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Treatment of Problematic Reactive Metal Wastes Using the GeoMelt® In-Container Vitrification (ICV™) Process – 20326

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ABSTRACT

Decommissioning of sodium-cooled reactors and fast reactor technologies has generated a number of reactive metal waste configurations that are problematic to treat and typically lack cost effective treatment methods and disposition options. As a result, Veolia Nuclear Solutions, under contract with Idaho National Laboratory (owned by the U.S. Department of Energy and managed and operated by Battelle Energy Alliance, LLC) demonstrated its GeoMelt® In-Container Vitrification (ICV)™ technology to safely convert sodium metal to a non-reactive vitrified oxide form. The demonstration project, supported by glass formulation and crucible testing, consisted of a series of ICV™ melts that processed elemental sodium into stable non-reactive glass.

INL is currently implementing GeoMelt® technology as a means to safely and reliably convert radioactive reactive metal residues that contaminate sodium cooled reactor components into waste forms that comply with existing disposition pathways. Reactive metal wastes require treatment in order to remove the Resource Conservation and Recovery Act (RCRA) reactivity and ignitability characteristics to comply with land disposal restrictions. GeoMelt®, which is an alternative to other potential treatment approaches, provides a robust approach that chemically converts the reactive metals to an inert oxide while also immobilizing radionuclides in a vitrified waste form with durability equal to or better than vitrified nuclear fuel reprocessing wastes (very robust and inert waste forms). Most other treatment approaches generate hydrogen gas which is problematic.

In 2016, Veolia Nuclear Solutions first demonstrated the effectiveness of the GeoMelt® ICV™ process in deactivating reactive sodium metal. Crucible, bench-scale, and engineering-scale demonstrations were conducted on several surrogate waste configurations with various ratios of sodium metal and glass-formers. Each ratio and configuration demonstrated complete deactivation of the surrogate sodium metal. Follow-on work in 2017 demonstrated the deactivation of reactive sodium by GeoMelt® ICV™ at a higher waste loading relative to previously demonstrated work performed in 2016; the higher waste loading optimized glass chemistry while enhancing the economical full-scale treatment of reactive metals.

Additionally, follow-on demonstration testing in 2018 and 2019 focused on more complex shapes and other reactive-metals (mocked up Experimental Breeder Reactor II [EBR-II] subassembly, sodium filled heat exchanger, and a can containing sodium potassium alloy) which were all performed at engineering-scale.

Veolia Nuclear Solutions designed, installed, and commissioned in September 2018, at Perma-Fix Northwest in Richland Washington, a 10-metric ton full-scale GeoMelt unit (GeoMelt® Richland) for the treatment of reactive metal wastes. As of September 2019, over 900 55-gallon drums containing a total of around 3,500 lb of sodium with low levels of radioactivity have been treated at GeoMelt ® Richland, with resulting glass monoliths disposed at the Nevada National Security Site (NNSS). A full-scale radiological demonstration melt on an actual EBR-II subassembly has also been performed using the full-scale melter in 2019.

The GeoMelt® technology is a proven radioactive waste treatment technology capable of immobilizing radioactive wastes, including bulk rubble such as drums and other steel vessels usually without pretreatment. Utilizing the GeoMelt® technology to treat reactive metals eliminates pretreatment steps resulting from having to separate the reactive metal from steel containers or jackets as GeoMelt® can easily operate at temperatures sufficient to melt the steel and expose the reactive metal for treatment. Eliminating handling steps of reactive metals is a significant safety advantage since reactive metals are pyrophoric.

The results generated as a part of the 2018-2019 demonstration program are presented in the paper.

INTRODUCTION

The operation and subsequent decommissioning of fast reactor technology programs around the world has resulted in a number of challenges including the treatment and dispositioning of components after sodium draining. Several technologies have been evaluated and some have been implemented to provide a disposition pathway for some of these materials and wastes. Due to the reactivity of the alkali metals used in these reactors and the unique shapes and configurations, a few technologies have proven to be either inefficient, unsafe or require significant preprocessing to enable complete treatment of the residual reactive metals and components.

Battelle Energy Alliance, LLC (BEA) is evaluating Veolia Nuclear Solutions' (VNS) GeoMelt® In-Container Vitrification (ICV)™ technology as a means to safely, reliably and cost effectively convert radioactive reactive metal residues (that contaminate sodium cooled reactor components) into waste forms that comply with existing disposition pathways. Reactive metal wastes at Idaho National Laboratory (INL) require treatment to comply with disposal restrictions.

GeoMelt® ICV™, which is an alternative to other potential treatment approaches, provides a robust approach that chemically converts the reactive metals to an inert oxide while also immobilizing radionuclides in a vitrified waste form with durability equal to or better than vitrified nuclear fuel reprocessing wastes. Due to the GeoMelt® process's unique design, the need to pretreat to allow removal of or access to the reactive metals and safety concerns such as the generation of potentially explosive hydrogen gas can be eliminated or substantially reduced. Additionally, the generation of secondary wastes such as sodium hydroxide that is generated when using water oxidation processes are eliminated when using the GeoMelt® process.

BEA is working with VNS to investigate the applicability of vitrification for the treatment of various reactive metal containing wastes and materials as a component of INL's waste and materials management program. In order to effectively and efficiently address these historical waste and materials inventories, as well as providing disposition paths for future wastes which may arise as the U.S. continues to develop reactor technologies to support national energy needs, it is important to have a variety of disposition options.

BACKGROUND

BEA manages and operates the INL for the U.S. Department of Energy (DOE). INL serves as the US center for advanced nuclear energy research, development, demonstration and deployment. Historically, the INL designed, built, and tested 52 mostly first-of-their-kind reactors. As a result of previous fast reactor operations and subsequent decommissioning activities both on the INL site and elsewhere in the U. S. the INL site has accumulated a variety of wastes and materials that either have been or require dispositioning. The majority of these wastes and materials are located at the Materials & Fuels Complex (MFC) formerly known as Argonne National Laboratory-West (ANL-W). Some of these wastes and materials include the following:

- *Fermi Power Plant Drums* - The Enrico Fermi Atomic Power Plant was a sodium metal-cooled 430 MWth reactor that operated from 1963 to 1972 [1]. After the reactor was permanently shut down in 1972, the primary sodium metal coolant was drained from the nuclear reactor into 208-liter steel barrels. In total, 291,000 liters were drained from the reactor into approximately 1,400 drums. The drums were shipped to ANL-W in the early 1970's for treatment. Subsequently, during the execution of the Experimental Breeder Reactor II (EBR-II) Plant Closure Project (active between 1999 and 2002), the sodium metal was drained from the drums and processed into 73 wt% sodium hydroxide in the ANL-W Sodium Processing Facility (SPF). After the draining process was completed, approximately 1.4 kg of residual sodium metal remained in each of the drums. The drums were sealed with a nitrogen cover gas and placed into storage in cargo containers that hold approximately 80 barrels in each container. The cargo containers were stored within the boundaries of the MFC. These drums met the Resource Conservation and Recovery Act (RCRA) definition of an empty container and are not regulated as hazardous waste; however, the residual elemental sodium has to be deactivated to remove the RCRA reactivity and ignitability characteristics to meet current LLW disposal facility waste acceptance criteria.

  As of September 2019, GeoMelt® ICV™ had successfully treated all the remaining drums (934) with a 10MT scale unit (GeoMelt® Richland), installed at Perma-Fix Northwest, in Richland, WA.

- *Experimental Breeder Reactor Subassemblies* – One of the reactive metal waste streams at INL consists of approximately 53 metric tons of heavy metal (MTHM) consisting of sodium-bonded uranium-based material produced during the development of Liquid Metal Fast Reactor (LMFR) technology. Most of this material is sodium-bonded blanket material, referred to as axial or radial depending on its position in the reactor, from the Experimental Breeder Reactor II (EBR-II) at INL and the Edison Detroit Fermi Reactor. The blanket material is made of depleted uranium (DU) and natural uranium (NU).

  At the time of writing this paper, GeoMelt® ICV™ has melted one un-irradiated blanket subassembly with a 10MT scale unit (GeoMelt® Richland), installed Perma-Fix Northwest, in Richland, WA; results from monolith inspection are in progress but have not yet been finalized.

- *Sodium Components Maintenance Shop (SCMS) CH MLLW Inventory* - Decommissioning of the sodium cooled EBR-II and other various INL projects generated a variety of waste items that range in size and configuration from small paint cans to large EBR-II sodium traps. The waste includes contaminated piping, reactor tools, pumps, valves, vapor traps, and other debris. As of September 30, 2019, the inventory is comprised of 65 items (boxes, drums, and free-standing components) that have a total volume of approximately 14.7 m^3 [2].

- *RSWF Liner Wastes* - The Radioactive Scrap and Waste Facility (RSWF), Building 771, is located at the MFC on the INL site [3]. RSWF was constructed in 1965 to store highly radioactive solid waste (e.g., irradiated subassembly hardware, melt refining crucibles, filters, etc.) generated primarily from EBR-II fuel refining operations performed at the facility currently known as the MFC Fuel Conditioning Facility (FCF). Much of the radioactive material stored at RSWF contains reactive sodium and/or toxic metals, thereby making RSWF subject to the hazardous waste regulations of the state of Idaho Hazardous Waste Management Act (HWMA) and RCRA. As such, RSWF also operates under a HWMA/RCRA mixed waste storage permit.

At the time of writing this paper, approval has been granted via treatability study to process one liner at GeoMelt® Richland; timing of treatment is subject to liner removal operations occurring at the INL site.

- *ZPPR Sodium Plates* -
  The Zero Power Physics Reactor (ZPPR) was a low power reactor used to study the feasibility of fast neutron reactors and nuclear criticality of mixed U/Pu configuration for reprocessing. Full size mock-ups were constructed by loading plates of fissile, fertile, and other typical reactor materials into drawers to simulate reactor composition. The ZPPR was essentially operated at zero power so the material plate inventory is essentially non-irradiated and does not contain fission or activated products. A large majority of these plates are stainless steel-clad sodium and, as such, are candidates for treatment.

The above-mentioned wastes, as well as some additional materials, were identified as potential candidates for demonstration testing to evaluate the feasibility of the GeoMelt® ICV™ process to treat reactive metal containing wastes and materials resulting in a compliant waste form for disposition at the appropriate disposal facility for each waste stream.

In 2016 BEA contracted VNS for the first phase of a multi-year multi-phase demonstration program. Since ending Phases 1 and 2 of this work, additional phases of work have been awarded for exploration of treatment of various reactive metal wastes at the engineering scale, and a 10 MT GeoMelt® ICV™ system has been designed, constructed, commissioned, and operated in Richland, WA to treat actual waste from INL.

The results from the following works are reported within this paper; note that Phases 1 and 2 were reported in a 2018 WM paper (18639) [4], and therefore are not discussed in detail within this paper.

- Demonstration Program
  - Phase 1 – Feasibility of treatment of sodium metal using GeoMelt® technology at the bench and engineering scale.
  - Phase 2 – Maximization of sodium metal loading and treatment using GeoMelt® technology at the engineering scale.
  - Phase 3 – Treatment of simulated ZPPR plates and SCMS waste items using GeoMelt® technology at the engineering scale.
  - Phase 4 – Treatment of sodium-potassium (NaK) alloy, simulated sodium metal-filled heat exchangers, and simulated sodium-bonded EBR subassemblies using GeoMelt® technology at the bench and engineering scale. Full-scale treatment of 1 un-irradiated subassembly.
- Full-Scale Waste Treatment
  - FERMI Drums – Treatment of 934 FERMI drums from the INL site using GeoMelt® technology at full scale (10MT).
  - Experimental Breeder Reactor Subassembly – Treatment of an un-irradiated axial EBR blanket subassembly from the INL site using GeoMelt® technology at full scale (10MT).

GEOMELT® ICV™ BACKGROUND

The GeoMelt® ICV™ process has treated hazardous and radioactive waste, producing more than 26,000 MT of stable vitrified product for government and commercial clients in various countries including Japan, Australia, the United Kingdom, and the United States. GeoMelt® incorporates a range of patented and proprietary vitrification processing technologies that are configured in a variety of ways depending on project specific needs. GeoMelt® transforms hazardous chemical and radioactive waste into a chemically-durable vitreous monolith.

Hazardous organics are destroyed by pyrolysis and heavy metals and radionuclides are generally immobilized within a glass matrix where they are not preferentially leached into the environment. Although limited reactive metals such as magnesium have been successfully processed using the GeoMelt® process, up until 2016, volatile heavy metals had not been evaluated.

DEMONSTRATION PROGRAM - PHASE 1

BEA selected the Fermi Reactor Drums to be the focus for the Phase 1 Demonstration Program. For these drums to be disposed of, it was necessary to fully react the sodium to remove the D001 (ignitability) and D003 (reactivity) waste codes thereby allowing disposal as an LLW waste. Objectives for the Phase 1 demonstration campaign were to:

1. Vitrify simulated drums containing elemental sodium using existing GeoMelt® ICV™ equipment and techniques.
2. Confirm that the resultant GeoMelt® vitrified product does not contain elemental sodium as determined by visual inspection, field testing, and by laboratory analysis for reactivity and ignitability.
3. Verify that the scientific and engineering understanding of the waste processing is supported by empirical data collected from multiple demonstrations.
4. Obtain data and experience necessary to recommend/plan the next phase of work for sodium drum treatment.

In order to accomplish these objectives a demonstration program was outlined which included four different tasks. These tasks included 1) Initial Desktop Study, 2) Crucible Melts, 3) Bench-Scale Melt and 4) Engineering-scale Melts.

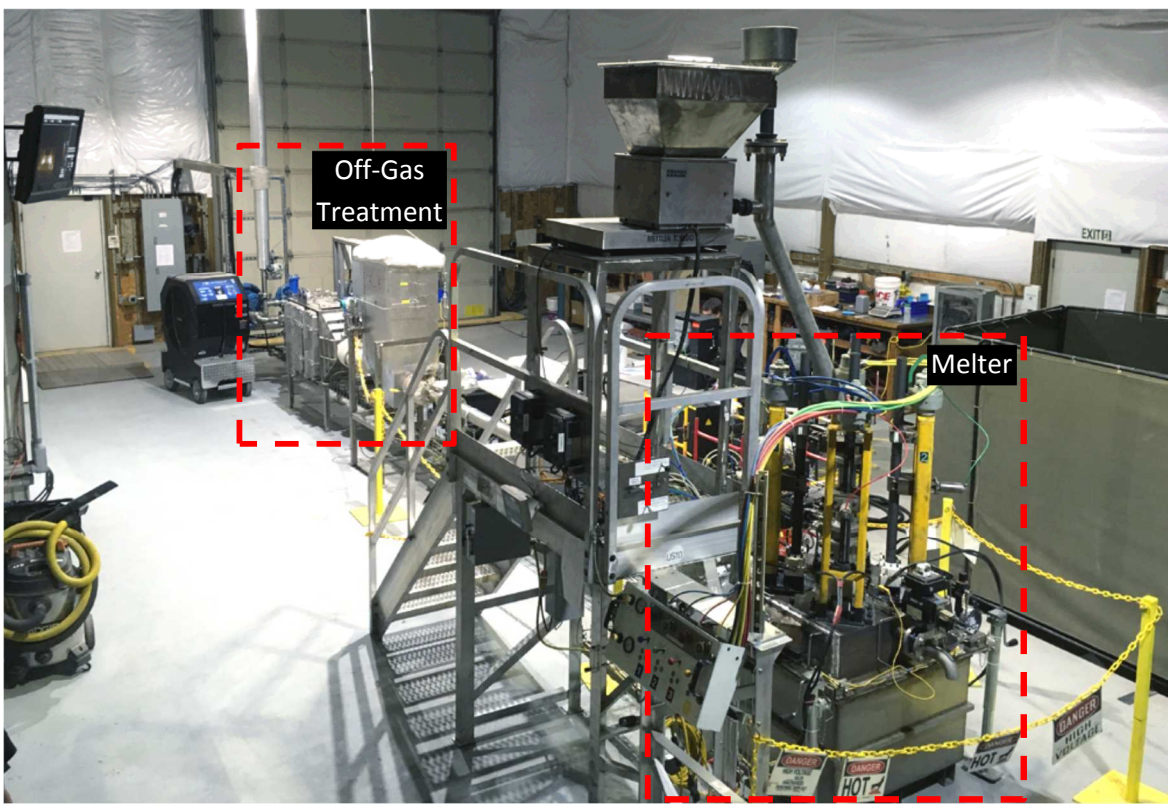

Fig. 1. Engineering Scale Melter System.

The engineering-scale melt system used for this phase, along with subsequent phases of the work, is shown in the Figure 1. The engineering-scale unit uses a GeoMelt® ICV™ melt container, and an off-gas system suited for particulate removal.

The activities performed in the crucible, bench-scale, and engineering scale demonstrations showed that the GeoMelt® ICV™ process completely oxidizes sodium metal, removing the ignitable and reactive characteristics in a passive and safe manner. The testing program demonstrated the ability to melt the simulated drums allowing exposure of all the sodium metal such that it could react and be oxidized. Additionally, the demonstration melts identified no difference in capability to react the sodium metal based on the configuration of the simulated drums (i.e. intact, cut or compacted). A review of the NNSS WAC against the GeoMelt ICV waste form identified no issues for disposal. No by-product secondary wastes such as sodium hydroxide are generated as a result of the process.

DEMONSTRATION PROGRAM - PHASE 2

Following a successful Phase 1 Program, BEA contracted VNS to further demonstrate deactivation of elemental sodium by GeoMelt® ICV™ at a higher waste loading than previously demonstrated at engineering scale. The higher waste loading allowed optimization of the glass chemistry and reflect a waste loading to accommodate economical full-scale treatment of Fermi drums. In addition, Phase 2 demonstration included sodium waste loading relevant to the treatment of other elemental sodium-contaminated equipment at INL. The objectives of this phase of work included calculating an optimal elemental sodium loading that would maximize the amount of sodium treated per batch while maintaining a melt temperature sufficient to melt the carbon steel drums throughout the duration of the melt (increased sodium concentration in the melt serves to reduce the melt temperature). The calculated waste loading was then validated by performing an engineering-scale melt to demonstrate ability to safely passivate sodium.

The results of the modelling and calculations predicted that vitrification as a process for oxidizing elemental sodium at 7.89 wt% is feasible using the GeoMelt® process and native soil as a glass former. Demonstration testing using engineering-scale equipment confirmed model predictions for sodium loading by completely converting elemental sodium to an oxide that is incorporated into the glass waste form. Waste form testing for leachability and ignitability plus a review of the NNSS WAC identified no issues for disposal of the GeoMelt®-generated waste form.

DEMONSTRATION PROGRAM - PHASE 3

Following a successful Phase 2 Program, BEA contracted VNS to further demonstrate deactivation of simulated sodium-bearing waste items which were representative of other items in their inventory by GeoMelt® ICV™. The objectives of this phase of work were as follows.

- Demonstrate the capability for GeoMelt® to remediate bulk quantities of simulated ZPPR plates
- Demonstrate the capability for GeoMelt® to remediate a selected representative item from the SCMS inventory
- Perform an initial study to evaluate the feasibility of treating sodium-potassium (NaK) alloy and lithium hydride (LiH)-contaminated items.

Phase 3 Engineering-Scale ZPPR Sodium Plate Melt Demonstration

The purpose of the Phase 3 ZPPR sodium plate melts were to validate ability for GeoMelt® to treat simulated ZPPR sodium plates in successively higher waste loading fractions. Simulated stainless steel ZPPR plates were constructed of 16-gauge 304 L stainless steel, were 20 cm by 5 cm by 1.25 cm, and were each filled with an average of 80 grams of sodium metal.

The first melt consisted of treatment of 12 simulated ZPPR sodium plates loaded into a total of 106 kg of glass forming materials and was considered as a preliminary trial; the resulting sodium loading was near 1 wt%. The second melt consisted of treatment of 48 simulated ZPPR sodium plates loaded into a total of 106 kg of glass forming materials; the resulting sodium loading was near 4 wt%.

Figure 2 shows the loading configuration utilized for the ZPPR sodium plates; for the first melt, 2 layers of plates were used (with glass forming materials between each layer), while for the second, 8 layers were used. Fourteen hours of melting was required to melt the staged material for each melt. Melting operations were typical and uneventful with no observable effect from the sodium being oxidized.

Fig. 2. Phase 3 ZPPR Sodium Plate Engineering-Scale Melt Preparation.

Figure 3 shows the resulting glass monolith and steel layer from the 48 ZPPR sodium plate melt.

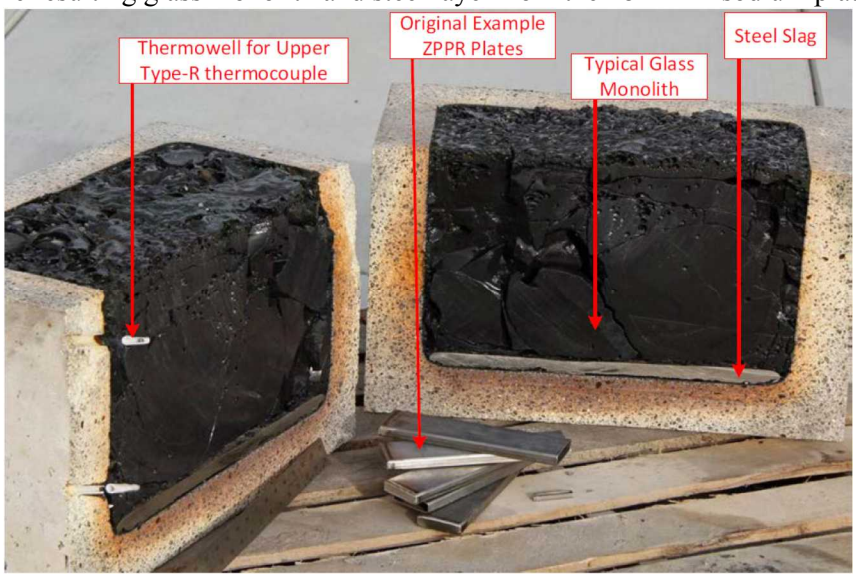

Fig. 3. Phase 3 48-Plate ZPPR Plate Engineering-Scale Monolith.

Phase 3 Engineering-Scale SCMS Melt Demonstration

The purpose of the Phase 3 SCMS melt was to validate ability for GeoMelt® to treat a simulated SCMS item (steel cylindrical waste container full of sodium metal).

The simulated SCMS item was fabricated from a 16.1 cm long, 10 cm in diameter 304 L stainless steel Sch 10 pipe with a flat bottom and flanged top. The simulated item weighed 11.3 kg and contained 1.5 liters (1.4 kg) of sodium metal.

Figure 4 shows the actual SCMS item next to the fabricated simulated SCMS item.

Fig. 4. Phase 3 Real (left) and simulated (right) SCMS item.

The simulated SCMS item was loaded into a GeoMelt® ICV™ engineering scale melt box along with 79 kg of glass forming materials; the total sodium loading was around 1.5 wt%. Ten hours of melting was required to melt the staged material. Melting did not produce any unexpected behavior, and the resulting monolith is as shown in Figure 5. Note that the picture to the right shows the steel layer which had settled to the bottom of the glass during melting and subsequently separated from the monolith during post-melt cutting; this is typical as the density of steel approximately three times that of glass.

Fig. 5. Phase 3 SCMS Item Engineering-Scale Monolith.

Phase 3 NaK and LiH Treatment Application Study

As part of supporting follow-on work, a literature survey was performed to examine the relevant chemistry and thermodynamics involved in extending the GeoMelt® process to encompass treatment of liquid NaK alloy and LiH pieces. This literature survey was followed by experimental trials which probed reaction kinetics, the effect of soil moisture, the hazards unique to each system and safe-handling techniques.

The literature survey showed that deactivation of both LiH and NaK were feasible, from a thermodynamic perspective, using GeoMelt®.

The results of the laboratory testing were 1) NaK is stable in air at ambient temperatures and LiH is stable in air at temperatures up to 100°C, 2) NaK is stable even agitated at glass former moisture contents up to 4.3 wt%, ignites with agitation in glass former with moisture between 4.3 to 8.3 wt%, and auto ignites without agitation in glass former above 8.3 wt% moisture, and 3) NaK and LiH heated with glass former reacts, melts, and oxidizes as temperature increases.

Based on the findings of the literature review and the testing, it was concluded that, with proper handling, NaK can be disposed of with roughly the same level of safety that Na can. LiH also is conducive to the GeoMelt® process, however it also introduces unique fire and near-term toxicity issues not seen with Na or NaK.

Phase 3 Demonstration Testing Program Results

During Phase 3 activities, demonstration testing using engineering-scale equipment confirmed the ability to completely convert elemental sodium to an oxide that is incorporated into the glass waste form for ZPPR plate and SCMS item simulated wastes.

For both simulated wastes, post-melt field evaluations showed there was no unprocessed sodium metal as indicated by spritzing and complete emersion in a water bath of the resulting glass and metal pieces, no free liquids, and no fine loose particles. Samples of the resulting product were subjected to EPA Method 1311 TCLP leach testing and EPA Method 1030 ignitability testing. The TCLP sample was analyzed for eight metals of concern and all were reported at less than the Regulatory Limit. Samples submitted for the Ignitability Test were reported as “no Burn” indicating that the sample did not ignite. Based on these results, there were no issues identified for disposal of the GeoMelt®-generated waste form.

Additional research and small-scale testing of LiH and NaK showed, although more precautions should be taken over handling sodium metal due to increased reactivity and potential formation of a superoxide with NaK, and the potential to generate flammable hydrogen and toxic lithium fumes with LiH, there is no anticipated issue for treatment using GeoMelt® technology.

DEMONSTRATION PROGRAM - PHASE 4

Following a successful Phase 3 Program, BEA contracted VNS to further demonstrate deactivation of simulated sodium-bearing waste items which were representative of other sodium contaminated materials and unique mixed waste streams in their inventory by GeoMelt® ICV™. The objectives of this phase of work were as follows.

- Demonstrate the capability for GeoMelt® to treat a simulated sodium-bonded blanket material subassembly at the engineering scale (uranium and sodium metal).
- Demonstrate the capability for GeoMelt® to treat a simulated difficult shape item containing sodium metal (a heat exchanger) at the engineering scale.
- Demonstrate the capability for GeoMelt® to treat a NaK at the bench and engineering scale.

Phase 4 Engineering-Scale Blanket Subassembly Melt Demonstration

The purpose of the Phase 4 Blanket Subassembly was to validate the ability of GeoMelt® to treat a simulated EBR subassembly, which contains uranium metal bonded to stainless steel cladding via sodium metal. The simulated subassembly contained sodium metal and misch metal, packed within a hexagonal 316 stainless-steel assembly. Misch metal is a natural blend of rare earth elements (~70% wt cerium, 30 wt% lanthanum, as well as trace neodymium and praseodymium) intended to mimic uranium metal and was utilized due to its close density to uranium and pyrophoric nature.

The simulated subassembly was 30 cm long, and 6 cm wide with a hexagonal shape. The subassembly was loaded with 2.4 kg of misch metal, 56 grams of sodium, and weighed a total of 3.3 kg. Figure 6 shows the simulated subassembly loaded with misch metal and sodium.

The simulated subassembly item was loaded into a GeoMelt® ICV™ engineering scale melt box along with 120 kg of glass forming materials; the total sodium loading was around 1.5 wt%.

Fig. 6. Phase 4 Simulated Subassembly

Thirteen hours of melting was required to melt the staged material. Melting did not produce any unexpected behavior. Minor flaring was observed from the center of the melt several times during processing and was due to interaction of glass with the simulated subassembly contents; flaring did not present operational difficulties. Figure 7 shows the melt surface, as recorded via infrared camera at 5.5 hours, where flaring was noticed.

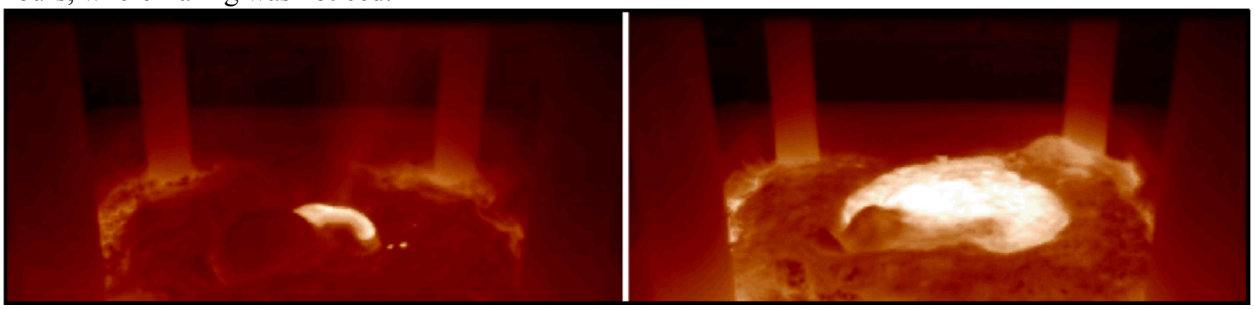

Fig. 7. Phase 4 Melt Surface at 5.5 hours

The resulting glass monolith was very similar in nature to the previous tests, with a metal ingot being formed, sinking to the bottom, and solidifying.

Phase 4 Engineering-Scale Heat Exchanger Melt Demonstration

The purpose of the Phase 4 Heat Exchanger treatment was to validate ability for GeoMelt® to process a difficult shape items containing sodium.

The simulated waste was that of a 60-cm x 7.6-cm diameter stainless steel shell and tube heat exchanger filled with elemental sodium. The heat exchanger was modified by cutting it in half resulting in two 30-cm long sections which would fit into the engineering- scale refractory.

Fig. 8. Phase 4 Simulated Heat Exchanger Segment

Approximately thirteen hours of melting was required to melt the staged material. Melting did not produce any unexpected behavior. Figure 9 shows the resulting (cut) monolith from the melt; note that M is the iron from the melted exchanger, R and C are the Type R and Type C thermocouples, respectively which are used to monitor melt temperatures.

Fig. 9. Phase 4 Heat Exchanger Monolith (cutaway).

Phase 4 Engineering-Scale NaK Melt Demonstrations

The purpose of the Phase 4 NaK treatment was to validate the ability to process NaK in configurations which are applicable to GeoMelt®. As a scoping exercise, NaK was first treated in bench scale melters at two different waste loadings. After treatment at the bench scale, and engineering scale melt was performed with a simulated SCMS item containing NaK.

The bench scale melt configurations consisted of loading 25.4 cm long by 7.6 cm wide by 10 cm deep cast-refractory melters with NaK and glass forming materials in a layered fashion. These melters were then joule-heated to the desired treatment temperature, cooled, and the monolith cooled and sectioned for testing. The first bench scale melt contained 1.9 wt% NaK, while the second contained 3.4 wt%. Successful treatment was observed for both melts, as evidence by no reactivity of the resulting monoliths.

Fig. 10. Phase 4 Bench Scale NaK Melt Monoliths

Figure 10 shows the halved monoliths for both the first (left) and second (right) bench scale melts. Successful treatment at the bench scale was used as a "go" decision for treatment of NaK at the engineering-scale.

An engineering-scale treatment to validate ability for GeoMelt® to process NaK was performed as part of this work. The waste simulated and treated in an engineering-scale melt was a simulated scaled-down SCMS item which contained NaK within a can that has been overpacked in soda ash. The simulated waste item was a 1L can (filled with 1 L of NaK) overpacked into a 2.5 L can; the resulting annulus between cans was filled with soda ash. The NaK-containing can was covered with a lid and vented. Figure 11 shows the inner can once filled with NaK; note that a slight surface oxidation (likely due to some residual air in the system) was observed although the can was filled in an argon atmosphere.

Fig. 11. Phase 4 Simulated SCMS Item Containing 1L of NaK

The simulated SCMS item weighed a total of 5.2 kg and was loaded into a GeoMelt® ICV™ engineering scale melt box along with around 100 kg of glass forming materials; the total sodium loading was around 0.8 wt%. Approximately 11 hours of melting was required to melt the staged material. An increase in bubbling from the melt and plenum temperature was observed around 3 hours of runtime. The increase in bubbling is normal and likely due to boiling of the NaK from heat produced by reaction with the glass. Power was managed accordingly to reduce the bubbling and manage system temperatures, and the melt continued without any issues. The resulting monolith was similar to the previous melts, with the exception of the metal having formed small iron beads rather than a single piece of iron. This phenomenon is not uncommon for lower wt% metal melts, as they do not have enough mass to counteract glass convection, coalesce, and settle to the bottom.

Phase 4 Demonstration Testing Program Results

During Phase 4 activities, demonstration testing using engineering-scale equipment confirmed the ability to completely convert elemental sodium and NaK to an oxide that is incorporated into the glass waste form for a simulated EBR subassembly filled with sodium metal and misch metal, a simulated heat exchanger filled with sodium metal, and a simulated SCMS item filled with NaK.

For all simulated wastes tested, post-melt field evaluations showed there was no unprocessed pyrophoric (Na, NaK, Misch metal) metal as indicated by spritzing and complete emersion in a water bath of the resulting glass and metal pieces, no free liquids, and no fine loose particles. Samples of the resulting product were subjected to EPA Method 1311 TCLP leach testing and EPA Method 1030 ignitability testing. The TCLP sample was analyzed for eight metals of concern and all were reported at less than the Regulatory Limit. Samples submitted for the Ignitability Test were reported as "no Burn" indicating that the sample did not ignite. Based on these results, there were no issues identified for disposal of the GeoMelt®-generated waste form.

FULL SCALE WASTE TREATMENT

In 2018, supported by the results of the phased demonstration testing, a 10MT GeoMelt® ICV™ system (GeoMelt® Richland) was designed, constructed, and commissioned for treatment of mixed (reactive metal) waste at Perma-Fix Northwest, located in Richland, WA. Figure 12 shows the GeoMelt® Richland unit; not shown is the AG-1 HEPA filtration system and blower (located downstream of the off-gas treatment shown in the figure) used to maintain off-gas flow and system confinement.

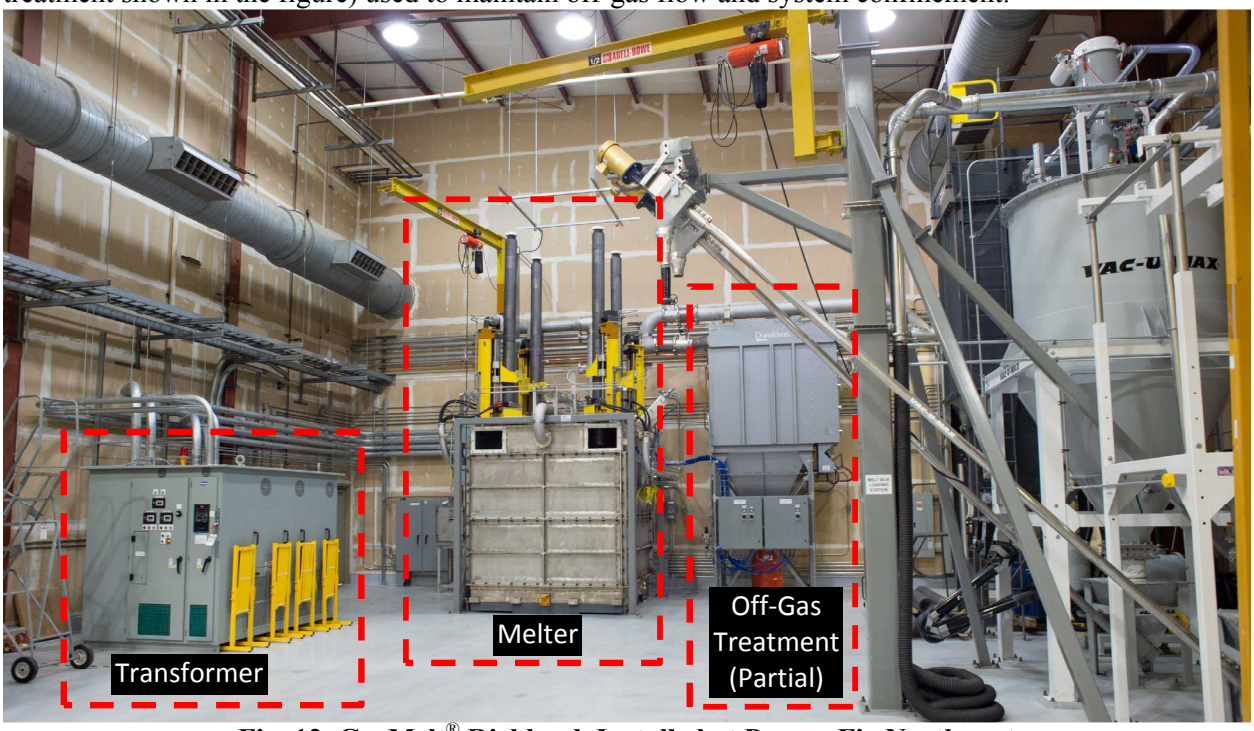

Fig. 12. GeoMelt® Richland, Installed at Perma-Fix Northwest

Under treatability studies, this facility has been used to treat 934 FERMI drums, one unirradiated EBR subassembly, and can handle a multitude of additional waste streams with reactive metals, such as ZPPR plates, SCMS items, etc. This system is capable of processing upwards of 10 MT of glass in a single batch and is equipped with an off-gas system designed for particulate removal. The following sections discuss the treatment activities that have occurred with this commissioned system.

FERMI Drum Treatment

In 2018, VFS received a contract from INL for the treatment of the remaining FERMI drums at GeoMelt® Richland. Treatment of the remaining 934 drums occurred over 16 melts and a period of 9 months. At the time of writing this paper, all monoliths produced from the treatment of these drums have been packed and shipped off-site for disposal at NNSS.

The treatment process for the drums involved crushing the drums in a super compactor to less than 8 cm thick, and manually loading the drums in a layered fashion with glass former within the melt box; a maximum of 65 drums were treated per melt during this study. Figure 12 shows 80–90 crushed FERMI drums awaiting loading into the melt box.

Fig. 13. Crushed FERMI Drums

Figure 14 the arrangement of drums within the melt box (left is a model showing the general arrangement, right is actual).

Fig. 14. Melt Box Drum Arrangement

After box loading, the box was moved underneath the melt hood, bolted to the system, and melted using joule-heating. Typical melt times were on the order of 48 to 60 hours, with melts producing glass monolith with a weight of at or below 10 MT. After approximately 1 week of cooling the glass monoliths were manually removed from their sand refractory via vacuum system and rigging, then packaged for transportation and disposal in an IP-1 bag.

Figure 15 shows a monolith produced from FERMI drum treatment; note that the “crust” around the outside of the glass is due to refractory silica sand sintering to the glass product which does not affect the glass integrity.

Fig. 15. Monolith Produced During FERMI Drum Treatment

EBR Subassembly Treatment

In 2019 (as part of phase 4 work), VFS received a contract from INL for the treatment of one EBR Blanket Subassembly at GeoMelt® Richland. At the time of writing this paper, the subassembly has been pre-treated and melted with no observed upsets; however, the monolith has not undergone final inspections and sampling. Results from this testing will be reported at a later date.

CONCLUSIONS

In the works presented in this paper, VNS demonstrated treatment of elemental sodium and NaK metal using GeoMelt® ICV™, a thermal method of oxidizing the sodium metal within a silica rich environment. The work performed as a part of this program has demonstrated that the GeoMelt® process is an effective method to completely oxidize elemental sodium and NaK passively and safely. The GeoMelt® process is sufficiently robust to allow treatment of elemental sodium and NaK by melting the metal containment surrounding the elemental sodium thereby exposing the sodium to the melt where it is then oxidized. This feature significantly reduces pretreatment requirements and worker exposure. In contrast with other sodium treatment processes, no hydrogen is generated during the GeoMelt® process thereby eliminating any explosive hazard. Additionally, common secondary wastes such as sodium hydroxide are not produced during GeoMelt® processing.

Success from the demonstration melts at the crucible, bench, and engineering scale led to the design and construction, and operation of a 10 MT GeoMelt® system at Perma-Fix Northwest in Richland, WA (GeoMelt® Richland). GeoMelt® Richland has been utilized to successfully treat the entire FERMI drum inventory (934 drums); the resulting 16 glass monoliths generated during treatment have been accepted for disposal at NNSS. Treatment of an un-irradiated EBR subassembly has occurred at GeoMelt® Richland; results will be reported as part of follow-on work.

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