have been identified/developed?	
3.16		Paper studies indicate that system components ought to work together?	
3.17		Customer identifies technology need date?	
3.18		Performance metrics for the system are established (What must it do)?	
3.19		Scaling studies have been started?	
3.20		Current manufacturability concepts assessed?	
3.21		Sources of key components for laboratory testing identified?	
3.22		Scientific feasibility fully demonstrated?	
3.23		Analysis of present state of the art shows that technology fills a need?	
3.24		Risk areas identified in general terms?	
3.25		Risk mitigation strategies identified?	
3.26		Rudimentary best value analysis performed for operations?	
3.27		Key physical and chemical properties have been characterized for a number of waste samples?	
3.28		A simulant has been developed that approximates key waste properties?	
3.29		Laboratory scale tests on a simulant have been completed?	
3.30		Specific waste(s) and waste site(s) has (have) been defined?	
3.31		The individual system components have been tested at the laboratory scale?	
3.32		Has the type of disposal environment(s) been defined?	
3.33		Is a general strategy for waste form qualification been developed?	
4.01		Key process variables/parameters been fully identified and preliminary hazard evaluations have been performed?	
4.02		Laboratory components tested are surrogates for system components?	
4.03		Individual components tested in laboratory or by supplier?	
4.04		Subsystems composed of multiple components tested at lab scale using simulants?	
4.05		Modeling & Simulation used to simulate some components and interfaces between components?	
4.06		Overall system requirements for end user’s application are known?	
4.07		Overall system requirements for end user’s application are documented?	
4.08		System performance metrics measuring requirements have been established?	
4.09		Laboratory testing requirements derived from system requirements are established?	
4.10		Available components assembled into laboratory scale system?	
4.11		Laboratory experiments with available components show that they work together?	
4.12		Analysis completed to establish component compatibility (Do components work together)?	

Table A.5. Canister cooling and crystallization criteria evaluation.

C#	Y/N	Criteria	Comments
4.13		Science and Technology Demonstration exit criteria established (S&T targets understood, documented, and agreed to by sponsor)?	
4.14		Technology demonstrates basic functionality in simulated environment?	
4.15		Scalable technology prototypes have been produced (Can components be made bigger than lab scale)?	
4.16		Draft conceptual designs have been documented (system description, process flow diagrams, general arrangement drawings, and material balance)?	
4.17		Equipment scale-up relationships are understood/accounted for in technology development program?	
4.18		Controlled laboratory environment used in testing?	
4.19		Initial cost drivers identified?	
4.20		Integration studies have been started?	
4.21		Formal risk management program initiated?	
4.22		Key manufacturing processes for equipment systems identified?	
4.23		Scaling documents and designs of technology have been completed?	
4.24		Key manufacturing processes assessed in laboratory?	
4.25		Functional process description developed. (Systems/subsystems identified)?	
4.26		Low fidelity technology “system” integration and engineering completed in a lab environment?	
4.27		Mitigation strategies identified to address manufacturability/producibility shortfalls?	
4.28		Key physical and chemical properties have been characterized for a range of wastes?	
4.29		A limited number of simulants have been developed that approximate the range of waste properties?	
4.30		Laboratory-scale tests on a limited range of simulants and real waste have been completed?	
4.31		Process/parameter limits and safety control strategies are being explored?	
4.32		Test plan documents for prototypical lab- scale tests completed?	
4.33		Technology availability dates established?	
4.34		Are current regulations and policy established for disposal of the form?	
4.35		Have waste form affecting process steps been identified?	
4.36		Has a detailed waste qualification plan been documented?	
4.37		Have the range of chemistry and processing parameters for acceptable waste form been identified and documented?	
5.01	Y	The relationships between major system and sub-system parameters are understood on a laboratory scale?	
5.02	Y	Plant size components available for testing?	
5.03	Y	System interface requirements known (How would system be integrated into the plant?)	This is true only for the WTP low activity waste vitrification facility.[96]
5.04		Preliminary design engineering begins?	
5.05	N	**Requirements for technology verification established?**	No.
5.06	Y	Interfaces between components/subsystems in testing are realistic (bench top with realistic interfaces)?	This is true only for the WTP low activity waste vitrification facility.[96]
5.07	Y	Prototypes of equipment system components have been created (know how to make equipment)?	
5.08	N/A	Tooling and machines demonstrated in lab for new manufacturing processes to make component?	NA, tooling does not apply to CD as the equipment are off the shelf.
5.09	N	**High fidelity lab integration of system completed, ready for test in relevant environments?**	No.

Table A.5. Canister cooling and crystallization criteria evaluation.

C#	Y/N	Criteria	Comments
5.10	Y	Manufacturing techniques have been defined to the point where largest problems defined?	
5.11	Y	Lab-scale, similar system tested with range of simulants?	Systems tested with a range of different canisters for different applications. The previous TMP evaluated these.[96]
5.12	N	**Fidelity of system mock-up improves from laboratory to bench-scale testing?**	No.
5.13	Y	Availability and reliability (RAMI) target levels identified?	This is true only for the WTP low activity waste vitrification facility.[96]
5.14	N	**Some special purpose components combined with available laboratory components for testing?**	No.
5.15	Y	Three dimensional drawings and P&IDs for the prototypical engineering-scale test facility have been prepared?	This is true only for the WTP low activity waste vitrification facility.[96]
5.16	Y	Laboratory environment for testing modified to approximate operational environment?	This is true only for the WTP low activity waste vitrification facility.[96]
5.17	N	**Component integration issues and requirements identified?**	No.
5.18	Y	Detailed design drawings have been completed to support specification of engineering-scale testing system?	This is true only for the WTP low activity waste vitrification facility.[96]
5.19	N	**Requirements definition with performance thresholds and objectives established for final plant design?**	No.
5.20	Y	Preliminary technology feasibility engineering report completed?	
5.21	N	**Integration of modules/functions demonstrated in a laboratory/bench-scale environment?**	No.
5.22	Y	Formal control of all components to be used in final prototypical test system?	This is true only for the WTP low activity waste vitrification facility.[96]
5.23	Y	Configuration management plan in place?	This is true only for the WTP low activity waste vitrification facility.[96]
5.24		The range of all relevant physical and chemical properties has been determined (to the extent possible)?	
5.25		Simulants have been developed that cover the full range of waste properties?	
5.26		Testing has verified that the properties/performance of the simulants match the properties/performance of the actual wastes?	
5.27		Laboratory-scale tests on the full range of simulants using a prototypical system have been completed?	
5.28		Laboratory-scale tests on a limited range of real wastes using a prototypical system have been completed?	
5.29		Test results for simulants and real waste are consistent?	
5.30		Laboratory to engineering scale scale-up issues are understood and resolved?	
5.31		Limits for all process variables/parameters and safety controls are being refined?	
5.32		Test plan for prototypical lab-scale tests executed - results validate design?	
5.33		Test plan documents for prototypical engineering-scale tests completed?	
5.34	Y	Risk management plan documented?	This is true only for the WTP low activity waste vitrification facility.[96]
5.35		Is a program in place to qualify the waste form and production process?	
5.36		Have all relevant physical and chemical properties been sufficiently well determined and bounded to meet proposed disposal criteria?	
5.37		Have the waste impacting process steps been demonstrated to function within acceptable range?	
5.38		Was the transportation and storage package been designed?	
5.39		Have release rate law models been established (for relevant environment(s))?	
6.01	N	**The relationships between system and sub-system parameters are understood at engineering scale allowing process/design variations and tradeoffs to be evaluated?**	No.
6.02	Y	Availability and reliability (RAMI) levels established?	This is true only for the WTP low activity waste vitrification facility.[96]
6.03	Y	Preliminary design drawings for final plant system are complete?	This is true only for the WTP low activity waste vitrification facility.[96]
6.04	Y	Operating environment for final system known?	This is true only for the WTP low activity waste vitrification facility.[96]

Table A.5. Canister cooling and crystallization criteria evaluation.

C#	Y/N	Criteria	Comments
6.05	Y	Collection of actual maintainability, reliability, and supportability data has been started?	This is true only for the WTP low activity waste vitrification facility.[96]
6.06		Performance Baseline (including total project cost, schedule, and scope) has been completed?	
6.07	Y	Operating limits for components determined (from design, safety and environmental compliance)?	This is true only for the WTP low activity waste vitrification facility.[96]
6.08	Y	Operational requirements document available?	This is true only for the WTP low activity waste vitrification facility.[96]
6.09	Y	Off-normal operating responses determined for engineering scale system?	This is true only for the WTP low activity waste vitrification facility.[96]
6.10	Y	System technical interfaces defined?	This is true only for the WTP low activity waste vitrification facility.[96]
6.11	N	**Component integration demonstrated at an engineering scale?**	
6.12	Y	Scaling issues that remain are identified and understood. Supporting analysis is complete?	
6.13	Y	Analysis of project timing ensures technology will be available when required?	
6.14	Y	Have established an interface control process?	This is true only for the WTP low activity waste vitrification facility.[96]
6.15	Y	Acquisition program milestones established for start of final design (CD-2)?	This is true only for the WTP low activity waste vitrification facility.[96]
6.16	Y	Critical manufacturing processes prototyped?	
6.17	Y	Most pre-production hardware is available to support fabrication of the system?	
6.18	N	**Engineering feasibility fully demonstrated (e.g., would it work)?**	No.
6.19	Y	Materials, process, design, and integration methods have been employed (e.g., can design be produced?)	
6.20	Y	Technology "system" design specification complete and ready for detailed design?	This is true only for the WTP low activity waste vitrification facility.[96]
6.21	N	**Components are functionally compatible with operational system?**	No.
6.22	N	**Engineering-scale system is high-fidelity functional prototype of operational system?**	No.
6.23	Y	Formal configuration management program defined to control change process?	This is true only for the WTP low activity waste vitrification facility.[96]
6.24	N	**Integration demonstrations have been completed (e.g., construction of testing system)?**	No.
6.25	N	**Final Technical Report on Technology completed?**	No.
6.26	Y	Process and tooling are mature to support fabrication of components/system?	
6.27	N	**Engineering-scale tests on the full range of simulants using a prototypical system have been completed?**	No.
6.28		Engineering to full-scale scale-up issues are understood and resolved?	
6.29		Laboratory and engineering-scale experiments are consistent?	
6.30		Limits for all process variables/parameters and safety controls are defined?	
6.31	N	**Plan for engineering-scale testing executed - results validate design?**	No.
6.32	N	**Production demonstrations are complete (at least one time)?**	No.
6.33		Have the transportation and storage systems been identified?	NA, transportation does not apply to CD.
6.34		Are performance assessment models available for the form/disposal environment?	NA, performance models do not apply to CD.
6.35		Has a preliminary performance assessment been done to determine the acceptability of the waste form?	NA, performance models do not apply to CD.

* A different set of questions were used to evaluate the technology readiness of canister decontamination process. The TMP was developed and reported for Hanford low-activity waste glass canisters.[96]

Table A.7. Planned activity to complete criteria.

C#	Criteria	MSA	FMP	GCF	CCC	CD
1.01	Back of envelope environment?	Y	Y	Y	Y	Y
1.02	Physical laws and assumptions used in new technologies defined?	Y	Y	Y	Y	Y
1.03	Paper studies confirm basic principles?	Y	Y	Y	Y	Y
1.04	Initial scientific observations reported in journals/conference proceedings/technical reports?	Y	Y	Y	Y	Y
1.05	Basic scientific principles observed and understood?	Y	Y	Y	Y	Y
1.06	Know who cares about the technology, e.g., sponsor, funding source, etc.?	Y	Y	Y	Y	Y
1.07	Research hypothesis formulated?	Y	Y	Y	Y	Y
1.08	Basic characterization data exists?	Characterize, estimate, and simulate the wastes to be treated	Y	Y	Y	Y
1.09	Know who would perform research and where it would be done?	Y	Y	Y	Y	Y
2.01	Customer identified?	Y	Y	Y	Y	Y
2.02	Potential system or components have been identified?	Y	Y	Y	Y	Y
2.03	Paper studies show that application is feasible?	Y	Y	Y	Y	Y
2.04	Know what program the technology would support?	Y	Y	Y	Y	Y
2.05	An apparent theoretical or empirical design solution identified?	Y	Y	Y	Y	Y
2.06	Basic elements of technology have been identified?	Y	Y	Y	Y	Y
2.07	Desktop environment (paper studies)?	Preliminary engineering study	Y	Y	Preliminary engineering study	Y
2.08	Components of technology have been partially characterized?	Y	Y	Y	Y	Y
2.09	Performance predictions made for each element?	Preliminary engineering study	Y	Laboratory glass ceramic testing	Preliminary engineering study	Y
2.10	Customer expresses interest in the application?	Y	Y	Y	Y	Y
2.11	Initial analysis shows what major functions need to be done?	Y	Y	Y	Y	Y
2.12	Modeling & Simulation only used to verify physical principles?	Y	Y	Laboratory glass ceramic testing	Preliminary engineering study	Y
2.13	System architecture defined in terms of major functions to be performed?	Y	Y	Laboratory glass ceramic testing	Laboratory glass ceramic testing	Y
2.14	Rigorous analytical studies confirm basic principles?	Test the mixing, sampling, and analyses	Y	Y	Preliminary engineering study	Y
2.15	Analytical studies reported in scientific journals/conference proceedings/technical reports?	Test the mixing, sampling, and analyses	Y	Y	Melter and off-gas tests with simulants	Y
2.16	Individual parts of the technology work (No real attempt at integration)?	Y	Y	Y	Y	Y
2.17	Know what output devices are available?	Y	Y	Y	Y	Y
2.18	Preliminary strategy to obtain TRL Level 6 developed (e.g., scope, schedule, cost)?	TMP	TMP	TMP	TMP	Y
2.19	Know capabilities and limitations of researchers and research facilities?	Y	Y	Y	Y	Y
2.20	The scope and scale of the waste problem has been determined?	Characterize, estimate, and simulate the wastes to be treated	Characterize, estimate, and simulate the wastes to be treated	Characterize, estimate, and simulate the wastes to be treated	Characterize, estimate, and simulate the wastes to be treated	Y
2.21	Know what experiments are required (research approach)?	Y	Y	Y	Y	Y
2.22	Qualitative idea of risk areas (cost, schedule, performance)?	Y	Y	Y	Y	Y
2.23	Have the range of waste species and waste loading for the waste form been identified?	NA	NA	Characterize, estimate, and simulate the wastes to be treated	Characterize, estimate, and simulate the wastes to be treated	Y
2.24	Are the general properties of the waste form well understood and published in peer review journals?	NA	NA	Laboratory glass ceramic testing	Laboratory glass ceramic testing	Y
2.25	Have experiments started with the goal of determining the mechanism for the release of radionuclides?	NA	NA	Y	Y	Y
3.01	Academic (basic science) environment?	Y	Y	Y	Y	Y
3.02	Some key process and safety requirements are identified?	Y	Y	Y	Y	Y
3.03	Predictions of elements of technology capability validated by analytical studies?	Test the mixing, sampling, and analyses	Melter and off-gas tests with simulants	Laboratory glass ceramic testing	Laboratory glass ceramic testing	Y
3.04	The basic science has been validated at the laboratory scale?	Y	Y	Y	Y	Y

Table A.7. Planned activity to complete criteria.

C#	Criteria	MSA	FMP	GCF	CCC	CD
3.05	Science known to extent that mathematical and/or computer models and simulations are possible?	Y	Y	Y	Y	Y
3.06	Preliminary system performance characteristics and measures have been identified and estimated?	Preliminary engineering study	Preliminary engineering study	Preliminary engineering study	Preliminary engineering study	Y
3.07	Predictions of elements of technology capability validated by Modeling and Simulation (M&S)?	Preliminary engineering study	Preliminary engineering study	Laboratory glass ceramic testing	Preliminary engineering study	Y
3.08	No system components, just basic laboratory research equipment to verify physical principles?	Y	Y	Y	Y	Y
3.09	Laboratory experiments verify feasibility of application?	Y	Y	Y	Y	Y
3.10	Predictions of elements of technology capability validated by laboratory experiments?	Test the mixing, sampling, and analyses	Melter and off-gas tests with simulants	Laboratory glass ceramic testing	Canister testing	Y
3.11	Customer representative identified to work with development team?	Y	Y	Y	Y	Y
3.12	Customer participates in requirements generation?	Requirements document	Requirements document	Requirements document	Requirements document	Y
3.13	Requirements tracking system defined to manage requirements creep?	Requirements document	Requirements document	Requirements document	Requirements document	Y
3.14	Key process parameters/variables and associated hazards have begun to be identified?	Y	Y	Y	Y	Y
3.15	Design techniques have been identified/developed?	Y	Y	Y	Y	Y
3.16	Paper studies indicate that system components ought to work together?	Preliminary engineering study	Preliminary engineering study	Preliminary engineering study	Preliminary engineering study	Y
3.17	Customer identifies technology need date?	Y	Y	Y	Y	Y
3.18	Performance metrics for the system are established (What must it do)?	Preliminary engineering study	Requirements document	Requirements document	Requirements document	Y
3.19	Scaling studies have been started?	Preliminary engineering study	Preliminary engineering study	Preliminary engineering study	Preliminary engineering study	Y
3.20	Current manufacturability concepts assessed?	Y	Y	Y	Y	Y
3.21	Sources of key components for laboratory testing identified?	Y	Y	Y	Y	Y
3.22	Scientific feasibility fully demonstrated?	Test the mixing, sampling, and analyses	Melter and off-gas tests with simulants	Laboratory glass ceramic testing	Canister testing	Y
3.23	Analysis of present state of the art shows that technology fills a need?	Y	Y	Y	Y	Y
3.24	Risk areas identified in general terms?	Y	Y	Y	Y	Y
3.25	Risk mitigation strategies identified?	Risk mitigation report	Risk mitigation report	Risk mitigation report	Risk mitigation report	Y
3.26	Rudimentary best value analysis performed for operations?	Preliminary engineering study	Preliminary engineering study	Preliminary engineering study	Preliminary engineering study	Y
3.27	Key physical and chemical properties have been characterized for a number of waste samples?	Characterize, estimate, and simulate the wastes to be treated	Melter and off-gas tests with simulants	Laboratory glass ceramic testing	Not in the cards	Y
3.28	A simulant has been developed that approximates key waste properties?	Characterize, estimate, and simulate the wastes to be treated	Characterize, estimate, and simulate the wastes to be treated	Y	Y	Y
3.29	Laboratory scale tests on a simulant have been completed?	Test the mixing, sampling, and analyses	Melter and off-gas tests with simulants	Y	Y	Y
3.30	Specific waste(s) and waste site(s) has (have) been defined?	Y	Y	Y	Y	Y
3.31	The individual system components have been tested at the laboratory scale?	Y	Y	Y	Y	Y
3.32	Has the type of disposal environment(s) been defined?	NA	NA	Not in the cards	Not in the cards	Y
3.33	Is a general strategy for waste form qualification been developed?	Waste compliance plan	Waste compliance plan	Waste compliance plan	Waste compliance plan	Y
4.01	Key process variables/parameters been fully identified and preliminary hazard evaluations have been performed?	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Y
4.02	Laboratory components tested are surrogates for system components?	Test the mixing, sampling, and analyses	Melter and off-gas tests with simulants	NA	Canister testing	Y
4.03	Individual components tested in laboratory or by supplier?	Y	Y	Y	Y	Y
4.04	Subsystems composed of multiple components tested at lab scale using simulants?	Test the mixing, sampling, and analyses	Melter and off-gas tests with simulants	Laboratory glass ceramic testing	Canister testing	Y
4.05	Modeling & Simulation used to simulate some components and interfaces between components?	Preliminary engineering study	Preliminary engineering study	Y	Preliminary engineering study	Y
4.06	Overall system requirements for end user's application are known?	Requirements document	Requirements document	Requirements document	Requirements document	Y
4.07	Overall system requirements for end user's application are documented?	Preliminary design	Requirements document	Requirements document	Requirements document	Y

Table A.7. Planned activity to complete criteria.

C#	Criteria	MSA	FMP	GCF	CCC	CD
4.08	System performance metrics measuring requirements have been established?	Requirements document	Requirements document	Requirements document	Requirements document	Y
4.09	Laboratory testing requirements derived from system requirements are established?	Requirements document	Requirements document	Requirements document	Requirements document	Y
4.10	Available components assembled into laboratory scale system?	Integrated pilot testing	Integrated pilot testing	NA	Integrated pilot testing	Y
4.11	Laboratory experiments with available components show that they work together?	Integrated pilot testing	Integrated pilot testing	Laboratory glass ceramic testing	Integrated pilot testing	Y
4.12	Analysis completed to establish component compatibility (Do components work together)?	Integrated pilot testing	Integrated pilot testing	Laboratory glass ceramic testing	Integrated pilot testing	Y
4.13	Science and Technology Demonstration exit criteria established (S&T targets understood, documented, and agreed to by sponsor)?	TMP	TMP	TMP	TMP	Y
4.14	Technology demonstrates basic functionality in simulated environment?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Y
4.15	Scalable technology prototypes have been produced (Can components be made bigger than lab scale)?	Y	Y	Y	Y	Y
4.16	Draft conceptual designs have been documented (system description, process flow diagrams, general arrangement drawings, and material balance)?	Preliminary design	Preliminary design	NA	Preliminary design	Y
4.17	Equipment scale-up relationships are understood/accounted for in technology development program?	Test the mixing, sampling, and analyses	Melter and off-gas tests with simulants	NA	Preliminary design	Y
4.18	Controlled laboratory environment used in testing?	Test the mixing, sampling, and analyses	Melter and off-gas tests with simulants	Laboratory glass ceramic testing	Laboratory glass ceramic testing	Y
4.19	Initial cost drivers identified?	Preliminary engineering study	Preliminary engineering study	Preliminary engineering study	Preliminary engineering study	Y
4.20	Integration studies have been started?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Y
4.21	Formal risk management program initiated?	Risk mitigation report	Risk mitigation report	Risk mitigation report	Risk mitigation report	Y
4.22	Key manufacturing processes for equipment systems identified?	Y	Y	NA	Y	Y
4.23	Scaling documents and designs of technology have been completed?	Preliminary design	Preliminary design	NA	Preliminary design	Y
4.24	Key manufacturing processes assessed in laboratory?	NA	NA	NA	Y	Y
4.25	Functional process description developed. (Systems/subsystems identified)?	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Y
4.26	Low fidelity technology "system" integration and engineering completed in a lab environment?	Integrated pilot testing	Integrated pilot testing	Laboratory glass ceramic testing	Canister testing	Y
4.27	Mitigation strategies identified to address manufacturability/producibility shortfalls?	NA	Preliminary design	Y	Y	Y
4.28	Key physical and chemical properties have been characterized for a range of wastes?	Characterize, estimate, and simulate the wastes to be treated	Characterize, estimate, and simulate the wastes to be treated	Laboratory glass ceramic testing	Laboratory glass ceramic testing	Y
4.29	A limited number of simulants have been developed that approximate the range of waste properties?	Test the mixing, sampling, and analyses	Melter and off-gas tests with simulants	Laboratory glass ceramic testing	Laboratory glass ceramic testing	Y
4.30	Laboratory-scale tests on a limited range of simulants and real waste have been completed?	Test the mixing, sampling, and analyses	Not in the cards	Laboratory glass ceramic testing	Laboratory glass ceramic testing	Y
4.31	Process/parameter limits and safety control strategies are being explored?	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Y
4.32	Test plan documents for prototypical lab- scale tests completed?	Test the mixing, sampling, and analyses	Melter and off-gas tests with simulants	Laboratory glass ceramic testing	Canister testing	Y
4.33	Technology availability dates established?	Y	Y	Y	Y	Y
4.34	Are current regulations and policy established for disposal of the form?	NA	NA	Y	NA	Y
4.35	Have waste form affecting process steps been identified?	Y	Y	Y	Y	Y
4.36	Has a detailed waste qualification plan been documented?	Waste Compliance Plan	Waste compliance plan	Waste compliance plan	Waste compliance plan	Y
4.37	Have the range of chemistry and processing parameters for acceptable waste form been identified and documented?	Test the mixing, sampling, and analyses	Melter and off-gas tests with simulants	Laboratory glass ceramic testing	Laboratory glass ceramic testing	Y
5.01	The relationships between major system and sub-system parameters are understood on a laboratory scale?	Integrated pilot testing	Integrated pilot testing	NA	Integrated pilot testing	Y
5.02	Plant size components available for testing?	Test the mixing, sampling, and analyses	Melter and off-gas tests with simulants	NA	Canister testing	Y
5.03	System interface requirements known (How would system be integrated into the plant?)	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Y
5.04	Preliminary design engineering begins?	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Not in list
5.05	Requirements for technology verification established?	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Preliminary design

Table A.7. Planned activity to complete criteria.

C#	Criteria	MSA	FMP	GCF	CCC	CD
5.06	Interfaces between components/subsystems in testing are realistic (bench top with realistic interfaces)?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Y
5.07	Prototypes of equipment system components have been created (know how to make equipment)?	Test the mixing, sampling, and analyses	Melter and off-gas tests with simulants	NA	Canister testing	Y
5.08	Tooling and machines demonstrated in lab for new manufacturing processes to make component?	NA	NA	NA	NA	N/A
5.09	High fidelity lab integration of system completed, ready for test in relevant environments?	Integrated pilot testing	Integrated pilot testing	NA	Integrated pilot testing	Decon testing
5.10	Manufacturing techniques have been defined to the point where largest problems defined?	NA	Y	NA	NA	Y
5.11	Lab-scale, similar system tested with range of simulants?	Integrated pilot testing	Integrated pilot testing	Laboratory glass ceramic testing	Integrated pilot testing	Y
5.12	Fidelity of system mock-up improves from laboratory to bench-scale testing?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing
5.13	Availability and reliability (RAMI) target levels identified?	Preliminary design	Preliminary design	NA	Preliminary design	Y
5.14	Some special purpose components combined with available laboratory components for testing?	Test the mixing, sampling, and analyses	Melter and off-gas tests with simulants	Melter and off-gas tests with simulants	Canister testing	Decon testing
5.15	Three dimensional drawings and P&IDs for the prototypical engineering-scale test facility have been prepared?	Preliminary design	Preliminary design	NA	Preliminary design	Y
5.16	Laboratory environment for testing modified to approximate operational environment?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Y
5.17	Component integration issues and requirements identified?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing
5.18	Detailed design drawings have been completed to support specification of engineering-scale testing system?	Preliminary design	Preliminary design	NA	Preliminary design	Y
5.19	Requirements definition with performance thresholds and objectives established for final plant design?	Requirements document	Requirements document	Requirements document	Requirements document	Requirements document
5.20	Preliminary technology feasibility engineering report completed?	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Y
5.21	Integration of modules/functions demonstrated in a laboratory/bench-scale environment?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing
5.22	Formal control of all components to be used in final prototypical test system?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Y
5.23	Configuration management plan in place?	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Y
5.24	The range of all relevant physical and chemical properties has been determined (to the extent possible)?	Characterize, estimate, and simulate the wastes to be treated	Characterize, estimate, and simulate the wastes to be treated	Laboratory glass ceramic testing	Laboratory glass ceramic testing	Not in list
5.25	Simulants have been developed that cover the full range of waste properties?	Characterize, estimate, and simulate the wastes to be treated	Characterize, estimate, and simulate the wastes to be treated	Characterize, estimate, and simulate the wastes to be treated	Characterize, estimate, and simulate the wastes to be treated	Not in list
5.26	Testing has verified that the properties/performance of the simulants match the properties/performance of the actual wastes?	Characterize, estimate, and simulate the wastes to be treated	Characterize, estimate, and simulate the wastes to be treated	Characterize, estimate, and simulate the wastes to be treated	Characterize, estimate, and simulate the wastes to be treated	Not in list
5.27	Laboratory-scale tests on the full range of simulants using a prototypical system have been completed?	Test the mixing, sampling, and analyses	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Not in list
5.28	Laboratory-scale tests on a limited range of real wastes using a prototypical system have been completed?	Not practical	Not practical	Not practical	Not practical	Not in list
5.29	Test results for simulants and real waste are consistent?	NA	NA	Laboratory glass ceramic testing	Laboratory glass ceramic testing	Not in list
5.30	Laboratory to engineering scale scale-up issues are understood and resolved?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Not in list
5.31	Limits for all process variables/parameters and safety controls are being refined?	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Not in list
5.32	Test plan for prototypical lab-scale tests executed - results validate design?	Integrated pilot testing	Integrated pilot testing	Laboratory glass ceramic testing	Integrated pilot testing	Not in list
5.33	Test plan documents for prototypical engineering-scale tests completed?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Not in list
5.34	Risk management plan documented?	Risk mitigation report	Risk mitigation report	Risk mitigation report	Risk mitigation report	Y
5.35	Is a program in place to qualify the waste form and production process?	Waste Compliance Plan	Waste compliance plan	Waste compliance plan	Waste compliance plan	Not in list
5.36	Have all relevant physical and chemical properties been sufficiently well determined and bounded to meet proposed disposal criteria?	Integrated pilot testing	Integrated pilot testing	Laboratory glass ceramic testing	Laboratory glass ceramic testing	Not in list
5.37	Have the waste impacting process steps been demonstrated to function within acceptable range?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Not in list
5.38	Was the transportation and storage package designed?	NA	NA	NA	Preliminary design	Not in list
5.39	Have release rate law models been established (for relevant environment(s))?	NA	NA	Laboratory glass ceramic testing	Laboratory glass ceramic testing	Not in list

Table A.7. Planned activity to complete criteria.

C#	Criteria	MSA	FMP	GCF	CCC	CD
6.01	The relationships between system and sub-system parameters are understood at engineering scale allowing process/design variations and tradeoffs to be evaluated?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing
6.02	Availability and reliability (RAMI) levels established?	Preliminary design	Preliminary design	NA	Preliminary design	Y
6.03	Preliminary design drawings for final plant system are complete?	Preliminary design	Preliminary design	NA	Preliminary design	Y
6.04	Operating environment for final system known?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Y
6.05	Collection of actual maintainability, reliability, and supportability data has been started?	Preliminary design	Preliminary design	NA	Preliminary design	Y
6.06	Performance Baseline (including total project cost, schedule, and scope) has been completed?	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Not in list
6.07	Operating limits for components determined (from design, safety and environmental compliance)?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Y
6.08	Operational requirements document available?	Requirements document	Requirements document	Requirements document	Requirements document	Y
6.09	Off-normal operating responses determined for engineering scale system?	Preliminary design	Preliminary design	Laboratory glass ceramic testing	Laboratory glass ceramic testing	Y
6.10	System technical interfaces defined?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Y
6.11	Component integration demonstrated at an engineering scale?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing
6.12	Scaling issues that remain are identified and understood. Supporting analysis is complete?	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Y
6.13	Analysis of project timing ensures technology will be available when required?	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Y
6.14	Have established an interface control process?	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Y
6.15	Acquisition program milestones established for start of final design (CD-2)?	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Y
6.16	Critical manufacturing processes prototyped?	Y	Y	NA	Y	Y
6.17	Most pre-production hardware is available to support fabrication of the system?	Y	Y	NA	Y	Y
6.18	Engineering feasibility fully demonstrated (e.g., would it work)?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing
6.19	Materials, process, design, and integration methods have been employed (e.g., can design be produced?)	Y	Y	NA	Y	Y
6.20	Technology “system” design specification complete and ready for detailed design?	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Y
6.21	Components are functionally compatible with operational system?	Integrated pilot testing	Integrated pilot testing	NA	Integrated pilot testing	Integrated pilot testing
6.22	Engineering-scale system is high-fidelity functional prototype of operational system?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing
6.23	Formal configuration management program defined to control change process?	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Y
6.24	Integration demonstrations have been completed (e.g., construction of testing system)?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing
6.25	Final Technical Report on Technology completed?	Preliminary design	Preliminary design	Preliminary design	Preliminary design	Preliminary design
6.26	Process and tooling are mature to support fabrication of components/system?	NA	Y	NA	Y	Y
6.27	Engineering-scale tests on the full range of simulants using a prototypical system have been completed?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing
6.28	Engineering to full-scale scale-up issues are understood and resolved?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Not in list
6.29	Laboratory and engineering-scale experiments are consistent?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Not in list
6.30	Limits for all process variables/parameters and safety controls are defined?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Not in list
6.31	Plan for engineering-scale testing executed - results validate design?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing
6.32	Production demonstrations are complete (at least one time)?	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing	Integrated pilot testing
6.33	Have the transportation and storage systems been identified?	NA	NA	NA	NA	Not in list
6.34	Are performance assessment models available for the form/disposal environment?	NA	NA	NA	NA	Not in list
6.35	Has a preliminary performance assessment been done to determine the acceptability of the waste form?	NA	NA	NA	NA	Not in list

Table A.8. Preliminary activity schedule and budget estimate.

Item	Criteria Satisfied					2012				2013				2014				2015				2016				2017				2018				Budget
Subitem	MSA	FMP	GCF	CCC	CD	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	est, $K
Technology maturation plan	2.18, 4.13	2.18, 4.13	2.18, 4.13	2.18, 4.13	-		x	x																										0
Preliminary engineering study	2.07, 2.09, 3.06, 3.07, 3.16, 3.18, 3.19, 3.26, 4.05, 4.19	3.06, 3.07, 3.16, 3.18, 3.19, 3.26, 4.05, 4.19	3.16, 3.18, 3.19, 3.26, 4.19	2.07, 2.09, 2.12, 2.14, 3.06, 3.07, 3.16, 3.18, 3.19, 3.26, 4.05, 4.19	-					x	x	x																						400
Characterize, estimate, and simulate waste to be treated																																		
Initial waste estimates and simulant recipes	1.08, 2.20, 3.28, 5.25	2.20, 3.28, 5.25	2.20, 2.23, 5.25	2.20, 2.23, 5.25	-					x	x																							50
Actual waste characterization	3.27, 4.28, 5.24	4.28, 5.24			-															x	x							x	x					0
Simulant/actual waste comparisons	5.26	5.26	5.26	5.26	-																	x	x							x	x			30
Laboratory scale glass ceramic testing																																		
Initial reference formulation			2.12			x	x	x																										0
Formulation and testing for initial compositions (incl. LSM)			2.09, 2.13, 2.24, 3.03, 3.10, 3.22, 3.27, 4.04, 4.11, 4.12, 4.18, 4.26, 4.32	2.13, 2.24, 3.03, 4.18								x	x	x	x	x	x	x																800
Preliminary model development (loading and heat models for cost benefit analyses)			3.07															x	x	x	x	x												400
Variability study			4.28, 4.29, 5.11, 5.32	4.28, 4.29, 5.32																				x	x	x	x	x	x	x	x	x	x	3000
Final model development			4.37, 5.24, 6.09	4.37, 5.24, 6.09																														800
Performance evaluation			5.36, 5.39	5.36, 5.39																x	x	x	x	x	x	x	x	x	x	x	x	x	x	2600
Compare actual and simulant			4.30, 5.29	4.30, 5.29																			x	x							x	x		2400
Melter and off-gas testing with simulants																																		
Initial proof of principle			2.15, 3.03, 3.10, 3.29, 4.32	2.15					x	x					x	x																		1200
Scaling tests			3.22, 4.02, 4.17, 5.02															x	x	x	x	x	x	x	x	x	x	x	x					2000
Off-gas functionality			4.04															x	x	x	x	x	x	x	x	x	x	x	x					4000
Variability tests			3.27, 4.29, 4.37															x	x	x	x	x	x	x	x	x	x	x	x					0
Long-term run-by-wire			4.18																							x	x	x	x	x	x			5000
Design data needs			5.07, 5.14																											x	x	x	x	4000
Test the mixing, sampling, and analyses																																		

Table A.8. Preliminary activity schedule and budget estimate.

Item	Criteria Satisfied					2012				2013				2014				2015				2016				2017				2018				Budget
Subitem	MSA	FMP	GCF	CCC	CD	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	est, $K
Preliminary study based on literature search	2.14, 2.15, 3.03										x	x	x																					200
Laboratory scale tests of mixing, sampling, and analyses	3.10, 3.22, 3.29, 4.02, 4.04, 4.17, 4.18, 4.29, 4.30, 4.32, 4.37, 5.02, 5.07, 5.14, 5.27																									x	x	x	x	x	x			3000
Canister testing				3.10, 3.22, 4.02, 4.04, 4.26, 4.32, 5.02, 5.07, 5.14																		x	x	x	x	x	x	x	x	x				2500
Decontamination system testing					5.09, 5.14																										x	x	x	1500
Requirements document																																		
Initial requirements document	3.12, 3.13, 3.18, 4.06, 4.07, 4.08	3.12, 3.13, 3.18, 4.06, 4.07, 4.08	3.12, 3.13, 3.18, 4.06, 4.07, 4.08	3.12, 3.13, 3.18, 4.06, 4.07, 4.08										x	x																			400
Final requirements management system	5.19, 6.08	5.19, 6.08	5.19, 6.08	5.19, 6.08	5.19																													400
Risk management document																																		
Initial risks identification	3.25	3.25	3.25	3.25										x	x																			200
Final risk management system	4.21, 5.34	4.21, 5.34	4.21, 5.34	4.21, 5.34	4.21, 5.34																													600
Preliminary design																																		
Conceptual design	4.01, 4.07, 4.16, 4.23, 4.25, 4.31, 5.03, 5.04, 5.05, 5.13, 5.15, 5.18, 5.20, 5.31	4.01, 4.16, 4.23, 4.25, 4.27, 4.31, 5.03, 5.04, 5.05, 5.13, 5.15, 5.18, 5.20, 5.31	4.01, 4.25, 4.31, 5.03, 5.04, 5.05, 5.20, 5.31	4.01, 4.16, 4.17, 4.23, 4.25, 4.31, 5.03, 5.04, 5.05, 5.13, 5.15, 5.18, 5.20, 5.31	5.05																													2000
Preliminary design	5.23, 6.02, 6.03, 6.05, 6.06, 6.09, 6.12, 6.13, 6.14, 6.15, 6.20, 6.23, 6.25	5.23, 6.02, 6.03, 6.05, 6.06, 6.09, 6.12, 6.13, 6.14, 6.15, 6.20, 6.23, 6.25	5.23, 6.06, 6.12, 6.13, 6.14, 6.15, 6.20, 6.23, 6.25	5.23, 5.38, 6.02, 6.03, 6.05, 6.06, 6.12, 6.13, 6.14, 6.15, 6.20, 6.23, 6.25	6.25																													5000
Integrated pilot testing																																		
Construct test bed	4.10, 4.12, 4.26, 5.17	4.10, 4.12, 4.26, 5.17	5.17	4.10, 4.12, 5.17	5.17																													11000
Shake-out testing (budget in construct)	4.11, 4.14, 4.20, 5.09	4.11, 4.14, 4.20, 5.09	4.14, 4.20	4.11, 4.14, 4.20, 5.09																														0

Table A.8. Preliminary activity schedule and budget estimate.

Item	Criteria Satisfied					2012				2013				2014				2015				2016				2017				2018				Budget
Subitem	MSA	FMP	GCF	CCC	CD	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	est, $K
Design data needs	5.01, 5.06, 5.11, 5.12, 5.16, 5.21, 5.22, 5.30, 5.32, 5.33, 5.36, 5.37, 6.01, 6.04, 6.07, 6.10, 6.11, 6.18, 6.21, 6.22, 6.27, 6.28, 6.29, 6.30, 6.31, 6.32	5.01, 5.06, 5.11, 5.12, 5.16, 5.21, 5.22, 5.27, 5.30, 5.32, 5.33, 5.36, 5.37, 6.01, 6.04, 6.07, 6.10, 6.11, 6.18, 6.21, 6.22, 6.27, 6.28, 6.29, 6.30, 6.31, 6.32	5.06, 5.12, 5.16, 5.21, 5.22, 5.27, 5.30, 5.33, 5.37, 6.01, 6.04, 6.07, 6.10, 6.11, 6.18, 6.21, 6.22, 6.27, 6.28, 6.29, 6.30, 6.31, 6.32	5.01, 5.06, 5.11, 5.12, 5.16, 5.21, 5.22, 5.27, 5.30, 5.32, 5.33, 5.37, 6.01, 6.04, 6.07, 6.10, 6.11, 6.18, 6.21, 6.22, 6.27, 6.28, 6.29, 6.30, 6.31, 6.32	5.12, 5.21, 6.01, 6.11, 6.18, 6.21, 6.22, 6.27, 6.31, 6.32																													33000
Waste compliance plan																																		
Develop waste qualification strategy	3.33	3.33	3.33	3.33	3.33								x	x																				200
Issue WCP	4.36, 5.35	4.36, 5.35	4.36, 5.35	4.36, 5.35	4.36, 5.35																													600
Technology maturation plan	2.18, 4.13	2.18, 4.13	2.18, 4.13	2.18, 4.13	-																													0
Preliminary engineering study	2.07, 2.09, 3.06, 3.07, 3.16, 3.18, 3.19, 3.26, 4.05, 4.19	3.06, 3.07, 3.16, 3.18, 3.19, 3.26, 4.05, 4.19	3.16, 3.18, 3.19, 3.26, 4.19	2.07, 2.09, 2.12, 2.14, 3.06, 3.07, 3.16, 3.18, 3.19, 3.26, 4.05, 4.19	-																													400
Characterize, estimate, and simulate waste to be treated																																		
Initial waste estimates and simulant recipes	1.08, 2.20, 3.28, 5.25	2.20, 3.28, 5.25	2.20, 2.23, 5.25	2.20, 2.23, 5.25	-																													50
Actual waste characterization	3.27, 4.28, 5.24	4.28, 5.24			-			x	x																									0
Simulant/actual waste comparisons	5.26	5.26	5.26	5.26	-					x	x																							30
Laboratory scale glass ceramic testing																																		
Initial Reference formulation			2.12																															0
Formulation and testing for initial compositions (incl. LSM)			2.09, 2.13, 2.24, 3.03, 3.10, 3.22, 3.27, 4.04, 4.11, 4.12, 4.18, 4.26, 4.32	2.13, 2.24, 3.03, 4.18																														800
Preliminary model development (loading and heat models for cost benefit analyses)			3.07																															400
Variability study			4.28, 4.29, 5.11, 5.32	4.28, 4.29, 5.32		x	x																											3000
Final model development			4.37, 5.24, 6.09	4.37, 5.24, 6.09		x	x	x	x	x	x	x	x																					800

Table A.8. Preliminary activity schedule and budget estimate.

Item	Criteria Satisfied					2012				2013				2014				2015				2016				2017				2018				Budget
Subitem	MSA	FMP	GCF	CCC	CD	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	est, $K
Performance evaluation			5.36, 5.39	5.36, 5.39		x	x	x	x	x	x	x	x	x	x	x	x																	2600
Compare actual and simulant			4.30, 5.29	4.30, 5.29							x	x																						2400
Melter and off-gas testing with simulants																																		
Initial proof of principle			2.15, 3.03, 3.10, 3.29, 4.32	2.15																														1200
Scaling tests			3.22, 4.02, 4.17, 5.02																															2000
Off-gas functionality			4.04																															4000
Variability tests			3.27, 4.29, 4.37																															0
Long-term run-by-wire			4.18																															5000
Design data needs			5.07, 5.14			x	x	x	x																									4000
Test the mixing, sampling, and analyses																																		
Preliminary study based on literature search	2.14, 2.15, 3.03																																	200
Laboratory scale tests of mixing, sampling, and analyses	3.10, 3.22, 3.29, 4.02, 4.04, 4.17, 4.18, 4.29, 4.30, 4.32, 4.37, 5.02, 5.07, 5.14, 5.27																																	3000
Canister testing				3.10, 3.22, 4.02, 4.04, 4.26, 4.32, 5.02, 5.07, 5.14																														2500
Decontamination system testing					5.09, 5.14	x	x	x																										1500
Requirements document																																		
Initial requirements document	3.12, 3.13, 3.18, 4.06, 4.07, 4.08	3.12, 3.13, 3.18, 4.06, 4.07, 4.08	3.12, 3.13, 3.18, 4.06, 4.07, 4.08	3.12, 3.13, 3.18, 4.06, 4.07, 4.08																														400
Final requirements management system	5.19, 6.08	5.19, 6.08	5.19, 6.08	5.19, 6.08	5.19					x	x	x																						400
Risk management document																																		
Initial risks identification	3.25	3.25	3.25	3.25																														200
Final risk management system	4.21, 5.34	4.21, 5.34	4.21, 5.34	4.21, 5.34	4.21, 5.34					x	x	x																						600
Preliminary design																																		
Conceptual design	4.01, 4.07, 4.16, 4.23, 4.25, 4.31, 5.03, 5.04, 5.05, 5.13, 5.15, 5.18, 5.20, 5.31	4.01, 4.16, 4.23, 4.25, 4.27, 4.31, 5.03, 5.04, 5.05, 5.13, 5.15, 5.18, 5.20, 5.31	4.01, 4.25, 4.31, 5.03, 5.04, 5.05, 5.20, 5.31	4.01, 4.16, 4.17, 4.23, 4.25, 4.31, 5.03, 5.04, 5.05, 5.13, 5.15, 5.18, 5.20, 5.31	5.05	x	x	x	x	x	x	x	x																					2000

Table A.8. Preliminary activity schedule and budget estimate.

Item	Criteria Satisfied					2012				2013				2014				2015				2016				2017				2018				Budget
Subitem	MSA	FMP	GCF	CCC	CD	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	q1	q2	q3	q4	est, $K
Preliminary design	5.23, 6.02, 6.03, 6.05, 6.06, 6.09, 6.12, 6.13, 6.14, 6.15, 6.20, 6.23, 6.25	5.23, 6.02, 6.03, 6.05, 6.06, 6.09, 6.12, 6.13, 6.14, 6.15, 6.20, 6.23, 6.25	5.23, 6.06, 6.12, 6.13, 6.14, 6.15, 6.20, 6.23, 6.25	5.23, 5.38, 6.02, 6.03, 6.05, 6.06, 6.12, 6.13, 6.14, 6.15, 6.20, 6.23, 6.25	6.25									x	x	x	x	x	x	x	x	x	x	x	x									5000
Integrated pilot testing																																		
Construct test bed	4.10, 4.12, 4.26, 5.17	4.10, 4.12, 4.26, 5.17	5.17	4.10, 4.12, 5.17	5.17					x	x	x	x																					11000
Shake-out testing (budget in construct)	4.11, 4.14, 4.20, 5.09	4.11, 4.14, 4.20, 5.09	4.14, 4.20	4.11, 4.14, 4.20, 5.09									x	x																				0
Design data needs	5.01, 5.06, 5.11, 5.12, 5.16, 5.21, 5.22, 5.30, 5.32, 5.33, 5.36, 5.37, 6.01, 6.04, 6.07, 6.10, 6.11, 6.18, 6.21, 6.22, 6.27, 6.28, 6.29, 6.30, 6.31, 6.32	5.01, 5.06, 5.11, 5.12, 5.16, 5.21, 5.22, 5.27, 5.30, 5.32, 5.33, 5.36, 5.37, 6.01, 6.04, 6.07, 6.10, 6.11, 6.18, 6.21, 6.22, 6.27, 6.28, 6.29, 6.30, 6.31, 6.32	5.06, 5.12, 5.16, 5.21, 5.22, 5.27, 5.30, 5.33, 5.37, 6.01, 6.04, 6.07, 6.10, 6.11, 6.18, 6.21, 6.22, 6.27, 6.28, 6.29, 6.30, 6.31, 6.32	5.01, 5.06, 5.11, 5.12, 5.16, 5.21, 5.22, 5.27, 5.30, 5.32, 5.33, 5.37, 6.01, 6.04, 6.07, 6.10, 6.11, 6.18, 6.21, 6.22, 6.27, 6.28, 6.29, 6.30, 6.31, 6.32	5.12, 5.21, 6.01, 6.11, 6.18, 6.21, 6.22, 6.27, 6.31, 6.32										x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	33000
Waste compliance plan																																		
Develop waste qualification strategy	3.33	3.33	3.33	3.33	3.33																													200
Issue WCP	4.36, 5.35	4.36, 5.35	4.36, 5.35	4.36, 5.35	4.36, 5.35																x	x	x	x										600

A.1 Appendix References

1. Crowe, C., M. Sommerfield, and Y. Tsuji, *Multiphase Flows with Droplets and Particles*. 1998, New York, NY: CRC Press.
2. Wells, B.E., P.A. Gauglitz, and D.R. Rector, *Comparison of Waste Feed Delivery Small Scale Mixing Demonstration Simulant to Hanford Waste*, 2011, Pacific Northwest National Laboratory: Richland, WA.
3. Rector, D.R., M.L. Stewart, and A.P. Poloski, *Modeling of Sediment Bed Behavior for Critical Velocity in Horizontal Piping*, in *Waste Management 2009*2009 WM Symposia, Inc.: Phoenix, AZ.
4. Poloski, A.P., et al., *Deposition Velocities of Newtonian and Non-Newtonian Slurries in Pipelines*, 2009, Pacific Northwest National Laboratory: Richland, WA.
5. Poloski, A.P., et al., *Estimate of Hanford Waste Rheology and Settling Behavior*, 2007, Pacific Northwest National Laboratory: Richland, WA.
6. Meacham, J.E., et al., *Evaluation of Waste Transferred to the Waste Treatment Plant*, 2012, Washington River Protection Solutions: Richland, WA.
7. Paul, E.L., V.A. Atiemo-Obeng, and S.M. Kresta, *Handbook of Industrial Mixing*. 2004, Hoboken, NJ: John Wiley and Sons, Inc.
8. Derksen, J. and H.E.A. Van der Akker, *Large Eddy Simulations on the Flow Driven by a Rushton Turbine.* AIChE J., 1999. **45**(2): p. 209-221.
9. Zwieterung, T.N., *Suspending of solid particles in liquid by agitators.* Chem. Eng. Sci., 1958. **8**: p. 244-253.
10. Baldi, G., R. Conti, and E. Alaria, *Complete suspension of particles in mechanically agitated vessels.* Chem. Eng. Sci., 1978. **33**: p. 21-25.
11. Rector, D.R. and M.L. Stewart, *A Semi-Implicit Lattice Method for Simulating Flow.* Journal of Computational Physics, 2010. **229**(19): p. 6732-6743.
12. Barnes, S.M., *WVDP Waste Form Qualification Report*, 1996, West Valley Nuclear Services: West Valley, NY.
13. Barnes, J.L., *DWPF Waste Form Compliance Plan (U)*, 2003, Westinghouse Savannah River Company: Aiken, SC.
14. Vienna, J.D., T.A. Todd, and M.E. Peterson, *Separations and Waste Forms Campaign Implementation Plan*, 2012, U.S. Department of Energy, Office of Nuclear Energy: Idaho Falls, ID.
15. Diener, G.A., et al., *Pretreated Waste and Melter Feed Composition Variability Testing using HLW Simulants*, 2009, Vitreous State Laboratory at the Catholic University of America: Washington, D.C.
16. Studd, M.G., *System Description, Vitrification Facility Sampling*, 1997, West Valley Nuclear Services: West Valley, NY.
17. ASTM, *Standard Guide for Characterization of Radioactive and/or Hazardous Wastes for Thermal Treatment*, 2012, ASTM International: West Conshohocken, PA.
18. Hull, H.L. and H.R. Zeitlin, *A Design and Cost Estimate Study of a PUREX Plant*, 1959, Oak Ridge National Laboratory: Oak Ridge, TN.
19. Petkus, L.L., *Evaluation of Mixing, Sampling, and Level Uncertianties for ILAW Glass Qualification*, 2012, River Protection Project, Hanford Tank Waste Treatment and Immobilization Plant: Richland, WA.
20. Meyer, P.A., et al., *Pulse Jet Mixing Tests With Noncohesive Solids*, 2008, Pacific Northwest National Laboratory: Richland, WA.
21. Rosendall, B., *Simulating pulse jet mixing in nuclear waste.* Radwaste Solutions, 2008. **15**(3): p. 52-56.
22. Takahashi, K., H. Fujita, and T. Yokota, *Effect of size of spherical particle on complete suspension speed in agitated vessels of different scale.* J. Chem. Eng. Japan, 1993. **26**: p. 98-100.
23. DOE, *Research Objective 3 Implementation Plan: Developing Sustainable Fuel Cycle Options*, 2010, U.S. Department of Energy, Office of Nuclear Energy: Washington, D.C.
24. Riley, B.J., et al., *FY09 AFCI Quartz Crucible Scale Melter Tests*, 2009, Pacific Northwest National Laboratory: Richland, WA.
25. Crum, J.V., et al., *Baseline Glass Development for Combined Fission Products Waste Streams*, 2009, Pacific Northwest National Laboratory: Richland, WA.
26. Nelson, J.L. and J.D. Vienna, *IHLW Waste Form Compliance Plan for the Hanford Tank Waste Treatment and Immobilization Plant*, 2008, River Protection Project, Hanford Tank Waste Treatment and Immobilization Plant: Richland, WA.
27. Maio, V., V. Rutledge, and B. Benefiel, *Test Plan for Demonstrating the Immobilization and Processability of a Simulated Future HLW Raffinate into a Glass Ceramic Waste Form Using INL's Bench Scale CCIM*, 2012, Idaho National Laboratory: Idaho Falls, ID.
28. Matsuo, T., T. Kondou, and K. Ueda, *Electrical properties and melting treatment rate of a continuous induction waste melter.* ISIJ International, 1999. **39**(4): p. 388-395.
29. Gombert, D. and J.R. Richardson, *Cold-crucible induction melter design and development.* Nuclear Technology, 2003. **141**(3): p. 301-308.
30. Ladirat, C., et al., *Advanced Cold Crucible Melter Pilot Plant Characteristics and First Results on HLLW Surrogates*, in *Waste Management 2004*2004: Tucson, AZ. p. 4223.
31. Sugilal, G., *Experimental analysis of the performance of cold crucible induction glass melter.* Applied Thermal Engineering, 2008. **28**(14-15): p. 1952-1961.
32. Sugilal, G., *Experimental study of natural convection in a glass pool inside a cold crucible induction melter.* International Journal of Thermal Sciences, 2008. **47**(7): p. 918-925.
33. Bonnetier, A., *Nuclear waste immobilization by vitrification in a cold crucible melter: 3D magnetic model of a melter*, in *Scientific Basis for Nuclear Waste Management XXXI*2008, Materials Research Society. p. 191-198.
34. Elliott, M.L., et al., *Hanford High-Level Waste Melter System Evaluation Data Package*, 1996, Pacific Northwest National Laboratory: Richaland, WA.
35. Ahearne, J.F., et al., *High-Level Waste Melter Review Report*, 2001, U.S. Department of Energy, Office of Environmental Management: Washington, D.C.
36. Perez, J.M., et al., *High-Level Waste Melter Study Report*, 2001, Pacific Northwest National Laboratory: Richland, WA.
37. Jain, V., *Survey of Waste Solidification Process Technologies*, 2001, U.S. Nuclear Regulatory Commission: Washington, D.C.
38. Jouan, A., et al., *The cold crucible melter: High-performance waste vitrification.* Environmental Issues and Waste Management Technologies in the Ceramic and Nuclear Industries Vii, 2002. **132**: p. 181-188.
39. Kushnikov, V.V., et al., *Use of induction melter with a cold crucible (CCIM) for HLLW and plutonium immobilization*, in *Scientific Basis for Nuclear Waste Management XX*1997, Materials Research Society. p. 55-64.
40. Demine, A.V., et al., *High level liquid waste solidification using a "cold" crucible induction melter*, in *Scientific Basis for Nuclear Waste Management XXIV*2000, Materials Research Society. p. 27-33.
41. Herman, C.C., et al., *Cold crucible induction-heated melter test results with surrogate DOE high-level wastes*, in *Environmental Issues and Waste Management Technologies in the Ceramic & Nuclear Industries IX*2004. p. 239-248.
42. Aloy, A.S., et al., *Iron-phosphate glass (IPG) waste forms produced using induction melter with cold crucible*, in *Scientific Basis for Nuclear Waste Management XXVII*2004, Materials Research Society. p. 187-192.
43. Kobelev, A.P., et al., *Maximizing Waste Loading for Application to Savannah River High Level Waste - 2006 & 2007 Scope: CCIM Testing to Demonstrate Maximized Waste Loading with SB2*, 2006, SIA Radon: Moscow, Russia.
44. Kobelev, A.P., et al., *Cold crucible vitrification of defense waste surrogate and vitrified product characterization*, in *Scientific Basis for Nuclear Waste Management XXIX*2006, Materials Research Society. p. 353-360.
45. Smith, M.E., et al., *NETEC Cold Crucible Induction Melter Demonstration for SRNL with Simulated Sludge Batch 4 DWPF Waste*, in *Ceramic Transactions*2009, American Ceramic Society. p. 29-37.
46. VEYER, C., M. DELAUNAY, and A. LEDOUX, *Vitrification of a representative simulated SB4 sludge in a CCIM pilot platform at Marcoule – Demonstration report*, 2009, Commissariat à l'énergie atomique (CEA): Marcoule, France.
47. Kobelev, A.P., et al., *Cold Crucible Vitrification of SRS SB4 HLW Surrogate at High Waste Loadings.* Advances in Materials Science for Environmental and Nuclear Technology, 2010. **222**: p. 91-103.
48. Marra, J., et al., *The Results of Testing to Evaluate Crystal Formation and Settling in the Cold Crucible Induction Melter*, in *12th International Conference on Environmental Remediation and Radioactive Waste Management 2009*2010. p. 851-857.

49. Lebedev, V., et al., *Adaptation of Ccim Technology for Hlw Treatment: Results of Research and Development*, in *13th International Conference on Environmental Remediation and Radioactive Waste Management*2011. p. 491-495.
50. Robert, S., et al., *A Milestone in Vitrification - the Replacement of a "Hot Metallic Crucible" with a "Cold Crucible Melter" in a Hot Cell at the La Hague Plant, France*, in *Proceedings of the 13th International Conference on Environmental Remediation and Radioactive Waste Management*2011. p. 399-406.
51. Naline, S., et al., *Vitrification 2010 - A Challenging French Vitrification Project to Retrofit a Cold Crucible Inductive Melter at the LaHague Plant*, in *Waste Management 2010*2010. p. 10382.
52. Gombert, D., et al., *Global Nuclear Energy Partnership Integrated Waste Management Strategy Waste Treatment Baseline Study*, 2007, Idaho National Laboratory: Idaho Falls, ID.
53. Fort, J., M. Garnich, and N. Klymyshyn, *Electromagnetic and thermal-flow modeling of a cold-wall crucible induction melter.* Metallurgical and Materials Transactions B-Process Metallurgy and Materials Processing Science, 2005. **36**(1): p. 141-152.
54. Hawkes, G., *Modeling a Cold Crucible Induction Heated Melter*, 2003, Idaho National Engineering and Environmental Laboratory: Idaho Falls, ID.
55. Jacoutot, L., et al., *Numerical modeling of coupled phenomena in a mechanically stirred molten-glass bath heated by induction.* Chemical Engineering Science, 2008. **63**(9): p. 2391-2401.
56. Hrma, P., et al., *EFFECT OF GLASS-BATCH MAKEUP ON THE MELTING PROCESS.* Ceramics-Silikaty, 2010. **54**(3): p. 193-211.
57. Pokorny, R., D.A. Pierce, and P. Hrma, *Melting of glass batch: Model for multiple overlapping gas-evolving reactions.* Thermochimica Acta, 2012. **541**: p. 8-14.
58. Pokorny, R. and P.R. Hrma, *Mathematical Model of Cold Cap—Preliminary One-Dimensional Model Development*, 2011, Pacific Northwest National Laboratory: Richland, WA.
59. Advocat, T., et al., *Alteration of cold crucible melter titanate-based ceramics: Comparison with hot-pressed titanate-based ceramic*, in *Scientific Basis for Nuclear Waste Management XX*1997, Materials Research Society: Boston, MA. p. 355-362.
60. Demin, A.V. and Y.I. Matyunin, *Investigation of the behavior of platinum-group elements during vitrification of model high-level wastes in application to an induction melter with a cold crucible.* Atomic Energy, 1995. **79**(1): p. 443-446.
61. Laverov, N.P., et al., *Murataite as a universal matrix for immobilization of actinides.* Geology of Ore Deposits, 2006. **48**(5): p. 335-356.
62. Nacke, B., et al., *Induction skull melting of oxides and glasses in a cold crucible.* Magnetohydrodynamics, 2007. **43**(2): p. 205-212.
63. Smelova, T.V., N.V. Krylova, and I.N. Shestoperov, *Synthetic mineral-like matrices for HLLW solidification: Preparation by induction melter with a cold crucible (CCIM)*, in *Scientific Basis for Nuclear Waste Management XX*1997, Materials Research Society. p. 425-431.
64. Stefanovsky, S.V., B.S. Nikonov, and J.C. Marra, *Characterization of the glass-ceramic material prepared upon vitrification of an iron-containing surrogate of high-level wastes in a cold crucible.* Glass Physics and Chemistry, 2007. **33**(6): p. 576-586.
65. Kobelev, A.P., et al., *Vitrification of a High-Level Iron-Aluminate Wastes Simulator in a Cold Crucible.* Atomic Energy, 2010. **108**(1): p. 33-39.
66. Kobelev, A.P., et al., *Vitrification of a simulator of Savannah River site (USA) wastes with high iron and aluminum content on bench and commercial facilities with a cold crucible.* Atomic Energy, 2008. **104**(5): p. 381-386.
67. Kobelev, A.P., et al., *Full-Scale Cold Crucible Test on Vitrification of Savannah River Site SB4 HLW Surrogate*, in *Environmental Issues and Waste Management Technologies in the Materials and Nuclear Industries XII*2009. p. 9-20.
68. Stefanovsky, S., et al., *Cold Crucible Vitrification of SRS SB4 Waste at High Waste Loadings*, in *12th International Conference on Environmental Remediation and Radioactive Waste Management 2009*2010. p. 843-849.
69. Crum, J.V., et al., *Glass Ceramic Waste Forms for Combined CS+LN+TM Fission Products Waste Streams*, 2010, Pacific Northwest National Laboratory: Richland, WA.
70. Naline, S., et al., *Cold crucible retrofit.* Nuclear Engineering International, 2011. **56**(679): p. 13.
71. Crum, J.V., et al., *Glass Ceramic Formulation Data Package*, 2012, Pacific Northwest National Laboratory: Richland, WA.
72. Crum, J.V., et al., *Multi-Phase Glass-Ceramics as a Waste Form for Combined Fission Products: Alkalis, Alkaline Earths, Lanthanides, and Transition Metals.* Journal of the American Ceramic Society, 2012. **95**(4): p. 1297-1303.
73. Gombert, D., et al., *Global Nuclear Energy Partnership Waste Treatment Baseline*, in *Atalante 2008*2008: Marcoule, France.
74. Gombert, D., et al., *Combined Waste Form Cost Trade Study*, 2008, Idaho National Laboratory: Idaho Falls, ID.
75. Kobelev, A.P., et al., *Vitrification of a surrogate for high-level wastes from the Savannah River facility (USA) in a commercial cold-crucible facility.* Atomic Energy, 2007. **102**(5): p. 369-374.
76. Song, M.-J., *The vitrified solution.* Nuclear Engineering International, 2003. **48**(583): p. 22-24.
77. Juoi, J.M., M.I. Ojovan, and W.E. Lee, *Microstructure and leaching durability of glass composite wasteforms for spent clinoptilolite immobilisation.* Journal of Nuclear Materials, 2008. **372**(2-3): p. 358-366.
78. Ojovan, M.I. and W.E. Lee, *Glassy wasteforms for nuclear waste immobilisation.* Metallurgical and Materials Transactions A, 2011. **42**(4): p. 837-851.
79. McMillan, P.W., *Glass-Ceramics*. 1979, New York, NY: Academic Press.
80. Höland, W. and G. Beall, *Glass-Ceramic Technology*. 2002, Westerville, OH: The American Ceramic Society.
81. Kingery, W.D., H.K. Bowen, and D.R. Uhlmann, *Introduction to ceramics*. 1976, New York, NY: Wiley.
82. Simmons, J.H., D.R. Uhlmann, and G.H. Beall, *Nucleation and Crystallization in Glasses*. Advances in Ceramics. Vol. 4. 1982, Columbus, OH: American Ceramic Society.
83. Lutze, W. and R.C. Ewing, *Radioactive Waste Forms for the Future*. 1988, Amsterdam, The Netherlands: North-Holland Publishing.
84. Juoi, J.M. and M.I. Ojovan, *The effect of waste loading on the microstructure of glass composite waste forms for the immobilisation of spent clinoptilolite.* Glass Technology-European Journal of Glass Science and Technology Part A, 2007. **48**(3): p. 124-129.
85. Taurines, T. and B. Boizot, *Microstructure of Powellite-Rich Glass-Ceramics: A Model System for High Level Waste Immobilization.* Journal of the American Ceramic Society, 2012. **95**(3): p. 1105-1111.
86. Bernardo, E., et al., *Fast-Sintered Gehlenite Glass-Ceramics from Plasma-Vitrified Municipal Solid Waste Incinerator Fly Ashes.* Journal of the American Ceramic Society, 2009. **92**(2): p. 528-530.
87. Loiseau, P. and D. Caurant, *Glass-ceramic nuclear waste forms obtained by crystallization of SiO2-Al2O3-CaO-ZrO2-TiO2 glasses containing lanthanides (Ce, Nd, Eu, Gd, Yb) and actinides (Th): Study of the crystallization from the surface.* Journal of Nuclear Materials, 2010. **402**(1): p. 38-54.
88. Tamburello, D.A., *Predicting Temperatures for AFCI Canistered Waste Glasses*, J.C. Marra, Editor 2009, Savannah River National Laboratory: Aiken, SC.
89. Holton, L.K., et al., *Processing summary report: Fabrication of cesium and strontium heat and radiation sources*, 1989 Pacific Northwest Laboratory: Richland, WA.
90. Petkus, L.L., *Low Activity Container Centerline Cooling Data*, C.A. Musick, Editor 2003, River Protection Project, Hanford Tank Waste Treatment and Immobilization Plant: Richland, WA.
91. Petkus, L.L., *Canister Centerline Cooling Data, Revision 1*, C.A. Musick, Editor 2003, River Protection Project, Hanford Tank Waste Treatment and Immobilization Plant: Richland, WA.
92. Lee, L., *Thermal Analysis of DWPF Canister During Pouring and Cooldown*, 1989, Savannah River Laboratory: Aiken, SC.
93. Edwards, R.E., *SGM Run 8 - Canister and Glass Temperature During Filling and Cooldown*, 1987, Savannah River Laboratory: Aiken, SC.
94. Pellarin, D.J., *DWPF Canister and Glass Temperatures During Filling and Cooldown*, 1985, Savannah River Laboratory, E.I. du Pont de Nemours and Co.: Aiken, SC.
95. Dubé, M., et al., *Modeling of thermal shock-induced damage in a borosilicate glass.* Mechanics of Materials, 2010. **42**(9): p. 863-872.
96. Holton, L., et al., *Technology Readiness Assessment for the Waste Treatment and Immobilization Plant (WTP) Analytical Laboratory, Balance of Facilities and LAW Waste Vitrification Facilities*, 2007, U.S. Department of Energy, Office of River Protection: Richland, WA.