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

Fuel Cycle Research & Development

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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

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LAW	low-activity waste
LETI	Leningrad Electrotechnical Institute (now Electrotechnical University of St. Petersburg)
М	manufacturing
MOF	metal-organic-framework
MSA	mixing, sampling, and analyses
ORR	operation readiness review
Р	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
Т	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

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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).

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

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

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. <u>Identifying critical technology elements (CTEs)</u>. 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. <u>Assessing the technology readiness level (TRL)</u>. 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. <u>Developing a technology maturation plan (TMP)</u>. 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.

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.

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

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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 I	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.

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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.

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 meltersCalciner 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 coolingControlled cooling with furnaceCooling, then controlled heating with furnace
Canister	• 2'\oplus × 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'\overline × 10') LaHague canister (1.4'\overline × 4.4')
Canister handling	 Arc-welded lid CO₂ 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

Table 3. Summary of reference process components.

Function	Reference Option	Reason for Selection	Other Options Considered
deposit buildup at melter gas outlet		• Demonstrated at WVDP, DWPF, and WTP.	Feed calcinerClose-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.	NOxIDIZERSCO.
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 WasteProcessing Facility; EVS = ejector venturi scrubber; GAC = granular activated carbon; HEME = high-efficiency mist eliminator; HEPA = high-efficiencyparticulate air; HWIM = hot-walled induction melter; JHCM = Joule-heated ceramic melter; MOF = metal-organic-framework; PIC = products ofincomplete 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 ValleyDemonstration 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 (Na₂O₂, LiBO₂, 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 RuO₂, PdO, and Rh₂O₃) (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 Set 1 – Criteria	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
Does the technology directly impact a functional	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
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?	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	Ν	N	N	N	N	N	N	N	N	N	N	N	N	N	N	Ν
Are there uncertainties in the definition of the end state requirements for this technology?	N	Ν	N	N	Ν	Y	N	N	N	N	N	N	N	N	N	N	N	N	N	Ν
Set 2 – Criteria																				
Is the technology new or novel?	Ν	N	Ν	Ν	N	Y	Ν	Ν	Ν	N	N	N	Ν	Ν	Ν	Ν	Ν	Ν	Ν	Ν
Is the technology modified?	Ν	Ν	Ν	Ν	Ν	Y	Y	Ν	Ν	Ν	Ν	Ν	Ν	Ν	Ν	Ν	Ν	Ν	Ν	Ν
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	Ν
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	Ν	Y	Ν	Y	Y	Y	Y	Ν	Ν	Ν	Ν	Ν	Ν	Ν	Ν	Ν	Ν	Ν	Y	Ν

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 (CO₂) 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 CO₂ 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.

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.								

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

*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.

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			$\begin{array}{c} 2.09, 2.12,\\ 2.13, 2.24,\\ 3.03, 3.07,\\ 3.10, 3.22,\\ 3.27, 4.04,\\ 4.11, 4.12,\\ 4.18, 4.26,\\ 4.28, 4.29,\\ 4.30, 4.32,\\ 4.37, 5.11,\\ 5.24, 5.29,\\ 5.32, 5.36,\\ 5.39, 6.09\end{array}$	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	

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

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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	$\begin{array}{r} 4.01, 4.07, \\ 4.16, 4.23, \\ 4.25, 4.31, \\ 5.03, 5.04, \\ 5.05, 5.13, \\ 5.15, 5.18, \\ 5.20, 5.23, \\ 5.31, 6.02, \\ 6.03, 6.05, \\ 6.06, 6.09, \\ 6.12, 6.13, \\ 6.14, 6.15, \\ 6.20, 6.23, \\ 6.25 \end{array}$	$\begin{array}{r} 4.01, 4.16, \\ 4.23, 4.25, \\ 4.27, 4.31, \\ 5.03, 5.04, \\ 5.05, 5.13, \\ 5.15, 5.18, \\ 5.20, 5.23, \\ 5.31, \\ 6.02, 6.03, \\ 6.05, 6.06, \\ 6.09, 6.12, \\ 6.13, 6.14, \\ 6.15, 6.20, \\ 6.23, 6.25 \end{array}$	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.

#	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?				\checkmark
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)?	~	~		√

Table 8. Criteria satisfied by preliminary engineering study.

#	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.

#	Criteria	MSA	FMP	GCF	CCC			
1.08	Basic characterization data exists?	✓						
2.20	The scope and scale of the waste problem has been determined?	\checkmark	✓	~	✓			
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?	\checkmark						
3.28	A simulant has been developed that approximates key waste properties?	\checkmark	~					
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)?	\checkmark	~					
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 = formula	CCC = canister cooling and crystallization; FMP = feeding, melting, and pouring; GCF = glass ceramic formulation; MSA = mixing, sampling, and analyses.							

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

#	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?	~	

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

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#	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?	\checkmark	\checkmark
4.30	Laboratory-scale tests on a limited range of simulants and real waste have been completed?	\checkmark	>
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?	~	\checkmark
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?	✓	\checkmark
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 simul	ation.

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.

#	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.		

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

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.

#	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?	✓

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

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.

#	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?	~	~	~	~	

Table 14. Criteria satisfied with requirements document.

#	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?	✓	v	v	~	
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?	✓	✓	~	~	\checkmark
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.

#	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)?	✓	~		~	

Table 16. Criteria satisfied with integrated pilot testing.

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#	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?	1	~	~	~	~
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?	✓	\checkmark	\checkmark	\checkmark	\checkmark
6.18	Engineering feasibility fully demonstrated (e.g. would it work)?	✓	\checkmark	\checkmark	\checkmark	\checkmark
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 = GCF =	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	20)12		2013	3	20	14		201	15	Т	2	016		:	201	17		20	18		20	019		:	2020	0		20	21		2	2022	2		20	23		;	202	4	T	20	25
Subitem	q1 q2	q3 q	4 q1	q2 q3	3 q4 (q1 q2	q3 q	4 q1	q2 (q3 o	4 c	1 q2	2 q3	q4	q1 c	q2 c	q3 q	4 q1	q2	q3 c	4 q	1 q2	2 q3	q4 (q1 c	2 q:	3 q4	4 q 1	q2	q3	q4 c	1 q	2 q3	3 q4	q1	q2	q3	q4 (q1 c	2q	3q	4 q1	q2	q3 q4
Technology maturation plan	x	x																																										
Preliminary engineering study			х	хx																																								
Characterize, estimate, and simulate waste to b	e treat	ed																																										
Initial waste estimates and simulant recipies			х	х																																								
Actual waste characterization										x	x						x>	:					х	х																				
Simulant/actual waste comparisons												x x						x	х						x	x																		
Laboratory scale glass ceramic testing																																												
Initial Reference formulation	хх	х																																										
Formulation and testing for initial composition	ns (incl	. LS	M)	x	x	хх	хх	x																																				
Preliminary model development (loading and	heat m	odel	s for	cost	bene	efit an	alys	е х	х	x	x	x																																
Variability study													х	х	x	x	x>	x	х	x	x>	x																						
Final model development																					>	x	х	х	x	x x	(x																	
Performance evaluation										x	x	x x	х	х	x	x	x>	x	х	x	x	x	х	х	x	x x	(x	x	х	х	х													
Compare actual and simulant												x	х						х	х						x x	(
Melter and off-gas testing with simulants																																												
Initial proof of principle		3	(X			x	х																																					
Scaling tests								х	х	x	x :	x x	x	х	x	x	x >	:																										
Off-gas functionality								x	х	x	x	x x	x	x	x	x	x >	:																										
Variability tests								x	х	x	x	x x	x	x	x	x	x >	:																										
Long-term run-by-wire															x	x	x >	x	х																									
Design data needs																		x	х	х	x>	x	х	х																				
Test the mixing, sampling, and analyses																																												
Preliminary study based on literature search				хx	x																																							
Laboratory scale tests of mixing, sampling, a	ind ana	alyse	s												x	x	x>	x	х																									
Canister testing												x x	x	х	x	x	x>	x																										
Decontamination system testing																			х	x	x>	x	х																					
Requirements document																																												
Initial requirements document						хх																																						
Final requirements management system																									x	хx	(
Risk management document																																												
Initial risks identification						хх																																						
Final risk management system																									x	хx	(
Preliminary design																																												
Conceptual design																					>	x	х	х	x	хx	(X																	
Preliminary design																												x	х	х	x	x)	< x	x	х	х	х	х						
Integrated pilot testing																																												
Construct test bed																									x	x x	(x																	
Shake-out testing (budget in construct)																											x	x																
Design data needs																													х	х	x	x	< x	x	x	x	x	х	x	x >	хх	x i	x	хx
Waste compliance plan																																												
Develop waste qualification strategy					x	x																																						
Issue WCP																																		x	х	х	х							

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	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	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	2025 6 6 6 6 6 6								
CCC = c decontar ceramic	CCC = canister cooling and crystallization; CD = canister decontamination; FMP = feeding, melting, and pouring; GCF = glass ceramic formulation; MSA = mixing, sampling, and analyses.								

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

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.

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Appendix

Criteria Lists

Table docum	A.1. Techi ientation: a	nology readiness assessment criteria list (T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus, nd O-Oualification, waste form qualification and compliance).	Imm
C#	T/M/P/Q	Criteria	obi
1.01	Т	Back of envelope environment?	liza
1.02	Т	Physical laws and assumptions used in new technologies defined?	tio
1.03	Т	Paper studies confirm basic principles?	n o
1.04	Р	Initial scientific observations reported in journals/conference proceedings/technical reports?	Т Н
1.05	Т	Basic scientific principles observed and understood?	ligh
1.06	Р	Know who cares about the technology, e.g., sponsor, funding source, etc.?	ר 9 קר
1.07	Т	Research hypothesis formulated?	eve
1.08	Т	Basic characterization data exists?	
1.09	Р	Know who would perform research and where it would be done?	Va
2.01	Р	Customer identified?	ste
2.02	Т	Potential system or components have been identified?	ji j
2.03	Т	Paper studies show that application is feasible?	G
2.04	Р	Know what program the technology would support?	as
2.05	Т	An apparent theoretical or empirical design solution identified?	ő
2.06	Т	Basic elements of technology have been identified?	era
2.07	Т	Desktop environment (paper studies)?	am
2.08	Т	Components of technology have been partially characterized?	ics
2.09	Т	Performance predictions made for each element?	
2.10	Р	Customer expresses interest in the application?	
2.11	Т	Initial analysis shows what major functions need to be done?	
2 1 2	т	Modeling & Simulation only used to varify physical principles?	

docun	nentation; an	nd Q-Qualification, waste form qualification and compliance).
C#	T/M/P/Q	Criteria
1.01	Т	Back of envelope environment?
1.02	Т	Physical laws and assumptions used in new technologies defined?
1.03	Т	Paper studies confirm basic principles?
1.04	Р	Initial scientific observations reported in journals/conference proceedings/technical reports?
1.05	Т	Basic scientific principles observed and understood?
1.06	Р	Know who cares about the technology, e.g., sponsor, funding source, etc.?
1.07	Т	Research hypothesis formulated?
1.08	Т	Basic characterization data exists?
1.09	Р	Know who would perform research and where it would be done?
2.01	Р	Customer identified?
2.02	Т	Potential system or components have been identified?
2.03	Т	Paper studies show that application is feasible?
2.04	Р	Know what program the technology would support?
2.05	Т	An apparent theoretical or empirical design solution identified?
2.06	Т	Basic elements of technology have been identified?
2.07	Т	Desktop environment (paper studies)?
2.08	Т	Components of technology have been partially characterized?
2.09	Т	Performance predictions made for each element?
2.10	Р	Customer expresses interest in the application?
2.11	Т	Initial analysis shows what major functions need to be done?
2.12	Т	Modeling & Simulation only used to verify physical principles?
2.13	Р	System architecture defined in terms of major functions to be performed?
2.14	Т	Rigorous analytical studies confirm basic principles?
2.15	Р	Analytical studies reported in scientific journals/conference proceedings/technical reports?
2.16	Т	Individual parts of the technology work (No real attempt at integration)?
2.17	Т	Know what output devices are available?
2.18	Р	Preliminary strategy to obtain TRL Level 6 developed (e.g., scope, schedule, cost)?
2.19	Р	Know capabilities and limitations of researchers and research facilities?
2.20	Т	The scope and scale of the waste problem has been determined?
2.21	Т	Know what experiments are required (research approach)?
2.22	Р	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. Techr	nology readiness assessment criteria list (T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus,
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	Т	Academic (basic science) environment?
3.02	Р	Some key process and safety requirements are identified?
3.03	Т	Predictions of elements of technology capability validated by analytical studies?
3.04	Р	The basic science has been validated at the laboratory scale?
3.05	Т	Science known to extent that mathematical and/or computer models and simulations are possible?
3.06	Р	Preliminary system performance characteristics and measures have been identified and estimated?
3.07	Т	Predictions of elements of technology capability validated by Modeling and Simulation (M&S)?
3.08	М	No system components, just basic laboratory research equipment to verify physical principles?
3.09	Т	Laboratory experiments verify feasibility of application?
3.10	Т	Predictions of elements of technology capability validated by laboratory experiments?
3.11	Р	Customer representative identified to work with development team?
3.12	Р	Customer participates in requirements generation?
3.13	Р	Requirements tracking system defined to manage requirements creep?
3.14	Т	Key process parameters/variables and associated hazards have begun to be identified?
3.15	М	Design techniques have been identified/developed?
3.16	Т	Paper studies indicate that system components ought to work together?
3.17	Р	Customer identifies technology need date?
3.18	Т	Performance metrics for the system are established (What must it do)?
3.19	Р	Scaling studies have been started?
3.20	М	Current manufacturability concepts assessed?
3.21	М	Sources of key components for laboratory testing identified?
3.22	Т	Scientific feasibility fully demonstrated?
3.23	Т	Analysis of present state of the art shows that technology fills a need?
3.24	Р	Risk areas identified in general terms?
3.25	Р	Risk mitigation strategies identified?
3.26	Р	Rudimentary best value analysis performed for operations?
3.27	Т	Key physical and chemical properties have been characterized for a number of waste samples?
3.28	Т	A simulant has been developed that approximates key waste properties?
3.29	Т	Laboratory scale tests on a simulant have been completed?
3.30	Т	Specific waste(s) and waste site(s) has (have) been defined?
3.31	Т	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. Techr	hology readiness assessment criteria list (T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus,							
docum	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	Т	Key process variables/parameters been fully identified and preliminary hazard evaluations have been performed?							
4.02	М	Laboratory components tested are surrogates for system components?							
4.03	Т	Individual components tested in laboratory or by supplier?							
4.04	Т	Subsystems composed of multiple components tested at lab scale using simulants?							
4.05	Т	Modeling & Simulation used to simulate some components and interfaces between components?							
4.06	Р	Overall system requirements for end user's application are known?							
4.07	Т	Overall system requirements for end user's application are documented?							
4.08	Р	System performance metrics measuring requirements have been established?							
4.09	Р	Laboratory testing requirements derived from system requirements are established?							
4.10	М	Available components assembled into laboratory scale system?							
4.11	Т	Laboratory experiments with available components show that they work together?							
4.12	Т	Analysis completed to establish component compatibility (Do components work together)?							
4.13	Р	Science and Technology Demonstration exit criteria established (S&T targets understood, documented, and agreed to by sponsor)?							
4.14	Т	Technology demonstrates basic functionality in simulated environment?							
4.15	М	Scalable technology prototypes have been produced (Can components be made bigger than lab scale)?							
4.16	Р	Draft conceptual designs have been documented (system description, process flow diagrams, general arrangement drawings, and material balance)?							
4.17	М	Equipment scale-up relationships are understood/accounted for in technology development program?							
4.18	Т	Controlled laboratory environment used in testing?							
4.19	Р	Initial cost drivers identified?							
4.20	М	Integration studies have been started?							
4.21	Р	Formal risk management program initiated?							
4.22	М	Key manufacturing processes for equipment systems identified?							
4.23	Р	Scaling documents and designs of technology have been completed?							
4.24	М	Key manufacturing processes assessed in laboratory?							
4.25	P/T	Functional process description developed. (Systems/subsystems identified)?							
4.26	Т	Low fidelity technology "system" integration and engineering completed in a lab environment?							
4.27	М	Mitigation strategies identified to address manufacturability/producibility shortfalls?							
4.28	Т	Key physical and chemical properties have been characterized for a range of wastes?							
4.29	Т	A limited number of simulants have been developed that approximate the range of waste properties?							
4.30	Т	Laboratory-scale tests on a limited range of simulants and real waste have been completed?							
4.31	Т	Process/parameter limits and safety control strategies are being explored?							

A.5

Table	A.1. Techr	nology readiness assessment criteria list (T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus,
C#	T/M/P/Q	Criteria
4.32	Т	Test plan documents for prototypical lab- scale tests completed?
4.33	Р	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	Т	The relationships between major system and sub-system parameters are understood on a laboratory scale?
5.02	Т	Plant size components available for testing?
5.03	Т	System interface requirements known (How would system be integrated into the plant?)
5.04	Р	Preliminary design engineering begins?
5.05	Т	Requirements for technology verification established?
5.06	Т	Interfaces between components/subsystems in testing are realistic (bench top with realistic interfaces)?
5.07	М	Prototypes of equipment system components have been created (know how to make equipment)?
5.08	М	Tooling and machines demonstrated in lab for new manufacturing processes to make component?
5.09	Т	High fidelity lab integration of system completed, ready for test in relevant environments?
5.10	М	Manufacturing techniques have been defined to the point where largest problems defined?
5.11	Т	Lab-scale, similar system tested with range of simulants?
5.12	Т	Fidelity of system mock-up improves from laboratory to bench-scale testing?
5.13	М	Availability and reliability (RAMI) target levels identified?
5.14	Μ	Some special purpose components combined with available laboratory components for testing?
5.15	Р	Three dimensional drawings and P&IDs for the prototypical engineering-scale test facility have been prepared?
5.16	Т	Laboratory environment for testing modified to approximate operational environment?
5.17	Т	Component integration issues and requirements identified?
5.18	Р	Detailed design drawings have been completed to support specification of engineering-scale testing system?
5.19	Т	Requirements definition with performance thresholds and objectives established for final plant design?
5.20	Р	Preliminary technology feasibility engineering report completed?
5.21	Т	Integration of modules/functions demonstrated in a laboratory/bench-scale environment?
5.22	Т	Formal control of all components to be used in final prototypical test system?
5.23	Р	Configuration management plan in place?
5.24	Т	The range of all relevant physical and chemical properties has been determined (to the extent possible)?
5.25	Т	Simulants have been developed that cover the full range of waste properties?
5.26	Т	Testing has verified that the properties/performance of the simulants match the properties/performance of the actual wastes?
5.27	Т	Laboratory-scale tests on the full range of simulants using a prototypical system have been completed?

Table	A.1. Techr	nology readiness assessment criteria list (T-Technology, technical aspects; M-Manufacturing and quality; P-Programmatic, customer focus,
docum	nentation; a	nd Q-Qualification, waste form qualification and compliance).
C#	T/M/P/Q	Criteria
5.28	Т	Laboratory-scale tests on a limited range of real wastes using a prototypical system have been completed?
5.29	Т	Test results for simulants and real waste are consistent?
5.30	Т	Laboratory to engineering scale scale-up issues are understood and resolved?
5.31	Т	Limits for all process variables/parameters and safety controls are being refined?
5.32	Р	Test plan for prototypical lab-scale tests executed - results validate design?
5.33	Р	Test plan documents for prototypical engineering-scale tests completed?
5.34	Р	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	Т	The relationships between system and sub-system parameters are understood at engineering scale allowing process/design variations and tradeoffs to be evaluated?
6.02	М	Availability and reliability (RAMI) levels established?
6.03	Р	Preliminary design drawings for final plant system are complete?
6.04	Т	Operating environment for final system known?
6.05	Р	Collection of actual maintainability, reliability, and supportability data has been started?
6.06	Р	Performance Baseline (including total project cost, schedule, and scope) has been completed?
6.07	Т	Operating limits for components determined (from design, safety and environmental compliance)?
6.08	Р	Operational requirements document available?
6.09	Р	Off-normal operating responses determined for engineering scale system?
6.10	Т	System technical interfaces defined?
6.11	Т	Component integration demonstrated at an engineering scale?
6.12	Р	Scaling issues that remain are identified and understood. Supporting analysis is complete?
6.13	Р	Analysis of project timing ensures technology will be available when required?
6.14	Р	Have established an interface control process?
6.15	Р	Acquisition program milestones established for start of final design (CD-2)?
6.16	М	Critical manufacturing processes prototyped?
6.17	М	Most pre-production hardware is available to support fabrication of the system?
6.18	Т	Engineering feasibility fully demonstrated (e.g., would it work)?
6.19	М	Materials, process, design, and integration methods have been employed (e.g., can design be produced?)
6.20	Р	Technology "system" design specification complete and ready for detailed design?

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C# T/MP/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 mode	Table docum	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)									
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	C#	T/M/P/Q	Criteria								
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	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.

Y/N Criteria

C#

1.01 Y Back of envelope environment? Back of the envelope calculations were performed to complete this report. 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 1.02 Y Physical laws and assumptions used in new technologies defined? methods are known.[1] 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 1.03 Y Paper studies confirm basic principles? Newtonian fluids with dense particles (waste) and non-Newtonian slurries (melter feed) must be managed for this application. Initial scientific observations reported in journals/conference 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 Y 1.04 proceedings/technical reports? 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] Know who cares about the technology, e.g., sponsor, funding source, etc.? DOE-NE is the sponsor.[14] 1.06 Y 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 1.07 Y Research hypothesis formulated? behavior sufficiently to design effective mixing and sampling systems. [2, 11] 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 1.08 **Basic characterization data exists?** Ν data. 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 1.09 Y Know who would perform research and where it would be done? at SRNL[13]. The customer is DOE-NE.[14] 2.01 Y Customer identified? 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] Paper studies show that application is feasible? Assume the PUREX type studies are adequate for this application at TRL-2.[18] 2.03 Y 2.04 Y Know what program the technology would support? A domestic reprocessing facility program that has not yet been initiated.[14] 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 Y An apparent theoretical or empirical design solution identified? 2.05 (EAS) and the Advanced Fuel Cycle Facility (AFCF). 2.06 Basic elements of technology have been identified? Mixing in vessels, sampling of slurries, pumping of slurries, fusion/dissolution of slurries and chemical analyses. Y 2.07 **Desktop environment (paper studies)?** Information such as the number of samples, mass and volumes in vessels, or processing rates have been estimated Ν 2.08 Y Components of technology have been partially characterized? Several components were characterized for other applications (mixers, pumps, samplers, analysis equipment, etc.). Performance predictions made for each element? No performance predictions yet made for mixing and sampling. 2.09 Ν Y Yes. Customer requested and funded the development of this TMP. 2.10 Customer expresses interest in the application? 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 Ν **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. Analytical studies reported in scientific journals/conference Ν 2.15 No analytical studies yet reported. proceedings/technical reports? Y Individual parts of the technology work (No real attempt at integration)? Parts of the technology tested within operating PUREX plants. 2.16 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 Know what output devices are available? 2.17 Y U.S. and likely internationally also. Preliminary strategy to obtain TRL Level 6 developed (e.g., scope, schedule, Y 2.18 This TMP documents the strategy. cost)? 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 Ν 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] 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 2.22 Y Qualitative idea of risk areas (cost, schedule, performance)? higher TRL levels. Have the range of waste species and waste loading for the waste form been 2.23

Comments

NA, waste species and loading are not applicable to MSA

NA, the waste form properties are not applicable to MSA

NA, the mechanism for release from the waste form is not applicable to MSA

By our interpretation, this question is answered yes by the academic study of mixing of multiphase slurries.[11]

Y

2.24

2.25

3.01

identified?

peer review journals?

release of radionuclides?

Academic (basic science) environment?

Are the general properties of the waste form well understood and published in

Have experiments started with the goal of determining the mechanism for the

CP V/N Contacts Contacts 1312 V Non-log mode by mode some and sets quartymouth are identified? The ability to infrain a representative sample analyses and run tank huldup are the key process and safety on analytical studies of technology capability validated is analytical studies. Or technology capability validated by Modeling and Studies. The studies and studies. Or technology capability. Studies of the superconstructure studies. Or technology capability. Studies of the superconstructure studies. The superconstructure studies. Or technology capability validated by Modeling and Studies. The superconstructure studies. The superconstetestudies. T	Table A.2	2. Mix	ing, sampling, and analyses criteria evaluation.	
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3.40 Y The basic science have been valuated at the laboratory scale? The basic science of mixing VAVMI and With datas solida have been movel, 2, 201 3.55 Y Science kown to extern than andhonizial addre computer simulations available for many problems in multi phane flow. Paraflow is one example individing and wind and estimated? The basic science of mixing VAVMI and estimated? 3.66 N Performance characteristics and measures have been individing and wind and estimated? No estimates of performance have been made. 3.67 VP Deductions of elements of the budge capability validated by Modeling and Science of mixing VAVMI and	3.03	Ν	Predictions of elements of technology capability validated by analytical studies?	No analytical studies of technology capability have been performed for this application.
3.05 v Science twown to extent that inductational computer models and inductions are performance characteristics and measures have been directified and entitied and entitated? There are computer simulations are aliable for many problems in multi-phase flow. Paraffore is one example simulations are problems in multi-phase flow. Paraffore is one example simulations are simulations are aliable for many problems in multi-phase flow. Paraffore is one example simulations are simulations are aliable for many problems in multi-phase flow. Paraffore is one example simulations are performance characteristics 300 N Predictions of examples predictions of the inducey capability validated by Modeling and simulations are simulations are simulations are simulations are simulations. Simulations predictions of the inducey capability validated by Hoberatory reperiments? Paper induce and and and induce and and induce and and induce and and and induce and and and induce and	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]
3.06 N Preliminary system performance characteristics and measures have been No estimates of performance have been made. 3.07 Y Predictions of clements 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 (M&S?) 3.08 N No system components, just basic laboratory research equipment to verify experiments? Equipment has not yet been selected, assembled, nor tested for this application. 3.09 N References of technology capability validated by Ishoratory experiments? Equipment has not yet been selected, assembled, nor tested for this application. 3.11 Y Castomer eparticipates in requirements generation? Requirements fraction selected, assembled, nor tested for this application. 3.12 Y Castomer participates in requirements generation? Requirements fraction selected, assembled, nor tested for this application. 3.13 N Castomer participates in requirements generation? No edita associated hours have hybric participates in requirements fraction selected, assembled, nor tested for this application. 3.14 Y Regimeents fraction selected, assembled, nor tested for this application. 3.15 Y Degree stable lobidate have hybric paricipates in testimator? 3.16	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
307 Predictions of elements of echonology capability validated by Modeling and Simulation (MKS)? Modeling and simulation work on mixing and sampling was performed for WTP.[21] Modeling and simulation (MKS)? 308 N No system components, just basic haboratory research equipment to verify physical principles? Equipment has not yet been selected, assembled, nor tested for this application. 309 N Predictions of elements of technology capability validated by Ishoratory experiments? Equipment has not yet been selected, assembled, nor tested for this application. 310 N Predictions of elements of technology capability validated by Ishoratory experiments? Equipment has not yet been selected, assembled, nor tested for this application. 311 Y Customer representative identified to work with development team? The cleft has been selected, assembled, nor tested for this application. 312 N Customer representative identified to work with development team? The cleft has been selected, assembled, nor tested for this application. 313 N Requirements tracking system defined to manage requirements recent the selected for this application. The implement has not yet been selected, assembled, nor tested for this application. 314 Y Requirements tracking system defined to manage requirements recent the selected for testing. Selected selected testing for testing. Selected testemology need date? <	3.06	Ν	Preliminary system performance characteristics and measures have been identified and estimated?	No estimates of performance have been made.
5.08 N No opstem components, just hask 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 tennohy creatibility validated by laboratory experiments? Equipment has not yet been selected, assembled, nor tested for this application. 3.11 Y Castomer predictingates in requirements generation? Requirements tracking store during the development team. 3.12 N Customer predicting of teams requirements creating the selected (kinserty of patient with development team. 3.13 N Requirements tracking store during the components onglt to work (bedreft and associated hazards have begin to be initial dise prechoingings with the used. 3.14 Y Key process parameters/values and associated hazards have begin to be initial dise technology and date? The implementation patient sealed. 3.15 Y Design techniques have been administed (VM tat must it do? Performance merics have not be easablished. 3.16 N Performance merics for the system started? No testing yet or ever and defining the capacity requirements and equipment will be ciseniff.	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 simulat
3.00 N Laboratory experiments verify feasibility of application? Equipment has not yet been selected, assembled, nor tested for this application. 3.10 N Perdictions of elements of exhology capability validated by laboratory experiments? Equipment has not yet been selected, assembled, nor tested for this application. 3.11 Y Customer participates in requirements generation? Requirements tracking base not yet been generated, but when they do, the customer will participate. 3.12 N Requirements tracking base not yet been generated, but when they do, the customer will participate. 3.14 Y Key process parameters and variables. 3.15 Y Design techniques have been identified/developed? The information plan for secure bigciver 3 shows a staff and at 2040,1231 3.16 N Paper studies indicate that system components ought to work togethe? The informance metrics for the system are established? 3.17 Y Customer identifies betwholey need date? No manufacturing acculations. 3.20 Y Customer identifies technology need date? No manufacturing acculations. 3.21 Y Scientific feashibility foll demonstrated? No manufacturing acculations. 3.22 Y Scientifin feashibil	3.08	Ν	No system components, just basic laboratory research equipment to verify physical principles?	Equipment has not yet been selected, assembled, nor tested for this application.
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3.13 N Requirements tracking has not yet been initiated. 3.14 Y Key process parameters/variables and associated hazards have begin 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 paper study defining the capacity requirements and equipment scaling has not been performed. 3.18 N Performance metrics for the system are established (What must if doy? Performance metrics on the system are established (What must if doy? 3.20 Y Current manufacturing difficonesysts in sead? No manufacturing difficulties are foreseen. 3.21 Y Sources of key components for laboratory testing identified? Miser, tans, sampler, and analyses equipment will be required for testing. Specific equipment will be identified in general terms? 3.22 Y Sale intified in general terms? Risk are identified in general terms? Risk are identified in general terms? 3.24 Y Risk initidigatin strategies identified?	3.12	Ν	Customer participates in requirements generation?	Requirements have not yet been generated, but when they do, the customer will participate.
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Preliminary Technology Maturation Plan for Immobilization of High-Level Waste in Glass-Ceramics

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ation work on mechanical rotary agitators.[22]

ified and/or procured at the time needed for testing. ssumptions.

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pected, only a unique application.

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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.	4.34		Are current regulations and policy established for disposal of the form?	NA, waste form disposal policy is not applicable to MSA.
4.36NHas a detailed waste qualification plan been documented?No.4.37NHave the range of chemistry and processing parameters for acceptable waste form been identified and documented?No.5.01NThe relationships between major system and sub-system parameters are understood on a laboratory scale?No.	4.35	Y	Have waste form affecting process steps been identified?	Yes, they are described in this TMP.
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.	4.36	Ν	Has a detailed waste qualification plan been documented?	No.
5.01 N The relationships between major system and sub-system parameters are understood on a laboratory scale? No.	4.37	Ν	Have the range of chemistry and processing parameters for acceptable waste form been identified and documented?	No.
	5.01	Ν	The relationships between major system and sub-system parameters are understood on a laboratory scale?	No.



Table A	Table A.2. Mixing, sampling, and analyses criteria evaluation.			
C#	Y/N	Criteria	Comments	
5.02	Ν	Plant size components available for testing?	No.	
5.03	Ν	System interface requirements known (How would system be integrated into the plant?)	No.	
5.04	Ν	Preliminary design engineering begins?	No.	
5.05	Ν	Requirements for technology verification established?	No.	
5.06	Ν	Interfaces between components/subsystems in testing are realistic (bench top with realistic interfaces)?	No.	
5.07	Ν	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	Ν	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	Ν	Lab-scale, similar system tested with range of simulants?	No.	
5.12	Ν	Fidelity of system mock-up improves from laboratory to bench-scale testing?	No.	
5.13	Ν	Availability and reliability (RAMI) target levels identified?	No.	
5.14	Ν	Some special purpose components combined with available laboratory components for testing?	No.	
5.15	Ν	Three dimensional drawings and P&IDs for the prototypical engineering- scale test facility have been prepared?	No.	
5.16	Ν	Laboratory environment for testing modified to approximate operational environment?	No.	
5.17	Ν	Component integration issues and requirements identified?	No.	
5.18	Ν	Detailed design drawings have been completed to support specification of engineering-scale testing system?	No.	
5.19	Ν	Requirements definition with performance thresholds and objectives established for final plant design?	No.	
5.20	Ν	Preliminary technology feasibility engineering report completed?	No.	
5.21	Ν	Integration of modules/functions demonstrated in a laboratory/bench-scale environment?	No.	
5.22	Ν	Formal control of all components to be used in final prototypical test system?	No.	
5.23	Ν	Configuration management plan in place?	No.	
5.24	Ν	The range of all relevant physical and chemical properties has been determined (to the extent possible)?	No.	
5.25	Ν	Simulants have been developed that cover the full range of waste properties?	No.	
5.26	Ν	Testing has verified that the properties/performance of the simulants match the properties/performance of the actual wastes?	No.	
5.27	Ν	Laboratory-scale tests on the full range of simulants using a prototypical system have been completed?	No.	
5.28	Ν	Laboratory-scale tests on a limited range of real wastes using a prototypical system have been completed?	No.	
5.29	Ν	Test results for simulants and real waste are consistent?	No.	
5.30	Ν	Laboratory to engineering scale scale-up issues are understood and resolved?	No.	

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

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

Table	A.Z. MIX	ing, sampling, and analyses chiefta 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	5 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	5	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 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	5 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	2 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	i Y	Critical manufacturing processes prototyped?	Standard equipment will be assembled to make the process. All sampling equipment has been procured a and WTP.
6.17	Y 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 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	2 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.

and installed under full nuclear QA systems at WVDP, DWPF,

Table	e A.2. Mix	ing, sampling, and analyses criteria evaluation.	
C#	Y/N	Criteria	Comments
6.2	5 N	Final Technical Report on Technology completed?	No.
6.20	6 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 an and WTP.
6.27	7 N	Engineering-scale tests on the full range of simulants using a prototypical system have been completed?	No.
6.28	8 N	Engineering to full-scale scale-up issues are understood and resolved?	No.
6.29	9 N	Laboratory and engineering-scale experiments are consistent?	No.
6.30	0 N	Limits for all process variables/parameters and safety controls are defined?	No.
6.3	1 N	Plan for engineering-scale testing executed - results validate design?	No.
6.32	2 N	Production demonstrations are complete (at least one time)?	No.
6.33	3	Have the transportation and storage systems been identified?	NA, transportation isn't applicable to MSA.
6.34	4 N	Are performance assessment models available for the form/disposal environment?	No.
6.3	5 N	Has a preliminary performance assessment been done to determine the acceptability of the waste form?	No.

nd installed under full nuclear QA systems at WVDP, DWPF,

Table	A.3. N	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, temperatu
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 observation
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 1.0
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 characterizat
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
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
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
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 hav 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 p
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 pomelting of waste glass in CCIM.
2.18	Ν	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/limitati Marcoule for waste form formulation and INL, CEA Marcoule, SIA Radon, KHNP, Bochvar, LETI, and H
2.20	Ν	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 devi
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 d
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 pe
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 academ
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	Ν	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]

ture capabilities, etc.).[31, 34-38]

ons as listed in the three previous questions.

02 through 1.04. tion at PNNL and SRNL.

d until replaced.

AFCF design.

melting are under development.[56-58]

ve been demonstrated to be successful for slurry feed partly

pouring of partly crystallized melts.[45, 48, 65-68] our-spout designs tested and developed specifically for the

ions. They primarily consist of PNNL, SRNL, and CEA KRI for melter system testing. velopment.

one.

erformed.[69]

mic endeavor.

CP Victoria Communic CP Victoria Communic Modeling of Hear, mass, and clarge transport in the melter have stanted, 135, 55-55] Models for cold-cap mell Modeling N Performance characteristics and measures have hear indified and estimated? No. Modeling N Performance characteristics and measures have hear indified and estimated? No. Modeling Y Relations of descent chemology capability validated by Modeling and Standaton (MSNS)? No. Modeling Y Relations of descent chemology capability validated by Modeling and policy informatics with the class contain will work in a CCIM (7) experiments. Performance means and indicating method will be descent and policy informatics with and policy and work in a CCIM (7) for apposition (chem ta scalars ty estimated informatics with development tame? Policy and policy (2), (1), (1), (1), (1), (1), (1), (1), (1	Table	Table A.3. Melter feeding, melting, and pouring criteria evaluation.				
19.0 Y Sciece known to extert that mathematical and oc computer andels and simulation Modeling of heat, mass, and charge transport in the melter have started J35, 53-551 Models for cold-cap melt 19.0 N Performance there characteristics and measures have been No. 19.0 N Performance there characteristics and measures have been No. 19.0 N Performance there characteristics and measures have been infinite and estimates and scales up to and including scales up	C#	Y/N	Criteria	Comments		
SN Relinding substrate programmer behaves behaves and substrate su	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 melter		
397 N Predictions of demonstor for thermology capability validated by Modeling and No. 308 Y No system components, just bois ideboratory research equipitent to verify physical principles'. Physical principles were demonstrated at scales up to and including scales up to 50 nm for the CCIM with of the inclusion of chemical principles'. 309 Y Information (MLSS)'' Physical principles'. Physical principles'. Physical principles were demonstrated at taboratory scale. [60, 71, 72] 310 Y Consomer presentative infinited to werk with development term? DOIC respresentative, Kimberly Grav, is movied with development term. 311 Y Consomer presentative infinited to work with development term? DOIC respresentative, Kimberly Grav, is movied with development term. 312 X Consomer presentative infinited to work with development term. DOIC will put ching the my set mentation (MLB matching terms). 313 X Consomer infinite the masses menomes output to work together? No. 313 X Consome infinite terms? Objective X stale and infinition (MLS my set menomes output to work together?) 314 X Consome infinite terms? Objective X stale and minited my set menomes output to work together? No. 315 X	3.06	Ν	Preliminary system performance characteristics and measures have been identified and estimated?	No.		
3.98 v No system components, just basic luboratory research equipment to verify physical Physical principle? Physical principles 3.09 Y Laboratory testas fully consisting and points werify feasibility of aplication? Laboratory tests of the melting and cooling processes suggest that the glass ceranic will work is a CCM17. 3.10 Y Laboratory tests of the melting and cooling processes suggest that the glass ceranic will work is a CCM17. 3.11 Y Customer perfective in requirements (and the work with development term? DOF representative, Kimberly Grup, is involved with development term. 3.12 Y Customer participates in requirements segration? DOF representative, Kimberly Grup, is involved with development term. 3.13 N Regimeents tracking system office to nanage requirements cerept No requirements tracking system type. No requirements tracking system set. 3.13 N Definities technology and biling to develop the work togethe? No. 3.14 N Contormance metrics of the system are established What must it do? No. 3.15 N Scaling studies have steem anduce transform this application. However, general equipment set, and for the system anduce steem studies the steem set, and the steem set, and the steem set, and the steem set, and the set and the steem set, and the steem set, and	3.07	Ν	Predictions of elements of technology capability validated by Modeling and Simulation (M&S)?	No.		
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3.10 v Predictions of chemens of chemology capability validated by laboratory Glass ceramic melting and pouring were tested at laboratory scale (69, 71, 72) 3.11 Y Costomer precipenative identified to work with development team? DCF expresentative. Kinnebry Gray, is involved with development team. 3.12 Y Costomer precipenative identified to manage requirements creep? No requirements generation (when it begins). 3.13 N Requirements tracking system defined to manage requirements creep? No requirements tracking system yet. 3.14 N Requirements tracking system defined to manage requirements creep? No requirements tracking system yet. 3.15 N Degin technique thave been idstoffield/eveloped? Melters and off-gas components have been made. Conling coil, pour-spont, and their coatings are any total data? 3.18 N Performance metrics for the system are established (What must it do)? No issues are explecied with manafacturchility of any components basel on the number of melters carenely it down are available at NN, KNPQ, CFA, KRI, and SI A Badon. 3.29 Y Analysis of present state of the at shows that technology fills a meel? No issues are explecied with manafacturchility of any components basel on the number of melters carenely it down areas in the its of the at shows that technology fills a meel? 3.23 Y Ask and sk areas isomitied in general terns	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.[7		
3.11 Y Customer processmative identified to work with development cam? DOE representative, Simolef Gray, is involved with development cam. 3.12 Y Customer processmative incluine system defined to manage requirements cree? No requirements practing system yet. 3.13 N Requirements tracking system defined to manage requirements cree? No requirements marking system yet. 3.14 N Key process parameters/variables and associated hazards have begun to be No. 3.14 N Requirements tracking system components ought to work together? 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 det 3.17 Y Customer information entrified for basessed? No. 3.18 N Performance metrified/developed? No scaling studes have started for this spication. However, general equipment scaling tenuts are fairly with a spication in any components have do in the number of melters currently and current manufacturability of any components have do in the number of melters currently and current manufacturability of any components have been indentified in a spication? 3.28 Y Current manufacturability of any components have do in the number of melters currently and currently currently indentified in any spication? No. 3.21 Y Statistified in general terms? No. 3.22	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]		
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3.13 N Requirements tracking system defined to manage requirements erecept? No requirements tracking system yet. 3.14 N Key process parameters/variables and associated hazards have hegen to be the distribution of the system components ought to work together? No. 3.15 N Design techniques have been identified/develope1? Melters and off-gas components have been made. Cooling coil, pour-spoat, and their coatings are not yet design to hing system are established (What must it do)? No. 3.17 Y Customer identifies technology need date? Objective 3 liss a pilot facility in 2040 [23] 3.18 N Performance metrics for the system are established (What must it do)? No. 3.19 N Stading studies have been started? No iscaling studies have started for this application. However, general equipment scaling tennts are fairly with a manifecturability of any components based on the number of melers currently? 3.21 Y Current manufacturability concept sassessed? No. 3.22 N Selentifie estability fully demonstrated? Melers are available at INL, KHNP, CEA, KRI, and SIA Radon. 3.22 N Selentifie estability fully demonstrate? No. 3.23 Y Analysis of present studies that approximates key mase properties? No. 3.24 <td< td=""><td>3.12</td><td>Y</td><td>Customer participates in requirements generation?</td><td>DOE will participate in requirements generation (when it begins).</td></td<>	3.12	Y	Customer participates in requirements generation?	DOE will participate in requirements generation (when it begins).		
1.1NKey process parameters/variables and associated hazards have begin to be No.No.1.15NDesign techniques have been identified/expoed?Melters and off-gis components have been made. Cooling coil, pour-spout, and their coatings are not yet design1.15NDesign techniques have been identified/expoed?Mo.1.17YCustomer identifies technology need date?Objective 3 lists a pilot facility in 2040 [23]1.18NPerformance metrics for the system are established (What must it dn?)No.1.20YCurrent mundfacturability concepts assessed?No iscuss are expacted with manufacturability of any components based on the number of melters currently1.21YSources of key components for laboratory esting identified?Melters are available at INK, KINP, CEA, KRI, and SIA Radon.1.22NScientific feasibility fully demonstrated?No.1.23YNalysis of present state of the art shows that technology fills a need?No.1.24YRisk areas identified in general terms?The risks are generally identified in this TMP.1.25NRodimentary best value analysis performed for operations?No.1.26NRodimentary best value analysis performed for a number of melter science sing [52, 73, 74]1.27NIaboratory scale tests on a simulant have been complete?No.1.28NIaboratory scale tests on a simulant have been complete?No.1.29NIaboratory scale tests on a simulant have been complete?No.1.29NIaboratory scale tes	3.13	Ν	Requirements tracking system defined to manage requirements creep?	No requirements tracking system yet.		
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	4.08	Ν	System performance metrics measuring requirements have been established?	No.		

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

ting are under development.[56-58]

similar materials.

71]

esigned.

well known for all the equipment to be used. in service.

e capabilities, etc.). method for treating HLW from

heir application.[70]

.[48, 65, 68, 75] ve been tested, but, not as an integrated system.

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

Table	Γable 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, B for liquid feeding and pouring. The off-gas treatment systems are different at each laboratory and none are		
4.11	N	Laboratory experiments with available components show that they work together?	No.		
4.12	Ν	Analysis completed to establish component compatibility (Do components work together)?	No.		
4.13	Ν	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	Ν	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	Ν	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	Ν	Controlled laboratory environment used in testing?	No.		
4.19	Ν	Initial cost drivers identified?	Not fully.		
4.20	Ν	Integration studies have been started?	No.		
4.21	Ν	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	Ν	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	Ν	Functional process description developed. (Systems/subsystems identified)?	No.		
4.26	Ν	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	Ν	Key physical and chemical properties have been characterized for a range of wastes?	No.		
4.29	Ν	A limited number of simulants have been developed that approximate the range of waste properties?	No.		
4.30	Ν	Laboratory-scale tests on a limited range of simulants and real waste have been completed?	No.		
4.31	Ν	Process/parameter limits and safety control strategies are being explored?	No		
4.32	Ν	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	Ν	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	Ν	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	Ν	System interface requirements known (How would system be integrated into the plant?)	No.		
5.04	N	Preliminary design engineering begins?	No.		

Bochvar, LETI, and KRI. All of these systems have the option e exactly the same as specified here.

Table	Fable A.3. Melter feeding, melting, and pouring criteria evaluation.				
C#	Y/N	Criteria	Comments		
5.05	Ν	Requirements for technology verification established?	No.		
5.06	Ν	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	Ν	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	Ν	Lab-scale, similar system tested with range of simulants?	No.		
5.12	Ν	Fidelity of system mock-up improves from laboratory to bench-scale testing?	No.		
5.13	Ν	Availability and reliability (RAMI) target levels identified?	No.		
5.14	Ν	Some special purpose components combined with available laboratory components for testing?	No.		
5.15	Ν	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	Ν	Component integration issues and requirements identified?	No.		
5.18	Ν	Detailed design drawings have been completed to support specification of engineering-scale testing system?	No.		
5.19	Ν	Requirements definition with performance thresholds and objectives established for final plant design?	No.		
5.20	Ν	Preliminary technology feasibility engineering report completed?	No.		
5.21	Ν	Integration of modules/functions demonstrated in a laboratory/bench-scale environment?	No.		
5.22	Ν	Formal control of all components to be used in final prototypical test system?	No.		
5.23	Ν	Configuration management plan in place?	No.		
5.24	Ν	The range of all relevant physical and chemical properties has been determined (to the extent possible)?	No.		
5.25	Ν	Simulants have been developed that cover the full range of waste properties?	No.		
5.26	Ν	Testing has verified that the properties/performance of the simulants match the properties/performance of the actual wastes?	No.		
5.27	Ν	Laboratory-scale tests on the full range of simulants using a prototypical system have been completed?	No.		
5.28	Ν	Laboratory-scale tests on a limited range of real wastes using a prototypical system have been completed?	No.		
5.29	Ν	Test results for simulants and real waste are consistent?	No.		
5.30	Ν	Laboratory to engineering scale scale-up issues are understood and resolved?	No.		
5.31	Ν	Limits for all process variables/parameters and safety controls are being refined?	No.		
5.32	Ν	Test plan for prototypical lab-scale tests executed - results validate design?	No.		
5.33	Ν	Test plan documents for prototypical engineering-scale tests completed?	No.		
5.34	Ν	Risk management plan documented?	No.		
5.35	Ν	Is a program in place to qualify the waste form and production process?	No.		
5.36	Ν	Have all relevant physical and chemical properties been sufficiently well determined and bounded to meet proposed disposal criteria?	No.		

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

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Table .	A.3. N	Aelter 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	Ν	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	Ν	Availability and reliability (RAMI) levels established?	No.
6.03	Ν	Preliminary design drawings for final plant system are complete?	No.
6.04	Ν	Operating environment for final system known?	No.
6.05	Ν	Collection of actual maintainability, reliability, and supportability data has been started?	No.
6.06	Ν	Performance Baseline (including total project cost, schedule, and scope) has been completed?	No.
6.07	Ν	Operating limits for components determined (from design, safety and environmental compliance)?	No.
6.08	Ν	Operational requirements document available?	No.
6.09	Ν	Off-normal operating responses determined for engineering scale system?	No.
6.10	Ν	System technical interfaces defined?	No.
6.11	Ν	Component integration demonstrated at an engineering scale?	No.
6.12	Ν	Scaling issues that remain are identified and understood. Supporting analysis is complete?	No.
6.13	Ν	Analysis of project timing ensures technology will be available when required?	No.
6.14	Ν	Have established an interface control process?	No.
6.15	Ν	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, ne
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
6.18	Ν	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	Ν	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	Ν	Integration demonstrations have been completed (e.g., construction of testing system)?	No.
6.25	Ν	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	Ν	Engineering-scale tests on the full range of simulants using a prototypical system have been completed?	No.
6.28	Ν	Engineering to full-scale scale-up issues are understood and resolved?	No.
6.29	Ν	Laboratory and engineering-scale experiments are consistent?	No.
6.30	Ν	Limits for all process variables/parameters and safety controls are defined?	No.
6.31	Ν	Plan for engineering-scale testing executed - results validate design?	No.
6.32	Ν	Production demonstrations are complete (at least one time)?	No.
6.33	Ν	Have the transportation and storage systems been identified?	No.

either are liquid fed and nor do they produce glass-ceramic. ese have been constructed at full scale for other applications.

Table	Table A.3. Melter feeding, melting, and pouring criteria evaluation.				
C#	Y/N	Criteria	Comments		
6.34	Ν	Are performance assessment models available for the form/disposal environment?	No.		
6.35	Ν	Has a preliminary performance assessment been done to determine the acceptability of the waste form?	No.		

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

Cite VN Connexes 101 Y Back of envelope environment? Initial glass-centrals formulations are complete [69, 71, 72] 112 Y Projectal laws and sumptions and in an environment? Projectal laws and dual analysis developed [69, 71, 72] 112 Y Projectal laws and dual analysis developed [69, 71, 72] 114 Y Projectal laws and dual analysis developed [69, 71, 72] 114 Y Back concepts were recently published [72] 115 Y Back concepts were recently published [72] 116 Y Rack concepts were recently published [72] 117 Y Race who words perform research and where it would be done? 118 Y Back data on glass-central cataly distribution. 119 Y Race who words perform research and where it would be done? 110 Y Race who words perform research and where it would be done? 110 Y Race who words perform research and where it would be done? 110 Y Race who words perform research and where it would be done? 110 Y Race who words perform research and where it would be done? 110 Y Race who words perform research and where it would be done? 1110 Y Race who words perform research and where it would be done? 11	Table	<u>л.</u> (
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102 Y Physical laws and assumptions used in new exhambles define? Physical laws and sham alphysical device padies (07). Physical laws and than alphysical device padies (07). Physical laws and the padies (07). Physical Phy	1.01	Y	Back of envelope environment?	Initial glass-ceramic formulations are complete.[69, 71, 72]
103 Y Page studies couliant basic principles? An evaluation of glass-cernatic shows waste loadings, places, heat observed. 104 Y Initial elevatific observed in informal/econference proceedings/technicalling. 105 Y Basic concepts. Basic concepts. 106 Y Know who cares about the technology, e.g., spoxer, funding source, etc.? DOF. NF is the goorser. DOF. NF is the goorser. 107 Y Rescarch hypothesis formulated? Extrastive understanding in multiphase waste formulated for higher heading and temperature onlemene than for U.S. domestic exproses. 108 Y Basic characterization data exists? DOF. NF is the ustormer [14] 107 Y Rescarch and whore it would be done? PNNL, LANE, SRNL as all Use into all formal is section 2. 108 Y Basic characterization of existing? Posterial system or components be ben identified? Posterial system or wein identified? 109 Y Know who wolf perform rescarch and whore it would be done? Posterial system or existing in information of the existing? 108 Y Basic characterization or components be technology wolf a support? Programs wolf Berling? 109 Y Know who wolf perform rescarch and whore it would be done? Poster wolf is induce intrescarce	1.02	Y	Physical laws and assumptions used in new technologies defined?	Physical laws known and data already developed.[69, 71, 72, 77-82]
1.04 v Initial scientific observations reported in journal/conference proceedings/technical Basic concepts were recently published [72] 1.05 Y Rasic concepts were recently published [72] 1.05 Y Rasic concepts were recently published [72] 1.05 Y Rasic concepts were recently published [72] 1.06 Y Rasic concepts were recently published [72] 1.07 Y Rescarch hypothesis formulated? Fettory concepts recently can be formulated for higher loading and temperature tolerance than to for U.S. domestics for lab-scale fortwated matrixis [97, 17.2] 1.08 Y Rasic characterization date exists? Basic character reprocessing. Basic character reprocessing. 2.01 Y Concorrel detailed settor components have been identified? Basic character reprocessing. Basic character reprocessing. 2.03 Y Paper andice show that apolication is feasibile? Paper andice show that apolication is feasibile? Paper andice show that apolication is feasibile? 2.04 Y Basic elements of this technology ware been identified? The basic elements of this technology ware from that can be fortherated by existing and bow that apolication is feasibile? 2.05 Y Basic denements of th	1.03	Y	Paper studies confirm basic principles?	An evaluation of glass-ceramic shows waste loadings, phases, heat tolerance, etc. [69, 71, 72]
105 Y Now who create should be therhology, e.g., sponsor, funding source, etc., P 106 Y Rose who create should be therhology, e.g., sponsor, funding source, etc., P 107 Y Research hypothesis formulated; DOE NE is the sponsor, [14] 108 Y Rose characterization data estats? Basic characterization and there is would be data? 108 Y Rose characterization and where it would be data? PNNL LANL, SRNL are all well suitation estats for his-scale fabricated materials [09, 71, 72] 109 Y Rose characterization and where it would be data? PNNL LANL, SRNL are all well suitation estats for his-scale fabricated materials [09, 71, 72] 109 Y Courser relativistican ocomponents have here identified? Portants would be U.S. densets represessing that have, it is call to a scale to a	1.04	Y	Initial scientific observations reported in journals/conference proceedings/technical reports?	Basic concepts were recently published.[72]
106 Y Now who cares about the technology, e.g., sponsor, funding source, etc.? DOE-NF is the sponsor, 1041 107 Y Rescarch hypothesis formulated? The hypothesis are higtas-certanic care be formulated for higher loading and temperature olerance than be (U.S. donnetice regressing). 108 Y Rois characerization and are sists? Basic data or glass-certanic exists for lab scale foltriculet materials (69, 71, 72] 109 Y Norw who would perform research and where it would be done? PNNL LANL SRNL and all well axied to stude foltriculet materials (69, 71, 72] 109 Y Procental syntamic har har harpitcation is fastable? Paper smally sensitive in the scale foltriculet materials (69, 71, 72] 109 Y Roow who approach the technology would support? Paper smally sensitive in the scale foltriculet material (5, 69) 100 Y Roor who approach the technology have been in dentified? The basic elements of this technology are tell abasit (72) 100 Y Roor who approach the technology have been in dentified? The basic elements of this technology are tell abasit. 101 Y Desktop environment (paper studies)? Wate form formulation variable in paper and horizons of loades (72) 102 Y Desktop environment (paper studies)? Wate form formaliation was values (71) 103 Y Costoone environment (paper studies)? Watabasit (72)	1.05	Y	Basic scientific principles observed and understood?	Extensive understanding in multiphase waste forms dating back to the 1960's.[83]
1.07 Y Research hypothesis formulatel? The hypotheses are that glass ceramic casts for higher loading and temperature tolerance than left. 1.08 Y Basic characterization data exists? Basic data exists? Basic data exists? 1.09 Y Cansomer infand? DOI-NE is the existomer exists of high source data exists? PNNL LANL SRNL are all well sailed to study this form. 2.01 Y Cansomer infand? DOI-NE is the existomer [14] 2.03 Y Paper studies slow that application is feasible? Paper study resulted in the selection of this technology for this stream [25, 69] 2.04 Y Know what pogram the technology wood support? Pograms wood be U.S. domestic reprocessing that hasn't yet startd. 2.05 Y Ansie elements of technology have been identified? The basic form formutation solution is envisored with somicalles to increase wases solubility, chernoid durability, and thermather and thore the paper and theorem predictions made for each element? 2.06 Y Desited environment (paper studies)? Wasts form formutation of wase valuated in paper and theorem paper and theor	1.06	Y	Know who cares about the technology, e.g., sponsor, funding source, etc.?	DOE-NE is the sponsor.[14]
108 Y Basic data or glass-caranic exists for lab-scale fabricated materials [6, 71, 72] 109 Y Know who wall perform research and where it would be done? PNL.LANL, SKNL areal used usined to study this form. 201 Y Costomer identified? Several potential unit operations were identified and listed in Section 2. 203 Y Paper studies show that application is trashib? Paper studies show that application is trashib? 204 Y Know what program the technology not identified? The glass formaldion solution is envisioned with some theoretical basis.[72] 205 Y An apparent theoretical or empirical design solution identified? The glass formaldion solution is envisioned with some theoretical basis.[72] 206 Y Basic elements or technology have been identified? The glass formaldion solution is envisioned with some theoretical basis.[72] 207 Y Desktop environment (apper studies)? Wate form formace and the trach to fabricated by existing motion is existing the shart existing t	1.07	Y	Research hypothesis formulated?	The hypotheses are that glass-ceramic can be formulated for higher loading and temperature tolerance than for U.S. domestic reprocessing.
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2.01 Y Customer identified? DOE-NE is the customer [14] 2.02 Y Dentifial system or components have been identified? Paper study resultion in a vertified and listed in Section 2. 2.03 Y An apparent theorehology would support? Pograms would be U.S. domestic reprocessing that have have identified? 2.04 Y Now what program the tachnology mould support? Pograms would be U.S. domestic reprocessing that have the start [2] 2.05 Y An apparent theorehology must be conditional identified? The basic elements of this technology run the glass certain waste form that can be fabricated by existing with two in the opticated with simulation was evaluated in paper and laboratory-scale studies.[72] 2.06 Y Destrop ervironment (paper studies)? Waste form formulating have been partially characterized? Secretal samples have been partially characterized (b), 71, 72] 2.07 Y Destrop ervironment (paper studies)? Waste form formulating have been partially characterized? 2.08 N Performance predictions ande for each element? Periformance. 2.10 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. 2.13 N System architecture defined in terms of major functions to be performe? The system is described in is remaine? 2.14 Y Rol	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.
202 Y Potential system or components have been identified? Several potential unit operations were identified and listed in Section 2. 204 Y Paper studies show that application is feasible? Paper study resulted in the Section of fits its chonlogy for this scenal (25, 60) 205 Y An apparent theoretical or empirical design solution identified? The gluss formulation solution is envisioned with some theoretical basis (72) 206 Y Basic clements of this technology much scenal design solution identified? The hasic iclements of this technology neuroper and laboratory-scale studies (72) 208 Y Components of technology have been patially characterized? Several samples have been matell. Howevert, predictions of log-form performance, temperature and 1 207 Y Desktop environment (paper studies (72) Waste form formulation have been matellity, characterized? 208 Y Components of technology have been patially characterized? Several samples have been matell. Howevert, predictions of log-form performance, temperature and 1 201 Y Desktop environment (paper studies contime basic principles? The technology leaves the environd. Howevert, predictions of log-form part of material man sign functions. This was done for covering and paper on this application was published. 213 N System architecture defined in terms of major functions. to be performed? The system i	2.01	Y	Customer identified?	DOE-NE is the customer.[14]
200 Y Paper studies show that application is feasible? Paper study exolution of this sechnology for this sterm.[25, 69] 201 Y Know what programm would be US. domesitic erprocessing that hasn't yet started 205 Y An apparent theoretical or empirical design solution identified? The basic elements of this technology are the glass ceranic waste form that can be fabricated by existing me those that will inmobility key rationational disc to increase waste solubility, chemical duratibily, and thermathy? 206 Y Desktop environment (paper studies)? Waste form foundation was evaluated in paper and laboratory-scale studies.[72] 207 Y Desktop environment (paper studies)? Waste form foundation was evaluated in paper and laboratory-scale studies.[72] 208 Y Omponents of technology have been application? Customer expresses interes in the application? 2010 Y Ustomer expresses interes in the application? Noteding simulation have been used. However, predictions of long trans, but not how cooling rates and compositor performance. 213 N Modeling & Simulation only used to verify physical principles? Predictions of unide transe form insier and regularity. 214 Y Rigoros analytical studies confirm basic principles? Analytical studies of the waste form insier and the formation of the right phases have been dome.[69, 71, 72] 2	2.02	Y	Potential system or components have been identified?	Several potential unit operations were identified and listed in Section 2.
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2.06 Y Basic elements of technology have been identified? The basic elements of this technology are the glass ceramic waste solution: chemical durability, and thermating those that will immodifies to prediouncidies to increase waste solutions; waste form that can be fabricated by existing me those that will immodifies to prediouncidies to increase waste solution; chemical durability, and thermating and the formation of long-term performance, temperature and a cuenosition performance. 2.11 Y Customer expresses interest in the application? Customer expresses interest in the application? No modeling & Simulation nutworks to the technology endems are described in pervisor documents [69, 71, 72] and summarized in this? 2.13 N System architecture defined in terms of major functions to be performance? No modeling & Simulation nutworks to the technology endems are described in terms of unit operations rather than major functions. This was done for convenied analytical studies confirm hasic principles? No modeling internation? A pair on this application was published [72], the general concept is well known and reported.[77, 78, 83-42] 2.14 Y Rigorous analyti	2.05	Y	An apparent theoretical or empirical design solution identified?	The glass formulation solution is envisioned with some theoretical basis.[72]
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2.08 Y Components of technology 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 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? The technology elements are described in previous documents [69, 71, 72] 2.13 N System architecture defined in terms of major functions to be performed? The technology elements are described in terms of unit operations rather than major functions. This was done for convenie analytical studies confirm basic principles? 2.14 Y Rigorous analytical studies confirm basic principles? Analytical studies reform tescli and the formation of the right phases have been done.[69, 71, 72] 2.15 Y Analytical studies confirm basic principles? No modeling/similation functions rather than major functions. This was done for convenie analytical studies confirm basic principles? Naper on this application was published [72], the general concept is well known and reported.[77, 78, 83-7 2.15 Y Analytical studies reported in scientific journals/coneference procecodings/technica	2.07	Y	Desktop environment (paper studies)?	Waste form formulation was evaluated in paper and laboratory-scale studies.[72]
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	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]

borosilicate glass and thereby reduce waste management costs

ethods with typical cooling schedules. The targeted phases are adiation stability.

radiation stability have not been predicted.

n impact crystallinity, process efficiency, or long-term

ence. However, all major functions are represented.

87]

ns. et to be determined process so they are only a place holder.

e a placeholder based on similar processes.

een predicted.

 Table A 4
 Glass-ceramic formulation criteria evaluation

	<u>л.</u> т . с	sass-ceramic formulation effectia 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	Ν	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
3.07	Ν	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.
3.10	Ν	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
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	Ν	Requirements tracking system defined to manage requirements creep?	No.
3.14	Ν	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, addition equilibrium phases as functions of composition and temperature.
3.16	Ν	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	Ν	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
3.22	Ν	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
3.24	Y	Risk areas identified in general terms?	The high risk areas are highlighted in this TMP.
3.25	Ν	Risk mitigation strategies identified?	Risk management plan has not yet been developed.
3.26	Ν	Rudimentary best value analysis performed for operations?	No.
3.27	Ν	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
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
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	Ν	Has the type of disposal environment(s) been defined?	No.
3.33	Ν	Is a general strategy for waste form qualification been developed?	No.
4.01	Ν	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	Ν	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	Ν	Overall system requirements for end user's application are known?	No.
4.07	Ν	Overall system requirements for end user's application are documented?	No.
4.08	Ν	System performance metrics measuring requirements have been established?	No.

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

e (canister size), or long-term durability.

.[69, 71, 72]

elements have been validated.

onally, thermodynamic models will be used to predict

nd LANL.

by glass-ceramic.[25, 69, 72]

ed with the waste simulant.[24] s and it's resulting waste have not yet been identified.
Table A	able 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	Ν	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	Ν	Initial cost drivers identified?	No.		
4.20		Integration studies have been started?	NA, integration studies do not apply to GCF.		
4.21	Ν	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	Ν	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		
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	Ν	Process/parameter limits and safety control strategies are being explored?	No.		
4.32	Ν	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		
4.35	Y	Have waste form affecting process steps been identified?	These are the same as for HLW glass.[12, 13, 26]		
4.36	Ν	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	Ν	Preliminary design engineering begins?	No.		
5.05	N	Paguirements for technology varification established?	No		

l in Section 2. on policy is not to pursue Yucca Mountain.

C# Y/N Criteria 5.06 N Interfaces between components/subsystems in testing are realistic with realistic interfaces)? Prototumes of againment system components have been created (known)	Comments (bench top No. v how to make NA, GCF does not have prototype equipment.
5.06 N Interfaces between components/subsystems in testing are realistic with realistic interfaces)?	(bench top No. r how to make NA, GCF does not have prototype equipment.
Prototypes of agginment system components have been created (know	how to make NA, GCF does not have prototype equipment.
5.07 Frontypes of equipment system components have been created (know equipment)?	
5.08 Tooling and machines demonstrated in lab for new manufacturing promake component?	NA, tooling does not apply to GCF.
5.09 High fidelity lab integration of system completed, ready for test in release environments?	NA, integration of system is covered by FMP and CCC.
5.10 Manufacturing techniques have been defined to the point where larges defined?	t problems 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-sc	ale 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 for testing?	v components No.
5.15 Three dimensional drawings and P&IDs for the prototypical engineering facility have been prepared?	ng-scale test NA, drawings and P&ID's do not apply to GCF.
5.16 N Laboratory environment for testing modified to approximate oper environment?	rational No.
5.17 N Component integration issues and requirements identified?	No.
5.18 Detailed design drawings have been completed to support specificatio engineering-scale testing system?	n of NA, drawings do not apply to GCF.
5.19 N Requirements definition with performance thresholds and objecti established for final plant design?	ves No.
5.20 N Preliminary technology feasibility engineering report completed?	No.
5.21 N Integration of modules/functions demonstrated in a laboratory/be environment?	nch-scale No.
5.22 N Formal control of all components to be used in final prototypical f	est 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 simula the properties/performance of the actual wastes?	nts match No.
5.27 N Laboratory-scale tests on the full range of simulants using a proto system have been completed?	typical No.
5.28 N Laboratory-scale tests on a limited range of real wastes using a pr system have been completed?	ototypical 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 an	d resolved? No.
5.31 N Limits for all process variables/parameters and safety controls are refined?	e being No.
5.32 N Test plan for prototypical lab-scale tests executed - results validat	e design? No.
5.33 N Test plan documents for prototypical engineering-scale tests comp	leted? No.
5.34 N Risk management plan documented?	No.
5.35 N Is a program in place to qualify the waste form and production p	rocess? No.
5.36 N Have all relevant physical and chemical properties been sufficient determined and bounded to meet proposed disposal criteria?	ly well No.

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

C#	Y/N	Criteria	Comments
		Have the waste impacting process steps been demonstrated to function within	
5.37	Ν	acceptable range?	No.
5.38		Was the transportation and storage package been designed?	NA, transportation package does not apply to GCF.
5.39	Ν	Have release rate law models been established (for relevant environment(s))?	No.
		The relationships between system and sub-system parameters are understood	
6.01	Ν	at engineering scale allowing process/design variations and tradeoffs to be	No.
< 0 2			NA DAMI Incontract to CCE
6.02		Availability and reliability (RAMI) levels established?	NA, RAMI does not apply to GCF.
6.03	NI	Preliminary design drawings for final plant system are complete?	NA, drawings do not apply to GCF.
0.04	IN	Collection of actual maintainability, raliability, and supportability, data has been	NO.
6.05		started?	NA, RAMI does not apply to GCF.
6.06	Ν	Performance Baseline (including total project cost, schedule, and scope) has been completed?	No.
6.07	Ν	Operating limits for components determined (from design, safety and environmental compliance)?	No.
6.08	Ν	Operational requirements document available?	No.
6.09	Ν	Off-normal operating responses determined for engineering scale system?	No.
6.10	Ν	System technical interfaces defined?	No.
6.11	Ν	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	Ν	Analysis of project timing ensures technology will be available when required?	No.
6.14	Ν	Have established an interface control process?	No.
6.15	Ν	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	Ν	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	Ν	Technology "system" design specification complete and ready for detailed design?	No.
6.21		Components are functionally compatible with operational system?	NA_GEC does not include system components in a traditional sense
0.21		Engineering-scale system is high-fidelity functional prototype of operational	Tra, et e dees not merade system components in a daamonal sense.
6.22	N	system?	No.
6.23	N	Formal configuration management program defined to control change process?	No.
6.24	Ν	Integration demonstrations have been completed (e.g., construction of testing system)?	No.
6.25	Ν	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	Ν	Engineering to full-scale scale-up issues are understood and resolved?	No.
6.29	Ν	Laboratory and engineering-scale experiments are consistent?	No.
6.30	Ν	Limits for all process variables/parameters and safety controls are defined?	No.
6.31	Ν	Plan for engineering-scale testing executed - results validate design?	No.
6.32	Ν	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	Table A.4. Glass-ceramic formulation criteria evaluation.			
C#	Y/N	Criteria	Comments	
6.34	Ν	Are performance assessment models available for the form/disposal environment?	No.	
6.35	Ν	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

	The A.S. Caniser 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 coo		
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 valida 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 "re 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	Ν	Desktop environment (paper studies)?	Only the most extreme condition paper study was performed (standard Hanford canister with 14 kW of wast		
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, 7		
2.09	Ν	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	Ν	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 c		
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	Ν	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/limitation		
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 separate 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		
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	Ν	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		
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 st		

oling environments. late that aspect. The FRG cans have surface temperature after

reheat." Canisters would be based on the standard Hanford,

ste). [88] Additional paper studies are required to meet TRL-2. 72]

composition impact crystallinity.

tions processes and their resulting wastes aren't yet known.

ng curve.[69]

other compositions.[85]

tarted.

Table	Fable 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	Ν	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,	
3.10	Ν	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	Ν	Requirements tracking system defined to manage requirements creep?	No.	
3.14	Ν	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	Ν	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	Ν	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-dow	
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	Ν	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 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	Ν	Risk mitigation strategies identified?	No formal risk assessment has been performed.	
3.26	Ν	Rudimentary best value analysis performed for operations?	No.	
3.27	Ν	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	Ν	Has the type of disposal environment(s) been defined?	No.	
3.33	Ν	Is a general strategy for waste form qualification been developed?	No.	
4.01	Ν	Key process variables/parameters been fully identified and preliminary hazard evaluations have been performed?	No.	
4.02	Ν	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	Ν	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 heat).[95]	
4.06	Ν	Overall system requirements for end user's application are known?	No.	
4.07	Ν	Overall system requirements for end user's application are documented?	No.	
4.08	Ν	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]	

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

, 72]

wn.[27]

glass-ceramic. Further, it's been shown at laboratory scale

ng developed to evaluate glass cracking on cooling (with decay

C Velocity Conume 11 N Subscience (C) control of control methanial balance methanis (C) of control of co	Table A	able A.5. Canister cooling and crystallization criteria evaluation.			
11.1 12.8 Isolarity control with a value control with with a value control wit	C#	Y/N	Criteria	Comments	
1.12 N Analysis completed to establish component compatibility (De components we how. No. 1.13 N Section and Technology Demonstration cell criteria established (SAT section) The general nethnology program is described in this TMP. Specific research exit criteria have nor yet how how how the section). 1.14 N Technology demonstrates basic functionality is simulated environment? The initial cooling schedule, the glass cerumic can be made without releating [7] 1.15 N Soluble technology prototypes have been produced (Can components be made basic). No. 1.16 N Controlled bosing schedules to regrowder the initial cooling schedules to regrowder the initial cooling, no challes a construct centre inter cooling have been proformed at 1 1.16 N Controlled bosing symmetry enrorment used in testing? No. 1.17 N Sequentia schedules have how started? No. 1.18 N Controlled bosing symmetry enrorment used in testing? No. 1.19 N Intervine schedules to regrowder the induloses. No. 1.20 N Section and fish anney entert or completed? No. 1.21 N Section and fish anney entert or completed? No. 1	4.11	N	Laboratory experiments with available components show that they work together?	No.	
1.1 N Science and Exclusions Demonstration citl circleri stabilished (SAT uses) Design and exclusions in the stable recting or produced (can component) the mail action of the initial cooling selectule, the glass cerumic can be made without reheating [72] 1.14 N Science and Exclusions produced (Can component) the mail action of the initial cooling selectule, the glass cerumic can be made without reheating [72] No. 1.15 N Science and Exclusions produced (Can component) the mail action of the initial cooling selectule, the glass cerumic can be made without reheating [72] No. 1.16 N Tennentical dispositions provide in the stable provide of the interbook provide methon the stable provide interbook provide methon the stable provide in the stable provide in the stable provide in the stable provide interbook provide methon the stable provide interbook provide methon the interbook provide methon the interbook provide methon the stable provide in the stable provide prov	4.12	N	Analysis completed to establish component compatibility (Do components work together)?	No.	
141 Y Technology demonstrates basic functionality in simulated environment? For the initial cooling schedule, the glass certanic can be made without reheating [72] 115 S Singler than in scale? No 116 S Technology demonstrates basic functionality in simulated environment? No 117 S For the initial cooling schedule, the glass certanic content designed environment designed environment? No 220 N Kerpanderstrating processes for equipment system identified? No No 231 N Keing documents and designed environment? No No 232 N Keing documents and environment? No No 233 N Keing documents and environment? No No 243	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	
1.11 No Selection of protocypes have been produced (Concernment) No. 1.11 No Selection of program is a concernment of protocypes have been documented (Option description) No. 1.11 No Selection of program is a concernment of protocypes have been documented (Option description) No. 1.11 No Control document option of protocypes have been documented (Option of protocypes have been document) No. 1.11 No Control document option of protocypes have been document of protocypes have been document. No. 1.11 No Interprotocypes have been document of protocypes have been document. No. 1.11 No Control documents and design of tochology have been document. No. 1.12 No Selection document option document. No. 1.12 No Selection document. No. 1.12 No	4.14	Y	Technology demonstrates basic functionality in simulated environment?	For the initial cooling schedule, the glass ceramic can be made without reheating.[72]	
4.16 No Profit conceptual designs have been documented (system description, process) No. 4.17 No Equipments scale-up relationships are understood/accounted for in technology No. 4.18 Y Controlled landomary environment used in ussing? Controlled cooling schedules to reproduce the high-beat canister centreline cooling, task deep enterline (sono direction), insuland cooling, insuland cooling, insuland cooling, insuland cooling, insuland cooling, insuland cooling, schedules to reproduce the high-beat canister centreline cooling has been particulary in an interaction of the schedule direction and technology. 4.21 N Indegration studies have been strict? No. 4.22 N Negation studies have been strict? No. 4.23 N Soling documents and designs interfield in advisory stream inducting in a mandatering in a matter technology. No. 4.24 N Negation stratting have been strict? No. No. 4.25 N Proceind direction stratting in advisory stratting in advis	4.15	N	Scalable technology prototypes have been produced (Can components be made bigger than lab scale)?	No.	
111 No. 121 V1 Controlled aboratory environment used in testing? Controlled cooling schedules to reproduce the high-stan canister caneerine cooling has been performed at I maintenance) will likely drive the cost. 121 V1 Initial cost drivers identified? Controlled cooling schedules to reproduce the high-stan canister caneerine cooling, or reheating). Full maintenance) will likely drive the cost. 122 V1 Formal risk management program initiated? Canister manufacturing is a mature technology. 123 V1 Regrando studies description developed. (Systems) identified? Canister manufacturing is a mature technology. 124 V1 Regrandu studies description developed. (Systems) identified? Canister manufacturing is a mature technology. 125 V1 Regrandu studies description developed. (Systems) identified? Canister manufacturing is a mature technology. 126 V1 Ni fluids to technolog "System" integrandu studies description developed. Systems/System. 127 V1 Mingation strategies identified to address manufacturability producibility other standu studies. Social manufacturing is a mature technology. 128 N1 Rescription developed that approximate the standu studies. Social manufacturing is a mature technology.	4.16	N	Draft conceptual designs have been documented (system description, process flow diagrams, general arrangement drawings, and material balance)?	No.	
4.18 Y Controlled cooling, schuldes to reproduce the high-heat carister centrilue cooling, so use heat performed at 1 4.19 Y Initial cost drivers identifief? Controlled cooling, schuldes to reproduce the high-heat carister centrolleg cooling, or reheating). Equ 4.20 N Initial cost drivers identifief? No. 4.21 N Formal risk management program initiate? No. 4.22 Y Key manufactuning processes sole saying and technology have been complete? No. 4.23 N Soling documents and designs of technology have been complete? No. 4.24 Y Key manufactuning processes assessed in habronatory? Carister manufacturing is a mature technology. 4.24 Y Ney functional process assessed in habronatory? Carister manufacturing is a mature technology. 4.25 N Invelcional process assessed in habronatory? Carister manufacturing is a mature technology. 4.26 N Invelcional process assessed in habronatory? Carister manufacturing is a mature technology. 4.27 Y Mitigation strategies identified to address manufacturatifity phonatory. Carister manufacturing is a mature technology. 4.28 N Initial mather of simulates have been characterized for a range of simulates. No. 4.29 N Initial duaration process assessed in habronatory.	4.17	N	Equipment scale-up relationships are understood/accounted for in technology development program?	No.	
4.19 Y Initial out sirver side single? Description set set single single side single side single side side side side side side side sid	4.18	Y	Controlled laboratory environment used in testing?	Controlled cooling schedules to reproduce the high-heat canister centerline cooling has been performed at l	
4.20NIntegration studies have been started?No.4.21NFormal risk management program initiated?No.4.22YKey manufacturing processes for equipment systems identified?Canister manufacturing is a mature technology.4.23NScaling documents and designs of technology have been completed?No.4.24YKey manufacturing processes assessed in laboratory?Canister manufacturing is a mature technology.4.25NFunctional processe assessed in laboratory?Canister manufacturing is a mature technology.4.26NFunctional processe assessed in a denineering completed in a fab environment?No.4.27YMitigation strategies identified to address manufacturability/producibility shorfalls?Canister manufacturing is a mature technology.4.28NKey physical and chenical properties have been characterized for a range of waster projecties?No.4.28NNergenties?No.4.29NA limited number of simulants have been developed that approximate the range of waster projecties?No.4.29NProcess/parameter limits and safety control strategies are being explore?No.4.30NProcess/parameter limits and safety control strategies are being explore?No.4.31NProcess/parameter limits and safety control strategies are being explore?No.4.32YHase aderind waste qualification pance exployed and the resulting phase assemblage and performance impacts.4.33YTest plan documents for prototypical lab-scale tests complete?	4.19	Y	Initial cost drivers identified?	The options are generally known, (natural cooling, insulated cooling, controlled cooling, or reheating). Equi maintenance) will likely drive the cost.	
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5.04NPreliminary design engineering begins?No.5.05NRequirements for technology verification established?No.5.06NInterfaces between components/subsystems in testing are realistic (bench top with realistic interfaces)?No.	5.03	N	System interface requirements known (How would system be integrated into the plant?)	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.	5.04	Ν	Preliminary design engineering begins?	No.	
5.06 N Interfaces between components/subsystems in testing are realistic (bench top with realistic interfaces)? No.	5.05	Ν	Requirements for technology verification established?	No.	
	5.06	N	Interfaces between components/subsystems in testing are realistic (bench top with realistic interfaces)?	No.	

n agreed upon.

laboratory scale.[72] uipment size and cost along with operating costs (including

Table A	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	Ν	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 equip		
5.11	Ν	Lab-scale, similar system tested with range of simulants?	No.		
5.12	Ν	Fidelity of system mock-up improves from laboratory to bench-scale testing?	No.		
5.13	Ν	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	Ν	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	Ν	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	Ν	Requirements definition with performance thresholds and objectives established for final plant design?	No.		
5.20	Ν	Preliminary technology feasibility engineering report completed?	No.		
5.21	Ν	Integration of modules/functions demonstrated in a laboratory/bench-scale environment?	No.		
5.22	Ν	Formal control of all components to be used in final prototypical test system?	No.		
5.23	Ν	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	Ν	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	Ν	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	Ν	Test plan for prototypical lab-scale tests executed - results validate design?	No.		
5.33	Ν	Test plan documents for prototypical engineering-scale tests completed?	No.		
5.34	Ν	Risk management plan documented?	No.		
5.35	Ν	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	Ν	Have the waste impacting process steps been demonstrated to function within acceptable range?	No.		
5.38	Ν	Was the transportation and storage package been designed?	No		

ent.		
ipment.		

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

Table F	able A.S. 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	Ν	Availability and reliability (RAMI) levels established?	No.		
6.03	Ν	Preliminary design drawings for final plant system are complete?	No.		
6.04	Ν	Operating environment for final system known?	No.		
6.05	Ν	Collection of actual maintainability, reliability, and supportability data has been started?	No.		
6.06	Ν	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	Ν	Operational requirements document available?	No.		
6.09	Ν	Off-normal operating responses determined for engineering scale system?	No.		
6.10	Ν	System technical interfaces defined?	No.		
6.11	Ν	Component integration demonstrated at an engineering scale?	No.		
6.12	Ν	Scaling issues that remain are identified and understood. Supporting analysis is complete?	No.		
6.13	Ν	Analysis of project timing ensures technology will be available when required?	No.		
6.14	Ν	Have established an interface control process?	No.		
6.15	Ν	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	Ν	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	Ν	Technology "system" design specification complete and ready for detailed design?	No.		
6.21	Ν	Components are functionally compatible with operational system?	No.		
6.22	Ν	Engineering-scale system is high-fidelity functional prototype of operational system?	No.		
6.23	Ν	Formal configuration management program defined to control change process?	No.		
6.24	Ν	Integration demonstrations have been completed (e.g., construction of testing system)?	No.		
6.25	Ν	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	Ν	Engineering-scale tests on the full range of simulants using a prototypical system have been completed?	No.		
6.28	Ν	Engineering to full-scale scale-up issues are understood and resolved?	No.		
6.29	Ν	Laboratory and engineering-scale experiments are consistent?	No.		
6.30	Ν	Limits for all process variables/parameters and safety controls are defined?	No.		
6.31	Ν	Plan for engineering-scale testing executed - results validate design?	No.		
6.32	Ν	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	Ν	Are performance assessment models available for the form/disposal environment?	No.		
6.35	Ν	Has a preliminary performance assessment been done to determine the acceptability of the waste form?	No.		



Table A	e A.6. Canister decon criteria evaluation.*	
C#	t Y/N Criteria Comme	ats
1.01	1 Back of envelope environment?	
1.02	2 Physical laws and assumptions used in new technologies defined?	
1.03	B Paper studies confirm basic principles?	
1.04	¹⁴ Initial scientific observations reported in journals/conference proceedings/technical reports?	
1.05	5 Basic scientific principles observed and understood?	
1.06	Know who cares about the technology, e.g., sponsor, funding source, etc.?	
1.07	7 Research hypothesis formulated?	
1.08	Basic characterization data exists?	
1.09	9 Know who would perform research and where it would be done?	
2.01	1 Customer identified?	
2.02	2 Potential system or components have been identified?	
2.03	Paper studies show that application is feasible?	
2.04	4 Know what program the technology would support?	
2.05	An apparent theoretical or empirical design solution identified?	
2.06	6 Basic elements of technology have been identified?	
2.07	Desktop environment (paper studies)?	
2.08	8 Components of technology have been partially characterized?	
2.09	9 Performance predictions made for each element?	
2.10	0 Customer expresses interest in the application?	
2.11	1 Initial analysis shows what major functions need to be done?	
2.12	2 Modeling & Simulation only used to verify physical principles?	
2.13	3 System architecture defined in terms of major functions to be performed?	
2.14	4 Rigorous analytical studies confirm basic principles?	
2.15	5 Analytical studies reported in scientific journals/conference proceedings/technical reports?	
2.16	6 Individual parts of the technology work (No real attempt at integration)?	
2.17	7 Know what output devices are available?	
2.18	8 Preliminary strategy to obtain TRL Level 6 developed (e.g., scope, schedule, cost)?	
2.19	9 Know capabilities and limitations of researchers and research facilities?	
2.20	.0 The scope and scale of the waste problem has been determined?	
2.21	1 Know what experiments are required (research approach)?	
2.22	2 Qualitative idea of risk areas (cost, schedule, performance)?	
2.23	.3 Have the range of waste species and waste loading for the waste form been identified?	
2.24	A Are the general properties of the waste form well understood and published in peer review journals?	
2.25	5 Have experiments started with the goal of determining the mechanism for the release of radionuclides?	
3.01	Academic (basic science) environment?	
3.02	2 Some key process and safety requirements are identified?	
3.03	B 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?	

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Table A	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	Ν	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.

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Ta	ble A	<u>A.5.</u>	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
5.	12	Ν	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	Ν	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	Ν	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	Ν	Requirements definition with performance thresholds and objectives established for final plant design?	No.
5.	20	Y	Preliminary technology feasibility engineering report completed?	
5.	.21	Ν	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	v	Piels management plan documented?	This is true only for the WTD law activity waste vitrification facility [06]
5.	34	ľ	Kisk management plan documented?	This is true only for the wTP fow activity waste vitrification facility.[96]
5.	.55		Have all relevant physical and chemical properties been sufficiently well determined	
5.	.36		and bounded to meet proposed disposal criteria?	
5.	.37		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	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	Ν	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	Ν	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	Ν	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	Ν	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	Ν	Plan for engineering-scale testing executed - results validate design?	No.
6.32	Ν	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 plan- design?	t 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 scl	hedule and bu	idget estimat	e.																															
Item	ied		2012					2013	3	-		2014	4			2015	5			201	6			201	7			201	18	-	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 Preliminary engineering study	2.18, 4.13 2.07, 2.09, 3.06, 3.07, 3.16, 3.18, 3.19, 3.26, 4.05, 4.19	2.18, 4.13 3.06, 3.07, 3.16, 3.18, 3.19, 3.26, 4.05, 4.19	2.18, 4.13 3.16, 3.18, 3.19, 3.26, 4.19	2.18, 4.13 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	x	x																						0 400
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	х																							50
Actual waste characterization	3.27, 4.28, 5.24	4.28, 5.24			-															Х	х							х	Х					0
Simulant/actual waste comparisons	5.26	5.26	5.26	5.26	-																	Х	Х							х	х			30
Laboratory scale glass ceramic testing																																		
Initial reference formulation			2.12			Х	Х	х																										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	х	х	х																800
Preliminary model development (loading and heat models for cost benefit analyses)			3.07															X	х	Х	х	х												400
Variability study			4.28, 4.29, 5.11, 5.32	4.28, 4.29, 5.32																				Х	X	X	Х	x	Х	х	х	х	Х	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																Х	х	х	х	х	х	х	Х	х	х	х	Х	х	х	2600
Compare actual and simulant			4.30, 5.29	4.30, 5.29																			Х	х							Х	х		2400
Melter and off-gas testing with simulants																																		
Initial proof of principle			2.15, 3.03, 3.10, 3.29, 4.32	2.15					Х	X					Х	X																		1200
Scaling tests			3.22, 4.02, 4.17, 5.02															Х	Х	Х	х	х	Х	Х	Х	Х	х	х	Х					2000
Off-gas functionality			4.04															x	х	x	х	х	х	х	х	х	X	х	х					4000
Variability tests			3.27, 4.29, 4.37															Х	Х	х	х	х	х	х	х	х	Х	х	х					0
Long-term run-by-wire			4.18																							х	Х	Х	х	х	х			5000
Design data needs			5.07, 5.14																											Х	х	х	х	4000
Test the mixing, sampling, and analyses																																		

Table A.8. Preliminary activity sc																																		
Item		С	riteria Satisfi	ed			20	12			201	13			201	4			201	5			201	16			20	17			201	18		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										х	х	Х																					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																		х	X	X	х	X	X	X	Х	х				2500
Decontamination system testing					5.09, 5.14																										х	х	Х	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										Х	х																			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										х	Х																			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	$\begin{array}{c} 4.01, 4.07, \\ 4.16, 4.23, \\ 4.25, 4.31, \\ 5.03, 5.04, \\ 5.05, 5.13, \\ 5.15, 5.18, \\ 5.20, 5.31 \end{array}$	$\begin{array}{r} 4.01, 4.16, \\ 4.23, 4.25, \\ 4.27, 4.31, \\ 5.03, 5.04, \\ 5.05, 5.13, \\ 5.15, 5.18, \\ 5.20, 5.31 \end{array}$	4.01, 4.25, 4.31, 5.03, 5.04, 5.05, 5.20, 5.31	$\begin{array}{c} 4.01, 4.16, \\ 4.17, 4.23, \\ 4.25, 4.31, \\ 5.03, 5.04, \\ 5.05, 5.13, \\ 5.15, 5.18, \\ 5.20, 5.31 \end{array}$	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	$\begin{array}{c} 5.23, 6.02,\\ 6.03, 6.05,\\ 6.06, 6.09,\\ 6.12, 6.13,\\ 6.14, 6.15,\\ 6.20, 6.23,\\ 6.25\end{array}$	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,	4.10, 4.12,	5.17	4.10, 4.12,	5.17																													11000
	4.26, 5.17	4.26, 5.17		5.17																														
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

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Itom			c. ritorio Sotiefi	ad		•	2012			2013	<u> </u>		2014			2015		,	2016		2017	7	•	2018		Budget
					CD	. 1	2012	2	. 1	2013	. 4	. 1 . /	2014	. 4	. 1 ./	2013	. 4	.1 .0	2010	. 4 . 1	201	/	1	2018	. 4	Budget
Subitem	MSA	FMP	GCF	5.01.5.06	CD	qI	<u>q</u> 2 q	<u>3 q4</u>	qI	q2 q3	q4	<u>q1 q</u>	2 q3	q4 q	q1 q.	2 q3	q4 c	<u>1 q</u> 2	2 q3	q4 q1	q 2	q3 q4	qI	q2 q3	q4	est, \$K
Design data needs	5.01, 5.06,	5.01, 5.06,	5.06, 5.12,	5.01, 5.06,	5.12, 5.21,																					33000
	5.11, 5.12,	5.11, 5.12,	5.10, 5.21,	5.11, 5.12,	0.01, 0.11, 6.11																					
	5.10, 5.21, 5.22, 5.30	5.10, 5.21, 5.22, 5.27	5.22, 5.21, 5.20, 5.23	5.10, 5.21, 5.22, 5.27	0.10, 0.21, 6.22, 6.27																					
	5.22, 5.30,	5.22, 5.27,	5.30, 5.33,	5.22, 5.27, 5.27, 5.30, 5.32	0.22, 0.27, 6.31, 6.32																					
	5 36 5 37	5 33 5 36	6 04 6 07	5 33 5 37	0.51, 0.52																					
	6 01 6 04	5 37 6 01	6 10 6 11	6.01 6.04																						
	6.07. 6.10.	6.04. 6.07.	6.18, 6.21.	6.07, 6.10.																						
	6.11, 6.18,	6.10, 6.11,	6.22, 6.27,	6.11, 6.18,																						
	6.21, 6.22,	6.18, 6.21,	6.28, 6.29,	6.21, 6.22,																						
	6.27, 6.28,	6.22, 6.27,	6.30, 6.31,	6.27, 6.28,																						
	6.29, 6.30,	6.28, 6.29,	6.32	6.29, 6.30,																						
	6.31, 6.32	6.30, 6.31,		6.31, 6.32																						
		6.32																								
Waste compliance plan																										
Develop waste qualification	3.33	3.33	3.33	3.33	3.33						Х	х														200
strategy																										
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,	2.07, 2.09,	-																					400
	3.06, 3.07,	3.16, 3.18,	3.19, 3.26,	2.12, 2.14,																						
	3.16, 3.18,	3.19, 3.26,	4.19	3.06, 3.07,																						
	3.19, 3.26,	4.05, 4.19		3.16, 3.18,																						
	4.05, 4.19			5.19, 5.20, 4.05, 4.19																						
Characterize estimate and				1.05, 1.19																						
simulate waste to be treated																										
Initial waste estimates and	1.08, 2.20,	2.20, 3.28,	2.20, 2.23,	2.20, 2.23,	-																					50
simulant recipes	3.28, 5.25	5.25	5.25	5.25																						
Actual waste characterization	3.27, 4.28,	4.28, 5.24			-		2	к х																		0
	5.24																									
Simulant/actual waste	5.26	5.26	5.26	5.26	-				х	Х																30
comparisons																										
Laboratory scale glass ceramic																										
Initial Paferance formulation			2.12																							0
Formulation and testing for initial			2.12	2 13 2 24																						800
compositions (incl. I SM)			2.09, 2.13, 2.24, 3.03	2.13, 2.24, 3.03, 4.18																						800
compositions (mei. ESW)			3 10 3 22	5.05, 4.10																						
			3.27, 4.04,																							
			4.11, 4.12,																							
			4.18, 4.26,																							
			4.32																							
Preliminary model development			3.07																							400
(loading and heat models for cost																										
benefit analyses)																										
Variability study			4.28, 4.29,	4.28, 4.29,		Х	х																			3000
			5.11, 5.32	5.32																						
Final model development			4.37, 5.24,	4.37, 5.24,		Х	х х	x x	Х	x x	Х															800
			6.09	6.09																						

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

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

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

Item		C	c. riteria Satisfi	ed		· ·	20	12			2013		·	20	014			2015		•		2016		•	20	17		2	018		Budget
Subitem	MSA	FMP	GCF		CD	a1	a2	<u>a</u> 3	a4 c	u1 a	2015 12 a ²	3 a4	L a1	2	3	a4	a1	a? (13 (4 a	· ′م ا	2010	a4	a1	<u>2</u>	<u></u>	<u>a4 a</u>	1 a2	a3	a4	est \$K
Performance evaluation	MD/X	1 1011	5 36 5 39	5 36 5 39	CD	<u> </u>	<u>q</u> 2 x	<u>q</u> 5 x	<u>y</u> <u>y</u>	<u>1 9</u> x 3	<u> - </u>	י <u>ץ ק</u> א	r q1 x	<u>q2</u> x	<u>q5</u> x	<u>q</u> -	<u>q1</u>	<u>q2</u>	1.5	<u>- 4</u>	<u> </u>	<u>- 4</u> 5	<u>4</u> -	<u> </u>	<u> </u>	<u> </u>	<u> </u>	<u>1 42</u>	<u>4</u> 5	<u> </u>	2600
Compare actual and simulant			4.30, 5.29	4.30. 5.29		Α	Α	1	Λ.	x 7	x x	л	Λ	Λ	Λ	A															2400
Melter and off-gas testing with																															2.00
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			Х	х	Х	Х																						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	х	х	х																							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 Z	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 z	x x																				600
Preliminary design																															
Conceptual design	$\begin{array}{c} 4.01, 4.07, \\ 4.16, 4.23, \\ 4.25, 4.31, \\ 5.03, 5.04, \\ 5.05, 5.13, \\ 5.15, 5.18, \\ 5.20, 5.31 \end{array}$	$\begin{array}{c} 4.01, 4.16,\\ 4.23, 4.25,\\ 4.27, 4.31,\\ 5.03, 5.04,\\ 5.05, 5.13,\\ 5.15, 5.18,\\ 5.20, 5.31\end{array}$	4.01, 4.25, 4.31, 5.03, 5.04, 5.05, 5.20, 5.31	$\begin{array}{c} 4.01, 4.16,\\ 4.17, 4.23,\\ 4.25, 4.31,\\ 5.03, 5.04,\\ 5.05, 5.13,\\ 5.15, 5.18,\\ 5.20, 5.31\end{array}$	5.05	Х	X	X	X	x 2	X X	x																			2000

Table A.8. Preliminary activity	schedule and b	udget estimat	te.																														
Item	-	С	riteria Satisfi	ied			2012	2		2	2013			20	14			20	15			20	16			2017				2018	8	-	Budget
Subitem	MSA	FMP	GCF	CCC	CD	q1	q2 (q3 q	q4 q1	l 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	$\begin{array}{c} 5.23,6.02,\\ 6.03,6.05,\\ 6.06,6.09,\\ 6.12,6.13,\\ 6.14,6.15,\\ 6.20,6.23,\\ 6.25\end{array}$	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								Х	Х	Х	Х	Х	X	Х	Χ	X	X	х	Х									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				Х	х	х	х																					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								х	х																				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	х	x	X	X	X	x	х	X	X	x	X	х	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															Х	х	х	Х										600

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

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