Project of Decommissioning and Contaminated Water Management
(Research and Development of Processing and Disposal of Solid Waste)

The Holistic Evaluation of Applicability of GeoMelt® ICV™ for Treatment of 1F Water Treatment Secondary Waste Fiscal Year 2019-2020

November 2021

Kurion Japan K.K . / Veolia Nuclear Solutions INC.

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1. Introduction: Purpose of the Project

- The Mid-and-Long-Term Roadmap states that 1F solid waste should be stored and managed safely and rationally according to its characteristics, and a system should be established to reasonably choose the preceding processing (processing methods for stabilization and immobilization, which will be performed considering disposal prior to the decision of technical requirements for disposal) methods.

- As a Subsidy Project following GeoMelt® research results (*) in FY2017 and FY2018 of the IRID program that Kurion Japan received an order from ATOX, "Comprehensive Evaluation on Applicability of GeoMelt® In-Container Vitrification (ICV) ™ for 1F Water treatment Secondary Waste processing" the FY 2019-FY2020 project aimed to the following:

  ① As a research and development test, verify the excellent cesium retention results of glass from the engineering-scale test of GeoMelt® ICV™ on major waste simulant at 1F in 2018 and improve cesium retention performance with a focus on engineering-scale test process optimization and equipment modifications.

  ② Based on the results of these R & D tests, conduct a preliminary conceptual design and individual evaluations to carry out the comprehensive evaluation of applicability of GeoMelt® ICV™ at 1F

  ③ Enhance and enlarge the database of the glass for waste treatment. Evaluate with modeling the effect of compositional variation of waste and melt temperature on the waste loading.

  ④ Study the suppression of Cs volatilization of Cs with the lab-scale experiments and simulation.

(*) : Survey on applicability evaluation of in-drum type vitrification technology in Subsidy for decommissioning / contaminated water countermeasures in FY2018 supplementary budget (research and development on processing / disposal of solid waste). Engineering-scale Melt Test 1 -3 were performed in this project (IRID Program, METI Subsidy Project)

1. Introduction：Implementation Structure

Subsidiary Project Organization

- Project management, technical supervision, report writing
- Cooperation / coordination with MRI / NDF / TEPCO

Kurion Japan K.K.
Sadaaki ABETA: Project Manager

Tokyo Institute of Technology (Consignment)	• Technical expertise & testing/researching capability on vitrification • Conduct research on Cs volatilization suppression
KK Techno (Consignment)	• Engineering knowhow and experiences of nuclear plants in Japan • Conduct PCD review
Nuclear Safety Research Association (Outsourcing and Consignment)	• Expertise on treatment & disposal of vitrified waste • Conduct glass performance evaluation
Daiei Kankyo Holdings (Outsourcing)	• Industrial experience of hazardous waste treatment using GeoMelt® ICV™ in Japan • Conduct a review on engineering scale test
Veolia Nuclear Solutions Federal Services (Outsourcing)	• Summarize reviews conducted by PNNL
└ **Pacific Northwest National Laboratory**	• Review a research result report of Tokyo Institute of Technology

Veolia Nuclear Solutions Inc.
Marc ROOD: Sub Project Manager

Veolia Nuclear Solutions Federal Services (Outsourcing)	• Expertise on GeoMelt® ICV™ • Conduct engineering scale tests, etc. • Engineering knowhow and industrial experience in hazardous and nuclear waste treatment worldwide
└ **Pacific Northwest National Laboratory**	• Conduct glass formulation and analysis
└ **CleanAir Engineering Inc.**	• Conduct emission measurement and atmospheric environment management
└ **ALS USA**	• Analyze glass samples
└ **Monarch Machine and Tool**	• Test equipment piping and support work
└ **Techweigh Technics Industries**	• Deliver supply containers and weighing equipment

1. Introduction: History of the development of GeoMelt® ICV™

- GeoMelt® was the technology of vitrification of hazardous waste such as radioactive waste to stable glass. This technology invented at Pacific Northwest National Laboratory (PNNL) for the U.S. Department of Energy. Commercially available since 1993.
- GeoMelt® was used initially for treatment of buried radioactive and hazardous wastes as In-Situ Vitrification GeoMelt®ISV™.
- GeoMelt®ICV™ was invented for the treatment of above-ground radioactive and hazardous wastes.
- Over 26,000 metric tons of waste have been treated to-date with GeoMelt®ICV™.

GeoMelt® ICV™ – Daieikankyou Hazardous Waste Treatment Plant 10 tons Melt, Japan

GeoMelt® is a proven technology with full-scale plants in operations in Japan and the U.S.

GeoMelt® ICV™ – Radioactive Test Rig Sellafield Site: 500 kg Melts, U.K.

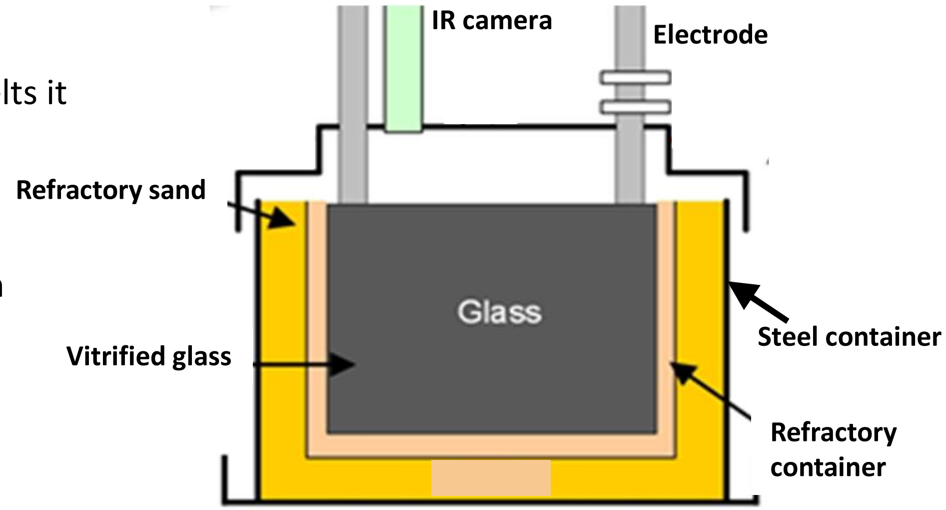
GeoMelt® ISV™ – Maralinga Nuclear Test Range: 500 tons Melts, Australia

GeoMelt® ICV™ – Hanford Demonstration Bulk Vitrification System (DBVS): 50 ton Melts, USA

1. Introduction: Characteristics of GeoMelt® ICV™（1/2）

① Glass melting and vitrification in the container
(hereinafter, see figure right)
It is a technology that supplies waste to a container, melts it by the Joule heating method, and vitrifies it as it is without pouring glass down.

② The melting container and waste are identical
It is a simple batch process without pouring glass down and the melting container for melting treatment itself becomes the waste form for disposal.
(Replace the melting container for each batch)



GeoMelt® ICV™ melting container

③ Structure of melting container

It features a structure in which a refractory container to store vitrified glass is placed, refractory sand as heat insulation are placed on the outside and a steel container is installed on the outermost side.

④ Reducing the effect of melting on the refractory container

Compared to melters being used continuously for a long period of time with repeated, the refractory container is less corroded and melting at a higher temperature is possible due to batch processing.

⑤ High waste loading is possible

Since the viscosity can be increased because of no need of pouring glass down, the amount of glass additives to lower the glass viscosity can be reduced. Therefore, the waste loading can be increased accordingly.

⑥ High viscosity and high temperature melting, and co-treatment with zeolite

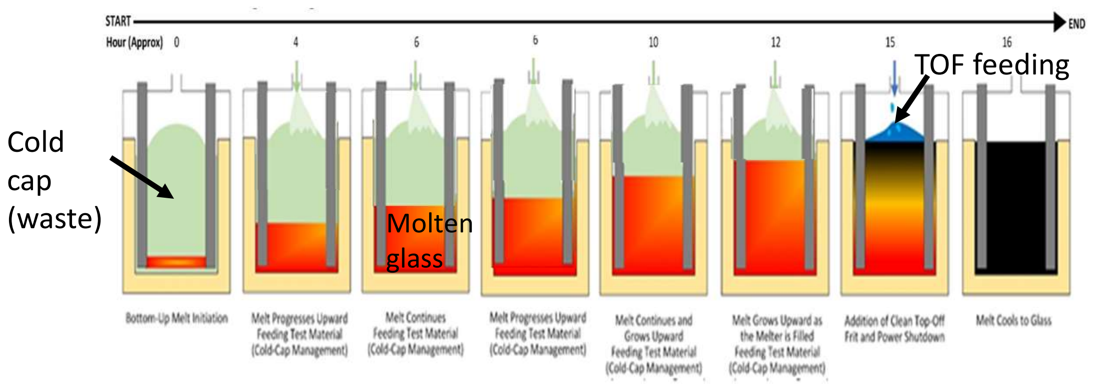
Since the viscosity can be increased, melting can be performed at a high temperature, so that the zeolite and the titanate adsorbents at 1F can be melted at a high temperature. In addition, zeolite can be used as a glass former required for vitrification of waste, and the waste loading of the glass can be improved by co-treating zeolite waste.

⑦ Suppression of volatile Cs emission by the cold cap management (see figure below)

- After the inside of the container is filled with waste to the top, melting is continued. The intermittent operation to feed additional waste is continued when the container has enough free space for the waste supply due to the volume reduction of waste. The emission of volatile Cs to the off-gas system is suppressed by constantly managing the un-melted waste layer on molten glass (the layer of low temperature on molten glass is referred as "cold cap") to keep its maximum thickness (cold cap management) in this operation .
  It is presumed that this is because Cs volatilized from the waste including the molten glass is trapped by condensing into the cold cap particles at the upper part where the temperature is low, then descends with the waste supply and is incorporated into the molten glass.
- Since the cold cap becomes thin at the final stage of melting, clean glass frit (top-off frit: TOF) is added as cold cap and Cs volatilized from the finally fed waste is condensed and captured by TOF. Ultimately, the melted TOF covers the waste glass and suppresses the Cs emission to the off-gas system.

⑧ Wide range of container size

The melting scale can be selected by an economical evaluation according to the treating needs. Containers have a track record of 250 kg (engineering scale) up to 50 tons.

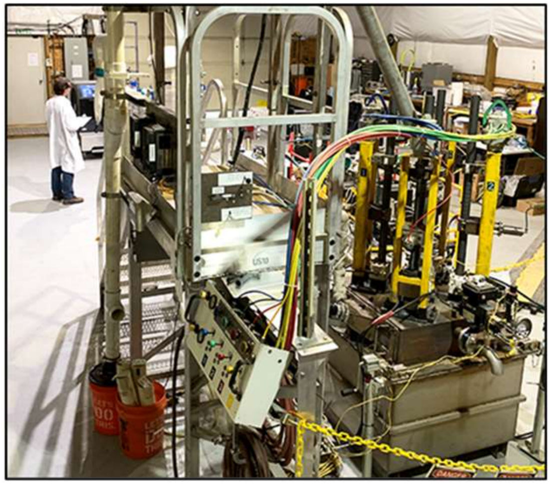


GeoMelt® ICV™ cold cap management

2. The Scope of FY2019-2020 Project（1/2）

Engineering scale melt test (conducted by VNSFS)

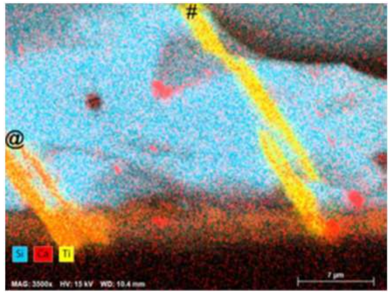
- Glass melt test for simulated waste of 1F water treatment secondary waste (including 1F simulated soil) (Melt tests 4-8 conducted)
- Demonstration of melting operations (including cold cap management), demonstration of remote re-start of melting after emergency stop of melting
- Measurement of the transferred amount of Cs and Sr to off-gas in the glass melting treatment, evaluation of Cs and Sr retention rate in vitrified waste form



GeoMelt® ICV™ engineering scale Melt test equipment

Basic experiments and modeling (1) (Glass science: conducted by PNNL）

- Enhance and enlarge of the 1F water treatment glass database for secondary waste treatment (analysis of glass composition, crucible test, detailed analysis of generated glass)
- Evaluation of the effect of glass composition (type and amount of waste contained) on glass performance, performance evaluation of low melting temperature glass (analysis by glass modeling) ）
- Detailed analysis of glass sample, leaching test (MCC-1 test)



SEM-EDS of alteration layer of engineering scale molten glass

Basic experiments and modeling (2) (Elucidation of mechanism that suppresses volatilization of Cs: conducted by Tokyo Institute of Technology)

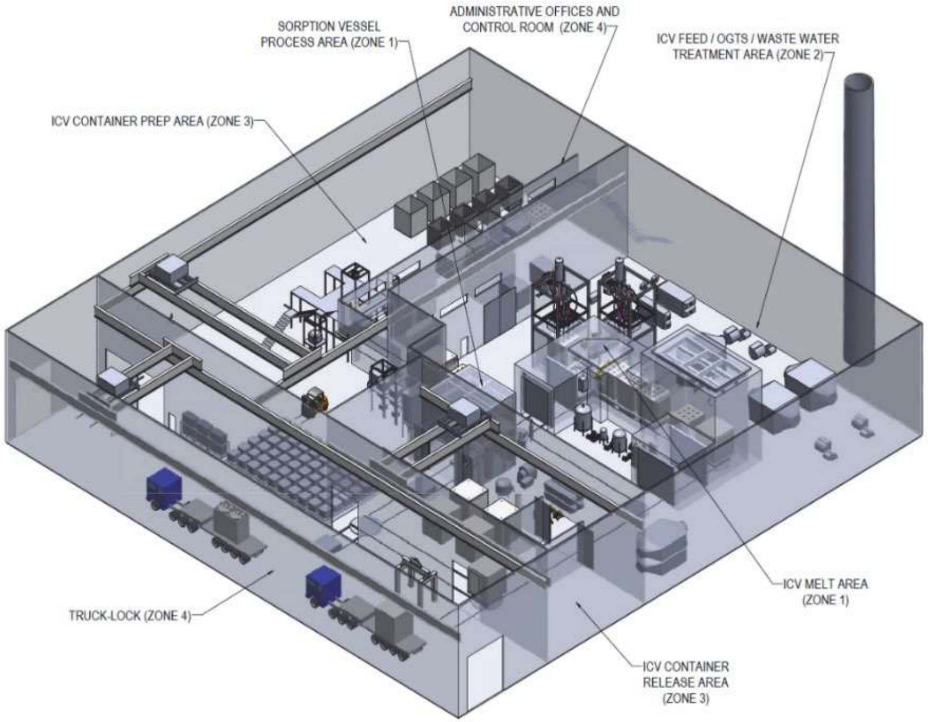
- Crucible test, analysis by a computer simulation model for elucidation of the mechanism of suppressing Cs volatilization in the cold cap

Molten glass in a quartz beaker removed after heating

2. The scope of the FY2019 – 2020 Project (2/2)

GeoMelt® ICV™ Plant Preliminary-Conceptual Design (PCD) and Assessments

- Examination of the plant to treat and vitrify 1F water treatment secondary waste by GeoMelt® ICV™ technology.
- Making full use of the results of the engineering-scale melt tests, the basic experiments and modeling and the experience of other GeoMelt® ICV™ plants for this examination.
- The GeoMelt® ICV™ Plant Preliminary-Conceptual Design (PCD), as the design of the stage prior to conceptual design, providing "big picture" or macro design of the plant, being based on the examination of process, equipment and piping, plant layout and process/system such as waste handling, etc.
- Assessments of the plant from the six viewpoints described below:
  - ➢ Operability and Maintainability Assessment
  - ➢ Product Package Assessment
  - ➢ Economic Efficiency Assessment
  - ➢ Safety Assessment
  - ➢ Evaluation of Waste Retrieval and Materials Handling Systems
  - ➢ Glass Performance Assessment (Containment function)



Bird's-eye view of inside of GeoMelt® ICV™ Plant

3. Engineering Scale Melt Test（1/28）: Overall overview

Conducted 5 engineering scale melt test (Melt 4-8 *)

①Test target: hereinafter, "A + B" is referred to as simulated waste, and "A + B + C" is referred to as test materials.

- A: Materials that simulate KUR-EH, KUR-TSG, ALPS slurry **, and AREVA sludge among 1F water treatment secondary wastes
- B: Aluminosilicate mineral-based waste (zeolite such as KUR-EH) can be used as a glass former necessary for the treatment of other water treatment secondary wastes in GeoMelt® ICV™.
- C: Glass additives (B_2O_3, $LiCO_3$, etc.) to reduce viscosity, improve durability and increase solubility are added, and the materials to be tested are blended.
- This blending ratio corresponds to the glass composition confirmed by the crucible test, which was analyzed and set by PNNL.

② Test purpose:

- Demonstration of reliable melting process (Melter operation): Understanding the melting state by measuring the melting temperature, observing the cold cap state of the upper surface of the Melter with a camera, realization of cold cap management by accurate implementation of additional waste supply and top-off frit supply.
- Demonstration of remote melting re-start method after melting stops
- Demonstration of high Cs retention rate: Achieving a higher and more stable retention rate compared to the results of the FY2018 Melt 1-3 (90% or more, but the variation between tests is large). Understanding the effects of the following factors on the Cs retention rate in addition to reliable cold cap management.
  - Decrease in melt surface area / volume ratio
  - Difference between 4-electrode and 2-electrode Melter (the latter has a smaller melt surface area)、
  - Difference in melting start method (top-down, bottom-up)
  - Water content of test material

* Test numbers continue from three engineering scale melt tests which were performed in FY2017 – 2018 project.
Simulated wastes used in melt tests 5 – 7 are identical with the simulated wastes used in melt tests 1-3

③ Acquired data, etc.:

- The Cs retention rate is obtained by calculating the transferred amount of Cs to off-gas by stack sampling and analysis of wiped samples such as off-gas piping after the test is completed.
- The homogeneity of the glass is confirmed by SEM-EDS analysis of glass samples.
- Detailed analysis (observation of secondary phase, etc.) and long-term leaching test for the glass sample by PNNL.

List of implementation contents of engineering scale melt test

Test*	Melter /Melting start method	Purpose	Simulated waste
Melt 4	4-electrodeMelter Top-down	・Demonstration of melting operation ・Ensuring achievement of high Cs retention rate	KUR-EH＋TSG
Melt 5	2-electrodeMelter Bottom-up	(Same as above)	KUR-EH＋ALPS Slurry
Melt 6	2-electrodeMelter Bottom-up	(Same as above)	KUR-EH＋TSG
Melt 7	2-electrodeMelter Bottom-up	(Same as above)	KUR-EH＋AREVA Sludge
Melt 8	2-electrodeMelter Bottom-up	・Confirming the applicability of simulated soil as a glass former ・Demonstration of restart of melting after melting has stopped	Simulated soil (based on 1F soil composition)

** KUR-EH is Kurion’s Engineered Herschelite. Ion exchange of Cs-134 and Cs-137 with zeolite material. KUR-TSG is Kurion‘s granular titanosilicate. Ion exchange of Sr-90 with silico titanate material. ALPS slurry is a carbonate and iron coprecipitated slurry, which is an adsorbent used for multi-nuclide removal.

3. Engineering-Scale Melt Test (2/28): Preparation of Waste Simulants and Tracers

- The mass of Cs to be used for each melt was calculated from the average activity of Cs-137 in KUR-EH ion exchange vessels at 1F.
- 150 g of CsCl was dissolved in 320 L of water.
- 168 kg of KUR-EH* was added to the water
- The KUR-EH and water was mixed with a rotary drum mixer.
- The water was sampled to verify that the Cs had absorbed onto the KUR-EH.
- The water was decanted, then the Cs-adsorbed KUR-EH was dried on a solar drying station.
- Once dry the KUR-EH was blended with the other 1F waste simulants (KUR-TSG**, ALPS Carbonate and Iron Coprecipitation Slurries***, or AREVA Sludge, glass additives, water, and $SrCO_3$.
- Once blended, the test materials were loaded into 5-gallon (19-L) buckets.
- Each bucket was sampled for laboratory analysis of bulk and trace (Cs, Sr) chemistry.

* KUR-EH is Kurion Engineered Herschelite. This is a zeolite material for ion exchange of Cs-134 & Cs-137 from 1F water. This is blended as glass former

** KUR-TSG is Kurion Titanosilicate Granular. This is a silicotitanate material for ion exchange of Sr-90 from 1F water.

*** ALPS Carbonate and Iron Coprecipitation Slurries are waste sorbent materials used at 1F for multi-nuclide removal.

Solar Drying Station

Rotary Drum Mixer

3. Engineering-Scale Melt Test (3/28): Melt 4

Melt 4 Objectives

- Demonstration of top-down melt startup.
- Improvement of Cs retention from previous Melt 2 with the same formulation.

KUR-EH is Kurion Engineered Herschelite. This is a zeolite material for ion exchange of Cs-134 & Cs-137 from 1F water.

KUR-TSG is Kurion Titanosilicate Granular. This is a silicotitanate material for ion exchange of Sr-90 from 1F water.

Melt 4 Recipe.

Component	Mass (kg)	wt%
KUR-EH	134.00	61.19
KUR-TSG	47.20	21.55
Glass additives	37.80	17.26
Subtotal	219.00	100.00
Water	20.00	15% moisture in KUR-EH; 9% water overall.
Total	239.00	
Tracers:		
CsCl	150.00 g	
$SrCO_3$	165.00 g	

Melt 4 Results

- All materials introduced into the melter were processed.
- The waste loading was 76.60% on a glass oxide basis. On a dry feed basis, the waste loading was 77.44%
- 99.44% Cs retention in glass. 99.99% Sr retention in glass.

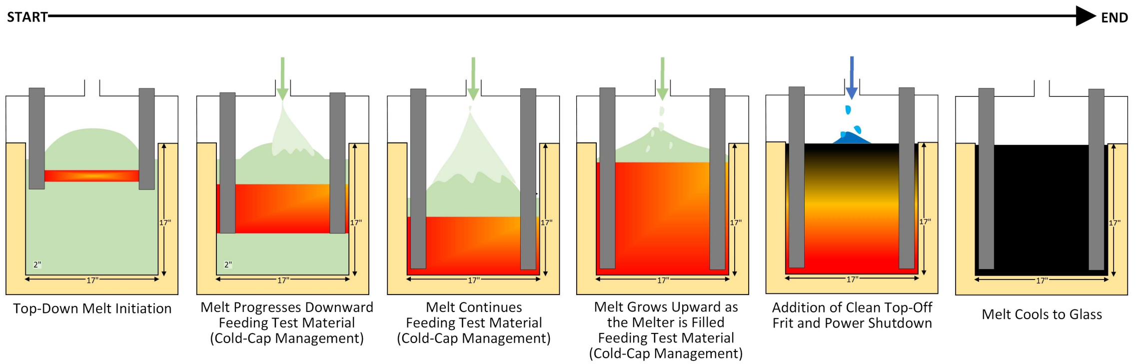
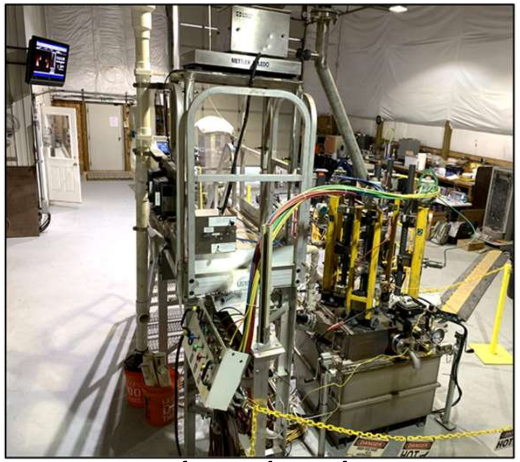


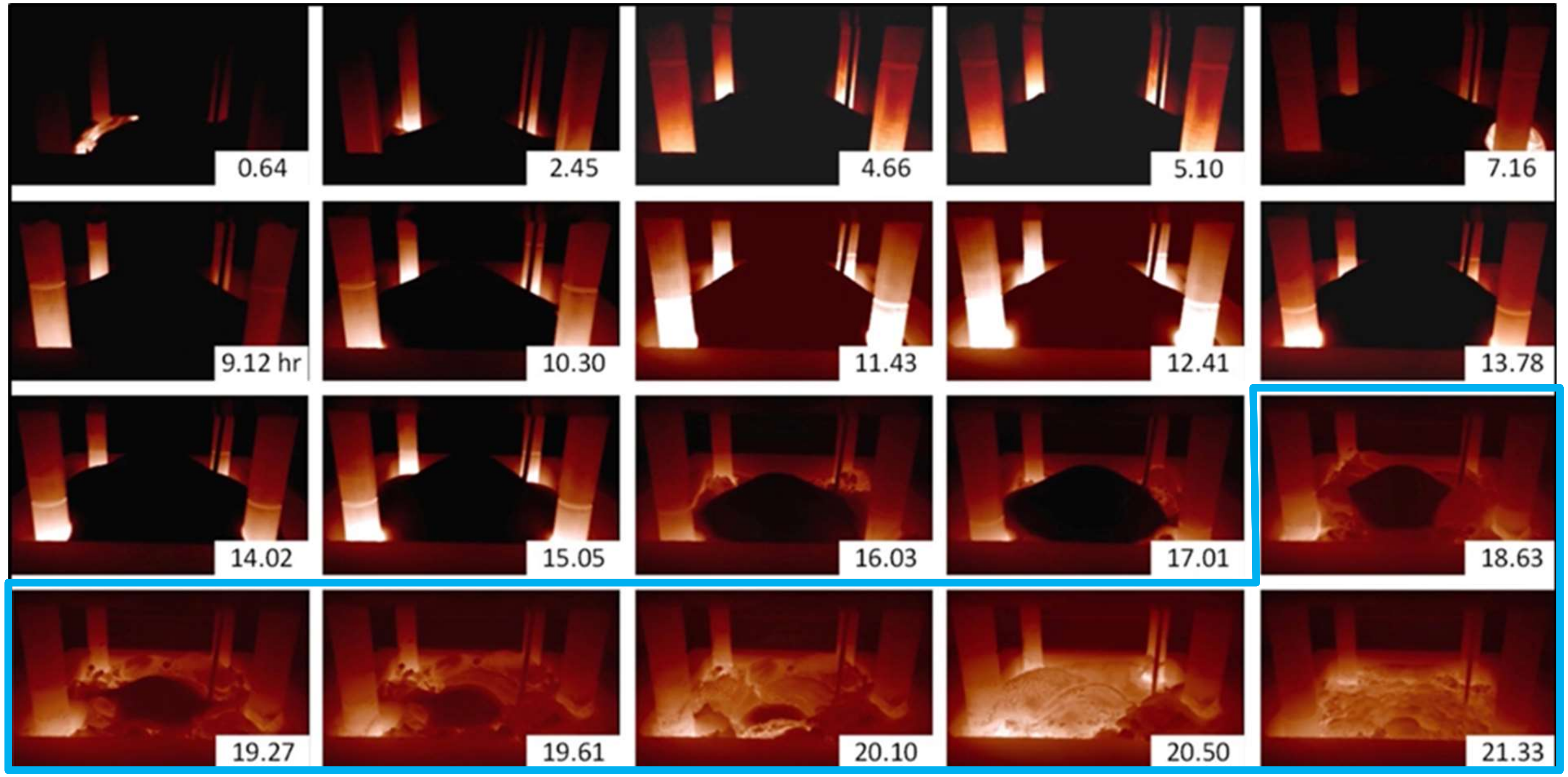
Diagram of GeoMelt® ICV™ Using a Top-Down Melt Startup from Start to Completion



4-Electrode Melter

3. Engineering-Scale Melt Test (4/28):
Melt 4 Infrared Camera View into the Melter

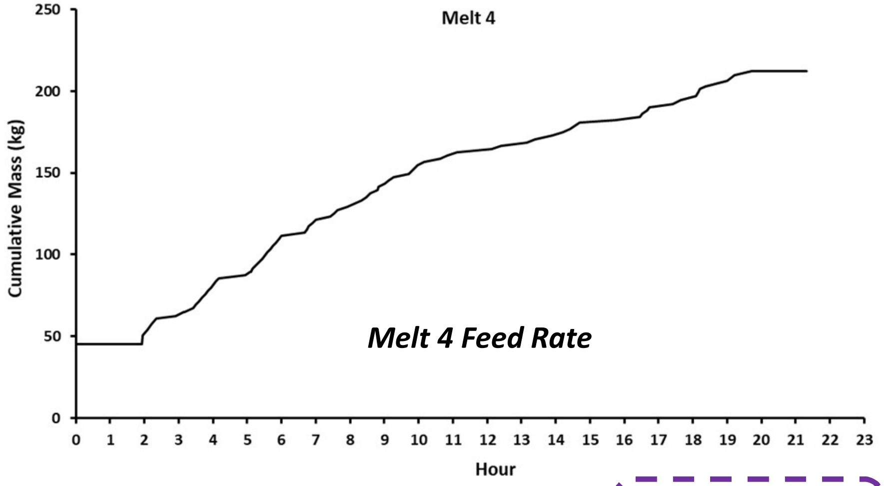
- Melts are monitored continuously with an infrared camera (IR camera).
- As the waste simulant materials are melted densification causes volume reduction.
- When volume is available more waste simulant materials are fed into the melter.
- In last stage, the glass frit containing no waste simulant are fed to suppress the release of Cs
- When all materials have been melted power is shut off and the glass cools.



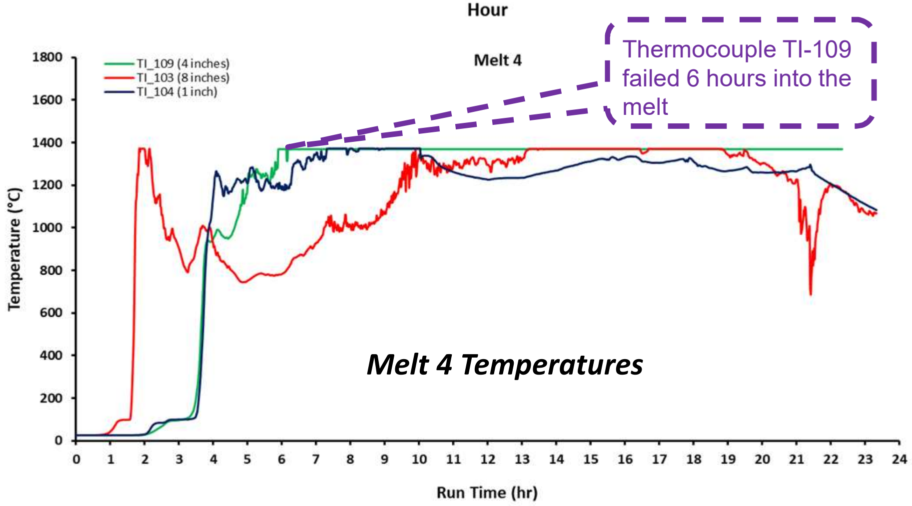
Sequence of IR Images During Melt 4（Blue framework indicates the situation after TOF feeding)

3. Engineering-Scale Melt Test (5/28): Melt 4 Feed Rate and Melt Temperatures

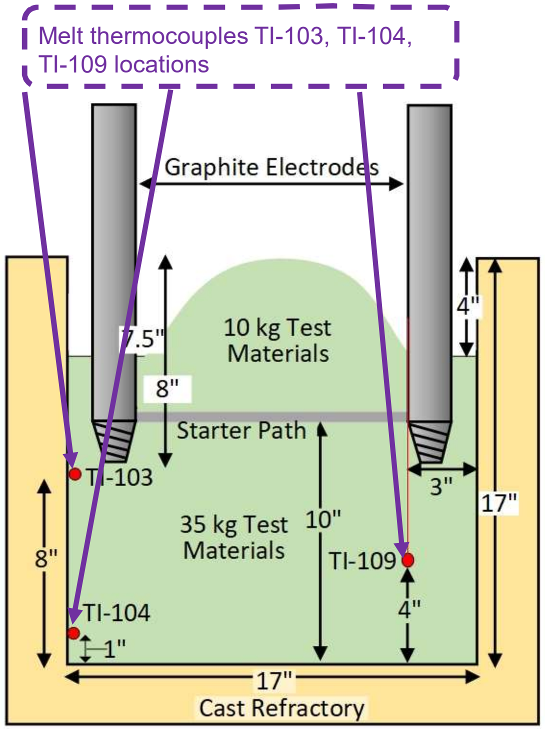
- The initial batch was 45 kg and 167 kg of materials were fed into the melter during operations. The test material consists of waste simulant of KUR-EH + KUR-TSG + glass additives.
- Thermocouples are installed in the melt to monitor melt progress.
- Type K thermocouples were used for this melt and the maximum temperatures recorded was 1371 °C, which is top of the Type K thermocouple range.



Melt 4 Feed Rate



Melt 4 Temperatures



Situation inside of the melter at the start of melting

3. Engineering-Scale Melt Test (6/28): Melt 4 Cs and Sr Retention in Glass

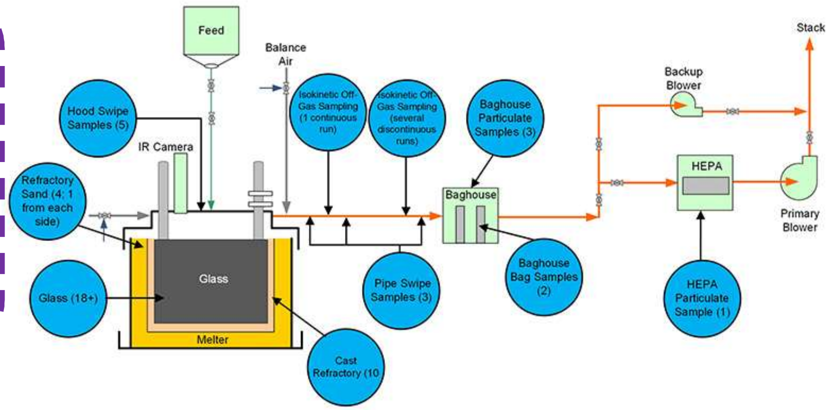
- Continuous isokinetic stack sampling determines mass of Cs and Sr leaving the melt.
- Inner surfaces of the melter hood and off-gas piping were wipe-sampled to determine mass of Cs and Sr plated out before continuous isokinetic stack sampling point. Refer to the next page for wipe sample locations.
- Mass of emissions are added to mass of Cs and Sr plated off to determine output mass.
- Input mass is the mass of Cs and Sr in the test feed.
- There are two standard methods to account for loss of components from the melter to the off-gas: 1) retention in glass(v_i) is the fraction of the i^{th} component in the feed that is retained in glass and 2) decontamination factor (DF_i) is the ratio of the i^{th} component's input to output (in this case the output is from the melter through the off-gas). These two factors are related according to:

$$v_1 = 1 - \frac{1}{DF_i} x\ 100$$

Where:

$$DF_i = \frac{input\ mass}{output\ mass}$$

Input mass of Cs and Sr is the average concentration of Cs and Sr multiplied by the mass of the feed. Output mass is calculated by multiplying emission rate by test duration and adding this product to mass determined from the first section of off-gas pipe (before the continuous stack sampling point), wipe sampling of the hood, and analysis of refractory sand and cast refractory. The mass of Cs and Sr in the second and third section of off-gas piping, baghouse bags, and HEPA filter paper are not included in this calculation because these are accounted for in the isokinetic stack sampling results.



- The values used for the calculation for Melt 4 is shown below:

Melt 4 Results

	Input Mass Mass in feed (g)	Mass in off-gas (g)	+	Mass in Hood, First Section of Pipe, Refractory Sand, and Cast Refractory (g)	=	Output Mass	$DF = \frac{input\_mass}{output\_mass}$	$Retention\ in\ glass = 1 - \frac{1}{DF} x\ 100$ Retention in glass (%)
Cs	85.72	0.466		0.016		0.482	177.78	99.44
Sr	217.93	0.017		0.002		0.019	11363.16	99.99

Lab analysis of feed samples

Continuous Isokinetic Stack Sampling

Lab analysis of piping and hood wipe, refractory sand, and cast refractory samples

Decontamination Factor is the ratio of the input to output mass of Cs, Sr

Good retention in glass

2. Engineering-Scale Melt Test (7/28): Melt 4 Cs and Sr Distribution

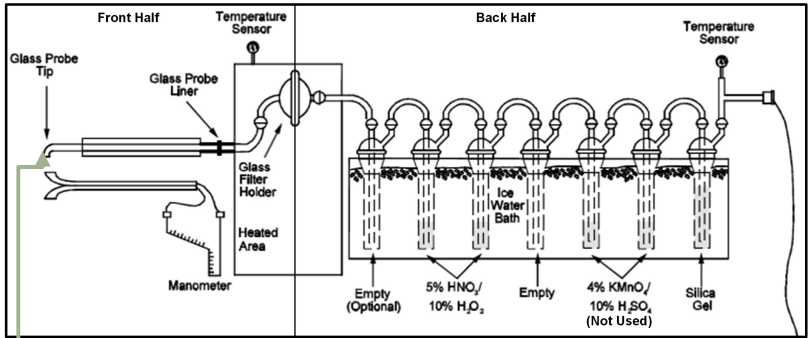
- 0.25 g of Cs and 0.05 g of Sr were detected in the melter hood interior, piping, and filters.
- Essentially no Cs or Sr was detected in the refractory after subtract the nature-origin Cs and Sr.
- 0.25 g of Cs equates to 99.70% retention in glass which agrees well with the continuous isokinetic stack sampling results (99.44%).

The sum of the mass of Cs and Sr in the melter hood, first section of pipe, refractory sand, and cast refractory is used in the calculation shown on the previous page. Note that only the results from the first section of off-gas pipe is used for the calculation shown on the previous page. The results shown on this page represent the sum of Cs and Sr on all three pipe sections.

Location	Cs		Sr	
	(g)	%	(g)	%
Refractory Sand	0.00003	0.01	0.00007	0.15
Cast Refractory	0.00	0.00	0.00	0.00
Melter Hood	0.01	5.63	0.00	2.16
Off-Gas Piping	0.02	1.40	0.003	3.61
Baghouse	0.13	53.10	0.001	1.14
HEPA Filter	0.10	39.87	0.04	92.94
Total	0.25	100.00	0.05	100.00

Cs and Sr Retention

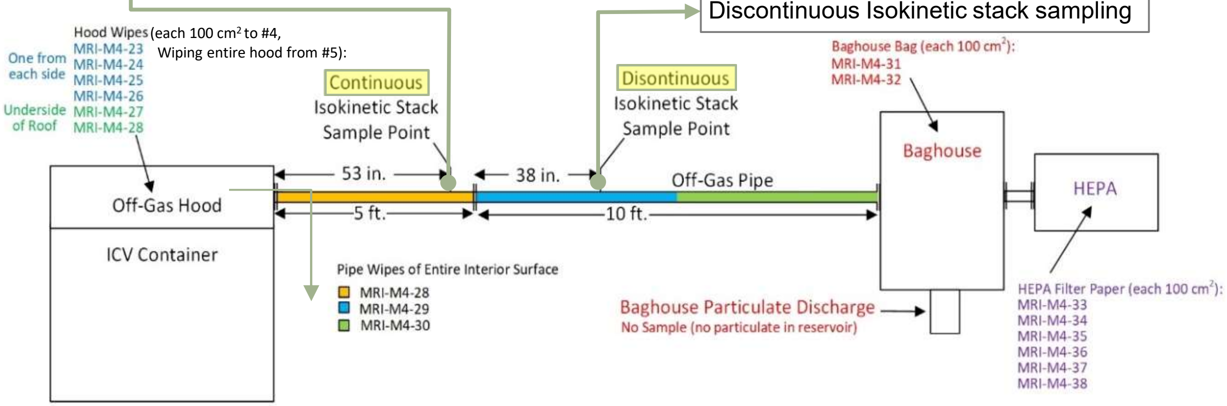
Continuous isokinetic stack sampling



← EPA Method 5 sample train

Discontinuous Isokinetic stack sampling

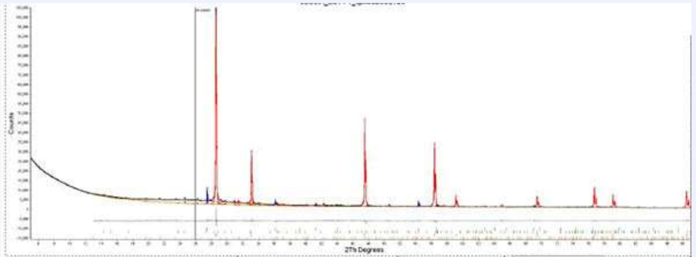
Sampling position in process sampling



3. Engineering-Scale Melt Test (8/28): Melt 4 Glass

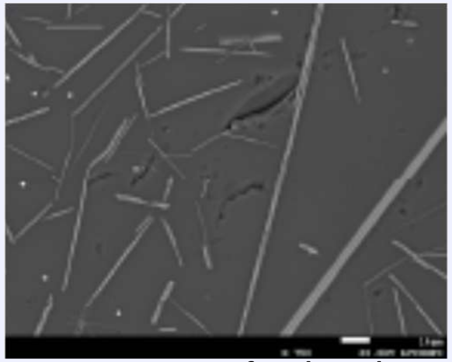
- The glass was cut into 4 sections for examination and sample collection.
- The glass was semi-crystalline with gray crystals and dark glass (see figure below).
- Samples were collected from 4 sections. Cs concentrations shown in the figure right are from sample locations projected onto the 2 halves before they were cut into 4 sections.
- The dispersion of Cs concentration was small, and the Cs is very homogenous in the glass.

PNNL performed Scanning Electron Microscopy-Back-Scattered Electron/Energy Dispersive x-ray Spectroscopy (SEM-BSE/EDS) and X-ray Diffraction (XRD) of bulk glass (bulk shaped glass sample). Crystals are various titanium oxides.



Name	Ideal Formula	Wt % in glass	Wt % in spiked sample
Rutile	TiO_2	3.0	2.7
Freudenbergite	$NaTi_3FeO_8$	2.3	2.1
Ca-Zn-Ti oxide	$Ca_2Zn_4Ti_{16}O_{38}$	3.7	3.3
Cerianite (internal standard)	CeO_2	–	10.8

XRD Results of Melt 4 Glass

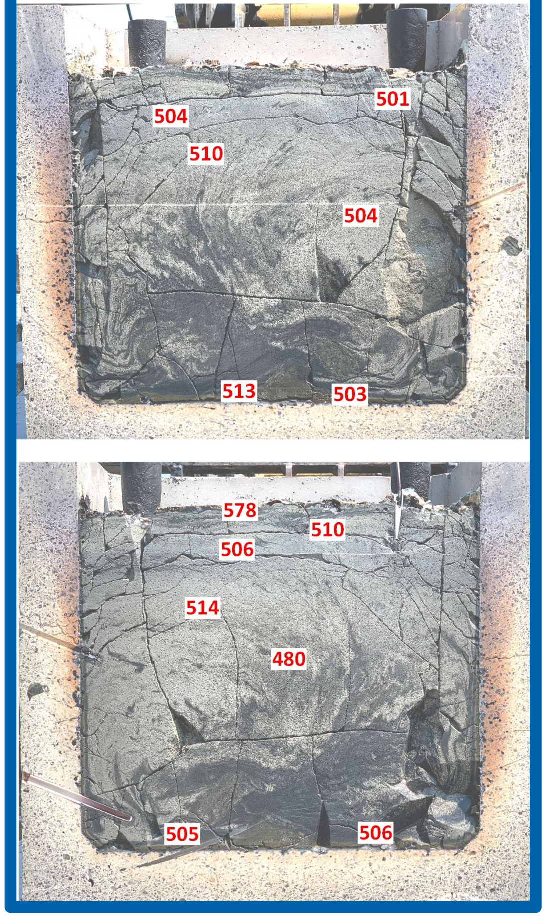


SEM-BSE Image of Melt 4 Glass

SEM-EDS Image (Ti)

Cs in Glass (mg/kg)

Melt 4 (KUR-EH + TSG)



3. Engineering-Scale Melt Test (9/28): Melt 5

Melt 5 Objectives

- Switching to a two-electrode, lower surface area melter which may reduce Cs emission.
- Demonstration of improvement of Cs retention from FY2018 Melt 1 (91.46%). Improvement was expected to be from 1) better cold cap management and 2) lower surface area melter.

ALPS Carbonate and Iron Coprecipitation Slurries are waste sorbent materials used at 1F for multi-nuclide removal.

Melt 5 Recipe.

Component	Mass (kg)	wt%
KUR-EH	116.16	56.97
ALPS Carbonate Surry	39.74	19.49
ALPS Iron Coprecipitation Slurry	10.56	5.18
Glass Additives	37.43	18.36
Subtotal	203.89	100
Water	22.11	19% moisture, KUR-EH basis; 9% water overall
Total	226	
Tracers:		
CsCl	150.00 g	
$SrCO_3$	165.00 g	

Melt 5 Results

- All materials introduced into the melter were processed.
- The waste loading was 75.55% on a glass oxide basis. On a dry feed basis, the waste loading was 71.70%
- 97.72% Cs retention in glass. 100% Sr retention in glass.

2-Electrode Melter

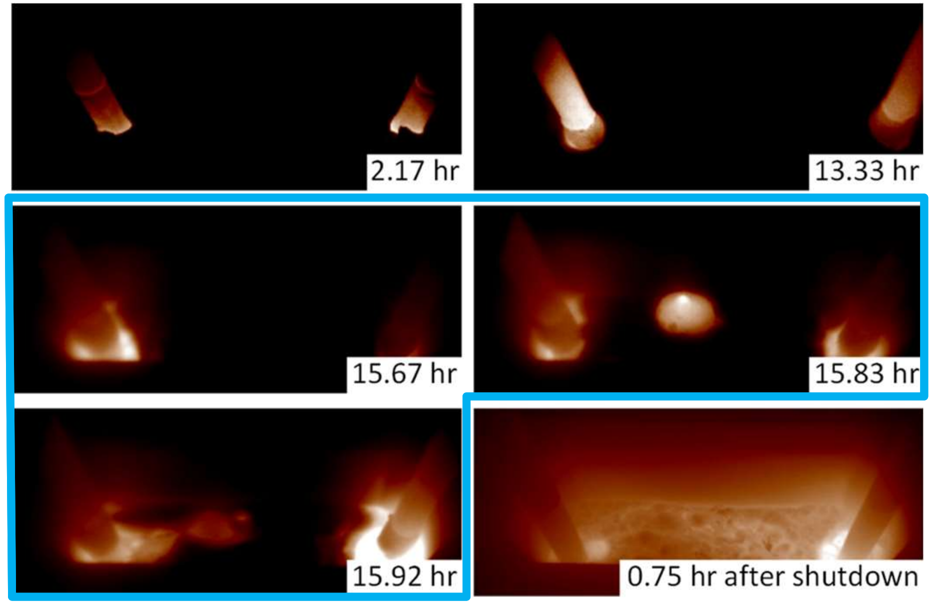
The volumes of the 4 and 2-electrodes melters are the same but the surface area is much less in the 2-electrode melter (rectangular rather than square electrode array). The lower surface area should reduce Cs emission into the off-gas.

	4-Electrode	2-Electrode
Surface Area (cm^2)	1865	1266
Volume (L)	80	80
Surface Area/Volume	23.31	15.83

3. Engineering-Scale Melt Test (10/28): Melt 5 Infrared Camera View into the Melter

Melt 5 IR Camera Images

- Melt 5 had good cold-cap management until 15.67 hours which is the time when melting of the final top-off frit began melting.
- Once the top-off frit was completely melted the test was concluded because at this point all materials fed into the melter had been converted into glass.



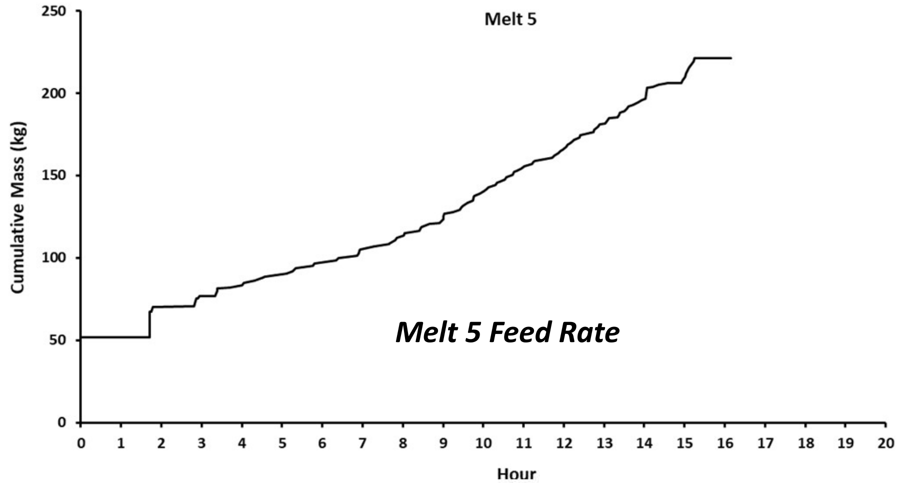
Infrared Images During Melt 5（Blue framework indicates the situation after TOF feeding (15.0-16.3h))

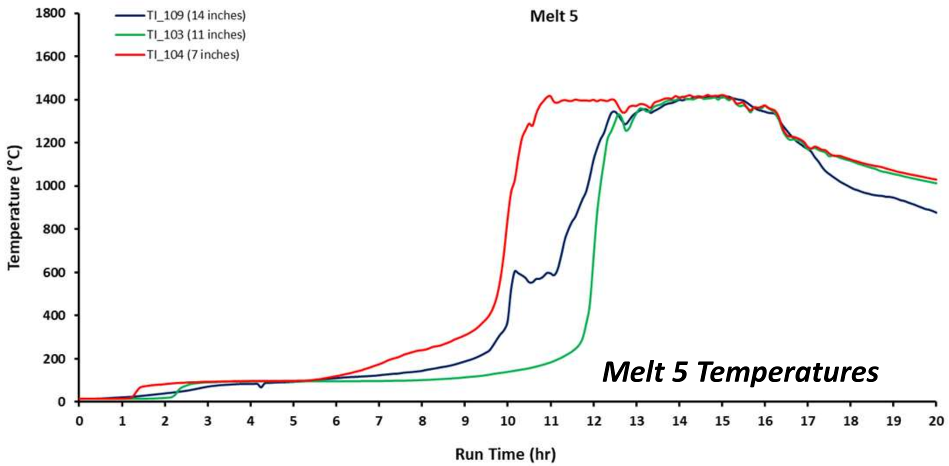
Infrared Image at End of Melt 5

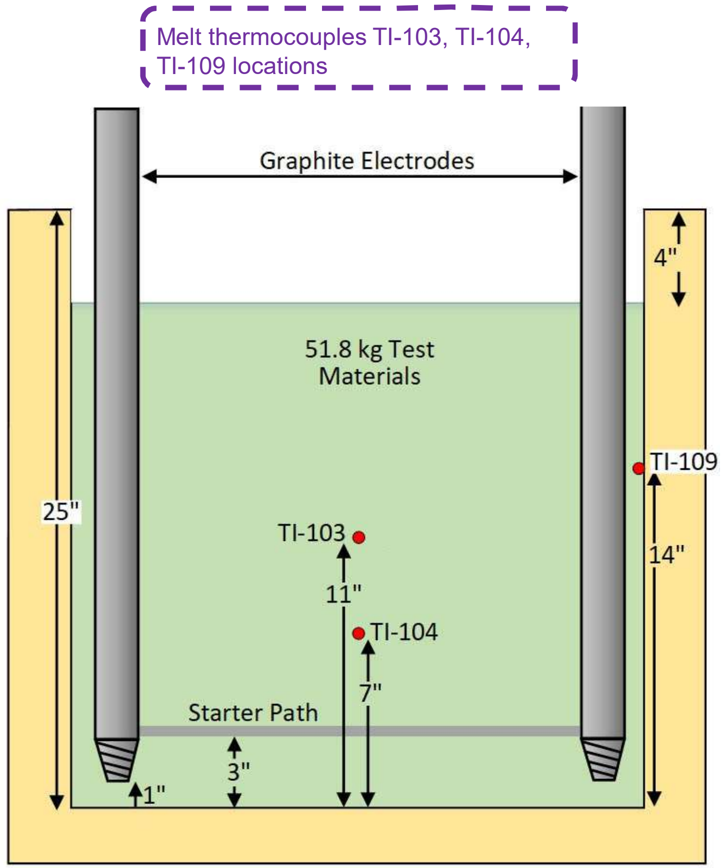
Glass Surface Before Cutting and Sampling

3. Engineering-Scale Melt Test (11/28): Melt 5 Feed Rate and Melt Temperatures

- The initial batch was 51.8 kg and 160 kg of materials were fed into the melter during operations. The test materials consist of KUR-EH + ALPS slurry + glass additives.
- Type R thermocouples were used for this melt and the maximum temperatures recorded was 1421 °C.



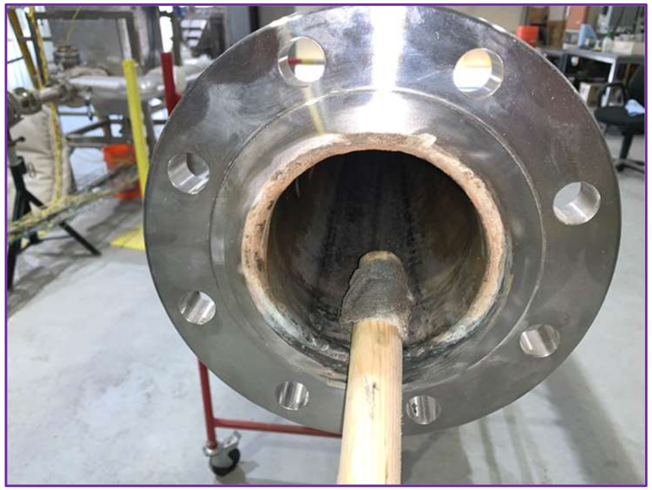




Situation inside of the melter at the start of melting

3. Engineering-Scale Melt Test (12/28): Melt 5 Cs and Sr Distribution

- 0.9481 g of Cs and 0.0077 g of Sr were detected in the melter hood interior, piping, and filters.
- Essentially no Cs or Sr was detected in the refractory after subtracting the natural concentration from the measured concentration of Cs and Sr.
- 0.9481 g of Cs equates to 98.90% retention in glass which agrees well with the continuous isokinetic stack sampling results (97.72%).



Pipe Wipe Sampling for Cs and Sr Analysis

Location	Cs		Sr	
	(g)	%	(g)	%
Refractory Sand	0.00	0.00	0.00	0.00
Cast Refractory	0.0007	0.07	0.00	0.00
Melter Hood	0.0399	4.21	0.0001	12.5
Off-Gas Piping	0.0004	0.04	0.0001	12.5
Baghouse	0.2219	23.40	0.0006	75.00
HEPA Filter	0.6852	72.28	0.00	0.00
Total	0.9481	100.00	0.0077	100.00

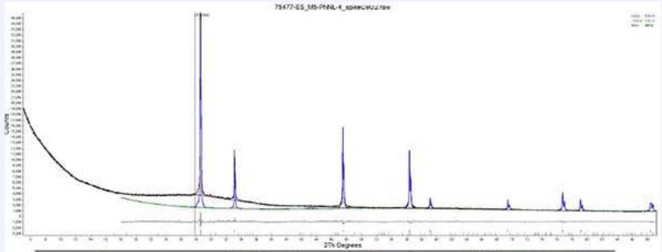
Melt 5 Results

	Input Mass Mass in feed (g)	Mass in off-gas (g)	+	Mass in Hood, First Section of Pipe, Refractory Sand, and Cast Refractory (g)	=	Output Mass	$DF = \frac{input\_mass}{output\_mass}$	$Retention\ in\ glass = 1 - \frac{1}{DF} x\ 100$ Retention in glass (%)
Cs	86.09	1.92		0.04		1.96	43.91	97.72
Sr	221.69	0.007		0.0003		0.007	29935.14	100.00

3. Engineering-Scale Melt Test (13/28): Melt 5 Glass

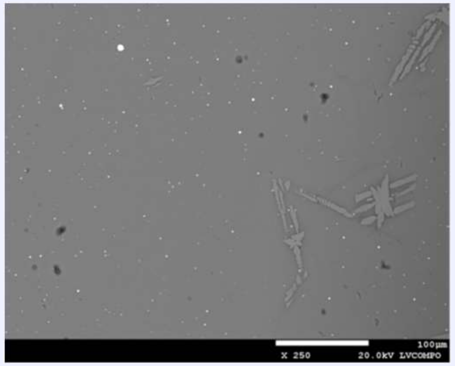
- The glass was cut into 4 sections for examination and sample collection.
- The glass was non-crystalline with some small troilite (FeS) nodules.
- Samples were collected from 4 sections. Cs concentrations shown in the figure right are from sample locations projected onto the 2 halves before they were cut into 4 sections.
- The dispersion of Cs concentration was small, and the Cs is very homogenous in the glass.

SEM-BSE Electron (Microscopy-Back-Scattered Electron/Energy Dispersive x-ray Spectroscopy) of bulk glass showed some dispersed metallic nodules which was conformed by XRD (X-ray Diffraction) to be FeS.



Name	Ideal Formula	Wt % in glass	Wt % in spiked sample
Troilite	FeS	1.0	0.9
Cerianite (internal standard)	CeO_2	–	5.0

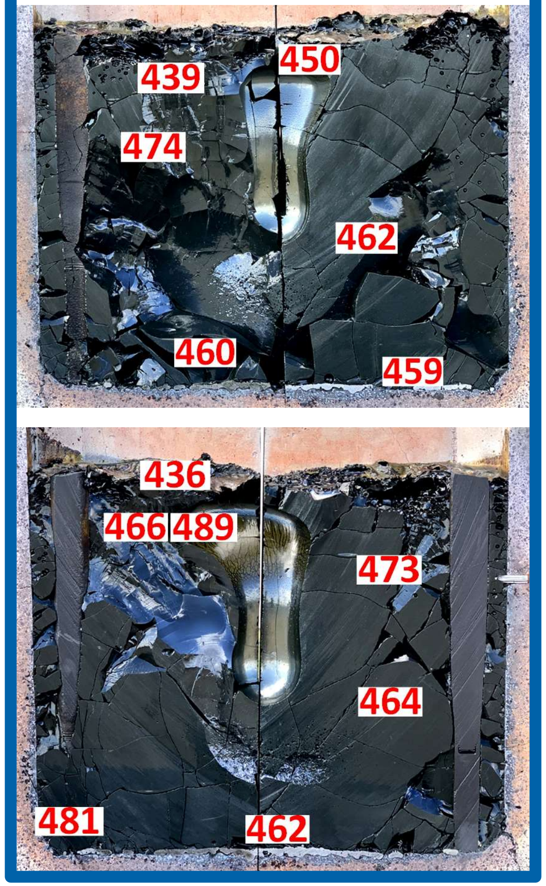
XRD Results of Melt 5 Glass



SEM-BSE Image of Melt 5 Glass

Cs in Glass (mg/kg)

Melt 5 (KUR-EH + ALPS)



3. Engineering-Scale Melt Test (14/28): Melt 6 Objectives and Results

Melt 6 Objectives

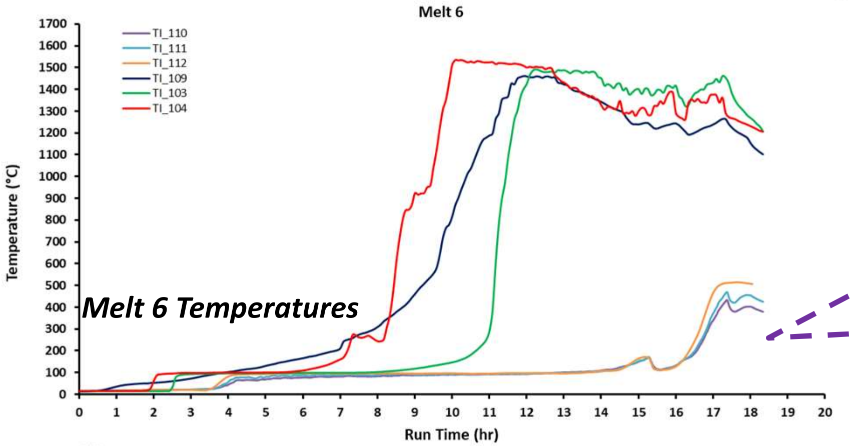
- Bottom-up startup, two-electrode melter
- Reproduction of excellent Cs retention from FY2018 Melt 2 (99.30%).

Melt 6 Results

- All materials introduced into the melter were processed. The maximum melt temperature was 1534 °C.
- The waste loading was 79.20% on a glass oxide basis. On a dry feed basis, the waste loading was 76.02%
- 98.77% Cs retention in glass. 100% Sr retention in glass.

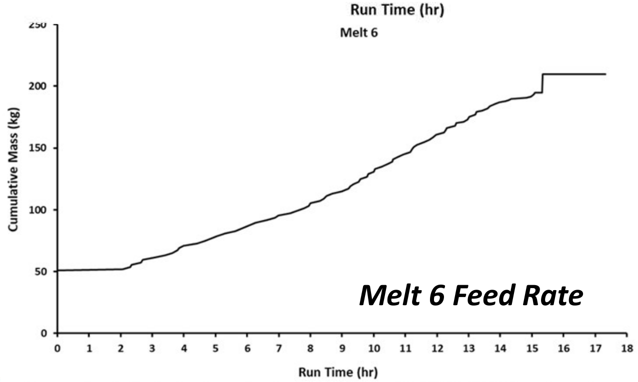
***Melt 6 Recipe*.**

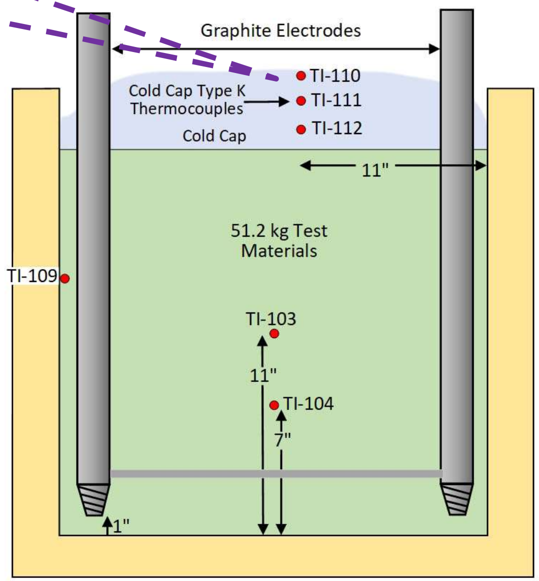
Component	Mass(kg)	wt%
KUR-EH	103.90	61.19
KUR-TSG	36.59	21.55
Glass Additives	29.31	17.26
Subtotal	169.80	100
Water	24.90	19% moisture, KUR-EH basis; 12% water overall
Total:	194.70	
Tracers:		
CsCl	142.46 g	
$SrCO_3$	156.71 g	



Type K thermocouples were installed in the top of the waste feed pile to monitor cold cap temperatures

The cold cap was cold throughout the melt indicating the likelihood of Cs to condense in the cold cap.





Situation inside of the melter at the start of melting

3. Engineering-Scale Melt Test (15/28): Melt 6 Cs and Sr Distribution

- 0.2917 g of Cs and 0.0004 g of Sr were detected in the melter hood interior, piping, and filters.
- Essentially no Cs or Sr was detected in the refractory.
- 0.2917 g of Cs equates to 99.67% retention in glass which agrees fairly well with the continuous isokinetic stack sampling results (98.77%).

Baghouse Bag Sampling for Cs and Sr Analysis

Location	Cs		Sr	
	(g)	%	(g)	%
Refractory Sand	0.00	0.00	0.00006	15.81
Cast Refractory	0.00	0.00	0.00	0.00
Melter Hood	0.02	5.50	0.002	46.04
Off-Gas Piping	0.0005	0.16	0.0001	38.15
Baghouse	0.12	42.62	0.00	0.00
HEPA Filter	0.15	51.72	0.00	0.00
Total	0.29	100.00	0.0004	100.00

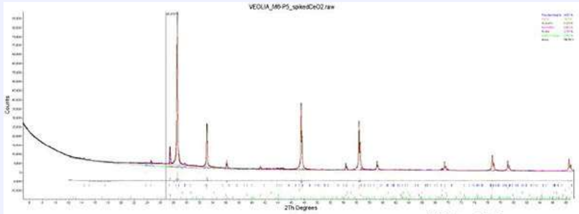
Melt 6 Results

	Input Mass Mass in feed (g)	Mass in off-gas (g)	+	Mass in Hood, First Section of Pipe, Refractory Sand, and Cast Refractory (g)	=	Output Mass	$DF = \frac{input\_mass}{output\_mass}$	$Retention\ in\ glass = 1 - \frac{1}{DF} x\,100$ Retention in glass (%)
Cs	88.83	1.07		0.02		1.09	81.37	98.77
Sr	246.36	0.008		0.0004		0.008	30955.92	100.00

3. Engineering-Scale Melt Test (16/28): Melt 6 Glass

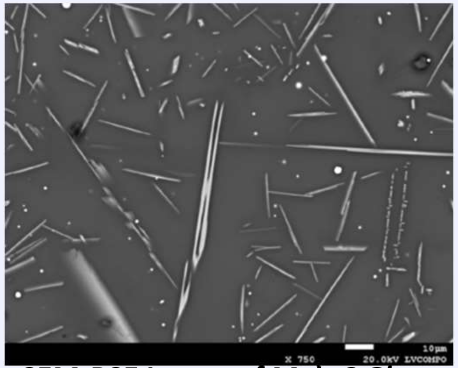
- The glass was cut into 4 sections for examination and sample collection.
- The glass was semi-crystalline with titanium phases similar to Melt 4.
- Samples were collected from 4 sections. Cs concentrations shown in the figure right are from sample locations projected onto the 2 halves before they were cut into 4 sections.
- The dispersion of Cs concentration was small, and the Cs is very homogenous in the glass.

XRD (X-ray Diffraction) of bulk glass identified rutile (TiO_2), freudenbergite ($NaTi_3FeO_8$)), chrichtonite ($(Sr,Ca)(Ti,Fe,V,Cr)_{20}O_{38}$) and minor iron phases

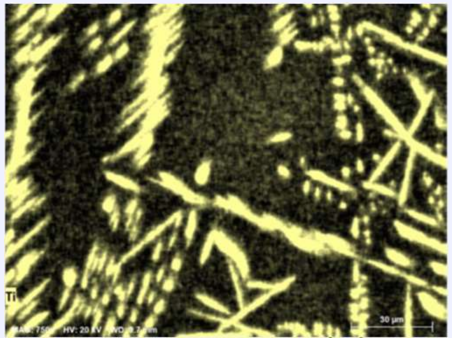


Name	Ideal Formula	Wt % in glass	Wt % in spiked sample
Rutile	TiO_2	4.2	3.8
Freudenbergite	$NaTi_3FeO_8$	4.5	4.1
α-Fe	Fe	0.3	0.2
Pyrrhotite	FeS	0.7	0.6
Ca-Zn-Ti oxide	$Ca_2Zn_4Ti_{16}O_{38}$	0.9	0.8
Cerianite (internal standard)	*CeO_2*	–	*10.7*

XRD Results of Melt 6 Glass



SEM-BSE Image of Melt 6 Glass



SEM-EDS Image (Ti)

Cs in Glass (mg/kg)

Melt 6 (KUR-EH + TSG)

Melt 7 Objectives

- Bottom-up startup, two-electrode melter.
- Improvement of Cs retention from FY2018 Melt 3.

Melt 7 Results

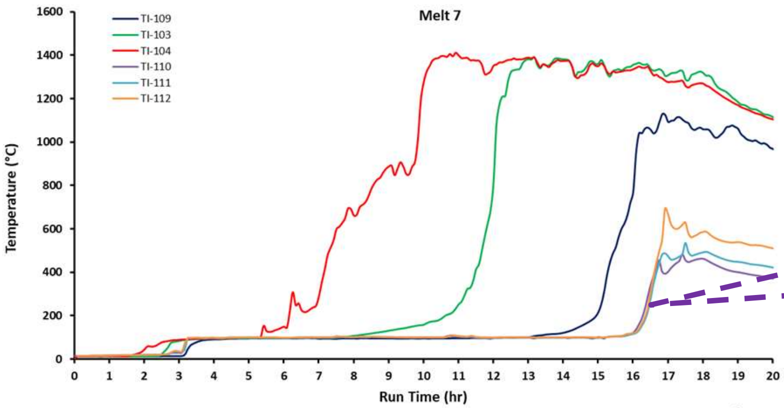
- All materials introduced into the melter were processed. The maximum melt temperature was 1398 °C.
- The waste loading was 67.00% on a glass oxide basis. On a dry feed basis, the waste loading was 64.00%.
- 98.47% Cs retention in glass. 100% Sr retention in glass.

Melt 7 Recipe

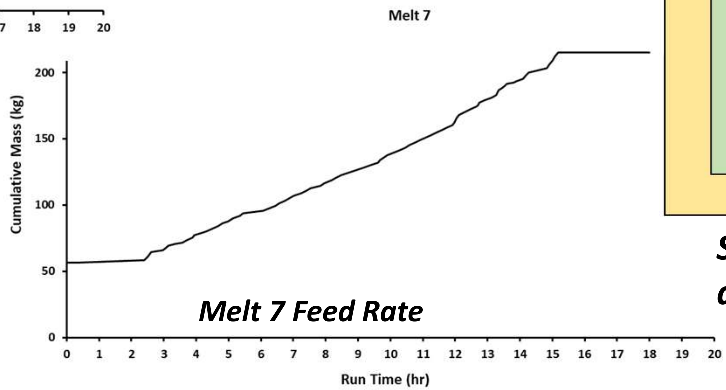
Component	Mass (kg)	wt%
KUR-EH	110.79	63.89
AREVA Sludge Simulant	9.80	5.65
Glass Additives	52.82	30.46
Subtotal	173.41	100.00
Water	26.59	24% moisture, KUR-EH basis; 12% water overall
Total	200.00	
Tracers:		
CsCl		127.65 g
$SrCO_3$		140.41 g

Type K thermocouples were installed in the top of the waste feed pile to monitor cold cap temperatures

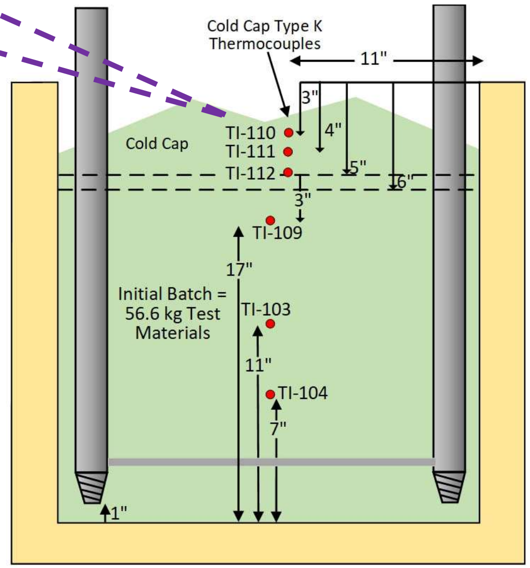
The cold cap was cold until the end of the melt indicating the ability of Cs to condense in the cold cap.



Melt 7 Temperatures



Melt 7 Feed Rate



Situation inside of the melter at the start of melting

3. Engineering-Scale Melt Test (18/28): Melt 7 Cs and Sr Distribution

- 0.4937 g of Cs and 0.0901 g of Sr were detected in the melter hood interior, piping, and filters.
- Essentially no Cs or Sr was detected in the refractory.
- 0.4937 g of Cs equates to 99.42% retention in glass which agrees fairly well with the continuous isokinetic stack sampling results (98.47%).

HEPA Filter Sampling for Cs and Sr Analysis

Location	Cs		Sr	
	(g)	%	(g)	%
Refractory Sand	0.00	0.00	0.00	0.00
Cast Refractory	0.00	0.00	0.00	0.00
Melter Hood	0.00749	1.52	0.00005	0.06
Off-Gas Piping	0.00168	0.34	0.00013	0.14
Baghouse	0.03385	6.86	0.00005	0.06
HEPA Filter	0.045072	91.29	0.08989	99.74
Total	0.4937	100.00	0.09012	100.00

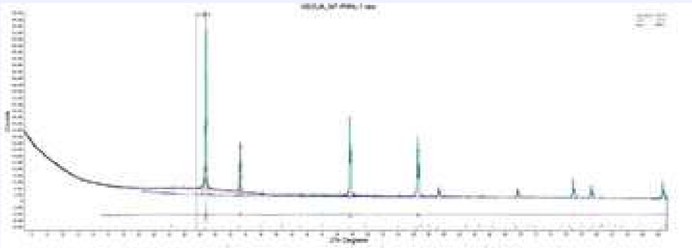
Melt 7 Results

	Input Mass Mass in feed (g)	Mass in off-gas (g)	+ Mass in Hood, First Section of Pipe, Refractory Sand, and Cast Refractory (g)	= Output Mass	$DF = \frac{input\_mass}{output\_mass}$	$Retention\ in\ glass = 1 - \frac{1}{DF} x\ 100$ Retention in glass (%)
Cs	84.76	1.29	0.01	1.30	65.30	98.47
Sr	284.20	0.002	0.0001	0.002	149,510.49	100.00

3. Engineering-Scale Melt Test (19/28): Melt 7 Glass

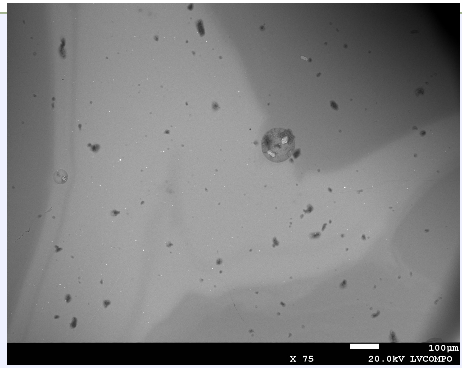
- The glass was cut into 4 sections for examination and sample collection.
- The glass was amorphous and homogenous with a small amount of karelianite ($(Cr_{0.05}V_{0.95})_2O_3$) crystals.
- Samples were collected from 4 sections. Cs concentrations shown in the figure right are from sample locations projected onto the 2 halves before they were cut into 4 sections.
- The dispersion of Cs concentration was small, and the Cs is very homogenous in the glass.

XRD of bulk glass identified a small amount of karelianite ($(Cr_{0.05}V_{0.95})_2O_3$)

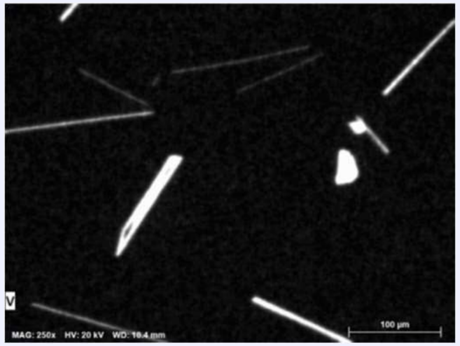


Name	Ideal Formula	Wt % in glass	Wt % in spiked sample
Karelianite, chromian	$(Cr_{0.05}V_{0.95})_2O_3$	0.9	0.8
Cerianite (internal standard)	CeO_2	–	10.0

XRD Results of Melt 7 Glass



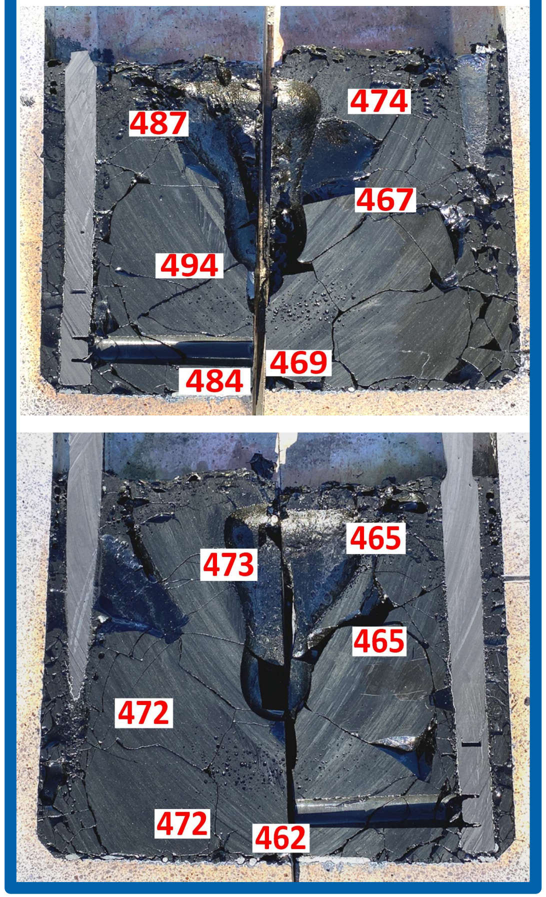
SEM-BSE Image of Melt Glass



SEM-EDS Image (V)

Cs in Glass (mg/kg)

Melt 7 (KUR-EH + AREVA)



Melt 8 Objectives

- Bottom-up startup, two-electrode melter.
- Demonstrate restarting method after emergency shutdown and assumed accidents/events.
- Demonstrate the use of 1F soil rather than KUR-EH to provide the glass formers for the melt.

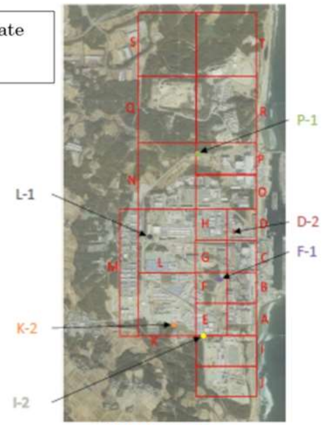
Sample/ Collection/ Area/ Collection/ Weight/ Dose rate
date depth

試料名	採取日	採取場所	採取深さ (cm)	重量 (g)	線量率※1 (μSv/h)
S2-D2-1	2015.3.24	Dエリア	0~5	106	13
S2-F1-1	2015.3.30	Fエリア	0~5	106	8
S2-I2-1	2015.4.16	Iエリア	0~5	105	6
S2-K2-1	2015.3.16	Kエリア	0~5	105	< 0.5
S2-L1-1	2015.4.20	Lエリア	0~5	106	< 0.5
S2-P1-1	2015.5.8	Pエリア	0~5	110	6

2. Analysis data of 1F soil

(1) Soil data by IRID

Sample	Elements (mg/g)							TOC (mg/g)
	Na	Mg	Al	Si	K	Ca	Fe	
S2-D2	6.9	4	52.6	235	8.5	3.6	23.4	24.4
S2-F1	6.7	3.2	62.1	258	10.8	2.3	30.3	15.5
S2-I2	3.1	5.8	40.4	107	6.7	7.6	23.7	48.4
S2-K2	3.1	3.7	60.3	183	8.2	24.2	31.7	24.9
S2-L1	6.6	3.6	44.5	175	8.7	3	18.2	28.9
S2-P1	6.4	4.1	51.1	194	7.4	7.6	20.7	30.7



土壌試料採取場所

"The results of analysis of the waste samples (soil, incineration ash and inlet/outlet water of water treatment facility (Cs absorption system, advanced liquid processing system))" IRID/JAEA March 30, 2017

1F soil simulant was prepared by blending additives with soil from the test site of Richland, WA, USA (HRTS in the table is abbreviation of test site) to have the nearly same composition as the average of 6 1F soil samples collected by IRID in 2015

1F Soil Simulant

Component	wt%
HRTS Soil	45.41
SiO_2	38.16
Al_2O_3	11.14
Fe_2O_3	3.33
$CaCO_3$	0.31
$Mg(OH)_2$	0.53
K_2CO_3	1.13
Total	100.00

***Melt 8 Recipe*.**

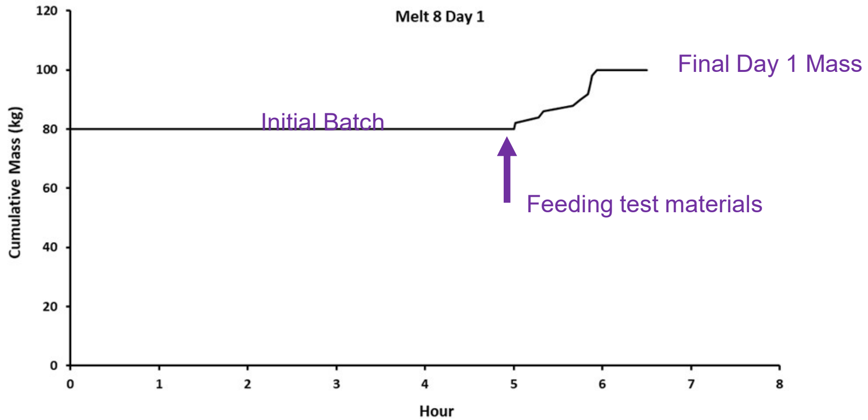
Component	Mass (kg)	wt%
1F Soil Simulant	74.31	60.00
ALPS Carbonate Slurry	24.77	20.00
Glass Additives	24.77	20.00
Subtotal	123.85	100.00
Water	11.15	15% moisture, 1F Soil basis
Total	135.00	

Melt 8 Methods

- Day 1: Bottom-up processing of initial batch + additional test material feed. Power suspended after 6.5 hours of operation.
- Cool glass for 4 days.
- Day 2: Remote installation of frit and starter path followed by top-down processing + additional test material feed + top-off frit. Melt ended after 13 hours of operation.

3. Engineering-Scale Melt Test (21/28): Melt 8 Day 1

- Day 1 started with an initial 80 kg batch.
- 20 kg of test materials was fed into the melter during operations according to the test plan.
- Power to the melt was shut off after 6.5 hours to simulate emergency shutdown and assumed accidents/events.



Melt 8 Day 1 Feed Rate

Looking into the melter showing 80 kg of test materials, feed pipes, electrodes, and refractory

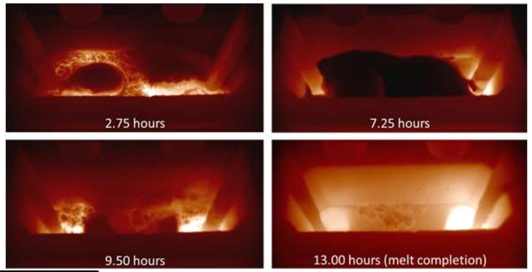
IR view into the melter at 2 hours

IR view into the melter at 6.5 hours (end of Day 1)

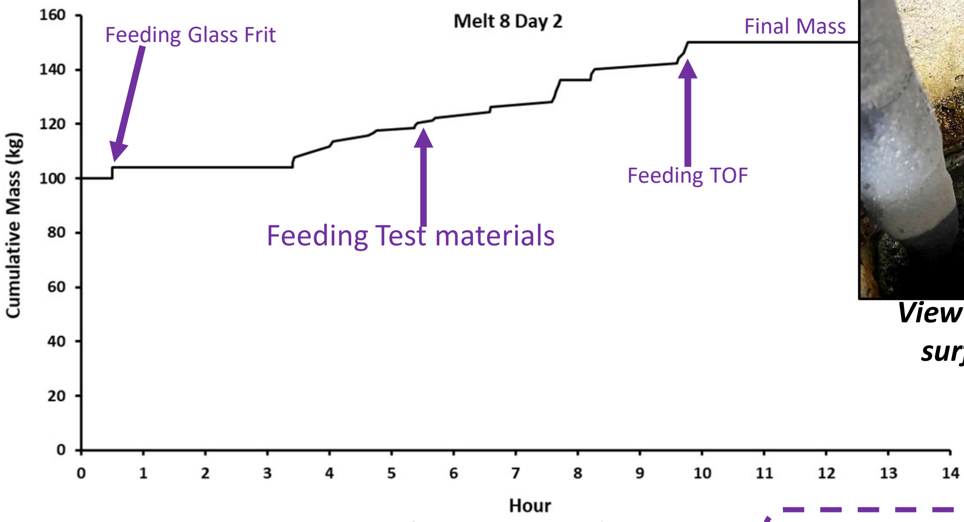
View into the melter showing surface of simulated failed melt. The material visible is not glass because the melt was suspended before completion according to the test plan

3. Engineering-Scale Melt Test (22/28): Melt 8 Day 2 and Results

- 4 kg of top off frit (TOF) was fed onto the Day 1 surface.
- 1.2 kg of starter path was fed onto the glass frit. This is remote application of a starter path.
- 35 kg of waste simulant was fed into the melter during operations.
- 11kg of TOF was fed at the final stage of melt (the amount of glass frit was 15 kg during melt operation including 4kg fed before restarting).

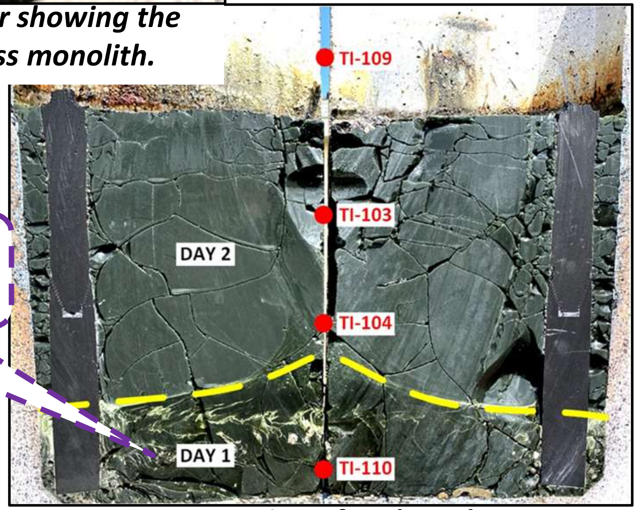


Melt 8 Day 2 IR Images



Melt 8 Day 2 Feed Rate

View into the melter showing the surface of the glass monolith.



Cross-Section of Melt 8 Glass

Melt 8 Results

- The restart was successful.
- The examination of the glass surface and the melt thermocouple temperatures realized during Day 1 and Day 2 indicates that all materials introduced into the melter were processed into glass. This was confirmed by cutting and examining the glass.

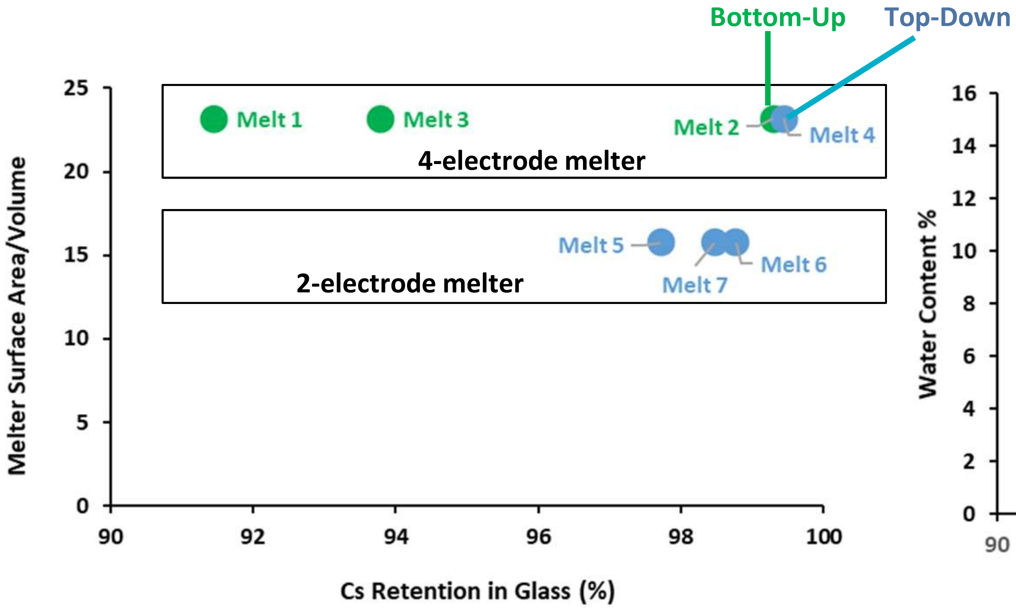
3. Engineering-Scale Melt Test (23/28): Test Metrics

Metric	Melt 1	Melt 2	Melt 3	Melt 4	Melt 5	Melt 6	Melt 7	Melt 8
Melter Surface Area/Volume	23.17	23.17	23.17	23.17	15.77	15.77	15.77	15.77
Waste Type	KUR-EH ALPS	KUR-EH KUR-TSG	KUR-EH AREVA	KUR-EH KUR-TSG	KUR-EH + ALPS	KUR-EH KUR-TSG	KUR-EH AREVA	1F Soil ALPS
Dry Feed Waste Loading (Includes Frit) (%)	75.77	77.44	64.39	77.44	75.55	76.02	64.00	71.00
Glass Oxide Waste Loading (%)	71.10	76.60	63.30	76.60	71.70	79.20	67.00	72.42
Dry Test Materials Processed (kg)	195.08	182.73	188.90	181.28	185.85	169.76	173.45	122.64
Water Processed (kg)	10.92	16.77	36.10	18.22	20.15	24.94	26.55	11.36
Water Processed (% of Total Mass Processed)	5	8	15	9	9	12	12	8
Water Processed (% of Total Mass; Not Including TOF)	5	8	16	9	10	13	13	8
Top-Off Frit (TOF) Processed (kg)	15.00	12.50	15.00	12.50	15.00	15.00	15.00	16.00*
Total Mass Processed (kg)	221.00	212.00	240.00	212.00	221	209.70	215.00	150.00
Energy (kWh)	219.82	232.67	336.06	365.02	303.09	345.40	349.04	376.71
Average Power (kW)	16.19	13.89	22.40	17.11	18.65	19.93	19.39	19.32
Melt Duration (hours)	13.58	16.75	15.00	21.33	16.25	17.33	18.00	19.50
Processing Rate (kg/hr)	16.29	12.66	16.00	9.94	13.6	12.10	11.94	7.69
Processing Efficiency (kWh/kg)	0.99	1.10	1.40	1.72	1.37	1.65	1.62	2.51
Mass of Glass (kg)	176.60	155.80	169.20	164.26	172.69	166.41	165.00	131.40
Mass Loss (%)	20	27	29	23	22	21	23	12
Volume Processed (L)	267.55	283.23	317.46	282.67	254.02	241.26	236.97	147.06
Volume of Glass (L)	68.67	63.93	66.00	67.77	60.29	60.29	61.15	51.65
Volume Reduction (%)	74	77	79	76	76	75	74	65
Cs Retention in Glass (%)	91.46	99.30	93.79	99.44	97.72	98.77	98.47	None
Sr Retention in Glass (%)	99.76	99.99	100.00	99.99	100.00	100.00	100.00	None

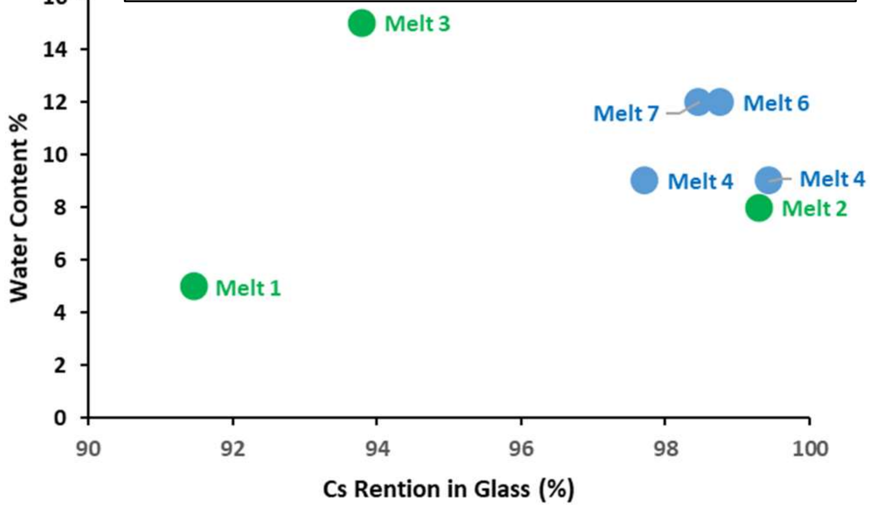
***includes 4 kg glass frit at top-down restart and 11 kg top-off-frit at last stage of melt**

3. Engineering-Scale Melt Test (24/28): Melt Surface Area, Start-up Method and Water Content

- Effect of Melt Surface Area: In Melts 5,6,7 the melter with reduced surface area/volume to see whether less surface area would lower Cs emission.
- Effect of Strat-up Method (Top-down/Bottom-up): With same waste simulant Melt 2 was bottom-up and Melt 4 was top-down.
- Effect of Water Content: Varied water content in Melts 4,5,6,7 to see if this had any affect on Cs retention.



Green circles are Melts in FY 2018. Blue circles are Melts in FY 2019-2020.



Conclusions:

- 99+% Cs retention is achievable with either 2 or 4-electrode melter. (These melters have different surface area but the surface area does not affect Cs retention if good cold cap management is used).
- 99+% Cs retention is achievable with top-down or bottom-up melt startup.
- It appears that 8-13% water content is best, but other factors (poor cold cap management in Melt 1 and relatively high power at the end of Melt 3) rather than water content caused lower Cs retention in those melts.

3. Engineering-Scale Melt Test (25/28): Summary of Discontinuous Isokinetic Stack Sampling Results

- Discontinuous isokinetic stack sampling was performed for each melt test to assess variability in Cs emissions.
- Conclusions:
  1) Emissions are highest at the final phase of melt (TOF feeding and processing; blue part in the table below)
     Cause : Final cold cap melting → It is extremely important to manage the TOF that functions as a cold cap.
  2) Emissions are very low for the most of melt test. (yellow part in the table below)
     Cause : Good cold cap management
  3) Emissions increased over several periods of melt test (red part in the table below)
     Cause: Insufficient cold cap management.

Insufficient cold cap management when feeding test materials

Because the output at the end of melt is relatively high (40 kW), the cold cap disappears early.

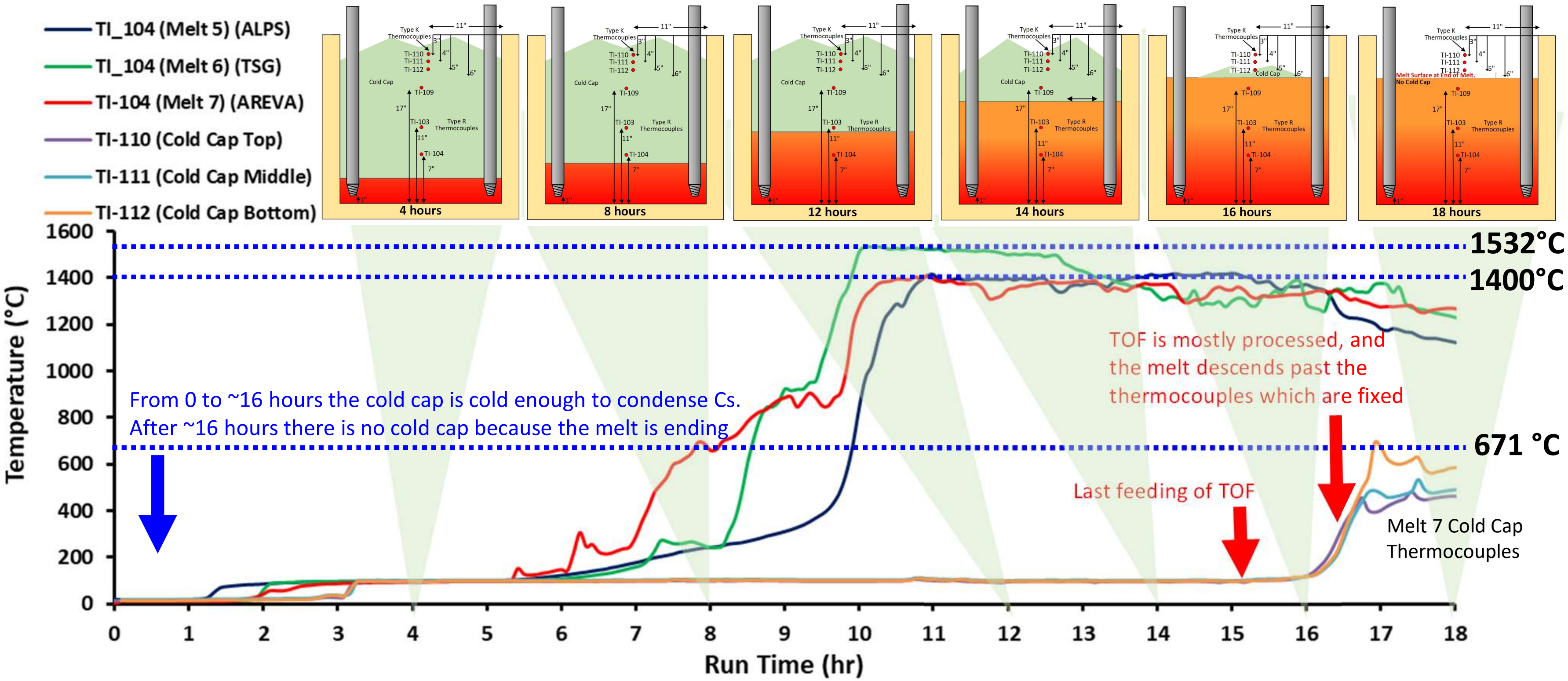
Cold cap partially disappears due to temporary delay in test material feeding

		Discontinuous isokinetic stack sampling run					
	Melt	**1**	**2**	**3**	**4**	**5**	**6**
Cs emissions (g)	**1**	0.28	1.98	3.03			
	2	0.004	0.003	0.0004			
	3	0.004	0.003	3.68			
	4	0.12	0.05	0.05	0.02		
	5	0.0001	0.0000	0.001	1.38		
	6	0.0000	0.0000	0.003	0.87	0.37	
	7	0.0002	0.0004	0.06	0.10	0.46	0.04

Very Low Emissions　　Slightly High Emissions　　TOF/End of Melt Stage

3. Engineering-Scale Melt Test (26/28): Melt Temperature and Cs Retention

- Maximum melt temperatures ranged from ~1400 °C to 1532 °C and Cs retention ranged from 97.72% and 98.77%.
- Cs condenses at ~671 °C. The cold cap is below ~671 °C until the end of the melt (TOF-stage), that means that Cs is kept condensed in the cold cap.
- The mechanism for Cs retention after transferred to the cold cap is condensation in the cold cap and continuous melting of the cold cap into glass.
- The three cold cap thermocouples in Melt 7 were exposed above the glass layer at the end of the melt; therefore, the three cold cap thermocouples never recorded molten glass temperatures. We are assured that the final cold cap achieved melt temperature because it was melted, even though we did not have a thermocouple at the level of the final melt surface.



3. Engineering-Scale Melt Test (27/28): 28-Day Leach Testing Results

PNNL tested glass from Melts 4 through 8 using the Materials Characterization Center-1 (MCC-1) test. The 28-day normalized mass loss (NL_{Na}) and 28-365-day leach rates (r_{Na}) are lower (better) than the U.S. and Japanese High-Level Waste (HLW) reference glasses (EA Glass and P0798)

Experiment	NL_{Na} at 28 days (g/m^2)	r_{Na} (g/m^2/d)(28 to 365 days)
Melt 4	8.4 ± 2.0	$(6.6 \pm 2.2) \times 10^{-3}$
Melt 5	6.2 ± 0.7	$(1.2 \pm 0.1) \times 10^{-2}$
Melt 6	5.9 ± 1.3	$(1.4 \pm 0.4) \times 10^{-2}$
Melt 7*	5.4 ± 0.4	$(1.2 \pm 0.9) \times 10^{-2}$
Melt 8	6.0 ± 8.4	Not Tested
Reference Glasses	**NL_{Na} at 28 days (g/m^2)**	**r_{Na} (g/m^2/d)(28 to 365 days)**
EA Glass	34.97	1.9×10^{-1}
P0798	9.59	9.0×10^{-2}

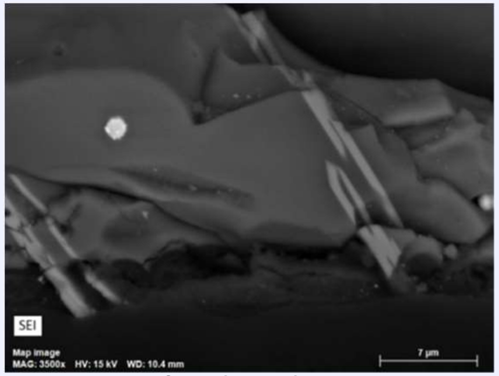
*Na calculated to 270 days because 365 data are not yet available

The semi-crystalline glass seen for the titanate Melts 4 and 6 was generally as durable as the non-crystalline glasses indicating no deleterious effects from TiO_2 crystals.

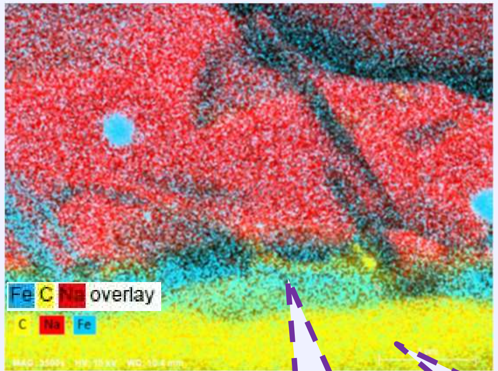
SEM examination of a 365-day MCC-1 alteration layer in Melt 4 glass indicates:

1. ***No preferential dissolution of the glass around the crystalline phases.***
2. ***Alteration zone is mostly depleted in Na confirming Na is a good tracer of glass alteration***

No preferential dissolution of Ti-rich crystals



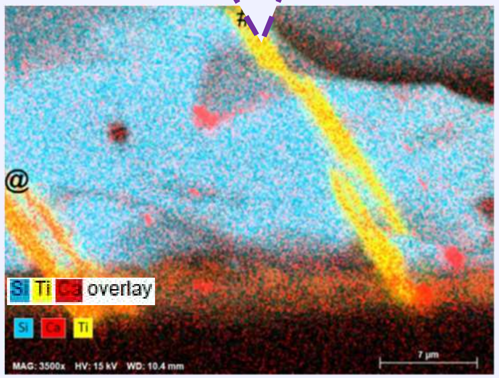
SEM-BSE of Melt 4 Alteration Layer



SEM-EDS of Melt 4 Alteration Layer

Depletion of Na in alteration layer

Resin in which the glass sample is embedded

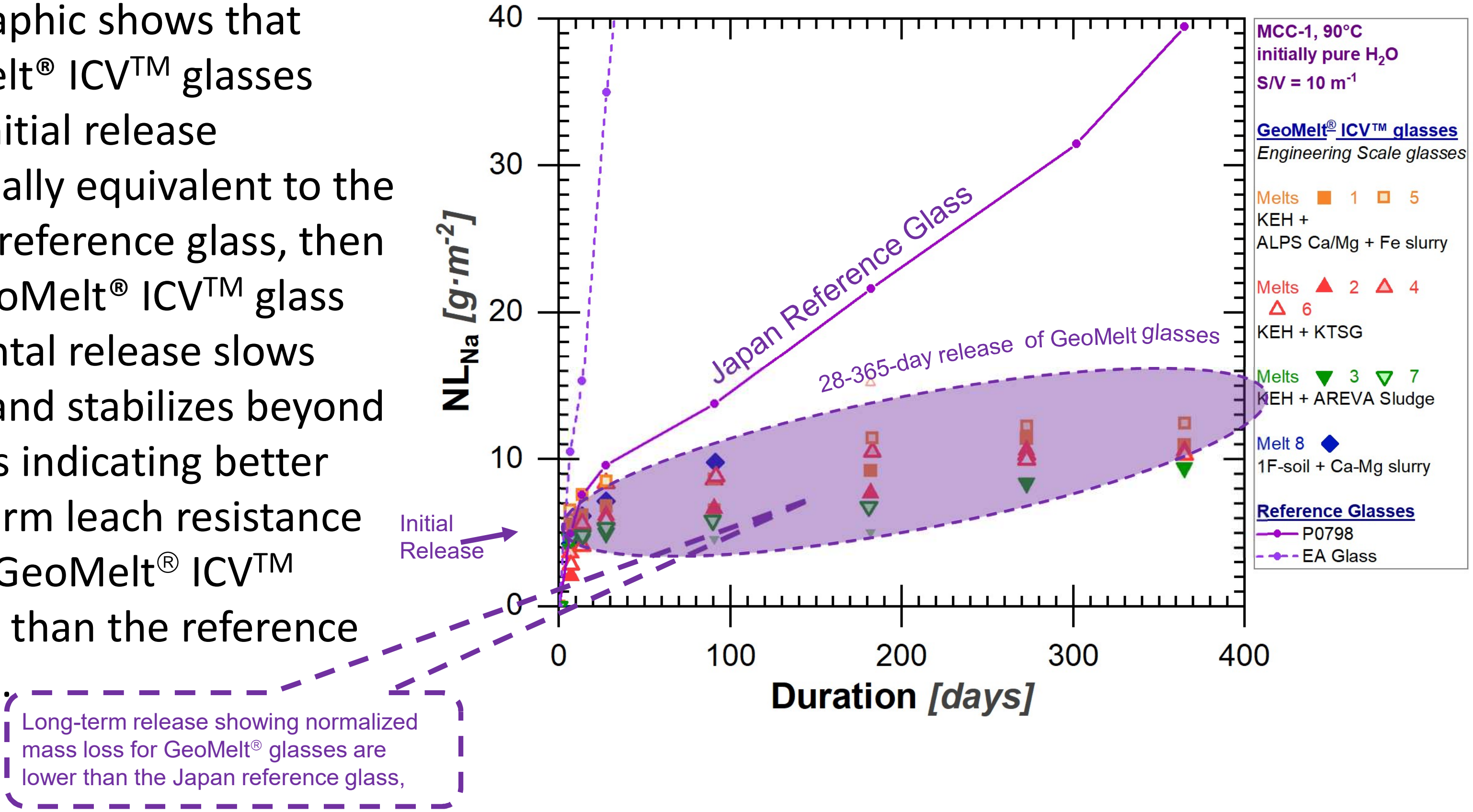


SEM-EDS of Melt 4 Alteration Layer

3. Engineering-Scale Melt Test (28/28): 365-Day Leach Testing Results

- The long-term normalized mass loss (NL_{Na}) of GeoMelt®ICV™ glasses obtained from Melt tests 4-8 in this study, and from Melts tests 1-3 in the FY2018 IRID project are shown in the graphic below. By obtaining plural data points between 28-day and 365-day, the quality of data can be evaluated adequately, and the leach rate can be calculated accurately.

- The graphic shows that GeoMelt® ICV™ glasses have initial release essentially equivalent to the P0798 reference glass, then the GeoMelt® ICV™ glass elemental release slows down and stabilizes beyond 90 days indicating better long-term leach resistance of the GeoMelt® ICV™ glasses than the reference glasses.



4. Basic Experiments and Modeling (1) (Glass Science): Enhance and enlarge of glass database for waste treatment (1/4)

- PNNL formulated new glass recipes for wastes not previously studied in the FY2017-2018 IRID project.

Glass	Wastes	Limiting component**	Results Summary
1F-49	KUR-SMZ	84.6% zeolite	Clear brown glass
1F-50	EN-101, KUR-EH	12.2% TiO_2	No crystals
1F-51	IE-911, KUR-EH	9.1% TiO_2, 5.5% Nb_2O_5	TiO_2 crystals
1F-52	FO-36, KUR-EH	20% Fe_2O_3	Fe_2O_3 crystals
1F-53	Hydro, KUR-EH	8.1% MgO	Clear brown glass
1F-54	GFH, KUR-EH	20% Fe_2O_3	Fe_2O_3 crystals
1F-55A*	SDVB, KUR-EH	10% SDVB	Clear brown glass
1F-55B	SDVB, KUR-EH	20% SDVB	Clear brown glass
1F-56	EN-101, KUR-EH	9.9% TiO_2	Small % iron-titanate
1F-57	IE-911, KUR-EH	7.6% TiO_2, 4.4% Nb_2O_5	No crystals
1F-58A*	SDVB, KUR-EH	25% SDVB	Clear brown glass
1F-58B	SDVB, KUR-EH	30% SDVB	Clear brown glass

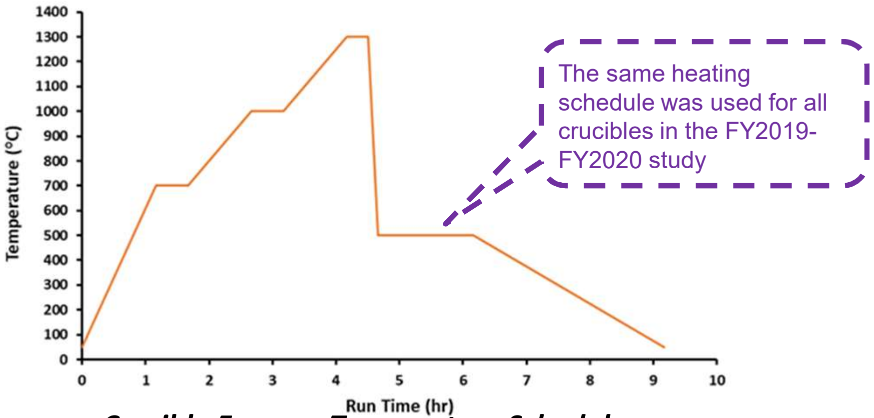
- A and B denote different organic concentrations for the same glass composition

** Chemicals/components which effect on the stability of glass

Waste Abbreviation	Composition
SMZ	Surfactant modified zeolite
IE-911	Silicon titanate
EN-101	Silicon titanate
FO-36	Chelate resin-based adsorbent (iron hydroxide)
Hydro	Hydrotalcite
SDVB	Styrene divinylbenzene resin (deposit: amine group)
GFH	Amorphous granular ferric hydroxide

・In FY2017, we formulated and fabricated total of 40 glasses in crucible melts. A total of 20 different waste simulants representing a broad range of chemistries were tested.

・In this study we formulated and fabricated another 12 glasses representing 7 previously untested 1F wastes.
In total we have tested wastes representing 94% of the volume of 1F water treatment secondary wastes (FY2018 volumes).



Crucible Furnace Temperature Schedule

4. Basic Experiments and Modeling (1) (Glass Science) : Enhance and enlarge of glass database for waste treatment (2/4)

- The purpose of the crucible testing was to manufacture glass to verify that the glass formulation was adequate in terms of 1) lack of secondary phases and crystals which are not glass, and 2) chemical durability.
- Each glass formulation was prepared by weighing the waste simulants and glass additives in accordance with the recipe in blue weigh boats.
- The waste simulant and additives were mixed then loaded into fused silica crucibles.
- The crucibles were loaded into the furnace and heated to the schedule shown in the previous page.
- The crucibles were removed from the furnace at 700 °C, 1,000 °C, and 1300 °C for observation and photography.
- After 1300 °C the crucibles were returned to the furnace and annealed at 500 °C to prevent fracturing of the glass during cutting.
- The crucibles were cut in half for inspection, checking for homogenous glass and the presence of secondary phases.
- Some of the crucibles that had secondary phases were re-run with a different glass formulation with lower amounts of limiting components. Limiting components are shown on the previous page. For example, IE-911 contains titanium (Ti) and niobium (Ni). These elements have limited solubility in glass. Lowering the proportion of IE-911 in the 1F-51 formulation reduced the TiO_2 and Nb_2O_5 fraction in the 1F-57 glass.
- Three crucible glasses were tested by MCC-1. Results are on Page 41.

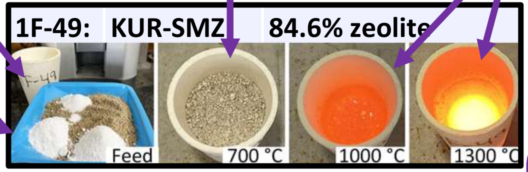
Fused silica crucible with the glass identification written with high-temperature ink

Blue weigh boat containing the ingredients of the glass recipe

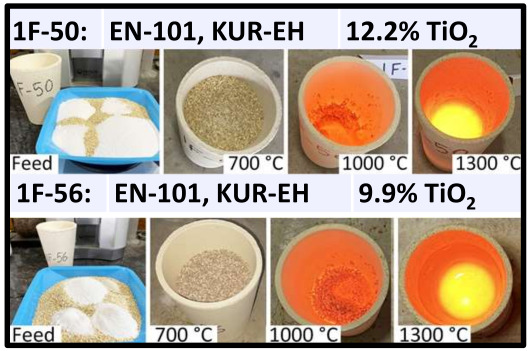
The contents of the crucible at 700 ℃ (not yet melted)

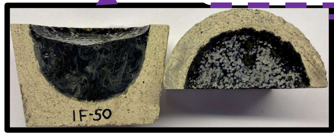
The molten contents at the 1000 ℃ and 1300℃

Top- and side-views of the glass in the crucible after cutting

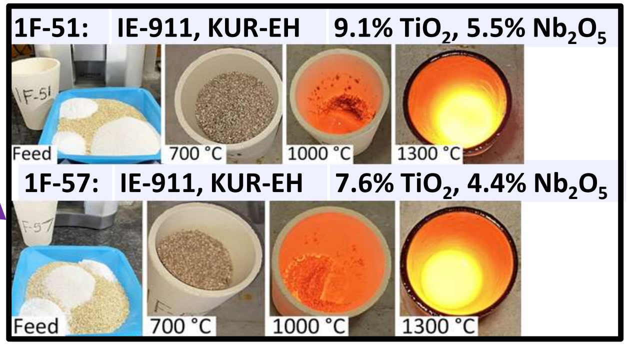


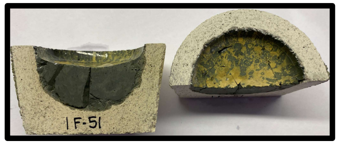
The bulk glass is amorphous with a non-crystalline surface secondary phase on the surface

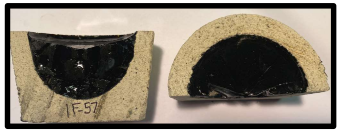




Iteration between higher and lower limiting components to reduce secondary phases

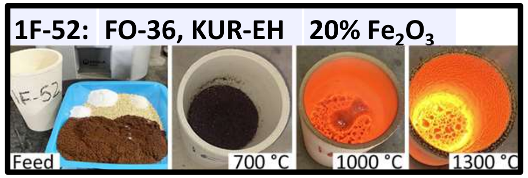


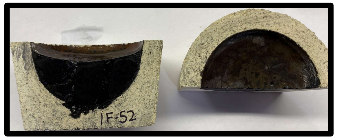




Iteration between higher and lower limiting componen ts to reduce secondary phases

Reduction in Ti and Nb eliminated TiO_2 surface phasecrystals and





4. Basic Experiments and Modeling (1) (Glass Science) : Enhance and enlarge of glass database for waste treatment (3/4)

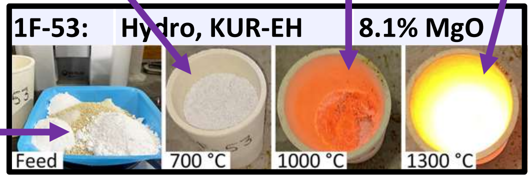
- This page shows more crucible tests. Please refer to the previous slide for a description of the methodology.

The contents of the crucible at 700 °C (not yet melted)

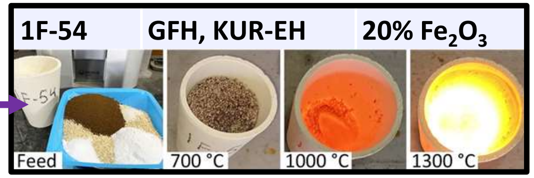
The molten contents at 1000 °C and 1300 °C

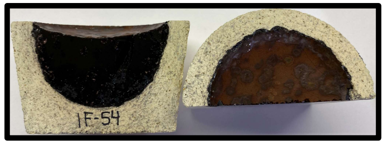
Top- and side-views of the glass in the crucible after cutting

Blue weigh boat containing the ingredients of the glass recipe

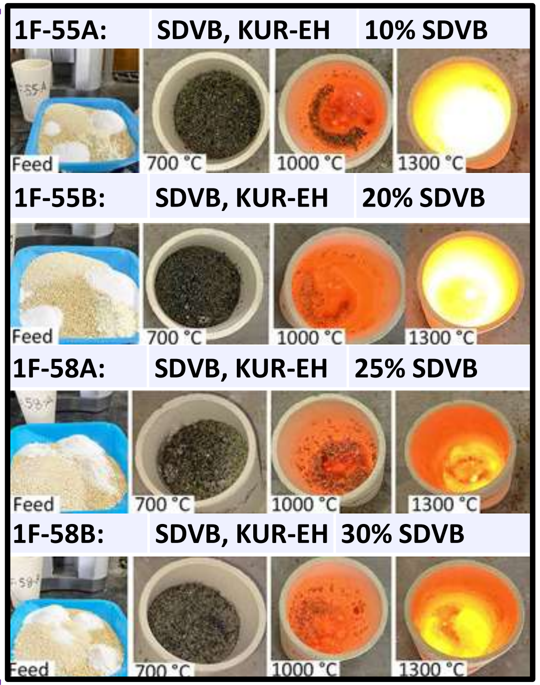


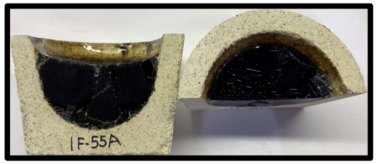
Fused silica crucible with the glass identification written with high-temperature ink

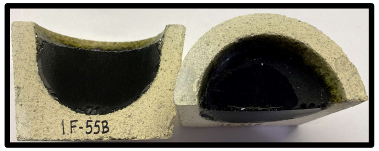


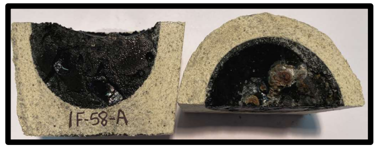


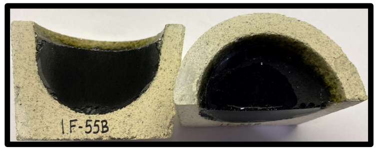
The glass formulation remained the same. The SDVP was incrementally increased from 1F-55A to 1F-58B to verify no residual organic material remained in crucible through 1F-55B







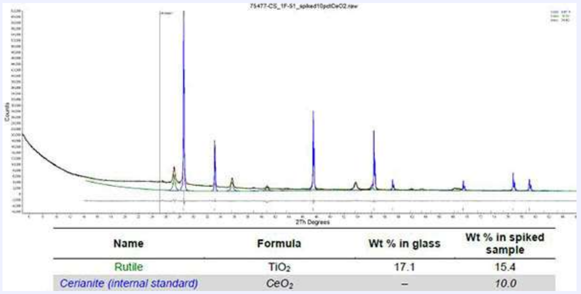




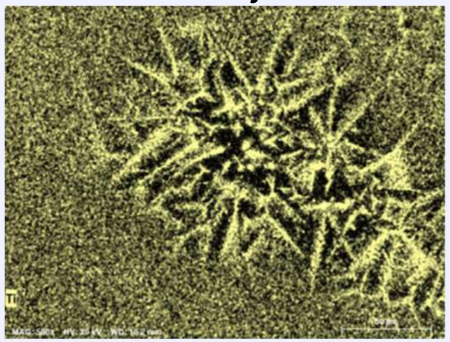
4. Basic Experiments and Modeling (1) (Glass Science): Enhance and enlarge of glass database for waste treatment (4/4)

- The purpose of the crucible testing was to manufacture glass to verify that the glass formulation was adequate in terms of 1) lack of secondary phases and crystals which are not glass, and 2) chemical durability.
- The test metrics provided on this page summarize waste loading, mass loss, and volume reduction. These metrics show high waste loading, significant mass loss, and high volume reduction. The ability to accommodate high amounts of waste in the glass with significant volume loss and high volume reduction are benefits of vitrification.
- The three crucible glasses (1F-49,53,57) tested by MCC-1 performed better (lower normalized mass loss [NLNa] than the reference glasses.
- The crucible testing indicated that the wastes are treatable by GeoMelt® ICV™.

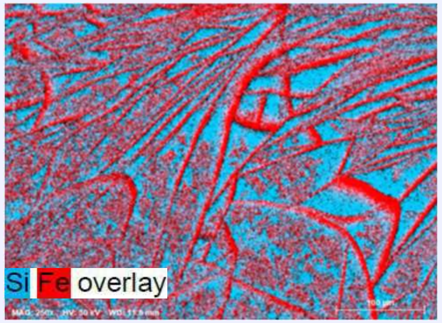
XRD of 1F-51 bulk glass identified rutile (TiO_2)



XRD Results of 1F-52



1F-51 SEM-EDS Image (T)



SEM-EDS Image 1F-54 (Fe)

Crucible Test Metrics

Crucible	Waste Type	Dry Feed Waste Loading (%)	Glass Oxide Waste Loading (%)	Mass Loss (%)	Volume Reduction (%)
1F-49	KUR-SMZ	76.93	81.93	28	79
1F-50	KUR-EH + EN-101 (18%)	86.9	90.01	24	80
1F-56	KUR-EH + EN-101 (14%)	85.96	87.58	22	82
1F-51	KUR-EH + IE-911 (21%)	88.94	91.95	29	89
1F-57	KUR-EH + IE-911 (17%)	86.58	89.58	26	81
1F-52	KUR-EH + FO-36	90.95	88.24	54	86
1F-53	KUR-EH + Hydrotalcite	80.9	81.93	27	83
1F-54	KUR-EH + GFH	84.41	70.11	24	83
1F-55-A	KUR-EH + Styrene divinylbenzene (10%)	82.56	84.34	31	82
1F-55-B	KUR-EH + Styrene divinylbenzene (20%)	84.5	84.35	37	84
1F-58-A	KUR-EH + Styrene divinylbenzene (25%)	85.46	84.35	39	82
1F-58-B	KUR-EH + Styrene divinylbenzene (30%)	86.43	84.32	42	85

MCC-1 Results of Select Crucible Glasses Compared to Reference Glasses

Experiment	NL_{Na} at 28 days (g/m^2)
1F-49	3.14
1F-53	11.49
1F-57	5.20
Reference Glasses	
	NL_{Na} at 28 days (g/m^2)
EA Glass	34.97
P0798	9.59

4. Basic Experiments and Modeling (1) (Glass Science): Modeling on the Effects of Waste Compositional Variability and Melt Temperature (1/5)

Purpose

- Study on the effect of waste compositional variability

Methodology

- Because compositional variations of the 1F wastes are unknown, the investigation on the effects of the compositional variation of wastes was investigated by computer modeling using variation in waste component concentration ranges input into the model. Components are expressed as glass oxides (for example, SiO_2, Al_2O_3, MgO, etc.).
- PNNL used their proprietary glass property-composition model which was also used to formulate the GeoMelt® ICV™ glasses used in the engineering-scale and crucible-scale testing in this Subsidy Project.
- The modeling evaluated
  - The potential impacts of 1F waste compositional variability on maximum waste loading.
  - The effects from blending various wastes on maximum waste loading.
  - The difference between high-melt temperature glass and low melt temperature glass on waste loading and total mass of glass produced when treating the total quantity of assessed wastes.
  - the effects of model prediction and process uncertainty on maximum waste loading and total glass mass to be produced.

Five Wastes Investigated in the Computer Modeling

- Zeolite (including KUR-EH and IE-96, from cesium removal vessels)
- ARS: AREVA Sludge, a barium sulfate sludge from a decontamination device.
- CST: Crystalline silicotitanate, used in several Sr removal devices.
- TSG: KUR-TSG (Titanosilicate granular) a different CST used in Kurion's Sr removal device.
- ALPS Ca-Mg: ALPS Carbonate Slurry used in the multi-nuclide removal equipment.

4. Basic Experiments and Modeling (1) (Glass Science): Modeling on the Effects of Waste Compositional Variability and Melt Temperature (2/5)

Glass Property Constraints used in the PNNL Modeling

- The table below lists the glass property constraints used in the modeling. MCC-1, PCT, and VHT are international leach test procedures. LAW SO_3 solubility is a property constraint used for the computer modeling of the U.S. Department of Energy (DOE) Waste Treatment Plant (WTP), a vitrification plant being commissioned at the U.S. DOE Hanford Site. SO_3 is known to have a limited solubility in glass so this component must be limited in glass formulations which includes sulfur (for example 1F AREVA Sludge formulations).
- High- and Low-Temperature melters are defined in the model as producing molten glass at high-temperatures (>1250 °C) and at low-temperatures <1050 °C.

Glass Property Constraints used in the Modeling

Properties	Criteria for high-temperature melters	Criteria for low-temperature melters
Melting temperature T_M	1250 °C and 1500 °C	1000 °C and 1050 °C
MCC-1 normalized B mass loss (NL_B), 28 d at 90 °C	≤ 7.46 $g \cdot m^{-2}$	≤ 7.46 $g \cdot m^{-2}$
PCT normalized B, Li and Na mass loss (NL_i, i = B, Li, Na), 7 d at 90 °C	≤ EA glass (8.35, 4.785, 6.675 $g \cdot m^{-2}$ for B, Li, Na)	≤ EA glass (8.35, 4.785, 6.675 $g \cdot m^{-2}$ for B, Li, Na)
VHT alteration depth, 24 d at 200 °C	≤ 453 µm	≤ 453 µm
LAW SO_3 solubility	Solubility > SO_3 in glass	0.85 × Solubility > SO_3 in glass
Viscosity (η_T) at melting temperature T_M	$1 \le \eta_T \le 15$ Pa·s	$2 \le \eta_T \le 8$ Pa·s
Electrical conductivity (ε_T) at melting temperature T_M	$10 \le \varepsilon_T \le 70$ $S \cdot m^{-1}$	None
Normalized alkali to avoid immiscibility	≥ 0.2 mass fraction	≥ 0.2 mass fraction
Normalized submixture to avoid nepheline formation	≤ 0.3 probability	≤ 0.3 probability
Ti crystallization	TiO_2 ≤ 12.18 wt%	TiO_2 ≤ 5.49 wt%

4. Basic Experiments and Modeling (1) (Glass Science): Modeling on the Effects of Waste Compositional Variability and Melt Temperature (3/5)

Wastes Investigated in the PNNL Modeling

- Fifteen cases with various waste blending estimates for five selected wastes were assessed.
- Glasses were formulated to the maximize waste loading while simultaneously satisfying the property (e.g., chemical durability, viscosity, electrical conductivity) and composition constraints.
- The table below lists the individual fifteen cases in the model and the mass ratio of the blended wastes in cases B1 through B10.

15 cases. Cases S1 through S5 are modeled glasses containing only 1 waste. Cases B1 through B10 are glasses containing 2 wastes.

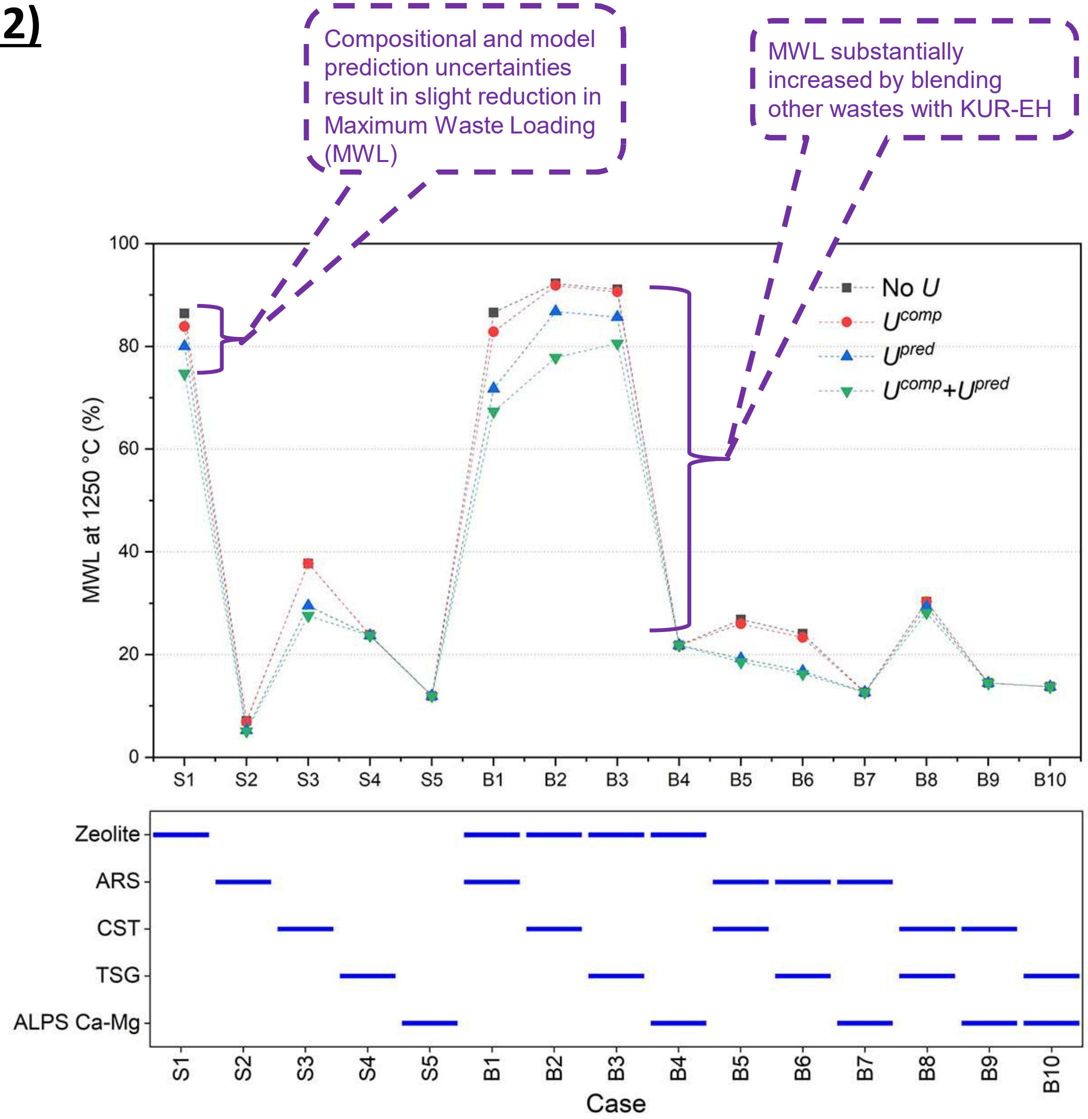
Waste Blending Information for the 15 Cases Modeled

Case	Waste 1	Waste 2	Mass ratio of waste 1 to waste 2
S1	KUR-EH/IE-96	None	—
S2	AREVA Sludge	None	—
S3	CST	None	—
S4	TSG	None	—
S5	ALPS Ca-Mg	ALPS Carbonate Slurry	—
B1	KUR-EH/IE-96	AREVA Sludge	15.31
B2	KUR-EH/IE-96	Crystalline Silicotitanate	4.06
B3	KUR-EH/IE-96	KUR-TSG	5.63
B4	KUR-EH/IE-96	ALPS Carbonate Slurry	0.87
B5	AREVA Sludge	Crystalline Silicotitanate	0.27
B6	AREVA Sludge	KUR-TSG	0.37
B7	AREVA Sludge	ALPS Carbonate Slutty	0.06
B8	CST	KUR-TSG	1.38
B9	CST	ALPS Carbonate Slurry	0.21
B10	KUR-TSG	ALPS Carbonate Slurry	0.15

4. Basic Experiments and Modeling (1) (Glass Science): Modeling on the Effects of Waste Compositional Variability and Melt Temperature (4/5)

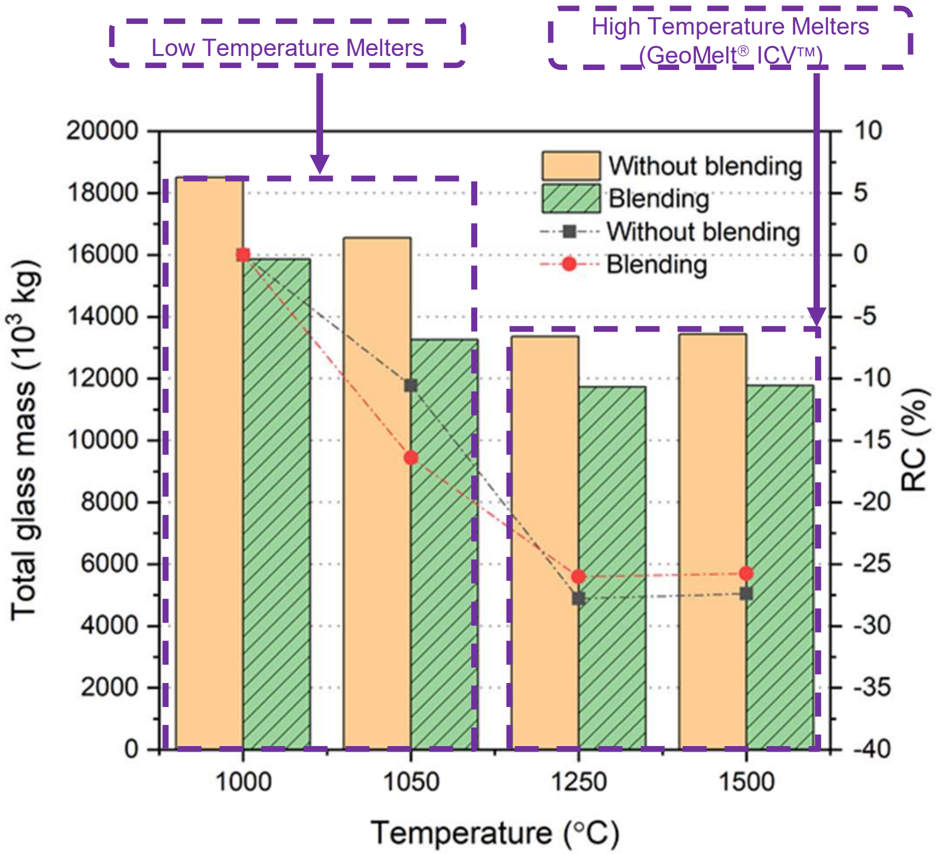
Results of the PNNL Modeling (1 of 2)

- The graphic below shows some results of the modeling.
- The top graphic shows maximum waste loadings of each of the 15 glasses modeled.
- The bottom graphic portrays the single waste (cases S1 through S5) or double wastes (B1 through B10) corresponding to the data points shown in the top graphic.
- Please understand that the top graphic also takes into account model uncertainty. "No U" is an abbreviation for no uncertainty. U_{comp} is an abbreviation for composition uncertainty which means waste variability. U_{pred} is an abbreviation for model prediction uncertainty. Computer models are not exact replications of real-life and the U_{pred} is related to the quantity of data in the compositional range being investigated in the model.
- The graphic below compares various glass chemistries to the Maximum Waste Loading (MWL) achieved when vitrifying the individual wastes (cases S1 through S5) or combination of two wastes (cases B1 through B10).



Results of the PNNL Modeling (2 of 2)

- The graphic on this page shows that using a high-temperature melter (such as GeoMelt® ICV™) to treat all the wastes considered in the modeling will result in much less (approx. 28% less) glass produced when all the wastes considered are vitrified. This is because high-temperature melters can achieve a higher waste loading. The higher the waste loading, the more waste is in the glass.
- The graphic on this page also shows that blending two wastes will also significantly reduce (approx.12% reduction) the total glass produced when treating the entire quantity of the five wastes considered.
- High temperature melters have more waste and less additives (non-wastes) resulting in higher waste loadings and a significant reduction (approx.37% reduction) in the total glass mass required to treat the five wastes considered.
- High temperature melters are more efficient than low temperature melters.

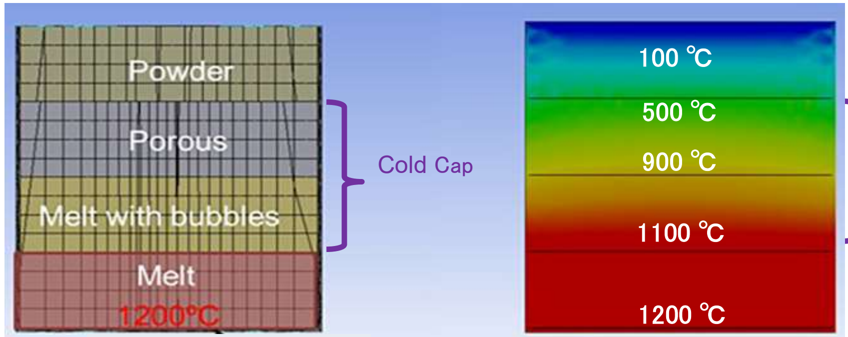


Effect of melting temperature and blending on total glass mass for treating of the five wastes, and relative change (RC) in total glass mass as compared to the values of low-temperature melters at 1000 °C (no uncertainties).

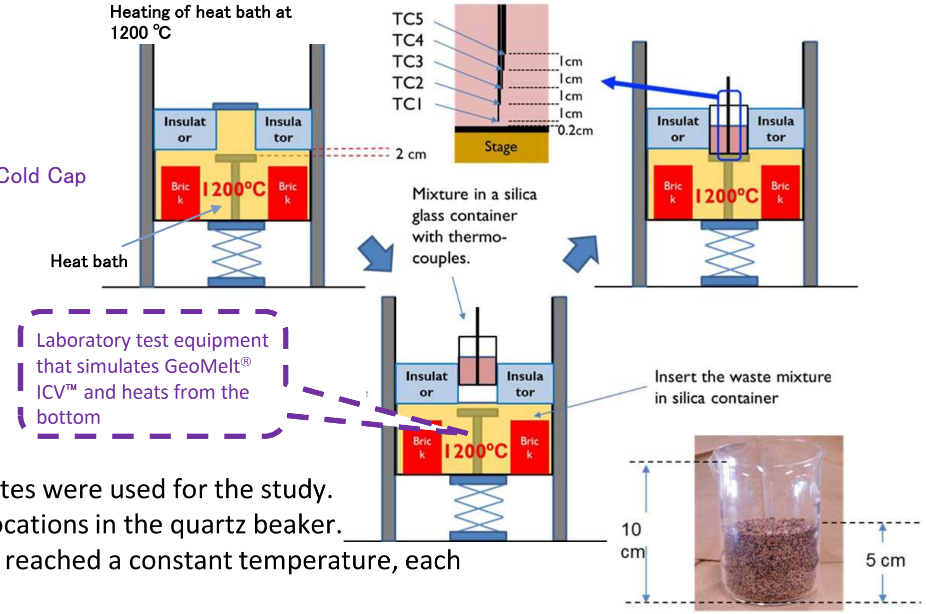
5. Basic Experiments and Modeling (2): (Elucidation of mechanism that suppresses volatilization of Cs)（1/2）

Study Contents

- Research on elucidation of quantitative and visible mechanism that suppresses volatilization of Cs.
- In order to understand the stabilization of Cs or its dissipation to the outside of the system, the GeoMelt® ICV™ process was simulated at the laboratory level to examine quantitatively. GeoMelt® ICV™ was simulated by preparing an equipment that can simulate the temperature gradient in which the lower molten glass is heated by an external electric heater and the input thermal energy is transmitted upward to proceed the melting.
- In GeoMelt® ICV™ operation, un-melted waste on molten glass is called a cold cap. Focusing the "foam layer and calcined layer" (together called cold cap) at the boundary between molten glass and un-melted waste on this study, and a three-layer structure consisting of un-melted waste / cold cap / glass melt was formed to understand their states.



Simulated 3 layers configuration: FEM mesh (left), Temperature gradient (right)



Simulated waste filled in a quartz beaker

Test Procedure

- Heat bath, which is the heat source at the bottom, is heated to 1200℃.
- Insert simulated waste in a 300 mL quartz beaker. Melt 5,6,7 simulated wastes were used for the study.
- Temperature gradient was measured by setting thermocouples at several locations in the quartz beaker.
- Once the melt at the bottom of the quartz beaker exceeded of 1000 ℃ and reached a constant temperature, each beaker was removed and allowed to cool.
- Samples were collected to evaluate the internal Cs concentration distribution and used as test pieces.

Evaluations

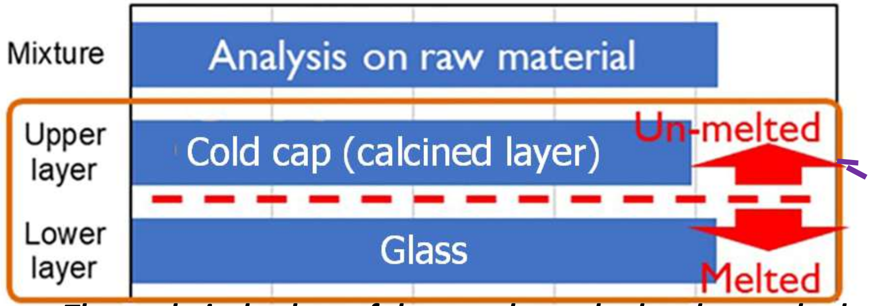
- Ca and Cs were analyzed by methods and procedures used for composition analysis of waste vitrified borosilicate glass (ICP-MS for Cs and ICP-AES for Ca).
- CaO was used as an internal standard (because absolute concentration cannot be determined) in this analysis method, and the degree of Cs migration was evaluated by using the Cs / Ca ratio of the analytical value.
- Regarding the movement of Cs in the GeoMelt® ICV™ Melter, based on the vapor pressure of Cs metal, it was thought that high vapor pressure was applied in the temperature range of 600 to 700 ℃, and diffusion movement was caused by the temperature gradient.

5. Basic Experiments and Modeling (2) (Elucidation of mechanism that suppresses volatilization of Cs)（2/2）

Result

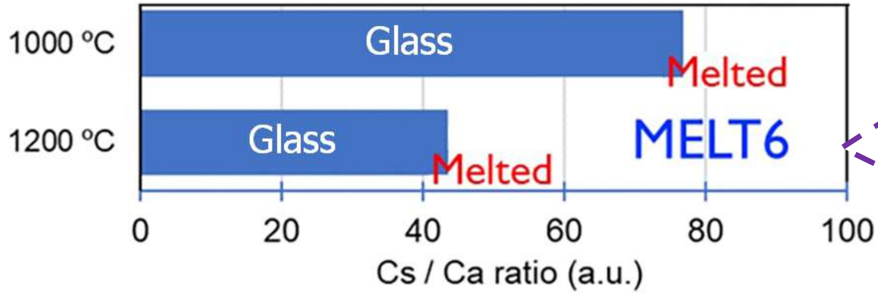
- Since the Cs concentration in the cold cap is about the same order as the concentration of the initial waste mixture and the molten glass under the cold cap, a lot of Cs still remains around the cold cap, suggesting that there is no significant movement of Cs above. It was confirmed that diffusion movement that causes a large composition change does not occur.

Condition of Quartz Beaker Removed After Heating (Melt 5 Material)



The analytical values of the samples melted and un-melted samples collected from the cold cap (Melt 6 composition)

① A lot of Cs still remains around the cold cap, indicating that the movement of Cs is not large in the cold cap.



The analytical values of samples collected from the glass melted at 1000 ℃ and 1200 ℃ with no cold cap (Melt 6 composition)

② Cs volatilization did not occur remarkably at 1000 ℃ for heating without a cold cap and with the molten surface exposed to the atmosphere. However, since it was halved when melted at 1200 ℃, it is suggested that volatilization of Cs occurs remarkably in the region above 1000 ℃ at the gas-liquid interface.

Areas where samples were collected to analyze Cs concentration (Melt 6)

6. GeoMelt® ICV™ Plant Preliminary Conceptual Design (PCD) (1/13)

Preliminary Conceptual Design (PCD) Objectives and Scope:

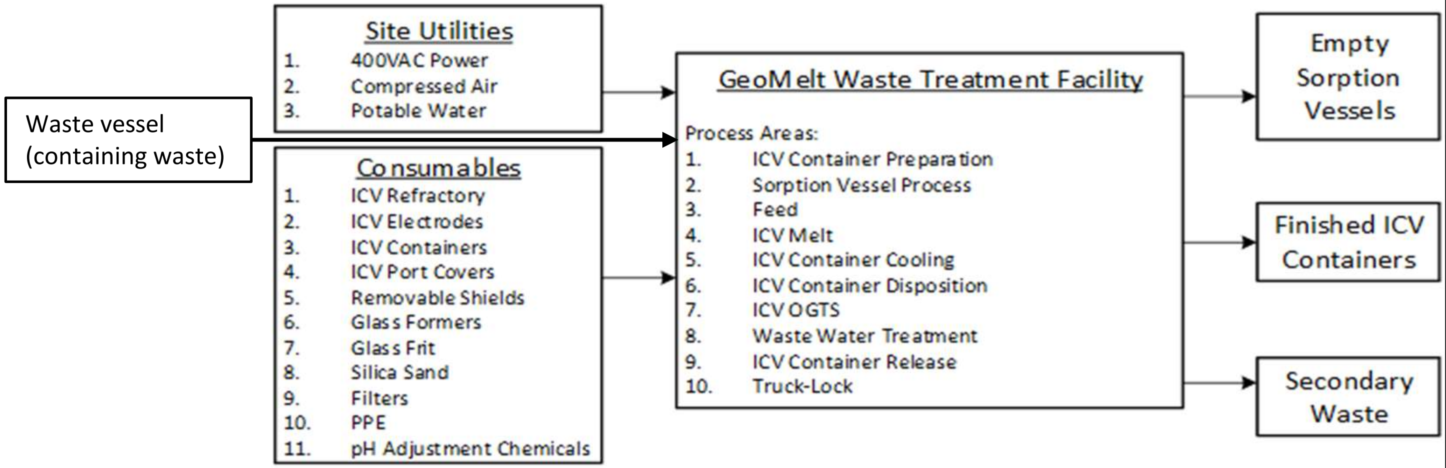
1) The Objectives of the Preliminary Conceptual Design of the GeoMelt® ICV™ Plant for treatment of 1F water treatment secondary waste are:

- Identify key design requirements, specifications, and assumptions for the GeoMelt® plant.
- Select operational equipment including material handling, vitrification, and off-gas treatment components.
- Provide a basic set of drawings (sketches) identifying the process flow, key piping and instrumentation, and general arrangement of equipment.
- Produce material balance calculations from a mass, energy, and activity perspective.
- Provide other important discussion points that define and communicate the components and operation of the system.

2) The following items were examined, and design documents were created:

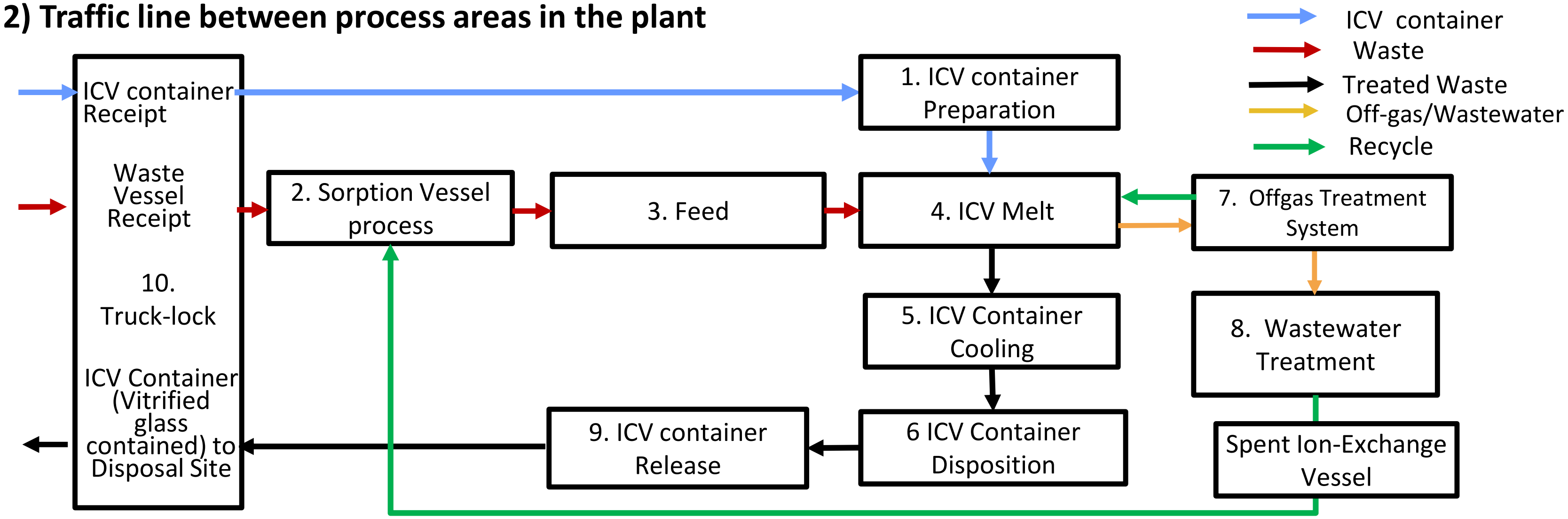
- Design Requirements and Assumptions
- Piping and Instrumentation Drawing (P&ID)
- Melter Feed System Evaluation
- Major Component Sizing
- General Arrangement Drawings
- Operational Sequence Animation
- Process Flow Diagram
- Mass, Energy, and Activity Balance
- System Design Description
- Utility Requirements
- Plant Equipment and Process
- Plant Efficiency and Throughput

1) Key Interface Points of Plant and Structure of process Area in Plant



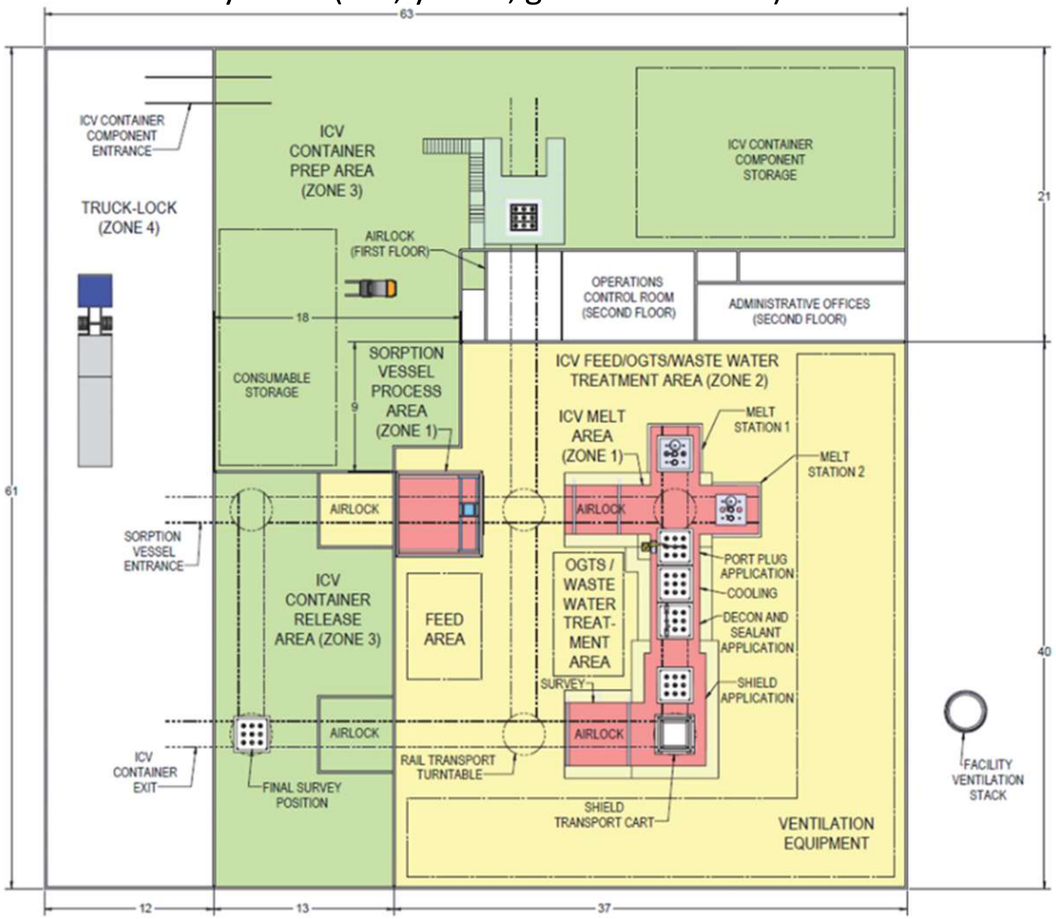
・Waste vessels containing waste to be treated, site utilities and consumables are received from outside of the plant.
・After treatment in the plant, ICV™ containers containing vitrified glass are released to the outside of the plant.
・10 process area are in the plant.(see figure left)
・The traffic line of main materials in the plant is shown in the figure below.

2) Traffic line between process areas in the plant



Physical Layout of GeoMelt®ICV™ Plant:

The zones in the plant are categorized 1 to 4 according to the radiation level and contamination potential level. Each categorized zone is indicated by color (red, yellow, green and white).



KEY

- ZONE 4 (white)
- ZONE 3 (green)
- ZONE 2 (yellow)
- ZONE 1 (red)

COLOR CODES:

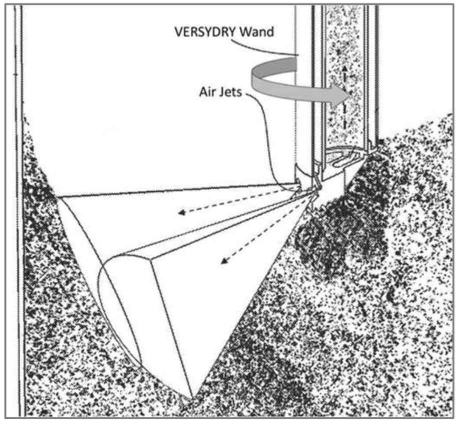
- ZONE 4 VENTILATION, CONTAMINATION POTENTIAL: CLEAN, RADIATION LEVEL: LOW OR BACKGROUND.
- ZONE 3 VENTILATION, CONTAMINATION POTENTIAL: LOW, RADIATION LEVEL: LOW OR BACKGROUND.
- ZONE 2 VENTILATION, CONTAMINATION POTENTIAL: MEDIUM, RADIATION LEVEL: POTENTIALLY ELEVATED LOCATIONS.
- ZONE 1 VENTILATION, CONTAMINATION POTENTIAL: HIGH, RADIATION LEVEL: HIGH.

Waste Retrieval Systems:

Waste vessels are delivered to the GeoMelt® ICV™ plant and waste must be removed so that it can be added to the ICV™ container for vitrification. Two methods of waste retrieval system (DRY and WET) will be used.

1. DRY method - Vessel Retrieval System Dry (VERSYDRY)

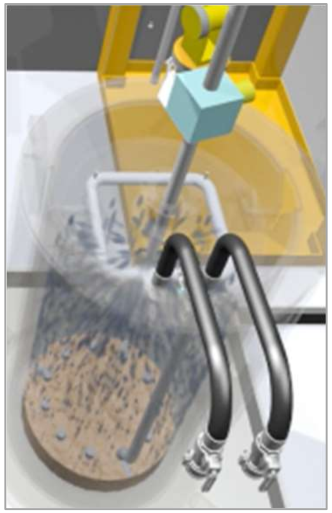
1) A Remote Manipulator controls the Dry Retrieval Wand.
2) The wand is a rotating hollow pipe which vacuums waste from the vessels.
3) The wand end blows air out from one side while vacuuming waste up the other side.
4) A down-wand camera is used to visually see the waste in the vessel.
5) Dry waste is moved to Dry Waste Receiver by dilute phase pneumatic conveyor



Dry Retrieval Wand End Features.

2. WET method - Vessel Retrieval System Wet (VERSYWET)

1) A Remote Manipulator controls the Wet Retrieval Wand.
2) The wand is a rotating hollow pipe which vacuums waste from the vessels.
3) The wand end pumps pressurized water out from one side while vacuuming waste up the other side.
4) A down-wand video camera is used to see the waste in the vessel.
5) Wet waste is moved to Air/Waste/Water Separator by dilute phase pneumatic conveyor.



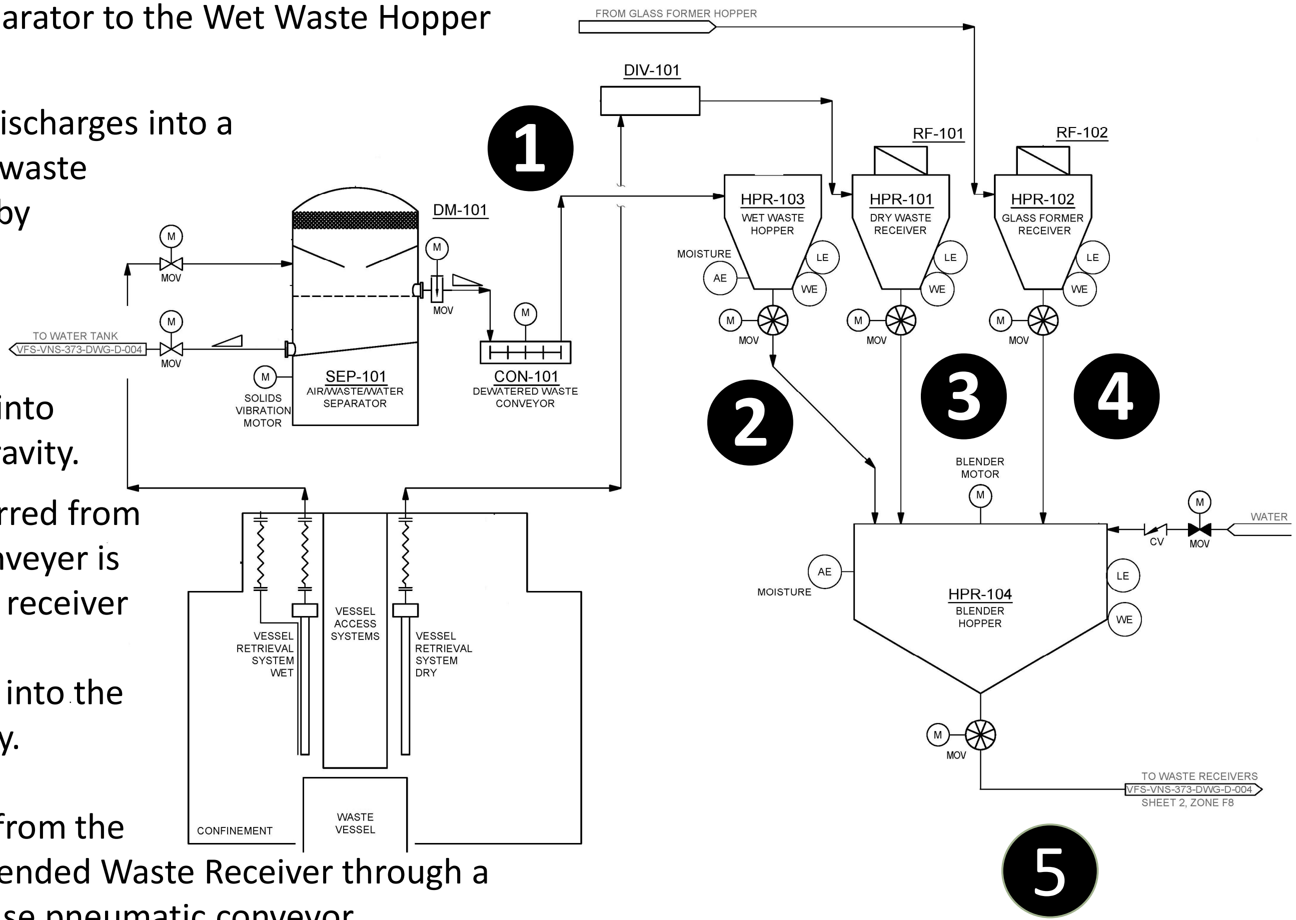
Wet Retrieval.

6. GeoMelt® ICV™ Plant Preliminary Conceptual Design (PCD) (5/13)

Waste Transfer Systems:

Transfer method of retrieved waste from vessel to blended waste receiver ("Feeder" to Melter)

1. Separated waste is moved from the Air/Waste/Water Separator to the Wet Waste Hopper by chain drag conveyor.
2. The Wet Waste Hopper discharges into a rotary valve which drops waste into the Blender Hopper by gravity.
3. The Dry Waste Receiver discharges into a rotary valve which drops waste into the Blender Hopper by gravity.
4. The Glass Former transferred from hopper by pneumatic conveyer is moved from glass former receiver into a rotary valve. which drops glass former into the Blender Hopper by gravity.
5. Blended waste is moved from the Blender Hopper to the Blended Waste Receiver through a rotary valve by dilute phase pneumatic conveyor.



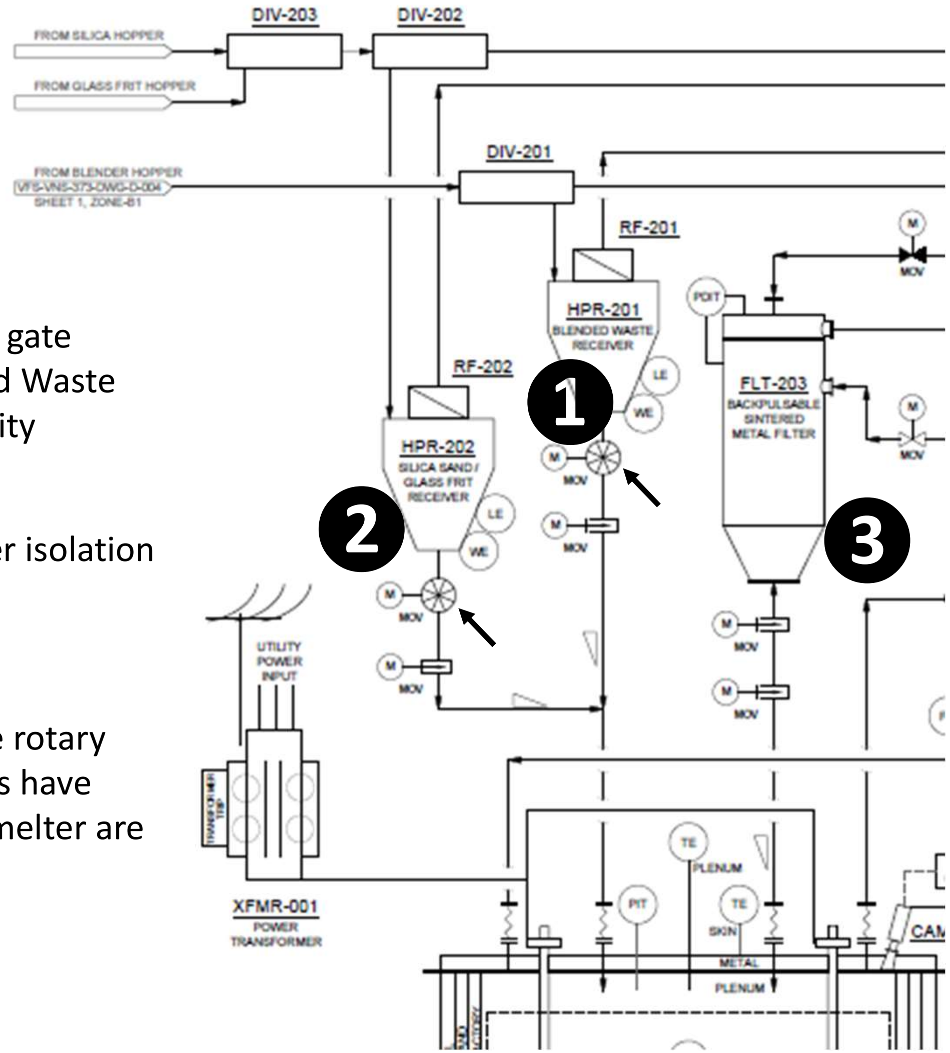
Waste Feeding:

Feed System to Melter

1 Blended waste is fed from the Blended Waste Receiver to the melter through a rotary and gate valve system (gravity feed).

2 Silica sand and glass frit is fed by from the Silica/Glass Frit Receiver through a rotary and gate valve system into a sloped pipe to the Blended Waste Receiver feed pipe, then into the melter (gravity feed).

3 The SMF discharges particulate into the melter isolation valves (gravity feed).



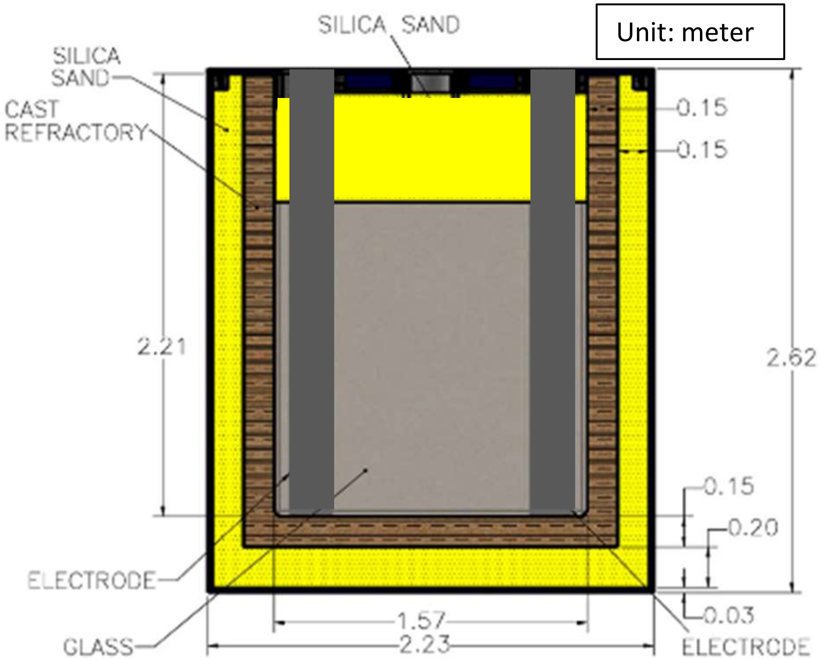
Blended waste, and silica/glass frit are metered by the rotary valve (shown by ↖ in the figure right) . Both receivers have loss-weight capability and mass of materials into the melter are tracked by digital readout.

6. GeoMelt® ICV™ Plant Preliminary Conceptual Design (PCD) (7/13)

ICV™ Container Specification

1. The ICV™ container and lid constitute the melter and the disposal container for the GeoMelt® ICV™ process.
2. The ICV™ container contains glass which is the result of vitrification of waste into a chemically stable and physically durable wasteform.
3. The ICV™ container is designed to hold 10,000 kg of glass.

Component Thickness	**mm**
Carbon Steel Exterior (Container and Lid)	25 thickness
Refractory Sand (sides)	150 thickness
Refractory Sand (base)	200 thickness
Refractory Sand (top) (If needed)	610 thickness
Cast Refractory (sides)	150 thickness
Cast Refractory (base)	150 thickness
Graphite electrodes (4)	200 diameter



ICV™ Container after Melting Complete
Upper part above glass was plenum while melting, then silica sand is added to fill upper void above glass

Container manufacture

1. The ICV™ container is made of 25 mm carbon steel plate.
2. It is manufactured by welding the base plate to the 4 sides.
3. There are no internal ribs or bracing.
4. The cast refractory is a single piece cast and fired to create a monolithic tub. Steel fibers are used in the mix for strength. A high-alumina low-cement castable refractory (service temperature = 1649 °C) will be used.
5. The refractory silica sand is composed of 99+ wt% SiO_2.
6. The lid manufactured by cutting penetrations into a single 25-mm steel plate. The underside of the lid has seal which fits to the inside of the cast refractory. This prevents waste from overflowing the cast refractory.

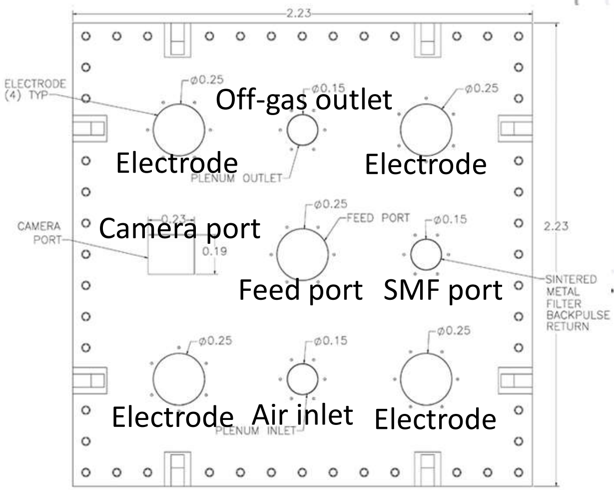
6. GeoMelt® ICV™ Plant Preliminary Conceptual Design (PCD) (8/13)

The ICV™ container is prepared for melt operation in ICV™ Preparation Area which is Zone 3 (green) with no radioactive dose or contamination present.

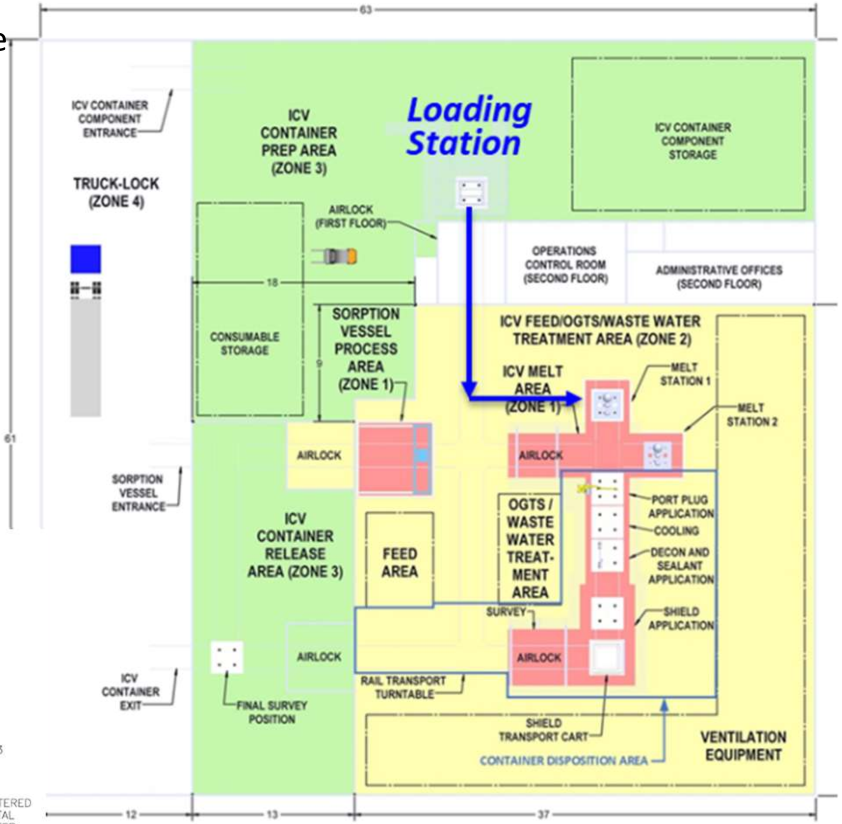
Basic Pre-Melt Container Preparation Steps:

1. Empty container is moved by rail to loading station beneath the mezzanine.
2. Refractory silica sand is loaded into container by chain-drag conveyor.
3. Cast refractory tub is loaded into container by overhead crane.
4. Refractory silica sand is loaded outside of the cast refractory tub by chain-drag conveyor.
5. Frit and starter path is installed in the base of the cast refractory tub.
6. Container lid is installed using the overhead crane.
7. Electrodes (4) are installed into the starter path.

Preparation completed. The ICV™ container is moved to the melt station on the rail:
The melt station is the place where container is connected with waste feed system, off-gas treatment system, electric power supply and instrumentation for melt treatment. The plant has two melt stations (1 and 2).



ICV™ Container Lid Detail (Top View)



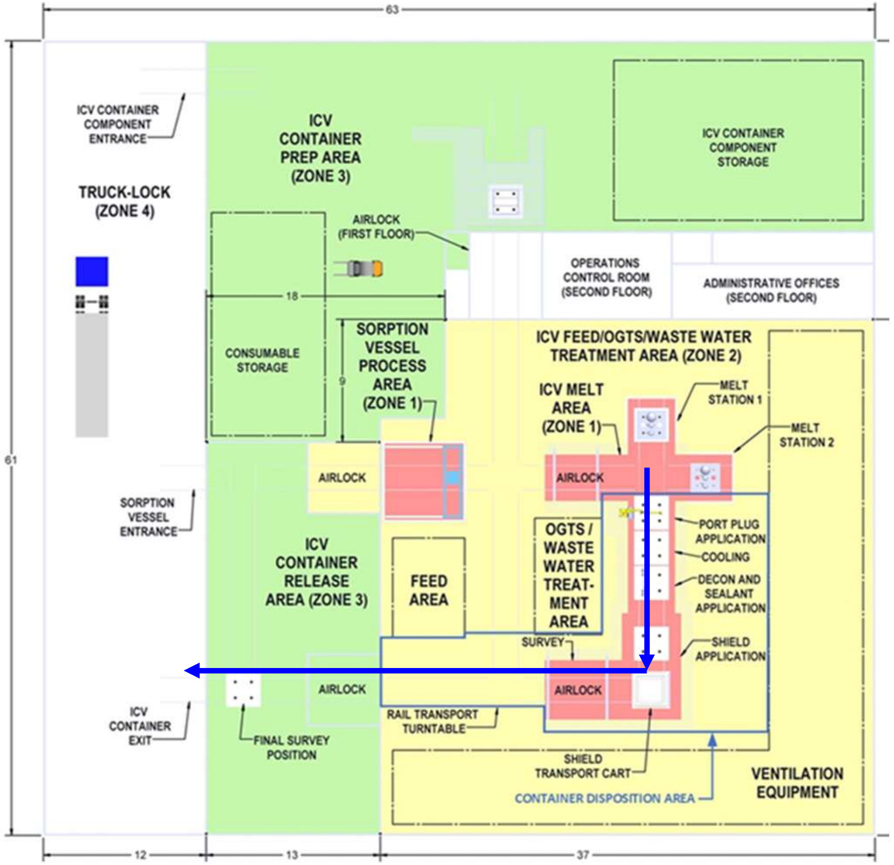
Physical Layout of GeoMelt® ICV™ Plant

6. GeoMelt® ICV™ Plant Preliminary Conceptual Design (PCD) (9/13)

After the melt, the container is cooled, sealed, surveyed, and shielded for transport in these areas

Basic Post-Melt Container Cooling and Disposition Steps:

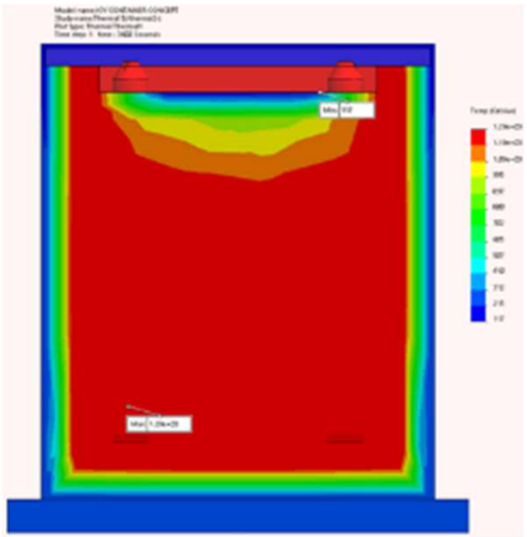
1. After the melt is complete instrumentation and port connections are disconnected at the melt station.
2. Container is transferred to the Container Cooling Area where port covers are installed remotely at the Lid Plugging Station.
3. Container is moved to Decontamination and Sealing Station where a vacuum wand is used to remove loose contamination and a sealing fixative is sprayed to fix residual contamination.
4. Container is moved to the Survey Station and the dose rate is measured to create the dose map for estimation of total product package activity created.
5. Container is moved to the Shield Install Location where removable modular shield panels (VNS Patent ref : US 10,311,989 B2) are installed. Removable panels: either 120 mm thick carbon steel or 60 mm carbon steel-encased lead.
6. Shielded ICV™ container: 0.9 mSv/hr at 5 cm from the outer surface of shield panel
7. Container moves through 2 airlocks from Zone 1 to Zone 3 Container Release Area.
8. Container is surveyed again and moved to the Zone 4 Truck-Lock for transport out of the plant for storage.



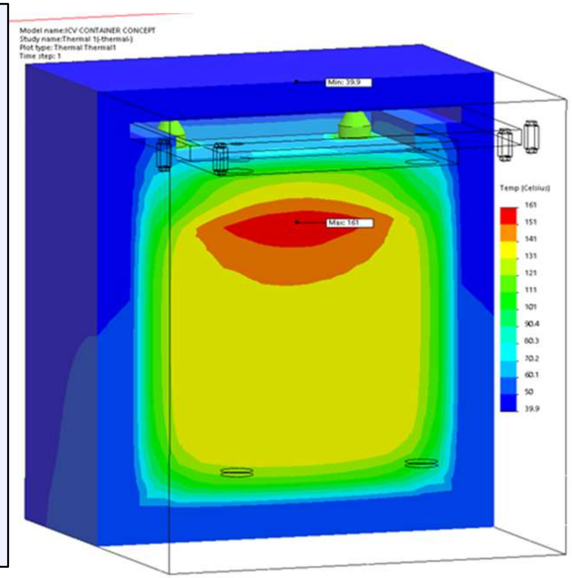
Physical Layout of GeoMelt®ICV™ Plant

6. GeoMelt® ICVTM Plant Preliminary Conceptual Design (PCD) (10/13)

1. The ICVTM container does not receive significant thermal influences from the melt process because it is insulated by the refractory.
2. Thermal modeling analysis indicated the maximum steel temperature of 400 °C which is below the steel softening temperature of 571 °C.
3. The maximum external temperature from radiolytic decay (only source of heat) will be 40.5 °C.



Analysis conditions
Initial temperature of external surfaces
(ICVTM container shield and ICVTM container) : 300 °C
the sand components : 800 °C
the refractory, electrodes, and glass: 1300 °C
Thermal conductivity of
Glass:1.11 W/(m*K)
Cast Refractory: 1.74 W/(m*K) @ 540 °C
1.89W/(m*K) @815 °C
2.03 W/(m*K) @1093 °C
Silica Sand: 0.5 W/(m*K)
Carbon Steel:
Decay heat generation density: 939 W/(m^3*K)
Ambient temperature: 38 ° C



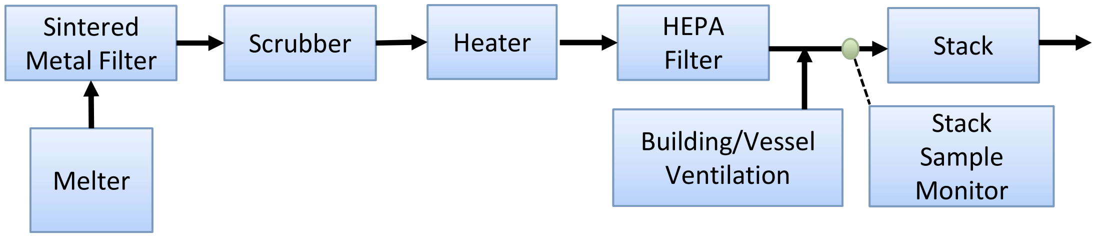
Thermal Analysis 1 Hour after Melt Completion (400 °C Maximum steel temperature)

Thermal Analysis of Radiolytic Decay Heat (40.5 °C. Maximum steel temperature)

6. GeoMelt® ICVTM Plant Preliminary Conceptual Design (PCD) (11/13)

Off-Gas Treatment System:

Off gas out of the melter is treated by filters and scrubber to remove radioactive contents



1. Off-gas treatment begins immediately above the ICV™ container with a sintered metal filter (SMF) where the majority of off-gas particulate (99.97%) is removed, and cool air is blended with the relatively low flow hot off-gas exhaust for further downstream processes.

2. The SMF contains an array of filter candles that are independently backpulsed upon high differential pressure. Because only a few of the filters are backpulsed simultaneously, the filter can remain online during cleaning cycles.

3. The SMF is also designed with water spray nozzles to remove residual material from filter candles and internal housing that is not completely removed by back-pulsing. The backpulsed particulate and cleaning water can then be recycled directly downward onto the feed pile within the ICV™ container below. Each melt station has its own SMF.

4. After passing through the SMF, Melter station 1 and 2 off-gas combines and enters a wet scrubber (e.g., packed bed scrubber) where minor organics and other dissolved solids are captured and treated.

5. After leaving the wet scrubber, the off-gas temperature is heated using an inline heater to prevent condensation, prior to entering the final HEPA filter treatment stage. This final HEPA filter step removes 99.97% of any remaining particulate before entering the OGTS Fan and exiting via the off-gas stack to atmosphere.

6. The OGTS Fan maintains negative pressure throughout the off-gas treatment system and the off-gas is treated safely in this system.

6. GeoMelt® ICV™ Plant Preliminary Conceptual Design (PCD) (12/13)

Mass and Activity Balance:

- Mass balance were calculated to provide an accounting of the inputs, outputs of GeoMelt® ICV™ Plant
- Activity balance were calculated to provide an accounting of the removable by off-gas treatment system and the release.

The Mass Balance of GeoMelt® ICV™ Treating Kurion Waste

Kilograms of Waste Feed per ICV™ Container	**9,612**
Kilograms of Glass Formers per ICV™ Container	**2,337**
Kilograms of Glass Frit per ICV™ Container	**888**

→ GeoMelt® Process →

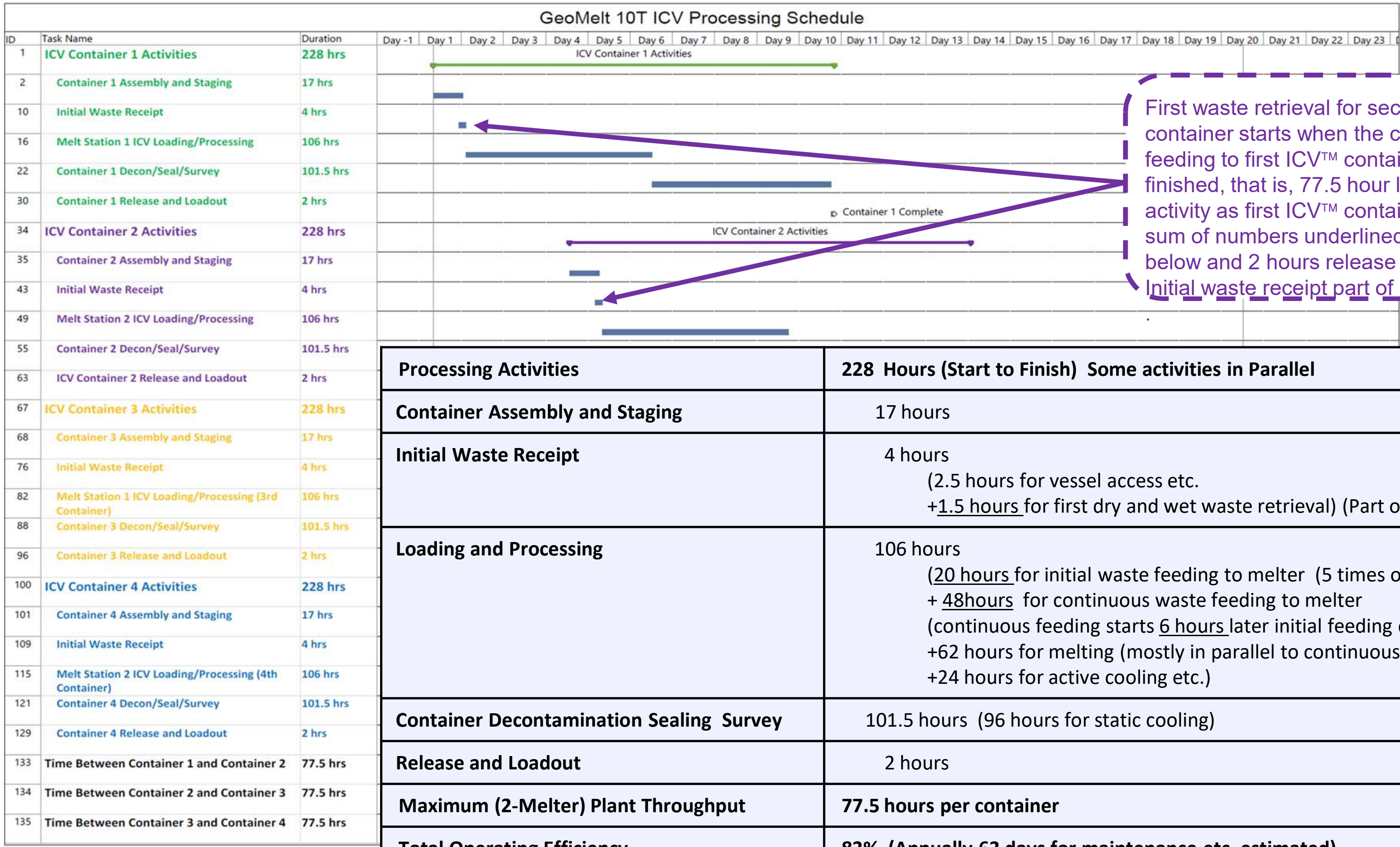
Kilograms of Glass per ICV™ Container	**10,000**

The Activity Balance of Treating 1 Kurion Vessel

		Sr-90	Cs-134	Cs-137
①	The amounts fed to Melter with waste per ICV container (TBq)	1.65E+03	5.58E+02	8.13E+03
②	The retention factor of glass (%)	99.99	99.3	99.3
③	The amounts in off gas just out of Melter (TBq)	1.65E-01	3.93E+00	5.73E+01
④	Capture Efficiency of sintered metal filter (%) And amounts after (TBq).	99.97 4.95E-05	99 1.18E-03 .97	99 1.72E-02 .97
⑤	Removal Efficiency of scrubber for (as submicron particle) (%) and amounts after (TBq)	90		
		4.95E-06	1.18E-04	1.72E-03
⑥	Removal Efficiency of pre-filter and HEPA filter (2 stages) (%) and amounts after (TBq)	90 (prefilter), 99.97 (HEPA filter each)		
		4.46E-14	1.06E-12	1.55E-11
⑦	The flow rate and batch hours	1566m3/hr 62hr		
⑧	Emission rate (Bq/cm3)	4.28E-13	1.15E-11	1.67E-10
	Discharge limit (outside of facility site boundary) (Bq/cm3)	5.00E-06	2.00E-05	3.00E-05

6. GeoMelt® ICV™ Plant Preliminary Conceptual Design (PCD) (13/13)

- **The processing schedule was examined to calculate Plant Efficiency (throughput)**



First waste retrieval for second ICV™ container starts when the continuous feeding to first ICV™ container has finished, that is, 77.5 hour later the same activity as first ICV™ container (77.5 is sum of numbers underlined in the table below and 2 hours release and loadout) Initial waste receipt part of staging

Processing Activities	**228 Hours (Start to Finish) Some activities in Parallel**
Container Assembly and Staging	17 hours
Initial Waste Receipt	4 hours (2.5 hours for vessel access etc. +1.5 hours for first dry and wet waste retrieval) (Part of Staging)
Loading and Processing	106 hours (20 hours for initial waste feeding to melter (5 times of waste receipt) + 48hours for continuous waste feeding to melter (continuous feeding starts 6 hours later initial feeding completed) +62 hours for melting (mostly in parallel to continuous feeding) +24 hours for active cooling etc.)
Container Decontamination Sealing Survey	101.5 hours (96 hours for static cooling)
Release and Loadout	2 hours
Maximum (2-Melter) Plant Throughput	**77.5 hours per container**
Total Operating Efficiency	**83% (Annually 63 days for maintenance etc. estimated)**
Annual Plant Throughput Rate	**93 containers per year**

6. GeoMelt® ICV™ Plant Preliminary Conceptual Design (PCD) (Summary)

1. A scale that contains 10 tons of vitrified glass was selected as an ICV™ container (Melter and disposal container) . A 4-electrode Melter and bottom-up melting method were adopted.

   Considering the melting process, subsequent container cooling and treatment time, two melt locations were installed. (melting station: ICV™ container and peripheral facilities (waste supply, off-gas treatment, power supply, etc.) are connected to perform melting process).

   During melting and cooling the container at the one station, another container can be under preparation.

2. The plant can produce one vitrified waste form every 77.5 hours and 93 vitrified waste form per year. (The wastes in the current 789 Kurion adsorption vessels and 188 SARRY adsorption vessels can be treated in one year.)

3. Preparatory work before the melting operation of the ICV™ container can be carried out in the green area where there is no radiation source nor risk of contamination. After the preparation is completed, the container is remotely moved to the melt station on the rail and installed.

4. A dry method and a wet method were examined for retrieval of the waste to be treated from the adsorption vessel, and their combination was adopted. The transfer and feed system of the retrieved waste to melter were examined.

5. The results of the engineering-scale melt test were reflected to the operation (melting process) method of melter.

6. A sintered metal filter was adopted in the first stage of the off-gas treatment system from the Melter. Furthermore, a high Cs retention rate of the vitrified waste form was ensured by a method of recycling the fine particles captured and collected by the filter into the Melter.

7. Assessments of GeoMelt®ICV™ Plant PCD : Safety Assessment (1/2)

A. Purpose:

1. Provide example US regulation “framework” for how to develop a future “Safety Basis”* for the GeoMelt® Vitrification Plant
2. Describe the method for developing the Safety Analysis from conceptual to final design

B. Scope:

1. A preliminary study based on U.S. regulations and guidance from other GeoMelt® projects (see table below)
2. A recommendation for the level of analysis and review necessary for conducting a future formal Safety Analysis
3. Identifies some key hazards and accident scenarios that could affect the safety of the treatment plant.
4. Provides corrective measures to mitigate or eliminate specific hazards

Not a Safety Analysis Report (SAR) since the design is in a preliminary conceptual stage. The SAR will be developed during future detailed design.

・At the stage of pre-conceptual design, it is concluded that there would be no problem on the compliance with Japanese domestic regulations (the Law for the regulations of Nuclear source material, Nuclear fuel material and reactors, Radiation hazard prevention law, etc.), and especially with Rule for safety of the facilities and protection of the specific nuclear fuel material of Fukushima Daiichi Nuclear Power Station nuclear reactor facilities

・From now on, as the design work proceeds, the study on the compliance with domestic regulations will be performed in detail and with broader extent and the design work will be performed referring to the plan of Fukushima Daiichi Nuclear Power Station Specified nuclear facility.

Regulatory and Guidance of USA

Criteria	US DOE	Guidance
Hazard Analysis	DOE-STD-3009-2014, Preparation of Nonreactor Nuclear Facility Documented Safety Analysis [Ref. 7] DOE-STD-1189-2008, Integration of Safety Into the Design Process [Ref. 8]	Center for Chemical Process Safety’s Guidelines for Hazard Evaluation Procedures, Part I [Ref. 3] DOE-HDBK-1224-2018, Hazard and Accident Analysis Handbook [Ref. 4]
Accident Analysis	DOE-STD-3009-2014, Preparation of Nonreactor Nuclear Facility Documented Safety Analysis [Ref. 7] DOE-STD-1189-2008, Integration of Safety Into the Design Process [Ref. 8] DOE-STD-1020-2012, Natural Phenomena Hazards Analysis and Design Criteria for DOE Facilities [Ref. 9]	DOE-STD-3014-2006, Accident Analysis for Aircraft Crash into Hazardous Facilities [Ref. 5] DOE-HDBK-1224-2018, Hazard and Accident Analysis Handbook [Ref 4]
Hazard Control	DOE-STD-3009-2014, Preparation of Nonreactor Nuclear Facility Documented Safety Analysis DOE-STD-1189-2008, Integration of Safety Into the Design Process	DOE G 423.1-1B, Implementation Guide for Use in Developing Technical Safety Requirements DOE-STD-1186-2004, Specific Administrative Controls. [Ref.11]
Hazard Categorization	DOE-STD-1027-92 [Ref.10]	-

7. Assessments of GeoMelt® ICV™ Plant PCD : Safety Assessment (2/2)

Example GeoMelt® ICV™ Plant Hazards

GeoMelt® ICV™ Plant Areas with "Materials at Risk (Radioactive materials etc.)"	• Waste Vessel Processing Area • Feed Transfer System • ICV™ Melt Station • Off-gas Treatment System • Wastewater Treatment Area
Possible Energy Sources	• Gravity • Flammable gas (propane) • Radiolysis • High heat • Residual energy in the melt pool • Electrical • Pressure (scrubber water, air) • Flowing air entraining waste
Natural or External Events	• Landslide, earthquake, tsunami, floods, etc. • Aircraft crash, vehicle accident, utility breakage, building collapse, explosion • Common causes (loss of electrical, air, water, staff)

7. Assessments of GeoMelt®ICV™ Plant PCD: Operation and Maintainability Assessment (1/2)

A. Purpose:

1. Evaluate the proposed GeoMelt® ICV™ plant to:
   a. Identify potential failure mechanisms that could degrade its operation or hinder maintenance
   b. Provide proactive steps to prevent or minimize the failure mechanism
2. Ensure the plant performs to its highest possible level of performance, safety and efficiency

B. Scope:

1. Systems directly related to the GeoMelt® ICV™ process including Vitrification and Waste Retrieval systems.
2. Three Project phases are evaluated:
   a. Design
   b. Build (Manufacture)
   c. Commissioning

Area	Key component	Key concern
ICV™ Container Preparation Area	<u>**ICV™ Container and Lid**</u> Silica Sand and Glass Frit Refractory Liner and In-melt TCs Starter Path Electrodes	Container Integrity Electrode Support Starter Path Placement Glass Containment Glass Processing
ICV™ Melt Station	Pre-Melt Readiness Feed Addition and Melt Startup Pressure and Flow Sensors Electrode Contactors IR Camera	Remote Process Line Connecting Flexible Connection Failure Proper Startup and Feeding Management Decontamination and Prepare for Transport Process Monitoring Control Post-Melt Port Plugging Decontamination and Prepare for Transport ICV™ Container Port Plugging and Passive Cooling Decontamination and Lid Fixative Container Dose Survey ICV™ Container Shields
Off-gas Treatment System	Sintered Metal Filter (SMF) Scrubber and Recirculation System OGTS Heaters HEPA Filter OGTS Fans	Long term reliability Filter and Process Line Cleaning Periodic Filter Change and Maintenance Redundancy of critical components
Waste Vessel Retrieval Area	Vessel Access Systems Vessel Retrieval Systems Remote Manipulator Arm Vacuum Tool Water Spraying Tool	Long term reliability Retrieval efficiency / vessel cleanliness Radiation tolerance Tool changeout
Wastewater Treatment Area	Wastewater Processing and Controls Scrubber Liquid Water Quality Control Water Filtration	Long term reliability Water Quality Maintenance Filter monitoring and changeout Water Separation Efficiency
Feed Handling Area	Pneumatic Transfer System Feed and Isolation Valves Feed Hoppers and Receivers	Dust Management Feed Line plugging/caking Transfer Line Erosion Transfer Line velocity

7. Assessments of GeoMelt® ICV™ Plant PCD: Operation and Maintainability Assessment (2/2)

a. Design phase

- It is necessary to identify potential failure mechanisms and take steps to eliminate the mechanism or provide methods to mitigate or minimize the consequences.
- Of special consideration are those areas relating to process components whose failure and subsequent replacement would cause a significant disruption in plant operations.
- The design should also consider maintenance of failed components by incorporating features to allow movement of the component to lower radiation/contamination areas, where possible.
- Certain components are essential for safe operation of the plant; and will require dedicated systems that are physically and electrically separate from non-safety class systems.
- Redundancy of critical components and safety related devices should be specified, where possible.
- The system design must also eliminate or reduce hazards to the greatest extent practical using the radiation safety principle of ALARA, (As Low as Reasonably Achievable) in all cases.

b. Build (manufacture) phase

- It is critical that appropriate quality levels are maintained to ensure operability and maintainability, and that other key characteristics are maintained.
- Proposed manufacturing facilities must be reviewed by quality assurance personnel to ensure their capabilities.
- Of special consideration are those systems that impact plant operations and those that are safety related.

c. Commissioning phase

- It is necessary to ensure all facility and support personnel have proper O&M training and have demonstrated proficiency in their assigned duties.
- Processes and procedures must be validated, and evidence of key maintenance activities must be demonstrated.
- The commissioning phase is also a unique opportunity to obtain baseline operational data that can be used for future equipment performance comparison
- A detailed spares assessment is also performed to ensure appropriate spare parts are on hand prior to "hot" operations.
- Routine maintenance activities should be practiced during this phase to ensure minimal interruptions to operations.
- Preventative maintenance should occur on critical moving parts (fans, pumps, agitators) to ensure optimal performance.

7. Assessments of GeoMelt® ICV™ Plant PCD: Economic Efficiency Assessment (1/5)

A. Purpose: Evaluate the advantage of the GeoMelt® ICV™ Plant on economic efficiency comparing with Continuous pour method.

B. Scope of Areas Evaluated:

1. Batch mode operation
2. Volume reduction
3. Waste loading and processing of multiple types of waste
4. Consumables
5. Secondary wastes and pre-treatment requirements
6. Plant efficiency and throughput
7. Use of proprietary shield panels
8. System simplicity and reliability

<u>Comparison of Batch to Continuous Pour:</u>

Batch method: Treat the waste in the melter batchwise. Vitrified glass is disposed together with the melter.

Continuous pour method: Pour the waste in form of melted glass out the bottom of the melter into the canister. Vitrified glass is disposed with the canister

Relative advantages of batch mode operation:

A. Batch mode means each ICV™ container is a new melter and melt chemistry can be uniquely tailored for optimized processing of a particular waste material, then subsequently altered for a different waste material in another batch. Continuous flow down means one melter only, but many glass containers.

B. Larger treatment vessels are possible because of good heat efficiency and vital melt convection inside container, which improves throughput and process efficiency.

C. One time-use refractory and its high heat tolerance allows higher melt temperature, which allows for silica-rich formulations , which allows higher waste loading.

D. Can accept recycle of large secondary waste streams (HEPA, process water filters, etc.) because of large lid size and possibility of uniquely tailored melt chemistry. (Special recycle melt with current design).

E. Container malfunction will not shut down process (such as malfunctioning sensor) – simply move offline until problem is cured as container transfer (moving) is designed as part of routine operation.

F. One melt/treat/dispose container reduces handling of dangerous nuclear material.

G. Simple = Safe → No bubblers, agitators, pour spouts, canister handling devices.

H. Disposable melter/disposal container uses common materials that are less expensive than traditional melter glass canisters.

Relative disadvantages:

A. Change out ICV™ container for each batch. → This increases risk of connection point failure. Careful and robust design, using verification R/D, will make risk small and manageable.

B. Some consumables are disposed with each melt. → A small part of overall cost, and optimization studies during design can identify most economical methods and materials.

7. Assessments of GeoMelt® ICV™ Plant PCD: Economic Efficiency Assessment (2/5)

Volume reduction

- A natural result of vitrification due to the low-density waste and glass former materials being converted into a high-density glass during melting.
  - Estimated volume of Kurion + SARRY waste to treat = 1,200 m^3.
  - Estimated volume of GeoMelt® ICV™ product after treatment = 360 m^3.
  - Equates to a 70% waste to glass volume reduction.
  - The current storage of waste at 1F (489 culverts = 17,291 m^3).
  - The proposed storage of fully shielded ICV™ containers (97 containers = 1756 m^3).
  - The reduction is even greater at (17,291 m^3-1756 m^3)/17,291 m^3 = 89.8% storage volume reduction.
- Reasons why GeoMelt® ICV™ process has high volume reduction:
  - The proposed 10t ICV™ container provides a higher glass/container ratio than smaller waste containers.
  - GeoMelt® operates at higher temperatures (1250-1600 °C), enabling a higher waste loading in the glass than continuous pour low temperature (1000-1200 °C) melters.
  - Rectangular ICV™ container allows more efficient storage configuration than round containers.

Relative Waste Loading

- Custom glass formulations and crucible and engineering-scale testing have maximized 1F waste loading during the Subsidy Project, while preserving glass quality.
- Blending different 1F wastes significantly improves waste loading, decreasing the total amount of disposal glass produced.
- Waste loading of up to 85%, depending on which wastes are combined.
- PNNL findings showing how blending and higher glass temperature allows greater waste loading than low temperature melters (Slide 46).
- Continuous pour melters cannot handle high heat and therefore have lower glass waste loading.

7. Assessments of GeoMelt® ICV™ Plant PCD: Economic Efficiency Assessment (3/5)

Relative Cost of Consumables (including ICV™ container)

- The ICV™ container is used only once as the melter, it is also the transport and disposal container, providing simplicity and cost savings
- A 10t ICV™ container is expected to be less expensive around 1/7 to 1/2 to fabricate than a typical US HLW waste canister, and it holds over 4 times more glass (3.85 m^3 vs 0.89 m^3) .
- Although more consumables (silica sand, refractory, thermocouples, electrodes) are used with GeoMelt® batch operation, these consumables are relatively inexpensive, as shown above. Even more so when compared to the initial capital cost, maintenance cost, and disposal cost of a continuous pour melter, including its complex pouring and canister handling and lidding equipment.

Relative Production of Secondary Waste

- GeoMelt® ICV™ process can accept many sizes and types of secondary waste
- GeoMelt®ICV™ Plant generates secondary waste such as bulk wastes, process water filters, HEPA filters, PPE, ion exchange media from process water cleaning
- Special ICV™ melt for secondary waste treatment can be set aside to load and treat accumulated secondary wastes in GeoMelt® ICV™ plant.

Pre-Treatment Requirements

- No pre-treatment of planned 1F wastes needed except dewatering to ensure proper waste transfer
- For the secondary waste the pretreatment such as shredding or blending is easy.

7. Assessments of GeoMelt® ICV™ Plant PCD: Economic Efficiency Assessment (4/5)

Relative Energy Transfer (efficiency of electrical energy added to the glass)

- Joule (resistive) heating melters have high throughput due to efficient energy transfer, through waste and glass.
- Other melter design (inductive, external heating, etc.) are less efficient due to inherent heat transfer (energy) losses.

Melter Replacement Schedule and Cost

- GeoMelt® ICV™ melter is replaced in hours and is normal procedure and part of schedule.
- Continuous pour melter needs several months to be replaced and operation needs to be shut down completely during this period. Also, it is estimated that dismantlement, transportation, disposal, etc. will cost around $4M -$12M (for waste treatment facilities in US).
- Relative Operating Efficiency.
  Simple and easy replacement and maintenance melter dramatically improves total operating efficiency.

Use of proprietary shield panels

- Removable shield panels reduce fabrication cost and handling difficulties compared to making thicker ICV steel walls
- Shield panels allow more efficient storage configuration by allowing removal of inside shielding that is not needed (adjacent containers provide the shielding).

7. Assessments of GeoMelt® ICV™ Plant PCD: Economic Efficiency Assessment (5/5)

System Reliability

Simple and Reliable - Design is made simple on purpose. This avoids possible failure mechanisms and increases life expectancy.

- Few mechanical failure points.
- Key components have redundancy (electrodes, offgas fan, HEPA filters, etc.).
- Melter can be easily removed if problem occurs, allowing process to continue.
- Passive air cooling of ICV™ container eliminates complex active cooling mechanisms used with other melters.
- Basic ICV™ design has been used in many shapes and sizes over the last 20years and has been continually improved along the way.
- Technology Readiness Level (TRL) can be evaluated to be high.

250 kg Engineering-Scale System - USA

500 kg System - UK

10 tons System - Japan

50 tons System - USA

7. Assessments of GeoMelt® ICV™ Plant PCD: Waste Retrieval and Handling Assessment (1/5)

Purpose: Evaluate ① Waste Retrieval, ② Material Handling and ③ Feeding Systems

Requirements to each system

①Retrieval: Removal of waste from their containers (retrieval).
②Materials Handling: Transporting these materials for pretreatment (water addition or removal and blending with glass-formers.
③Feeding: Conveying the blended waste into the melter (ICV™ container).

① Requirements Common to Dry and Wet Waste Retrieval:

- Retrieval of waste from vessel to transfer piping.
- Remotely operated.
- Waste removed until no visible waste remains in vessel as indicated by wand camera.
- Contamination control.

Dry Retrieval Requirement:

- Dust control.

Residual visible waste not removed using dry retrieval will be removed by wet retrieval.

Wet Retrieval Requirement:

- Liquid control.

② Materials Handling System Requirements:

- Remotely operated.
- Conveyance of dry and wet retrieved waste through transfer piping to waste receiver.
- Dewatering wet retrieved waste to 20 ±5 wt% before transferred to waste receiver.
- Conveyance of waste from receivers to to blender hopper.

③ Feed System Requirements:

- Remotely operated.
- Blending waste and GFMs (glass former materials) in blender hopper.
- Ability to add water to blender hopper to achieve 20 ±5 wt% water content.
- Feed blended waste to ICV™ container.
- Feed TOF and silica sand at the end of the melt.

① Waste retrieval: Comparison between two systems

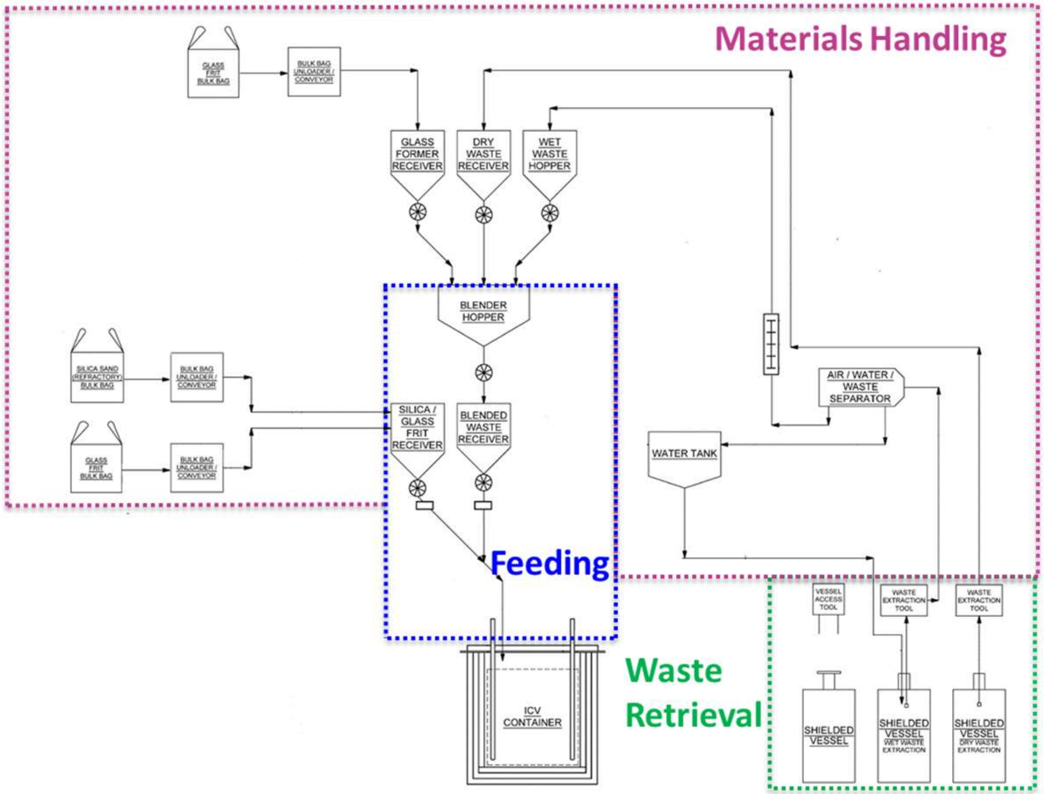
(a) "VERSYDRY" (Vessel Retrieval System Dry) = Dry Vacuum Retrieval.
(b) "VERSYWET" (Vessel Retrieval System Wet) = Wet Sluicing Retrieval.

1) Similarities:

(1) Both systems uses a hollow rigid pipe (wand) to vacuum waste from waste vessels.
(2) Both wands have a lighted camera to see outside the wand into the vessel.
(3) Both systems remove waste by vacuuming.

2) Differences:

(1) The wet system pumps water down the wand with end features consisting of sluice nozzles for water jetting dislodging of material.
(2) The dry system blows air down the wand with end features consisting of air jets and a grinding plate for dislodging material.

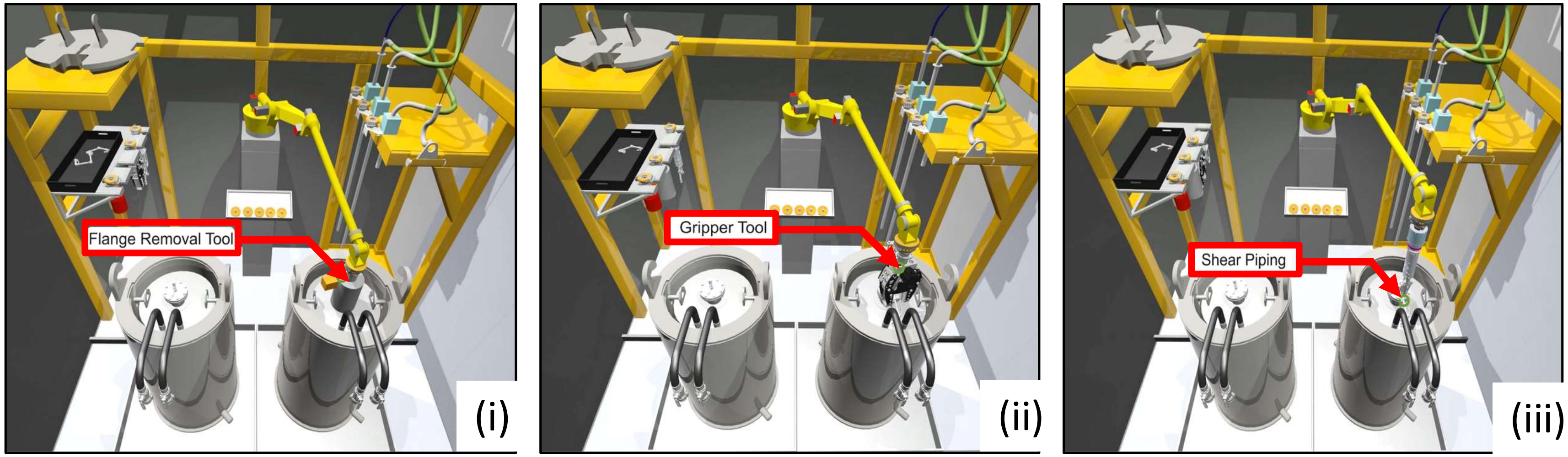


PCD waste retrieval, materials handling, and feed

① Waste retrieval: Retrieval Operations

- A Remote Manipulator controls the Waste Vessel Access Tooling which removes and reinstalls the vessel shield cover, access the waste vessel through the top flange and installs a plug after the waste has been retrieved.
- For SARRY vessels, the Waste Vessel Access Tooling removes the cover and lead shot (SARRY) and installs the plug after the waste has been retrieved.

Shown below:
(i) Removing Kurion vessel top flange with Flange Removal Tool.
(ii) Gripping pipe.
(iii) Shearing pipe.
- Once the pipe is sheared the vessel may be accessed with the Retrieval Suction Wand.



7. Assessments of GeoMelt® ICV™ Plant PCD: Waste Retrieval and Handling Assessment (4/5)

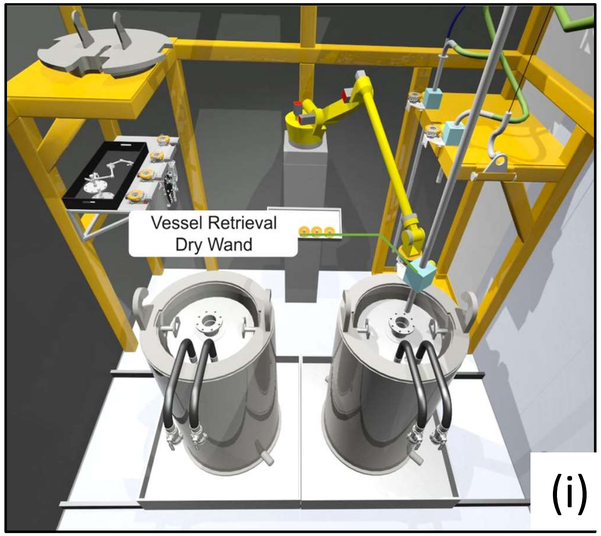
① Waste Retrieval: Tools and Equipment

(a) Dry Retrieval Wand: (see the figure right upper (i))

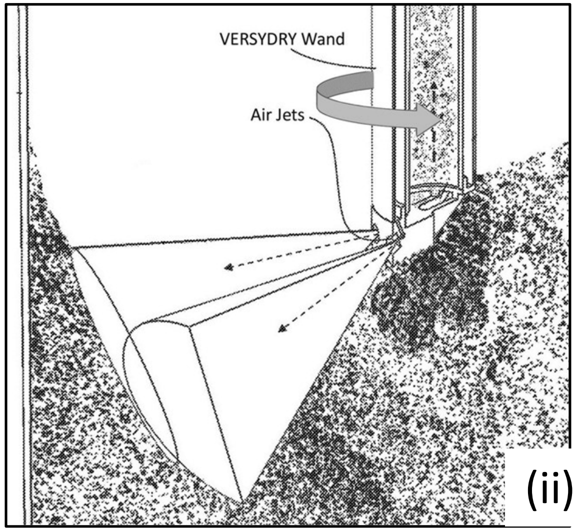
- A Remote Manipulator controls the Dry Retrieval Wand.
- The wand is a rotating hollow pipe which vacuums waste from the vessels.
- The wand end blows air out from one side while vacuuming waste up the other side.(see the figure right lower (ii))
- The wand end also may have a grinding plate to help dislodge material.
- A down-wand camera is used to visually see the waste in the vessel.
- Dry waste is moved to Dry Waste Receiver by dilute phase pneumatic conveyor.

(b) Wet Retrieval Wand:

- A Remote Manipulator controls the Wet Retrieval Wand.
- The wand is a rotating hollow pipe which vacuums waste from the vessels.
- The wand end pumps water out from one side while vacuuming waste up the other side.
- A down-wand camera is used to visually see the waste in the vessel.
- Wet waste is moved to Air/Waste/Water Separator by dilute phase pneumatic conveyor.



(i) Dry Retrieval Wand



(ii) Dry Retrieval Wand End Features

7. Assessments of GeoMelt® ICV™ Plant PCD: Waste Retrieval and Handling Assessment (5/5)

① Waste Retrieval: Selection and designation of the system

- Dry retrieval is simpler and faster than the wet retrieval method.
- Dry retrieval is preferred but the PCD plant has have both.
- The PCD Mass and Energy Balance assumes throughputs consistent with 75% dry retrieval and 25% wet retrieval.

② Materials Handling:

- Bulk Bag Unloader/Conveyors are dilute phase pneumatic conveyors which move:
  - -glass-formers to the Blender Hopper.
  - -silica sand to the Silica/Glass Frit Receiver.
  - -glass Frit to the Silica/Glass Frit Receiver.
- Separated waste is moved from the Air/Waste/Water Separator to the Wet Waste Hopper by chain drag conveyor.
- Waste is moved from the Dry Waste Receiver and the Wet Waste Hopper to the Blender Hopper through a rotary valve by gravity.
- Blended waste is moved from the Blender Hopper to the Blended Waste Receiver through a rotary valve by dilute phase pneumatic conveyor.

③ Feeding:

- Waste is fed from the Blended Waste Receiver to the melter through a rotary and gate valve system by dilute phase pneumatic conveyor.
- Silica sand and glass frit is fed from the Silica/Glass Frit Receiver through a rotary and gate valve system by dilute phase pneumatic conveyor.

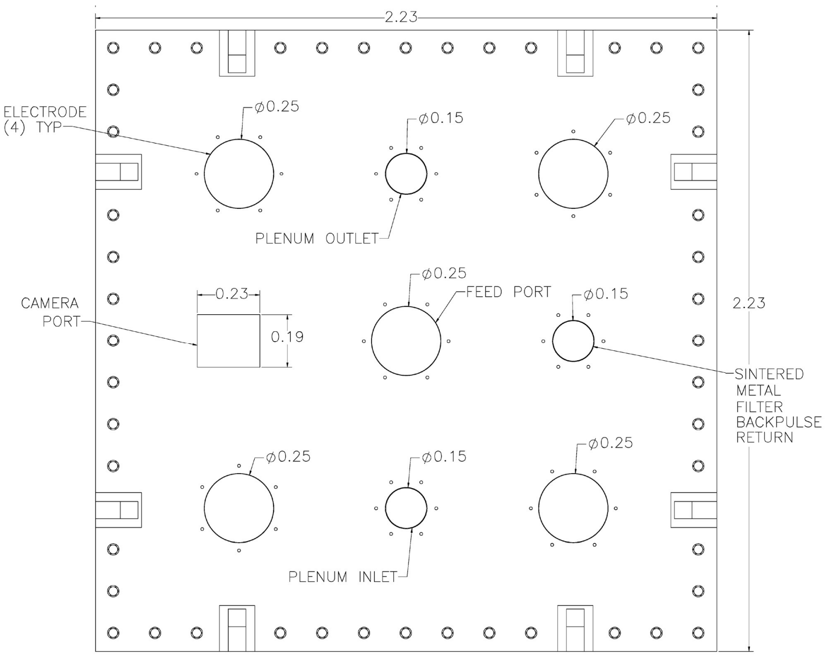
7. Assessments of GeoMelt® ICV™ Plant PCD: Product Package Assessment (1/2)

Purpose

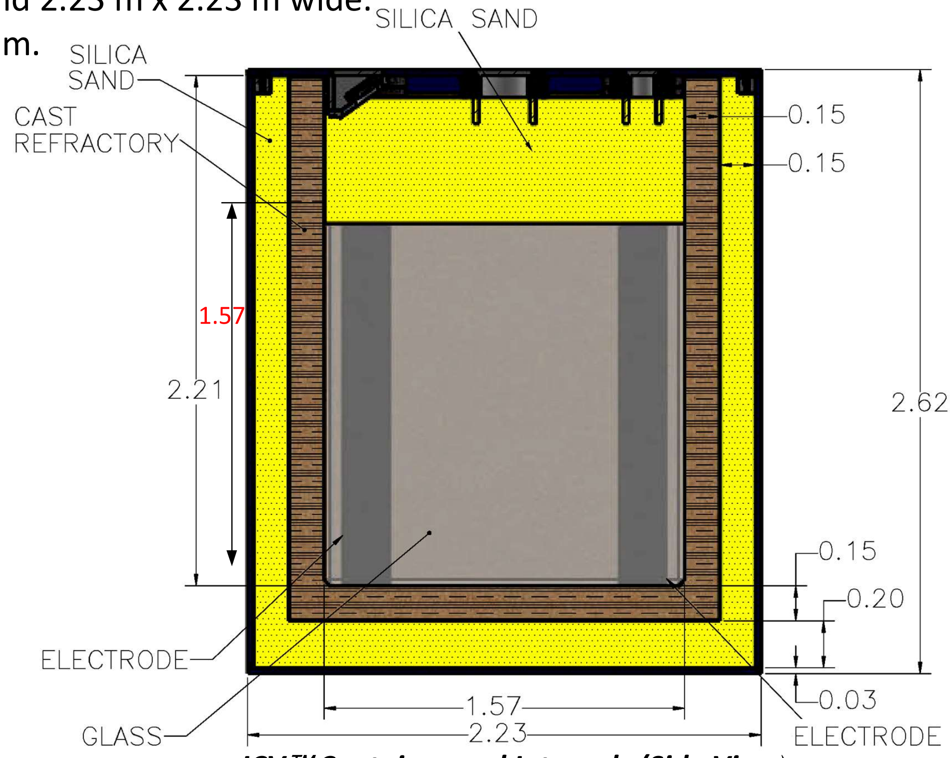
- The purpose of the Product Package Assessment is to provide detailed description of the physical configuration of the final waste package (the PCD GeoMelt® ICV™ container).

Physical Description

- The ICV™ container is designed to hold 10 tons of glass.
- The overall product package (glass, cast refractory, refractory silica sand, the steel ICV Container and lid) weighs 30,212 kg.
- With the removable modular shield panels included, the product package weighs 65,340 kg.
- ICV™ container exterior dimensions: 2.62 m high and 2.23 m x 2.23 m wide.
- Glass monolith dimensions: 1.57 m x 1.57 m x 1.57 m.



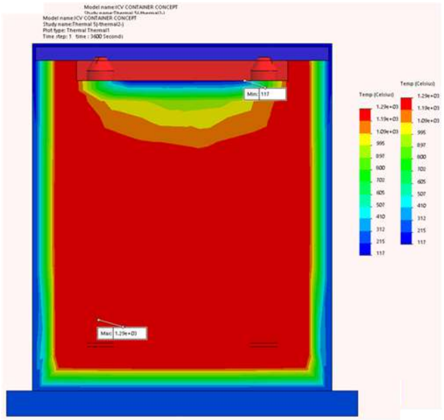
ICV™ Container Lid Detail (Top View)



ICV™ Container and Internals (Side View)

Soundness of ICV Container Because of Short-Term Thermal Influences:

- The ICV container does not receive significant thermal influences from the melt process because it is insulated by the refractory. The PCD included thermal analysis which indicated the maximum steel temperature of 400 °C which is below the steel softening temperature of 571 °C.
- The maximum external temperature from radiolytic decay will be 40.5 °C.



Thermal Analysis 1 Hour after Melt Completion (400 °C Maximum steel temperature)

Removable Shield Panels *:

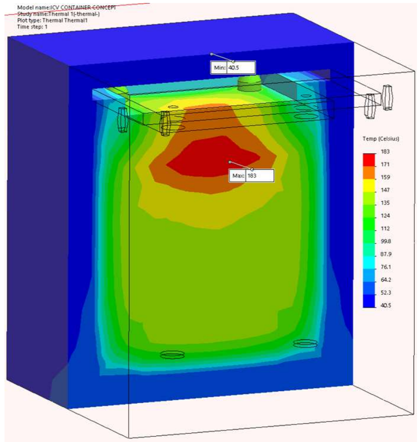
- Removable panels: 120 mm thick carbon steel (or 60 mm thick carbon steel-encased lead).
- Installed on mounting points on the outside of the container.
- These are installed in the Zone 1 Shield Install Location before the container is moved to the Zone 3 Container Release Area.
- Containers can be stored next to each other and stacked.
- Panels are removed from adjacent faces before adjacent/stacked storage.

ICV Containers (8) with Removable Shield Panels

Contact Dose Rate

- Shielded ICV™ container: 0.9 mSv/hr.

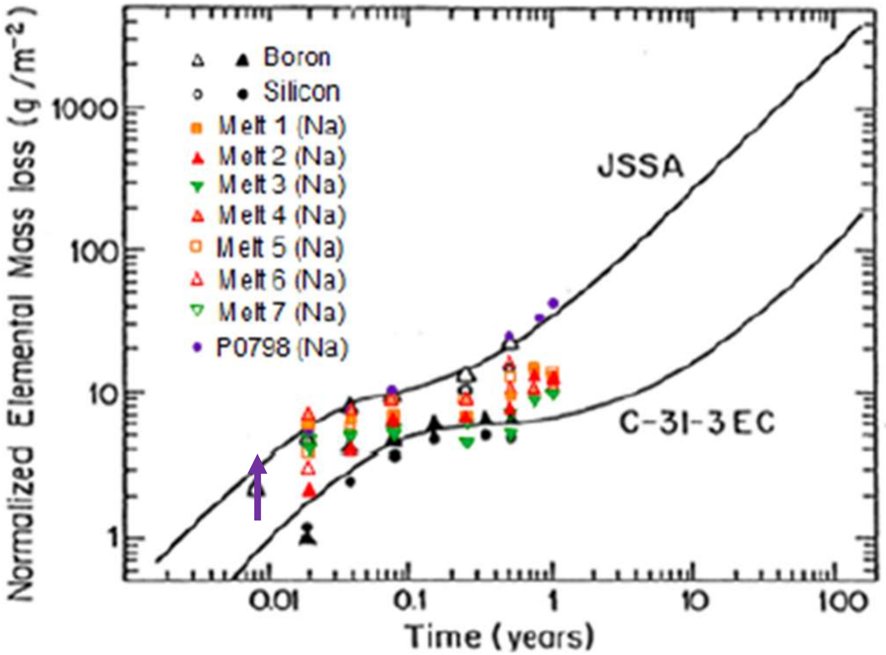
* VNS Patent ref. (US 10,311,989 B2)



Thermal Analysis of Radiolytic Decay Heat (40.5 °C Maximum steel temperature)

7. Assessments of GeoMelt® ICV™ Plant PCD: Glass Performance Assessment (1/2)

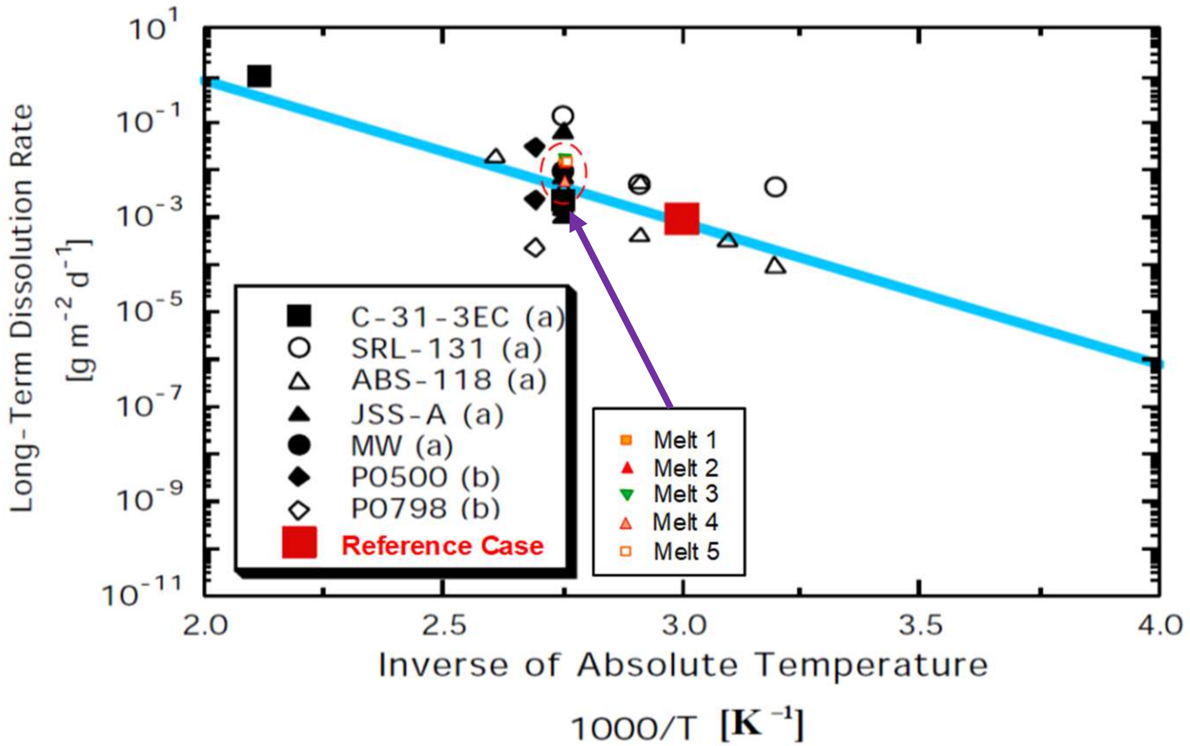
- Based on the data regarding the chemical durability and so on of the GeoMelt® vitrified waste from the engineering scale tests, the dissolution rate to the groundwater of the vitrified waste is evaluated.
- Comparison of the normalized mass loss of Na for engineering melt tests 1 to 7 and Na for reference glasses with the normalized mass loss of B and Si for other leaching test results.
- The dissolution characteristic of vitrified waste consists of 3 stages ; 1) initial dissolution rate-controlled stage, 2) steady state stage closed to saturation and 3) accelerated corrosion caused by fast silicate mineral dissolution.



JSS A: Vitrified waste of liquid radioactive waste produced in 'JSS Project' performed by CRIEPI (Japan), NAGRA (Switzerland) and SKB (Sweden) (1984-1988) C-31-3EC: Simulated vitrified waste of EC

7. Assessments of GeoMelt® ICV™ Plant PCD: Glass Performance Assessment (2/2)

- The long-term dissolution rate of various vitrified wastes for HLW geological disposal has been calculated based on the leaching rate after saturation of the dissolved silicic acid concentration.
- The long-term dissolution rate for Japanese HLW disposal program (reference case) at assumed repository temperature of 60℃ was calculated to be 1E-3 $g/m^2 \cdot d$ from regression expression shown in this Figure.



- MCC-1 test results (shown in the figures in page 37 and 79) confirms that GeoMelt® glass is more chemically durable than HLW glass
- The dissolution rate of the GeoMelt® ICV™ vitrified waste is equivalent to the long-term dissolution rate (1E-3 $g/m^2 \cdot d$) which uses to evaluate HLW vitrified waste and high radionuclide containment function is expected.

7. Assessments of GeoMelt® ICV™ Plant PCD : Summary

1. In the safety assessment, the method to organize plant safety basis along with US regulatory guidance was considered, and the materials at risk and possible energy source were identified. It is considered that there is no problem in compliance with Japanese domestic laws and regulations, but a wide range of specific studies are required according to the future design progress.

2. Potential failures that may reduce operability or interfere with maintenance were identified in the operability / maintainability evaluation, and preventive procedures were summarized.

3. The economic advantage of the batch operation method, which is a feature of GeoMelt® ICV™, was clarified in the economic efficiency assessment. Furthermore, it was shown that it is economically superior in terms of consumables and secondary waste.

4. Dry retrieval and wet retrieval system were compared in the waste retrieval and handling assessment, and the optimum combination of them was determined.

5. The overall structure of the product package (ICV)™ (container containing vitrified glass treated by melting the waste) was summarized in the product package assessment, including the shielding installed on the outside.

6. In the glass performance assessment, it was confirmed that the GeoMelt® ICV™ vitrified waste form has a dissolution rate equivalent to the long-term dissolution rate (1E-3 $g/m^2 \cdot d$) used in the evaluation of the HLW vitrified waste form and has a high radionuclide confinement function.

8. Summary

1. Engineering-scale Melts 4 through 7 on waste simulants representing the bulk of the 1F secondary water treatment wastes successfully demonstrated high waste loadings (67% to 79%), high volume reduction (74% to 76%, with very low cesium emissions (corresponding to 97.72 to 99.44% retention in glass), and excellent glass durability compared to Japanese HLW reference glasses.
2. Engineering-scale Melt 8 successfully demonstrated the GeoMelt® remote restarting method after emergency shutdown and assumed accidents/events and processing 1F soil in place of zeolite as the primary glass former for the melt.
3. New glass formulation and crucible testing of more 1F wastes resulted in verification that GeoMelt® is applicable to the large part of the 1F water treatment secondary wastes.
4. PNNL's modeling of the effects of waste variability and melt temperature supports the benefits of the waste blending scheme and high melt temperature to reduce the total number of vitrified waste packages for disposal.
5. The research on the elucidation of quantitative and visible aspects of Cs capture in the cold cap verified the cold cap management techniques.
6. A detailed and comprehensive preliminary conceptual design for a GeoMelt ICV plant at 1F has been completed. The plant designed is equipped with two melters of 4 electrode with the capacity of 10 ton/batch each and can produce one vitrified glass every 77.5 hours, that is 93 vitrified glass annually. The design has clarified the waste retrieval/handling system with both dry and wet method, melter feeding system and off-gas treatment system, etc.
7. The pathway to the GeoMelt® ICV™ Plant Safety Analysis Report (SAR) was studied, and potential hazards were identified. The method to develop the basis of safety of the plant was considered. The GeoMelt® ICV™ Plant Operation and Maintainability and Economic Efficiency Assessments ensure the preliminary conceptual plant performs to its highest possible level of performance and economic efficiency. The GeoMelt® ICV™ Plant Waste Retrieval and Handling Assessment assessed preliminary conceptual waste retrieval and handling, and the Product Package Assessment provided a detailed description of the physical configuration of the final waste package. Glass Performance Assessment confirmed that the glass has high radionuclide containment function.

Finally

That is the Results of the Holistic Evaluation of GeoMelt® ICV™ for Treatment of 1F Water Treatment Secondary Waste conducted as Subsidiary project of Decommissioning and Contaminated Water Management (Fiscal Year 2019-2020) (Research and Development of Processing and Disposal of Solid Waste)