INL/RPT-22-66033

Removal of Bond Sodium from Full-Length Unirradiated Fermi-1 Blanket Elements and Assembly via Melt-Drain-Evaporate Process

February 2022

S. D. Herrmann, B. D. Preussner,
R. C. Campbell, T. DiSanto,
J. A. Charboneau, and I. M. Hobbs

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

DISCLAIMER

This information was prepared as an account of work sponsored by an agency of the U.S. Government. Neither the U.S. Government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness, of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. References herein to any specific commercial product, process, or service by trade name, trade mark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the U.S. Government or any agency thereof.

INL/RPT-22-66033

Removal of Bond Sodium from Full-Length Unirradiated Fermi-1 Blanket Elements and Assembly via Melt-Drain-Evaporate Process

S. D. Herrmann, B. D. Preussner,
R. C. Campbell, T. DiSanto,
J. A. Charboneau, and I. M. Hobbs

February 2022

Idaho National Laboratory
Pyrochemistry and Molten Salt Systems
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Office of Environmental Management
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

SUMMARY

Equipment was designed, fabricated, tested, and operated in an inert atmosphere radiological glovebox at Idaho National Laboratory to demonstrate the removal of bond sodium from full-length unirradiated Fermi-1 radial blanket elements and an entire radial blanket assembly using a Melt-Drain-Evaporate process. A series of three runs was performed with individual and multiple radial Fermi-1 blanket elements, and a fourth run was conducted with an entire Fermi-1 radial blanket assembly. After each run, the depleted uranium alloy slugs in every element slid out of its cladding, mechanically exhibiting the effectual absence of bond sodium. Further qualitative and quantitative analyses of the treated Fermi-1 material revealed the substantive, if not complete, absence of sodium metal in blanket element components. Quantitatively, no detectable sodium metal (<7 μg) was found on the surfaces of multiple depleted uranium alloy slugs after removal from its cladding. Detectable sodium metal, ranging from 14 to 30 μg, was found on the surfaces of one separated column of slugs and two separated full-length cladding segments. Each element originally contained ~25 g of bond sodium, resulting in quantitative sodium metal removal efficiencies of ≥99.9998%. The remaining separated uranium alloy slugs and cladding segments from the four runs were immersed in alcohol for qualitative analysis, identifying the predominant absence of sodium reactivity on the balance of treated Fermi-1 blanket material. The results of this demonstration substantiate a path forward for treatment and disposal of 34 metric tons heavy metal of irradiated sodium-bonded Fermi-1 blanket material currently stored at Idaho National Laboratory.

CONTENTS

FIGURES

TABLES

ACRONYMS

ARL	Analytical Research Laboratory
DOE	U.S. Department of Energy
EDL	Engineering Development Laboratory
FASB	Fuels and Applied Science Building
FCF	Fuel Conditioning Facility
ICP-OES	Inductively Coupled Plasma-Optical Emission Spectroscopy
INL	Idaho National Laboratory
MEDE	Melt-Drain-Evaporate
MTHM	Metric Tons Heavy Metal
OCS	Operating Command Station
PLC	Programmable Logic Controller
Q-GasMS	Quadrupole Gas Mass Spectroscopy
TE	Temperature Element

Removal of Bond Sodium from Full-Length Unirradiated Fermi-1 Blanket Elements and Assembly via Melt-Drain-Evaporate Process

1. OBJECTIVE

The objective of this work was to design, fabricate, test, and operate equipment in an inert atmosphere radiological glovebox at Idaho National Laboratory (INL) to demonstrate the removal of bond sodium from full-length unirradiated Fermi-1 blanket elements and an entire blanket assembly using a Melt-Drain-Evaporate (MEDE) process. Quantitative and qualitative analyses were performed to characterize the extent of sodium removal from the blanket material. This work was directly funded by the U.S. Department of Energy, Office of Environmental Management.

2. BACKGROUND

The U.S. Department of Energy (DOE) manages 34 metric tons of sodium-bonded blanket material from the decommissioned Fermi-1 reactor. This material is currently stored at INL, awaiting removal from the state of Idaho by 2035, per a 1995 Settlement Agreement. The Fermi-1 blanket material is not suitable for disposal in its current configuration due to the reactive characteristic of its bond sodium. A technical feasibility study to remove the bond sodium from the Fermi-1 blanket material via a melt-drain-evaporate-carbonate technique was completed in 2003 by researchers at Argonne National Laboratory-West (prior to becoming INL's Materials and Fuels Complex in 2005). [1] The study included a demonstration of bond-sodium removal from cut segments of unirradiated Fermi-1 blanket elements. The study also included a life-cycle cost estimate, which proposed treatment of the Fermi-1 blanket material as full-length assemblies. [2] However, bond-sodium removal from full-length assemblies of Fermi-1 blanket materials was not demonstrated in the 2003 study. Demonstration of bond-sodium removal from full-length Fermi-1 blanket material, including a radial blanket assembly, was completed as part of the current study, the results of which are reported herein.

2.1 Fermi-1 Blanket Material Characteristics

According to available records there are 406 axial (see Figure 1) and 559 radial (see Figure 2) irradiated Fermi-1 blanket assemblies in storage at INL, totaling 34 metric tons heavy metal (MTHM). The axial blanket assemblies include upper and lower sections that were separated from a midsection that contained the fuel. The axial blanket assemblies are comprised of 16 elements within a square stainless-steel duct. The radial blanket assemblies, devoid of a fueled section, are intact and comprised of 25 elements within a similar duct configuration. The lengths and masses of the assemblies vary depending on whether they are inner or outer radial blankets, upper or lower axial blankets, or whether inlet flow nozzle hardware was removed prior to shipment to INL. Nominal characteristics of the axial and radial Fermi-1 blanket assemblies are listed in Table 1. The axial and radial blanket elements contain solid cylinders, or slugs, of depleted uranium—3 wt% molybdenum metal alloy within stainless-steel cladding. The slugs are bonded to the cladding with sodium metal filling the anulus between the slugs and cladding and extending a few inches above the slug column. Above the head of sodium is a plenum region, or void space, of a few to several inches. The slug lengths are 14 inches in each of the axial blanket elements, whereas the radial blanket elements are comprised of four 14-inch-long slugs and one 5.75-inch-long slug for a total slug column height of 61.75 inches. The nominal characteristics of the axial and radial Fermi-1 blanket elements are summarized in Table 2.

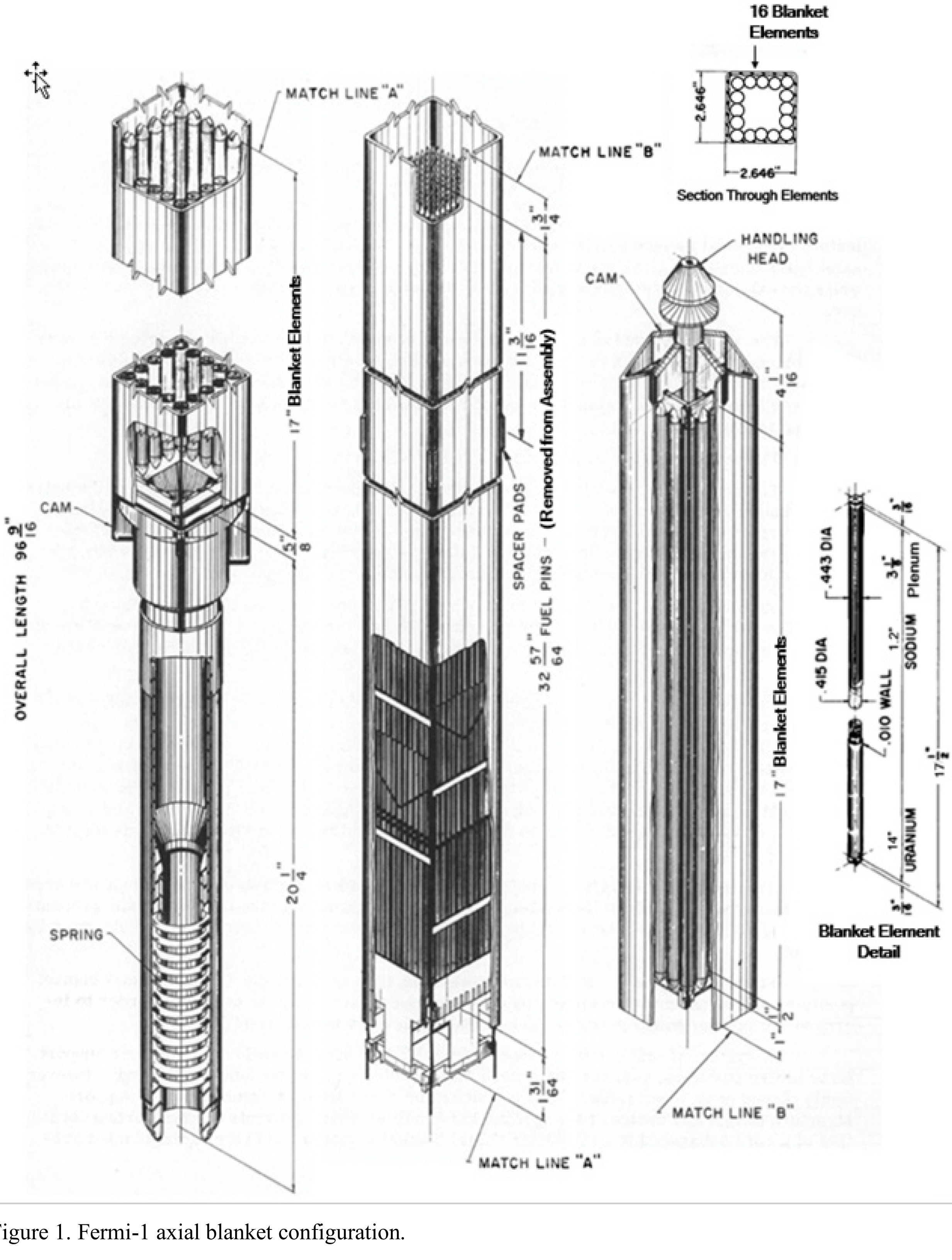

Figure 1. Fermi-1 axial blanket configuration.

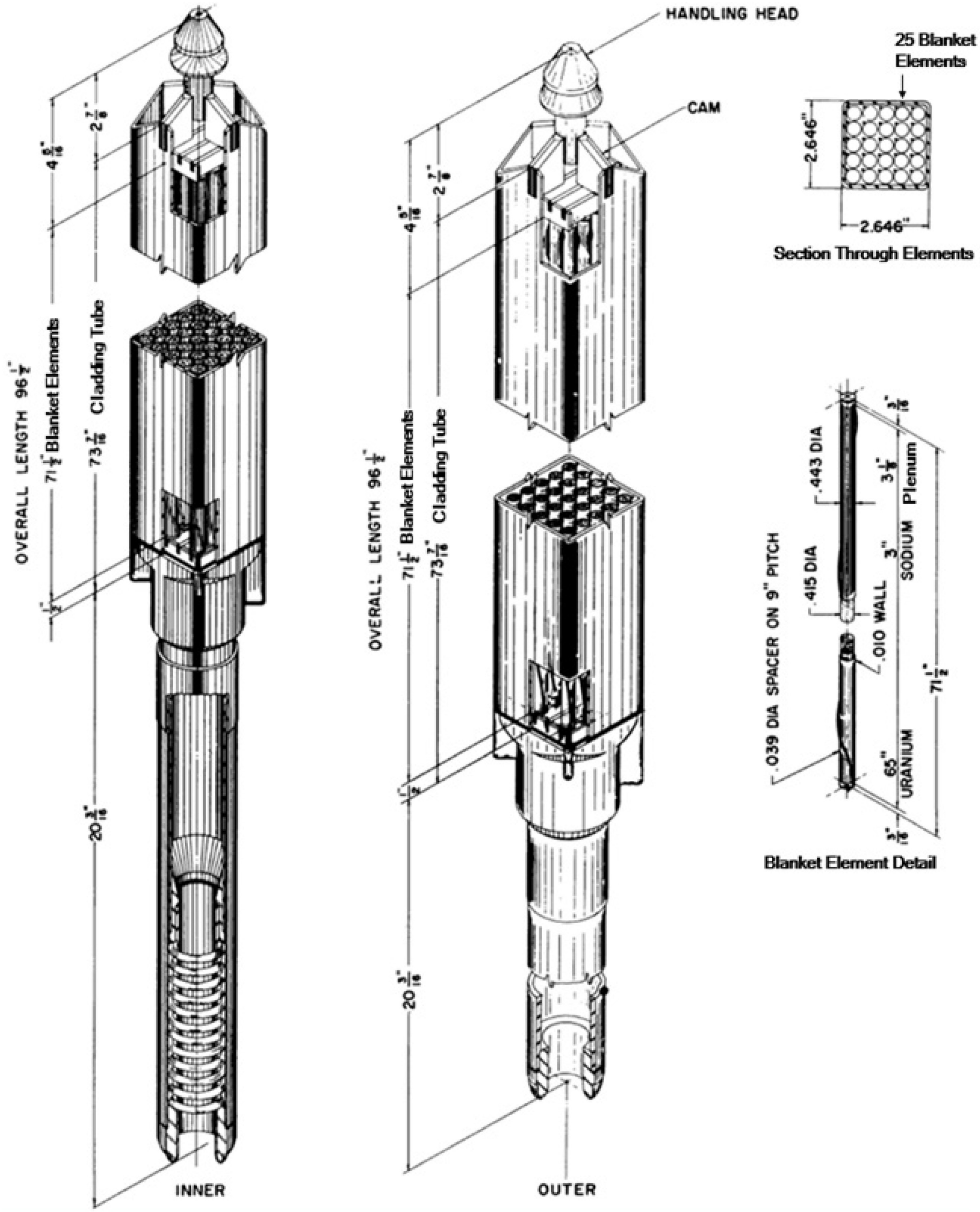

Figure 2. Inner and outer radial blanket assemblies used in the Fermi-1 reactor.

Table 1. Nominal characteristics of axial and radial Fermi-1 blanket assemblies.

Characteristic		Axial	Radial
Number of elements per assembly		16	25
Assembly hardware material		304SS	304SS
Square duct dimensions, in.		2.646	2.646
Duct wall thickness, in.		0.096	0.096
Assembly length, in.	with nozzle	40.2 or 41.8 (lower section)	96.5 or 99.5
	without nozzle	22.73 (upper section)	76.5
Assembly weight, g	with nozzle	15,053 (lower section)	75,015 (outer blanket)
	without nozzle	11,495 (lower section) 12,063 (upper section)	72,500 (outer blanket) 75,913 (inner blanket)

Table 2. Nominal characteristics of axial and radial Fermi-1 blanket elements.

Characteristic	Axial	Radial
Cladding material	304SS	304SS
Cladding outer diameter, in.	0.443	0.443
Cladding wall thickness, in.	0.010	0.010
Radial annulus thickness, in.	0.014	0.014
Slug diameter, in.	0.395	0.395
Slug composition (wt %)	U-3Mo	U-3Mo
Slug uranium enrichment	0.35 %	0.35 %
Slug column height, in.	14	61.75
Total uranium mass per element, g	501	2211
Sodium height above slug column, in.	1.2	2.5
Sodium mass per element, g	5.53–6.22	20.7–23.17
Blanket element height, in.	17.5	71.5
Blanket element mass, g	569	2458
Blanket element spacer wire diameter / helical pitch, in.	none	0.039/9

3. EXPERIMENTAL ASPECTS

3.1 Approach

The general approach for this study began with the design, fabrication, and procurement of equipment to facilitate the removal of bond sodium from full-length unirradiated Fermi-1 radial blanket material. The equipment was then assembled and tested with a non-radiological, sodium-free, stainless-steel mock assembly on the floor in INL’s Engineering Development Laboratory (EDL). Following fit and function checks, operation of the equipment produced a centerline temperature profile of the mockup assembly vis-à-vis the furnace control temperatures and enabled programmed operating recipe development. Testing of cutting equipment was also performed in EDL. The MEDE and assembly-cutting equipment were then installed inside a new multiprogrammatic use argon-atmosphere glovebox (i.e., the pyrochemistry glovebox), at INL’s Fuels and Applied Science Building (FASB). After verifying proper operation of the MEDE system in the glovebox, it was sealed for radiological use.

One intact unirradiated Fermi-1 radial blanket assembly and 15 loose radial blanket elements were transferred into the glovebox. A series of three runs was performed with the loose radial blanket elements. The first run consisted of a single element that was cut open at both ends using a tubing cutter and subjected to MEDE operating conditions of elevated temperature (~ 650°C) and reduced pressure (below 200 mTorr). The second run consisted of a bundle of seven elements, each of which was cut open at both ends. The third run consisted of a bundle of seven elements, three of which were only opened on the plenum end and four on both ends. A fourth run was performed with an intact radial blanket assembly containing 25 elements. The assembly was cut with a chop saw to remove the nozzle piece from the bottom of the assembly and the lifting fixture from the top of the assembly without breaching the elements. The chop saw was then used to cut the assembly through the plenum region of all 25 elements, after which the assembly with only a single opening of the elements was subjected to MEDE operating conditions. The blanket materials were positioned vertically with the plenum end down in each run.

The depleted uranium alloy slugs from every treated element in all four MEDE runs were separated from the respective cladding using a tubing cutter and sliding the slugs out of the cladding. The slugs and cladding were then subjected to quantitative or qualitative analysis for residual sodium. Quantitative analysis involved separately sealing entire columns of slugs and associated cladding from select elements in transfer containers and subjecting each container separately to analysis at INL's Analytical Research Laboratory (ARL). Specifically, a transfer container was flooded with water, contacting all surfaces of an entire column of blanket slugs or its associated cladding. A sample of the gas above the water mark was collected and analyzed for hydrogen, which would form from any residual sodium metal on the slugs or cladding reacting with water. The water solution within each container was analyzed for total sodium. All the remaining slugs and cladding pieces in the glovebox were qualitatively analyzed for residual sodium by immersing every slug and cladding segment in alcohol with videography and observing the presence or absence of hydrogen gas formation from reaction of sodium metal with alcohol.

A matrix of test conditions is summarized in Table 3. The following subsections describe the processing equipment, Fermi-1 blanket material, and the sample analysis technique in more detail. Subsequent sections describe and discuss the operations and results of the equipment testing with mock materials and the MEDE demonstration with unirradiated full-length Fermi-1 blanket material.

Table 3. Test matrix for removal of bond sodium from full-length unirradiated Fermi-1 blanket material.

Run	Loading	Number of elements	Element cutting		Quantitative analysis	Qualitative analysis
			Bottom end	Plenum end		
1	Loose element	One	open	open	Column of slugs; empty cladding	Not applicable
2	Bundle of elements	Seven	open	open	No samples taken	Slugs and cladding pieces from seven elements
3	Bundle of elements	Seven	three closed; four open	open	Center element column of slugs (one end cut); perimeter element column of slugs (both ends cut)	Slugs from five elements; cladding pieces from seven elements
4	Intact assembly	25	closed	open	Center element column of slugs; empty cladding from center element	Slugs and cladding pieces from 24 elements

3.2 Equipment

The MEDE equipment consisted primarily of a sectional retort that was enveloped with a resistance heated furnace and connected to a vacuum system. The furnace and vacuum system were operated with a programmable logic controller (PLC). A sectional view of the MEDE retort is shown in Figure 3. A model view of the MEDE retort and furnace inside a new glovebox is shown in Figure 4.

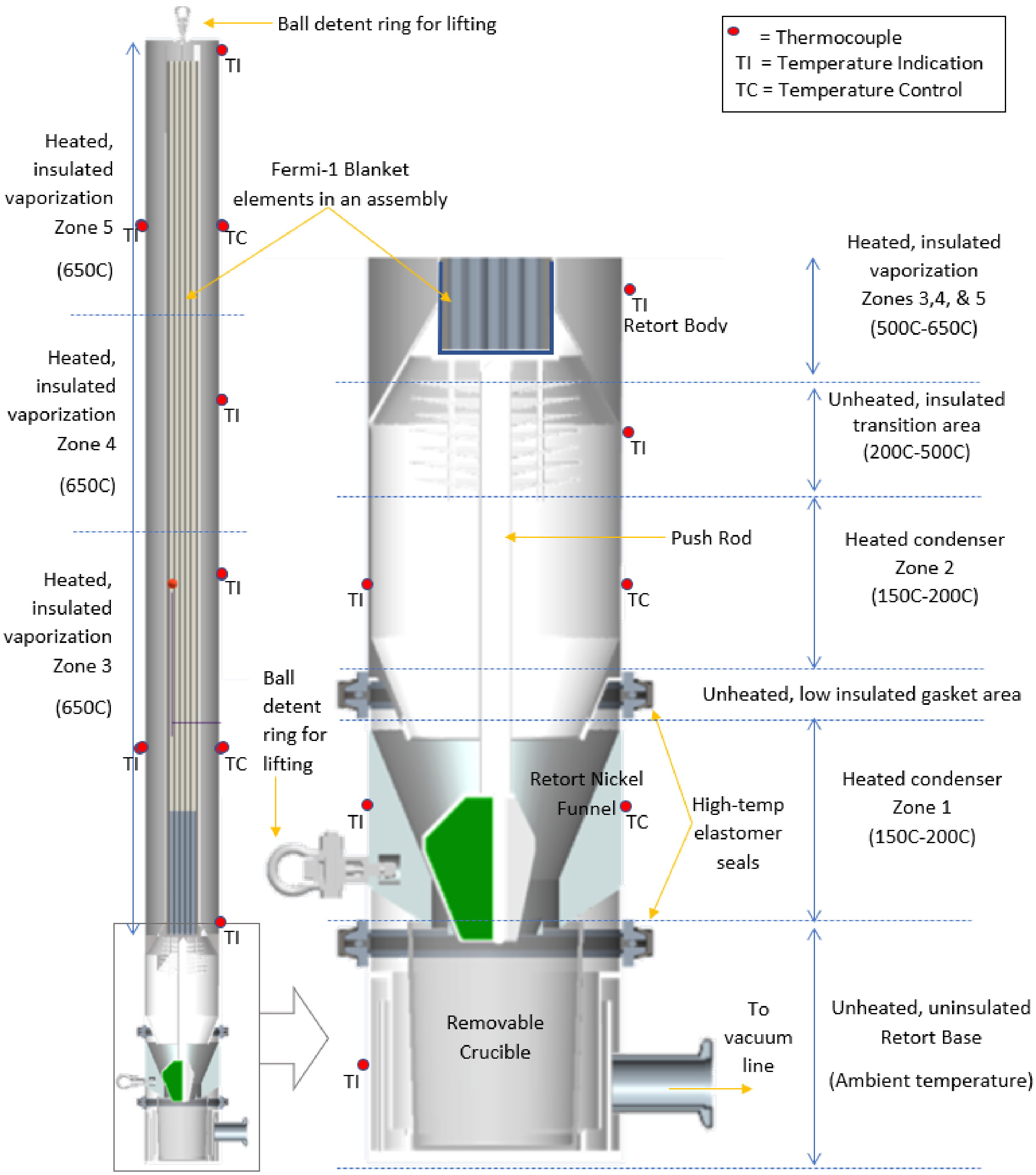

Figure 3. Sectional view of MEDE retort.

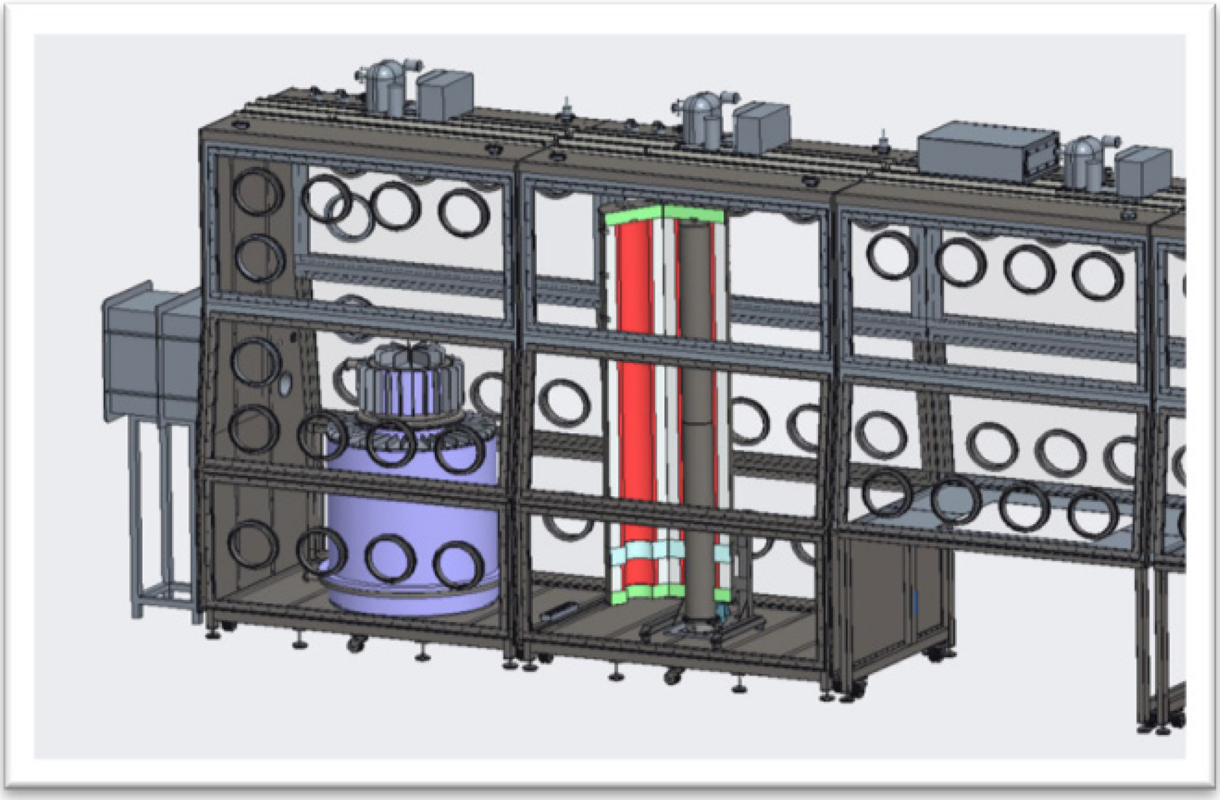

Figure 4. Model view of MEDE retort and furnace (tall unit) inside new multiprogrammatic use pyrochemistry glovebox.

The MEDE retort was designed to contain a full-length Fermi-1 radial blanket assembly (after removing the nozzle piece and breaching the elements) with the plenum end down in a vertical position. The retort was designed with three functional regions from top down for sodium vaporization, condensing, and collection. Each of these regions was divided into operating zones. Accordingly, the heated and insulated vaporization region was divided into three separately controlled zones labeled 5, 4, and 3 from top down. The heated, cooled, and insulated condenser region was divided into separately controlled zones labeled 2 and 1 from top down. The collection region was unheated and uninsulated to facilitate solidification of the sodium. Between the vaporization region (zone 3) and the upper condenser region (zone 2) was an unheated insulated transition zone. The lower condenser (zone 1) consisted of a nickel funnel, both ends of which were flanged to mate with the retort body on the top end and a retort base on the bottom collection end.

With the nickel funnel removed, the retort design facilitated loading of cut Fermi-1 radial blanket elements or an entire cut radial blanket assembly into the retort body in a horizontal position with the open plenum end of the element(s) toward the open end of the retort. Blanket elements, or an assembly, were pushed into the closed end of the retort with a push rod. The nickel funnel was then sealed to the retort body with an elastomer O-ring and clamp, capturing the blanket material inside. The retort was then positioned vertically, placed on the collection region's retort base, and sealed with an elastomer O-ring and clamp. In this configuration the blanket elements or assembly stood atop the push rod, which rested in the nickel funnel. The retort base was connected to a vacuum system that included in-line metal and cellulose filters and a pressure monitor upstream of a dry scroll vacuum pump. With the retort standing on its base, a clam-shell furnace was moved toward the retort and closed around it.

Operation of a PLC enabled reduced pressure and zoned heating of the retort to facilitate melting, vaporization, and condensing of bond sodium from blanket elements. Specifically, zones 3, 4, and 5 were operated to facilitate zoned melting of the sodium (typically 150–200°C) in the blanket elements from the open ends toward the center (for elements with both ends open) or from one open end toward the closed end (for elements with one open end). Likewise, zones 1 and 2 were operated to control the condensers in a nominal range of 150–200°C. After melting the sodium, the temperatures in zones 3, 4, and 5 were raised at a controlled rate toward a nominal 650°C to facilitate vaporization of the sodium. With the condenser zones maintained at 150–200°C, sodium vapor was driven to the condenser and collector regions, where it condensed and collected in a removable crucible beneath the nickel funnel. The condenser zones were fitted with cooling fans to remove heat from condensing sodium, if needed.

The MEDE system was designed in accordance with functional, operational, and technical requirements as part of engineering packages. [3–5] The furnace was fabricated by Mellen in accordance with engineering specifications generated by INL researchers [6].

A mock, sodium-free, Fermi-1 radial blanket assembly was fabricated from stainless-steel components for use in temperature profile testing of the MEDE system. The mock assembly was also used to test different off-the-shelf chop and band saws prior to performing the same evolution with the intact Fermi-1 radial blanket assembly in a radiological glovebox.

3.3 Fermi-1 Blanket Elements and Assembly

Two intact Fermi-1 radial blanket assemblies and several loose radial and axial blanket elements were received in 2001 at INL's Fuel Conditioning Facility (FCF) from the Henry Ford Museum in Michigan to support the previously cited study. [1–2] These materials constitute the only known remaining unirradiated Fermi-1 blanket materials that are identical to the 34 MTHM of irradiated Fermi-1 blanket materials in storage at INL. In the previous study, one (M346) of the two radial assemblies was disassembled to support sodium removal testing. Pictures of the as-received and first-disassembled assembly are shown in Figure 5. Thus, only one intact radial assembly (M893) remained for use in the current study.

Figure 5. As received (left and center) and cut (right) unirradiated Fermi-1 radial blanket assembly, M346.

To verify the actual positioning of uranium alloy slugs and bond sodium within elements and the configuration of elements within an assembly, 15 loose unirradiated Fermi-1 radial blanket elements (from assembly M346) and an intact radial blanket assembly (M893, containing 25 elements) were subjected to radiography at a radiography station within INL's Materials and Fuels Complex. The 15 loose elements were radiographed in three groups of five. Radiographs of the bottom and top ends of one group of five elements are shown in Figure 6, while the same for the intact assembly are shown in Figure 7.

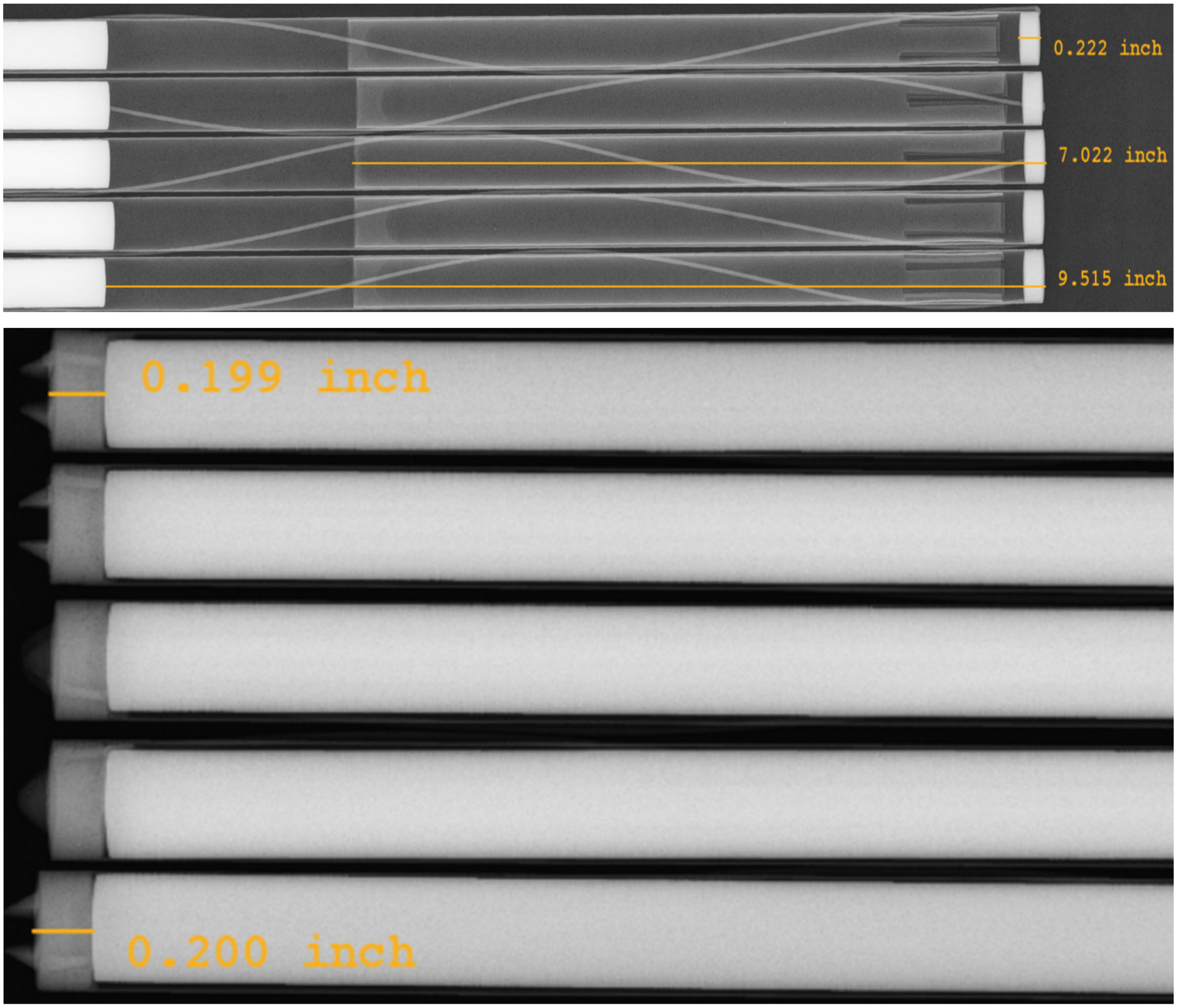

Figure 6. Radiographs of top (above) and bottom (below) ends of one group of five loose Fermi-1 unirradiated blanket elements.

Radiographs of the loose blanket elements identified the roughly 0.2-inch-long bottom and top-end plugs, the top of the slug column at approximately 9.5 inches below the top of the element, and the top of the sodium fill level at approximately 7 inches below the top of the element. Spacer pieces in the plenum region above the slug column were also evident, as well as the spiral wound element spacer wire.

Radiographs of the intact assembly identified the positioning of the grid plates above the flow nozzle on the bottom end and below the handling fixture on the top end. The slug columns, sodium fill levels, spacer pieces, and wire wraps were also evident in the plenum region of the elements within the assembly. These radiographs provided dimensional information necessary to facilitate breaching of the elements and assembly during testing.

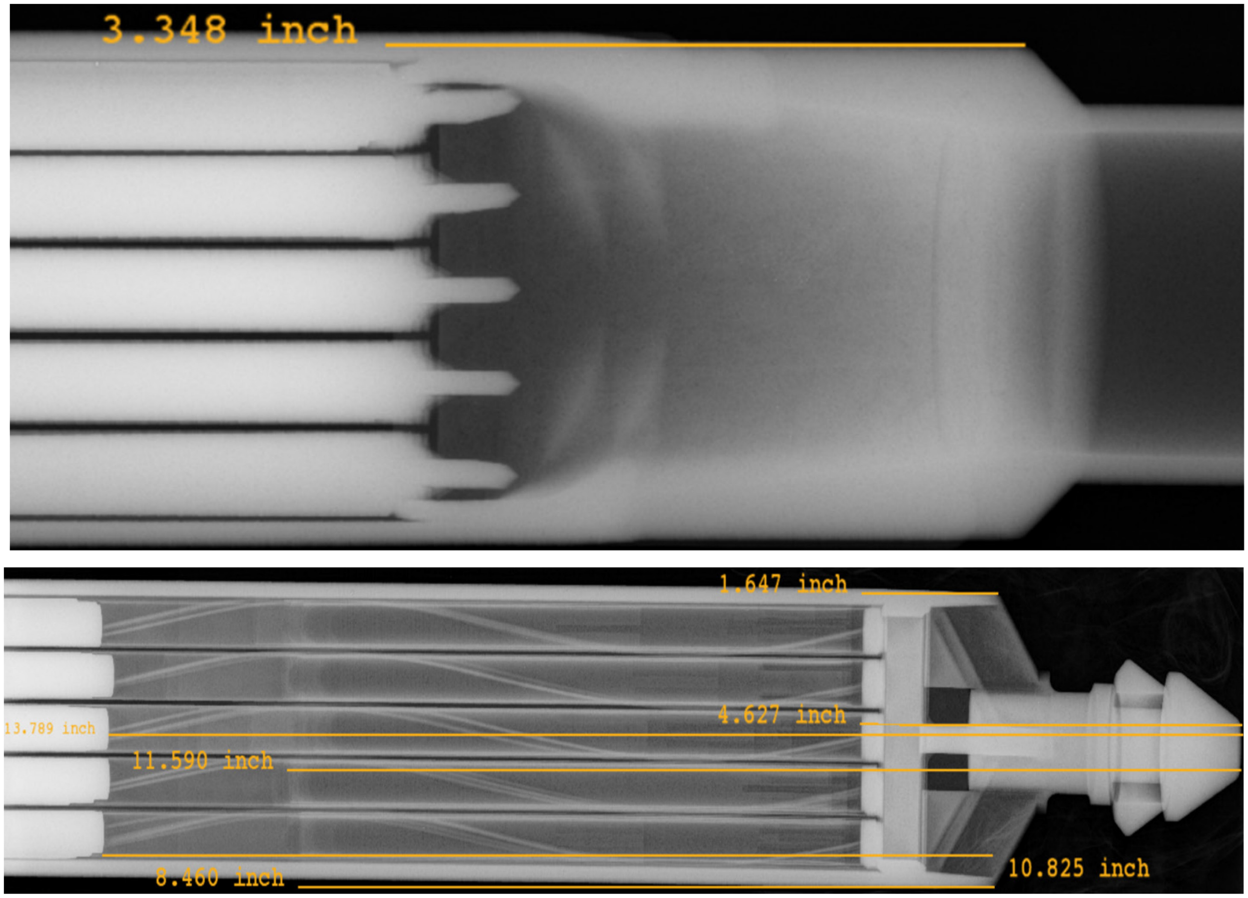

Figure 7. Radiographs of the bottom (above) and top (below) ends of an intact Fermi-1 unirradiated blanket assembly.

3.4 Sample Analyses

Sample analyses of the treated Fermi-1 unirradiated blanket materials were divided into qualitative and quantitative analyses. Qualitative analyses involved visual observations of (1) the mechanical separation of uranium alloy slugs from the respective cladding and (2) the slug and cladding segment immersion in ethyl alcohol. In the latter case, any sodium metal on the slug or cladding segment surfaces would rapidly react with ethyl alcohol to form sodium ethoxide and hydrogen gas via the following reaction.

$$2\ Na\ (s) + 2\ C_2H_5OH \rightarrow 2\ C_2H_5ONa + H_2\ (g) \tag{1}$$

The resultant sodium ethoxide is soluble in ethyl alcohol, while the formation and rising of hydrogen gas in a column of alcohol is readily observable. This qualitative analysis was accomplished by immersing every treated Fermi-1 blanket slug and cladding segment, that was not subjected to quantitative analysis, in a glass graduated cylinder of ethyl alcohol and recording the results.

Quantitative analysis of entire columns of depleted uranium alloy slugs or cladding from select treated Fermi-1 blanket elements, as outlined in Table 3, were performed in ARL to quantify trace amounts of residual metallic sodium on their surfaces. Specifically, either an entire column of five slugs or its associated cladding was loaded into a lab transfer cartridge (LTC) under an argon atmosphere within the pyrochemistry glovebox. A schematic of an LTC is shown in Figure 8. The LTC was removed from the glovebox and transferred to the ARL, where it was connected to a manifold as shown in Figure 9.

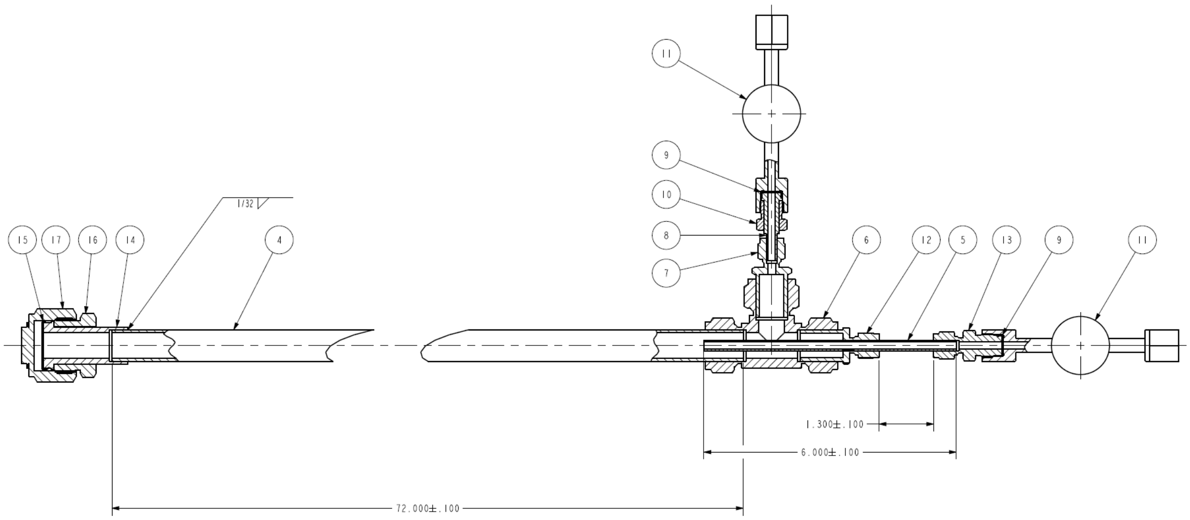

Figure 8. Schematic of LTC.

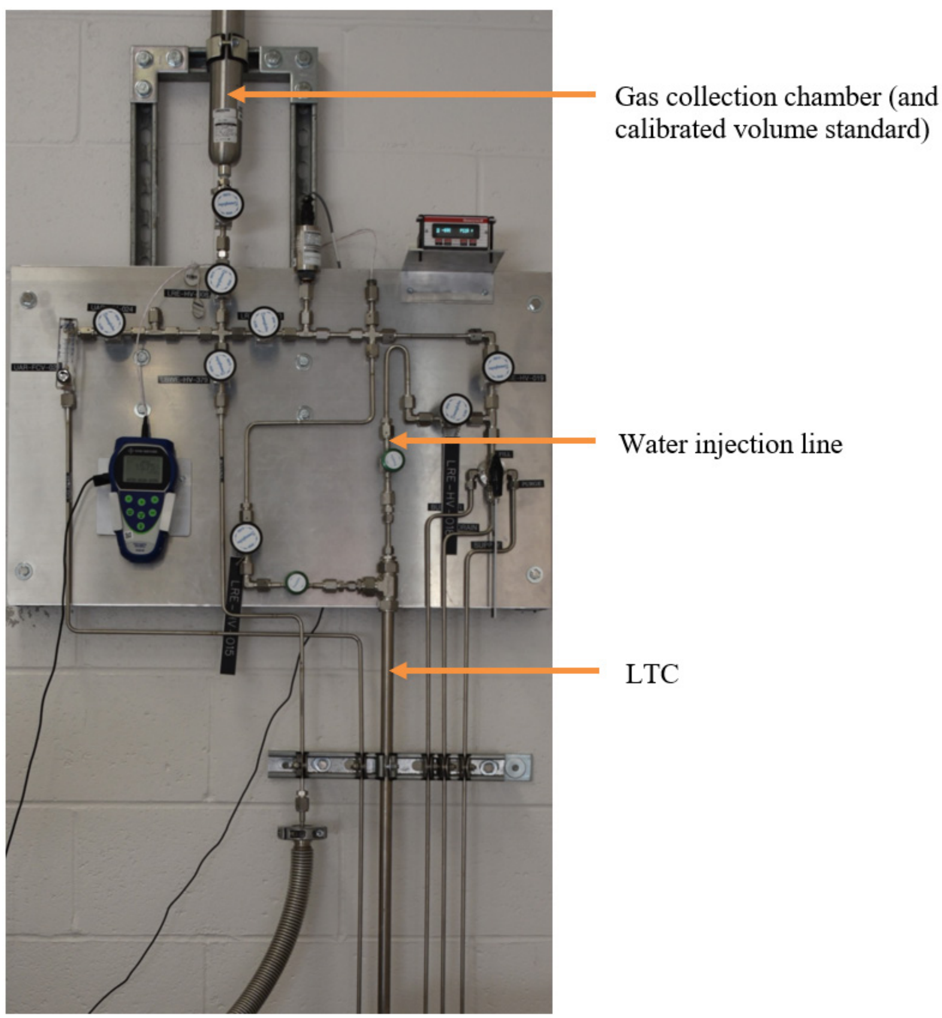

Figure 9. Picture of LTC connected to manifold in ARL.

Using the manifold, the free volume of a loaded LTC was first measured to determine how much water was necessary to ensure complete submersion of a treated blanket element sample. To measure the free volume, the manifold was evacuated, and the calibrated volume standard was charged with argon gas. The gas was then expanded into the manifold first, followed by an expansion of the gas into the LTC to measure the system volume as shown in Eq. 2. The volume of the LTC was determined from Eq. 3. This process was repeated at least two times to reduce the uncertainty in the volume measurement. After the free volume of the system was measured, the entire system was purged for 2 hours with high-purity argon for seven system volume equivalents to ensure that no residual atmosphere remained in the manifold before the sample was submerged in water. The injection lines were primed with high-purity water, and a pre-determined volume of water (based on the LTC volume measurement) was subsequently injected into the LTC. The pressure and temperature of the system were recorded at several points throughout the process. Any residual metallic sodium on the surfaces of the slugs or cladding pieces reacted with the water to form sodium hydroxide and hydrogen gas per Eq. 4.

$$V_{Manifold} = \frac{P_{STD} * V_{STD} * T_{Manifold}}{P_{Manifold} * T_{STD}}, V_{System} = \frac{P_{STD} * V_{STD} * T_{LTC}}{P_{LTC} * T_{STD}} \tag{2}$$

where V = volume, P = pressure, T = temperature, and STD = standard

$$V_{LTC} = V_{System} - V_{Manifold} \tag{3}$$

$$2\ Na\ (s) + 2\ H_2O\ (l) \rightarrow 2\ NaOH\ (aq) + H_2\ (g) \tag{4}$$

The above reaction proceeded rapidly and was allowed to progress for 5 minutes before the head space gas was sampled. The remaining pressure in the LTC and manifold was then evacuated to atmospheric pressure. Following evacuation, the LTC was removed from the manifold and attached to a drain and rinse setup as shown in Figure 10. The water was collected, from which a sample was taken. The LTC was then rinsed and flushed three times with high-purity water to remove dissolved materials and reattached to the manifold, where vacuum was applied for a minimum of 24 hours to remove any residual water from the LTC prior to its reuse.

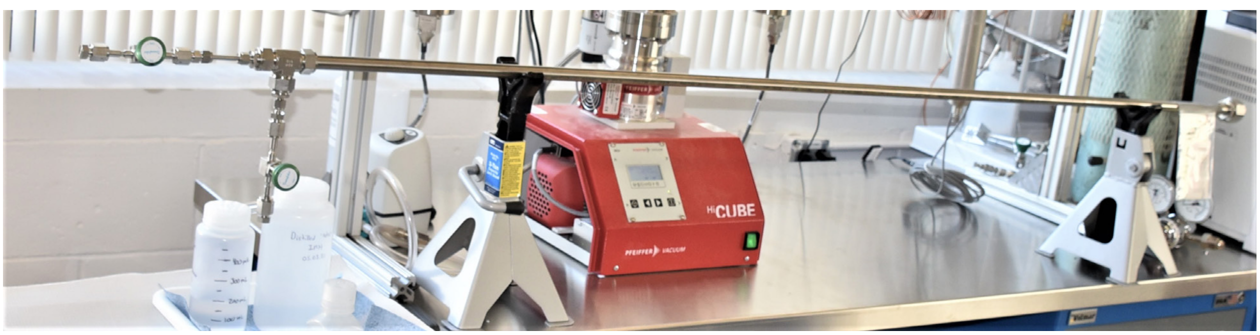

Figure 10. LTC drain and rinse setup in ARL.

Analysis of the gas and water samples was performed during the LTC drying operation. Specifically, the gas sample was analyzed for hydrogen via Quadrupole Gas Mass Spectroscopy (Q-GasMS). The mass of any detectable hydrogen in the gas samples was ascribed to sodium metal per Eq. 4 to determine a residual sodium metal mass within a sample. The water was analyzed for elemental sodium content via Inductively Coupled Plasma-Optical Emission Spectroscopy (ICP-OES). The elemental sodium analysis would account for any sodium hydroxide from Eq. 4 as well as any preexisting nonreactive (including oxidized) sodium resident with the depleted uranium alloy slug or cladding samples. The difference between the sodium contents derived from the elemental sodium analysis via ICP-OES and the metallic sodium via Q-GasMS defined the nonreactive sodium content in the samples.

4. OPERATIONS AND RESULTS

Operation of the MEDE system was divided into non-radiological and radiological testing. Non-radiological testing involved the initial assembly and operation of the MEDE system on the floor of EDL. Non-radiological testing also involved the initial installation and testing of the MEDE system in the new pyrochemistry glovebox before it was sealed for radiological use. Radiological testing involved operation of the MEDE system with actual unirradiated Fermi-1 radial blanket materials. The following describes specific objectives, operations, and results of the non-radiological and radiological test campaigns.

4.1 Non-Radiological MEDE Testing

4.1.1 Operations in EDL

Specific objectives of the MEDE testing in a non-radiological environment included performing mechanical fit of equipment, verifying functional requirements through system operations, and developing operating recipes prior to use of the system in a radiological environment. The MEDE system was initially assembled on the floor of EDL. Power and control leads were connected between the MEDE equipment and a PLC, and independent operation of all furnace zones, cooling fans, and vacuum pump were verified from the PLC's operating command station (OCS).

The furnace was closed without the retort inside, and a vendor-prescribed bake-out of the furnace was performed to burn off binders within the furnace insulation. The bake-out run involved stepping and holding the furnace at 100 to 200°C increments for 1 to 2 hours up to 700°C. A picture of the MEDE furnace after the bake-out run is shown in Figure 11.

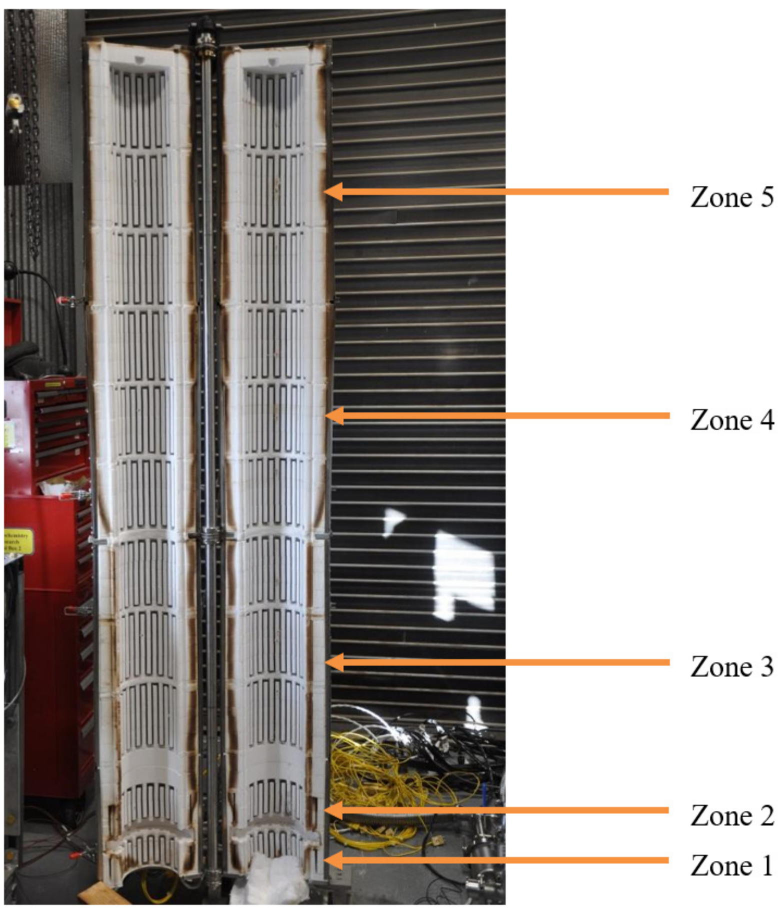

Figure 11. MEDE furnace after bake-out run in EDL.

A sodium-free mock Fermi-1 assembly was cut using three different saws, including two chop saws and one band saw, as shown in Figure 12. Lessons learned from this operation included the need to perform two cuts on each closed end. An initial cut on each end was needed to remove the end plate, so that the element end pieces were free to fall away during a second cut through the array of elements. Cutting through the elements without first removing the end plate resulted in element end pieces tumbling, binding, and damaging the saw blade, regardless of the saw type. A screw was also inserted through the assembly wall and into the element array to swage the elements together and preclude their rotation by the saw blades. The larger of two chop saws was selected for cutting the Fermi-1 blanket assembly due to its relative ease of use and resistance to binding amongst the three saws.

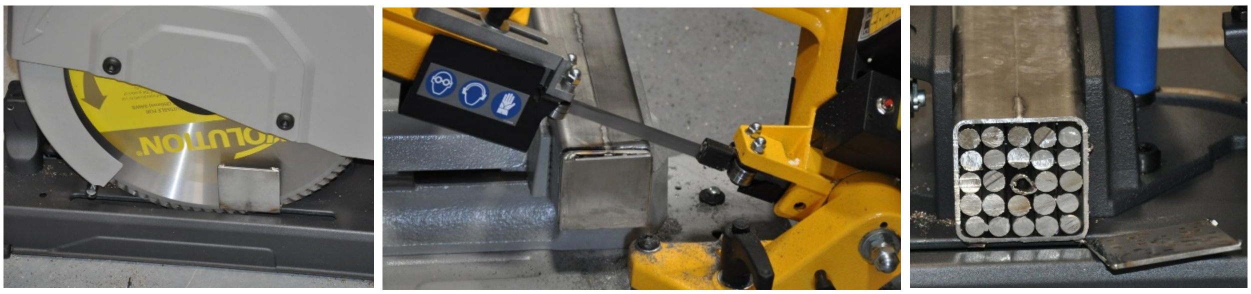

Figure 12. Cutting of mock Fermi-1 blanket assembly with chop (left) and band (center) saws, revealing cut end of assembly (right).

The cut mock Fermi-1 blanket assembly was loaded into the retort body and positioned to the back with a modified push rod. The push rod was modified with a center hole that aligned with the center tube (see Figure 12, far right) of the mock assembly to facilitate positioning of a centerline thermocouple probe that measured temperatures inside the assembly near the top, middle, and bottom of each of zones 3, 4, and 5, as well as near the top and bottom of zone 2. The funnel had two thermocouples fixed near its inside top and bottom surfaces, representing the process temperature at these points in furnace zone 1. The leads for the centerline thermocouple probe and funnel thermocouples were directed through a modified vacuum manifold that contained sealed thermocouple connections. Thus, the centerline profile testing was able to be conducted while the retort was under vacuum. The centerline profile and furnace thermocouples for the MEDE system are delineated in Table 4. A sectional view of the positioning of centerline profile thermocouples vis-à-vis the furnace control and monitoring thermocouples in the MEDE system is shown in Figure 13.

Table 4. Delineation of centerline profile and furnace thermocouples in MEDE system.

Furnace Zone	Centerline Profile Thermocouples	Furnace Control/Monitoring Thermocouples
5	Ch 101, Ch 102, Ch 103	TE-026, TE-027, TE-028, TE-029
4	Ch 104, Ch 105, Ch 106	TE-009, TE-010, TE-011, TE-012
3	Ch 107, Ch 108, Ch 109	TE-013, TE-014, TE-015, TE-016
Between 3 and 2	n/a	TE-017
2	Ch 110, Ch 111	TE-018, TE-019
Between 2 and 1	n/a	TE-022
1	Ch 112, Ch 113	TE-020, TE-021

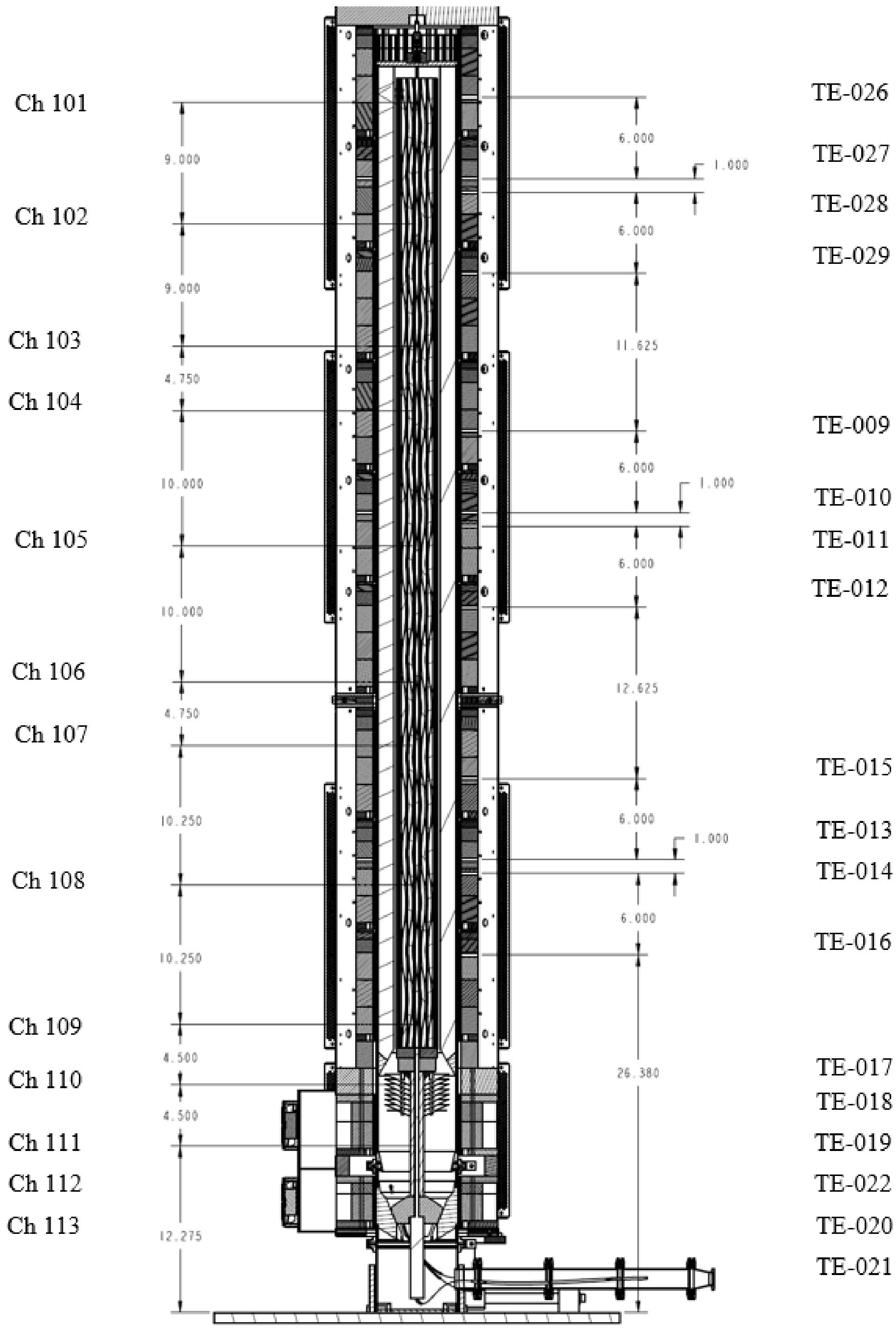

Figure 13. Sectional view of relative positioning of centerline profile thermocouples (left column) and furnace control/monitoring thermocouples (right column) in the MEDE system.

With the centerline profile thermocouples positioned inside the mock assembly and retort, a reduced pressure below 200 mTorr was established. With the clam-shell furnace closed around the retort, a series of furnace operations was performed to compare the centerline profile thermocouple readings to the corresponding furnace thermocouples and establish an appropriate operating recipe that could be applied to MEDE operations with actual sodium-bonded Fermi-1 blanket material. These operations led to a baseline operating recipe, as shown in Figure 14.

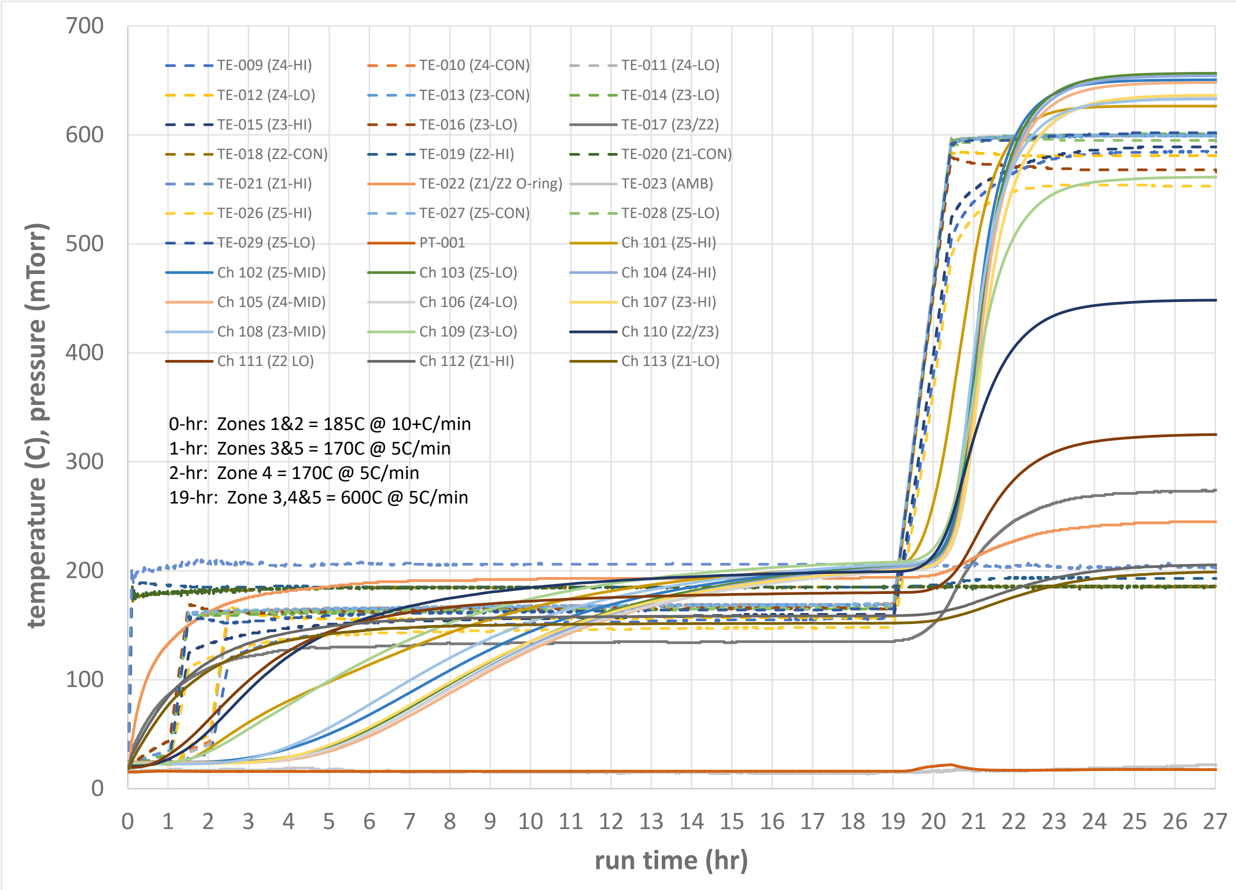

Figure 14. Time plot of furnace and centerline temperatures and pressure using recipe developed in EDL for forthcoming MEDE operations.

The recipe started with zones 1 and 2 heating to 185°C at >10°C/minute. After a 1-hour hold, zones 3 and 5 were heated to 170°C at 5°C/minute. After another 1-hour hold, zone 4 was heated to 170°C at 5°C/minute. This initial melting sequence raised zones 1 and 2 process (i.e., centerline) temperatures to a range of 150 to 200°C to facilitate the passing of any melted sodium from the blanket materials directly to the collection crucible without solidifying in the condenser. This sequence also raised zones 3 and 5 process temperatures to a range of 150 to 200°C to facilitate melting of bond sodium in a blanket element/assembly from the top and bottom open ends toward the center of an element, providing a relief path for expanding bond sodium upon melting. In this melting sequence, it was observed that several hours was needed for the centerline temperature in zones 3–5 to exceed the melting point of sodium (i.e., 98°C). Thus, it was determined that the melting sequence in an actual MEDE operation should occur during an overnight period, followed by vaporization the next day. Accordingly, after 19-hours from the start of the recipe (coinciding with the next morning), zones 3, 4, and 5 were raised to 600°C at 5°C/minute. This adjustment raised the process temperature in zones 3–5 to approximately 650°C (excepting the low end of zone 3, i.e., Ch 109, which settled near 560°C) and exhibited an approximate 2-hour lag from the furnace temperatures. This last sequence would facilitate vaporization of bond sodium in an actual blanket element and its subsequent transport to the condenser and collection crucible. The vaporization temperatures in zones 3–5 were held for a total of 8 hours before ending the recipe and shutting down the furnace.

4.1.2 Operations in FASB

After completing operations in EDL, the MEDE system was disassembled and reassembled in the pyrochemistry glovebox at FASB. The furnace and retort are shown inside the glovebox in Figure 15, while the PLC and OCS were positioned outside and adjacent to the glovebox, as shown in Figure 16. In this configuration, the mock assembly was loaded into the retort, but no centerline thermocouples were installed. Thus, a non-modified push rod and vacuum manifold were used. The vacuum pump was located outside the glovebox and connected to the vacuum line via a glovebox feed through. All furnace power, control, and monitoring leads were also routed from the PLC through feed throughs to equipment inside the glovebox.

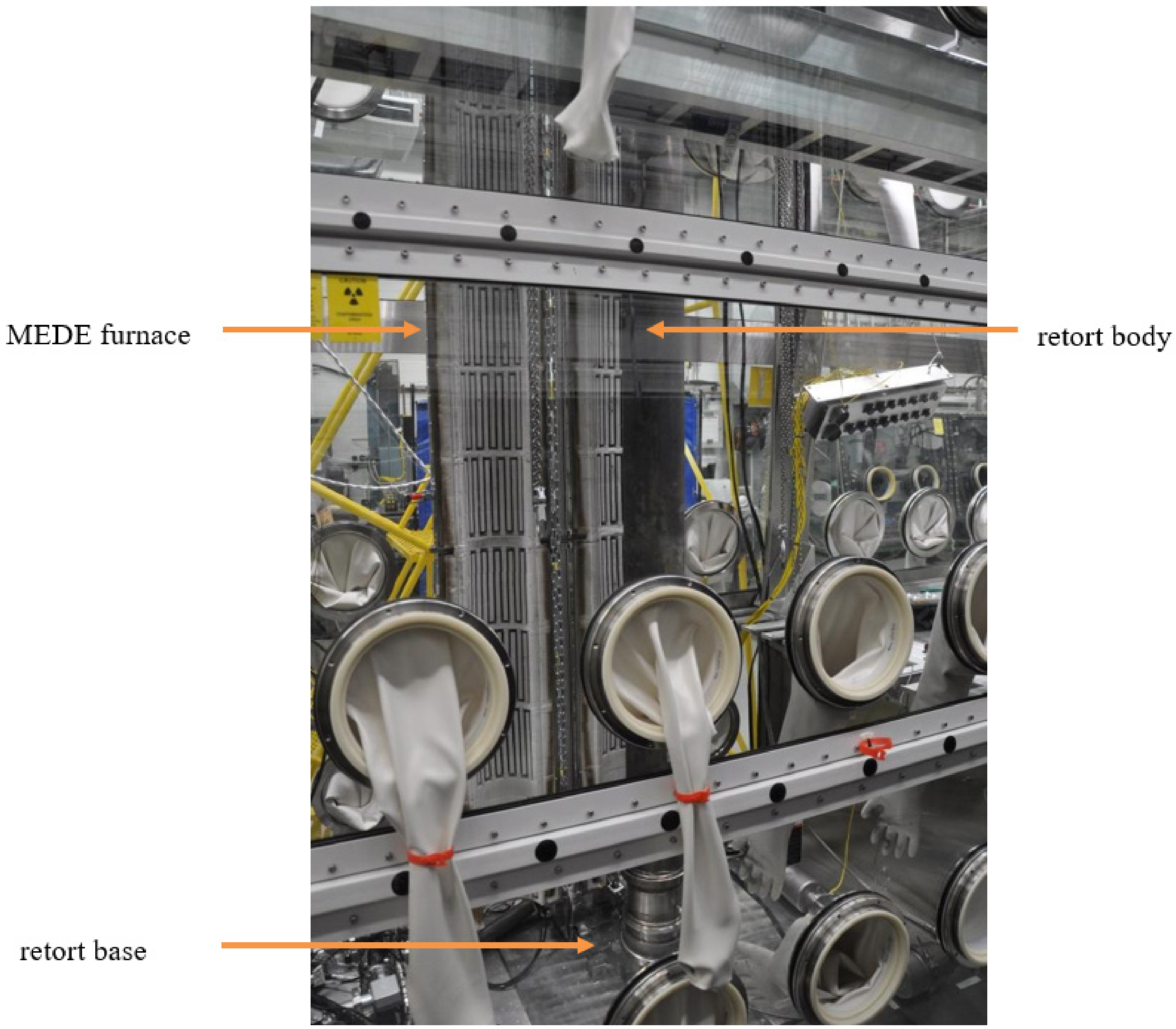

Figure 15. Picture of MEDE retort and furnace inside pyrochemistry glovebox at FASB.

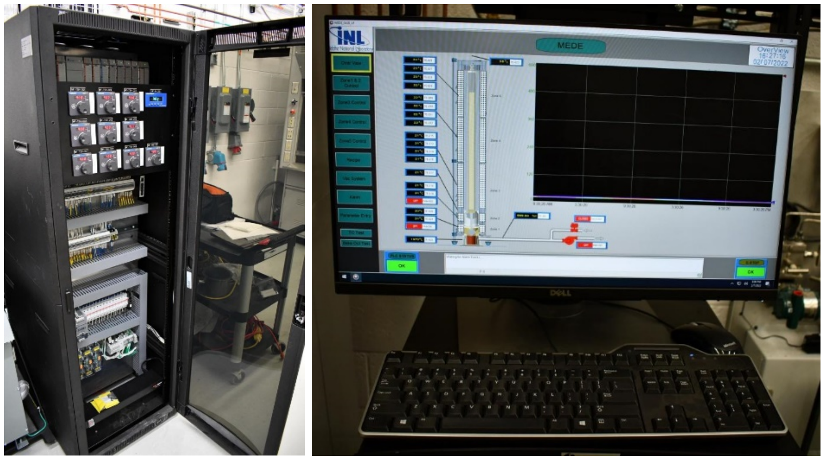

Figure 16. Installed PLC (left) and OCS (right) adjacent to pyrochemistry glovebox in FASB.

To verify proper operation of the MEDE system after installing it in the glovebox, the same operating recipe that was developed in EDL was conducted in FASB as a dry run of the system. A time plot of temperatures and pressure for the dry run is shown in Figure 17. In contrast to the run plot in EDL (see Figure 14) the dry run in FASB did not include centerline temperatures. Also, the plot of the dry run in FASB illustrates the time needed for ambient cool down of the MEDE system in an argon-atmosphere glovebox, which equates to one overnight period.

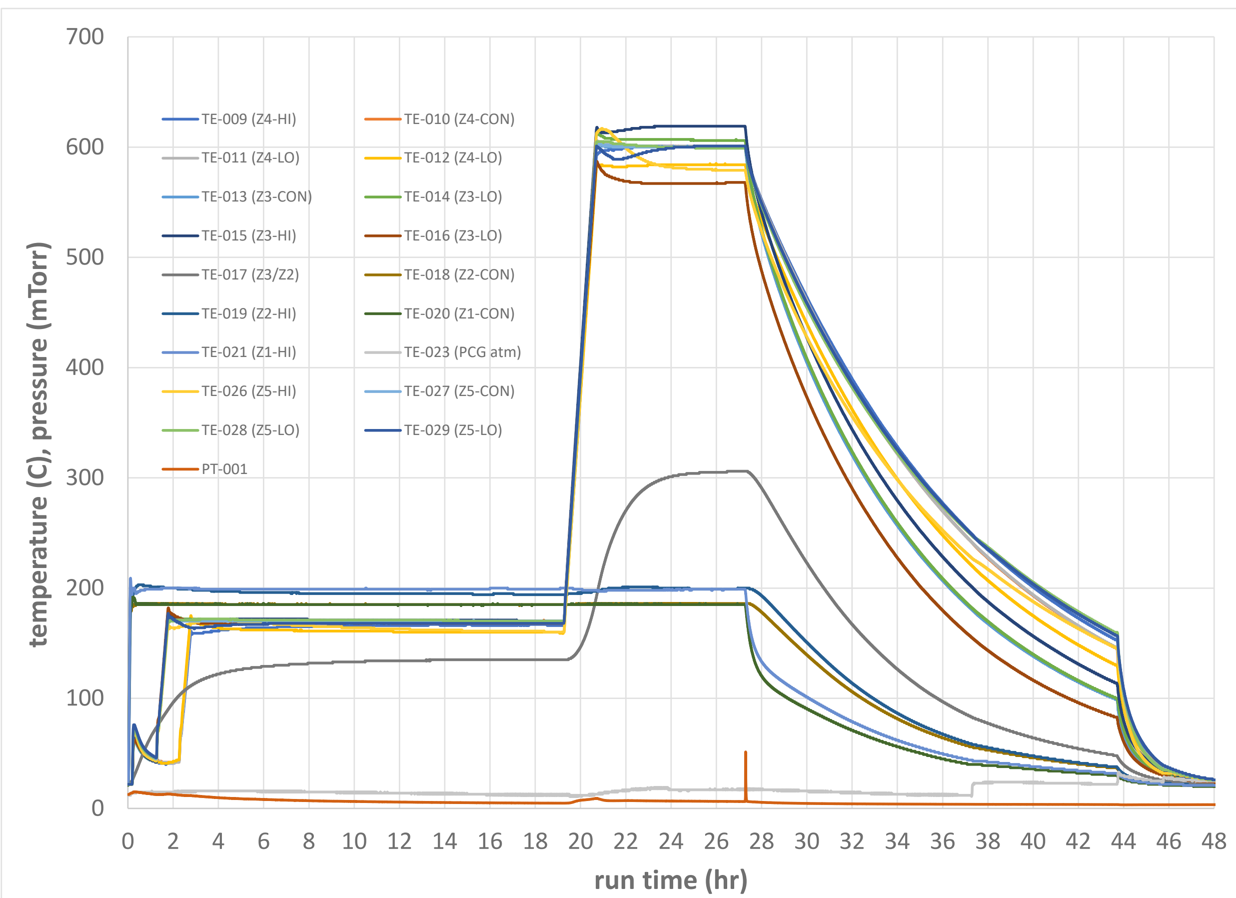

Figure 17. Time plot of temperature and pressure for MEDE dry run in the pyrochemistry glovebox.

4.2 Radiological MEDE Operations

After verifying dry operations of the MEDE system in the pyrochemistry glovebox in FASB, the box was sealed for radiological use and the previously described loose elements and intact assembly of Fermi-1 radial blanket materials were transferred in. The atmosphere in the glovebox was typically controlled below 20 ppm oxygen and 1 ppm moisture throughout the MEDE operations. A series of MEDE runs with the Fermi-1 blanket material was performed as outlined in Table 3, the operations and results of which are described in the following subsections.

4.2.1 Run 1

Tare weights of the retort body (42140 g), push rod (2633.4 g), nickel funnel (9181.6 g), and a new glassy carbon crucible (198.66 g) for sodium collection were obtained. A single Fermi-1 radial blanket element was selected, and the wire wrap was removed from both ends. Both end pieces of the element were removed with a tubing cutter, breaching the element and exposing the bond sodium. The breached element was weighed (2429.6 g) and connected to the push rod with a hose clamp and wire rope to facilitate post-run removal of the element. Pictures of the element cutting and retort loading are shown in Figure 18. The retort was assembled with the nickel funnel and moved horizontally through the glovebox to the MEDE furnace station, as shown in Figure 19, where it was positioned vertically on the retort base (see Figure 15).

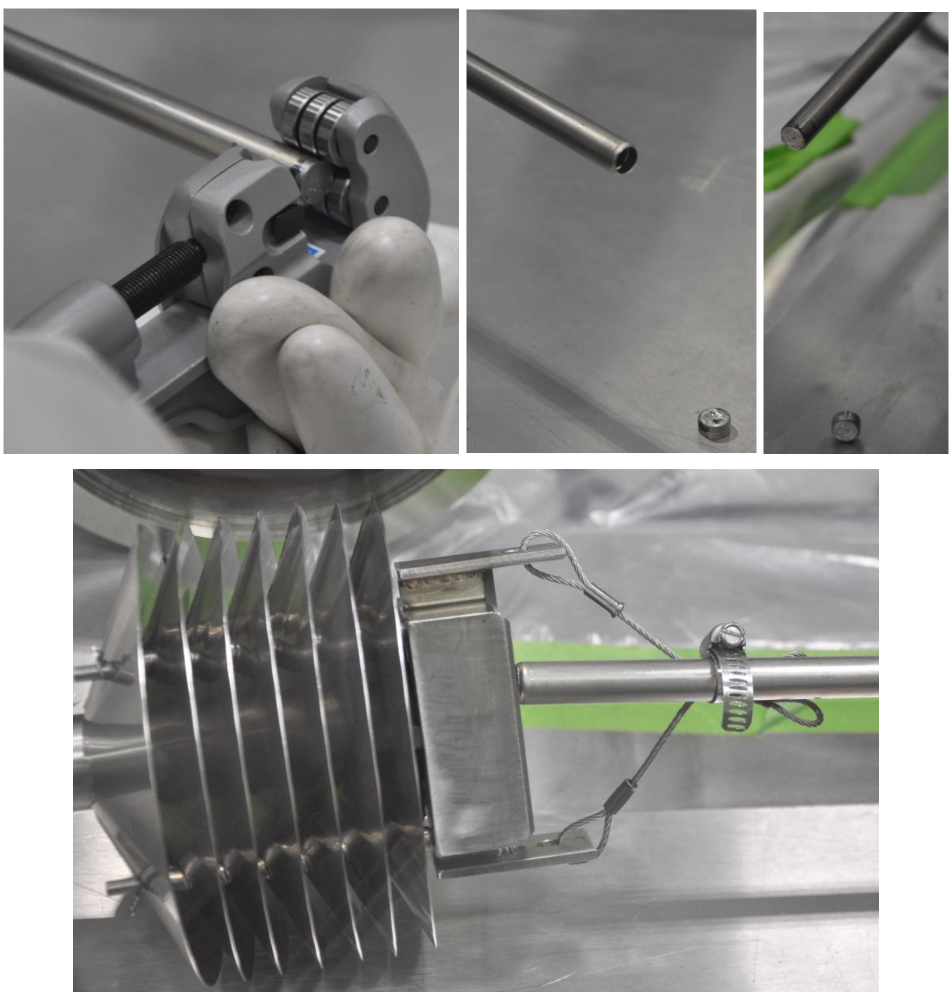

Figure 18. Cutting of Fermi-1 radial blanket element top-end piece (upper left and center), bottom end piece (upper right) and loading in retort (bottom).

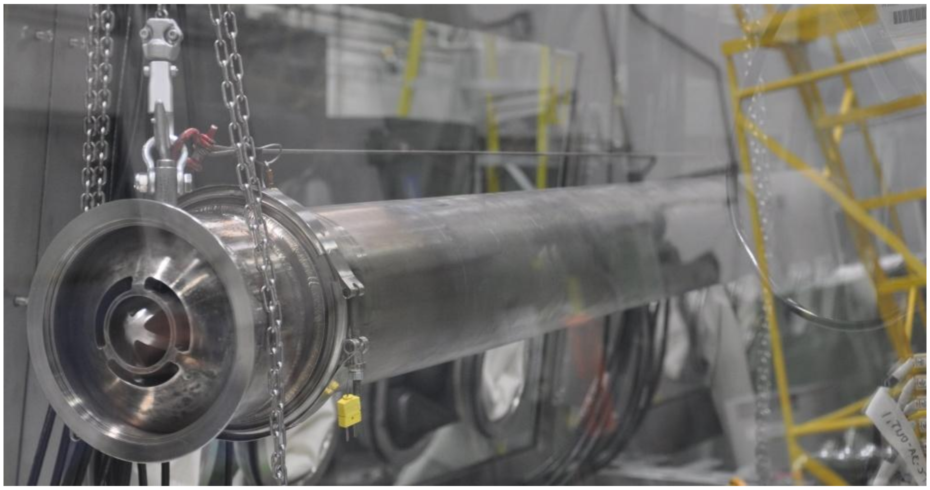

Figure 19. Horizontal movement of loaded retort through glovebox toward MEDE furnace station.

The vacuum pump was started and a reduced pressure below 200 mTorr was verified prior to closing the MEDE clam-shell furnace. The operating recipe was started, as developed previously for the EDL and FASB dry runs. A time plot of furnace temperature and retort pressure is shown in Figure 20.

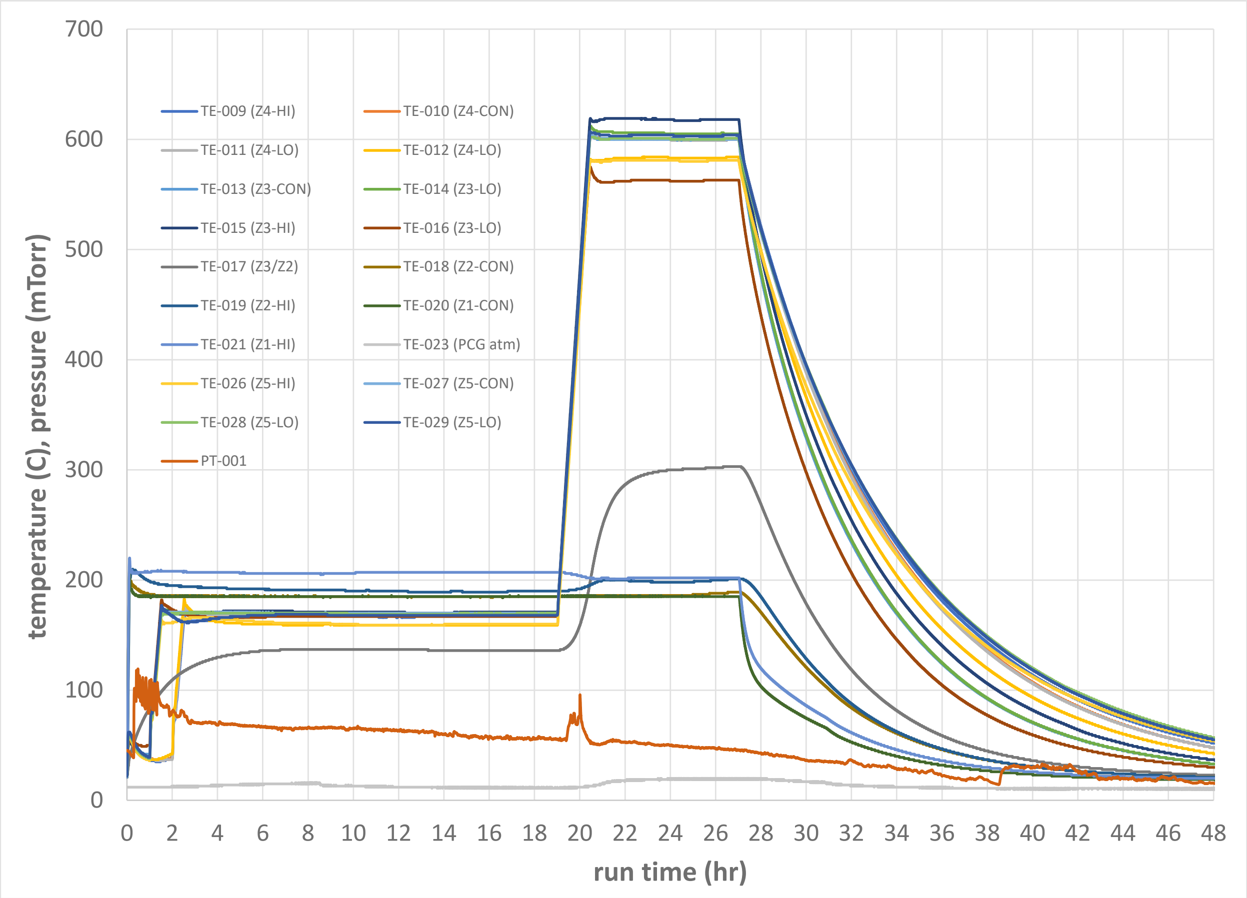

Figure 20. Time plot of furnace temperature and retort pressure for MEDE run 1.

After cooling down, the pressure in the retort (PT-001) was equalized. The retort was removed from its base and moved horizontally to its loading/unloading station. The glassy carbon crucible inside the retort base was removed, revealing a reasonable amount of sodium in the bottom. A single bead of sodium was observed on the underside of the nickel funnel. After separating the nickel funnel from the retort body, fine beads of sodium metal were observed on the inside surface of the funnel. Relatively few beads of sodium were observed on the push rod, and no sodium was observed on the element or retort body. Pictures of sodium in the crucible, nickel funnel, and push rod are shown in Figure 21.

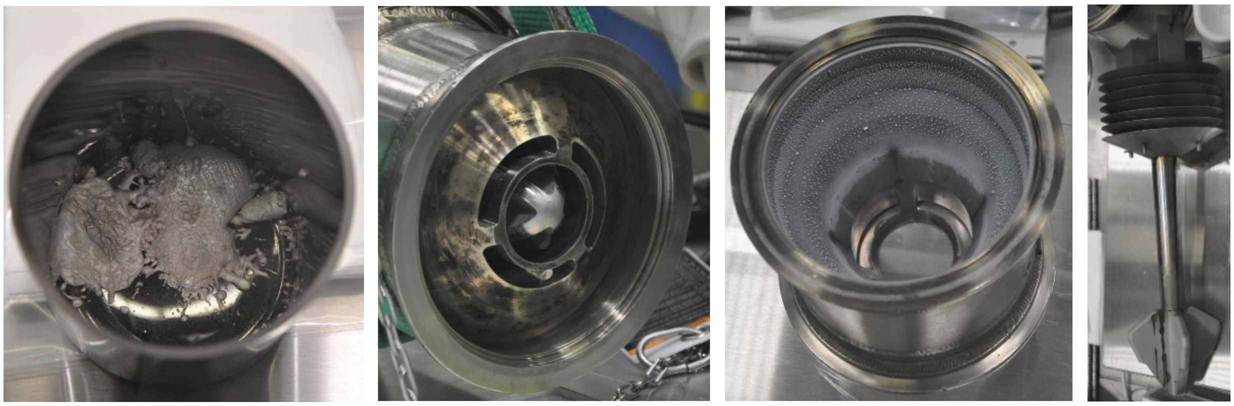

Figure 21. Post-run 1 crucible, nickel funnel bottom and top, and push rod (from left to right).

Post-run masses of the retort body (42160 g), push rod (2634.3 g), nickel funnel (9183.0 g), glassy carbon crucible (219.53 g) and the element (2404.9 g) were obtained. The element was tipped over a steel tray, causing the spacer and all five depleted uranium alloy slugs to slide out of the cladding, as illustrated in Figure 22. The mass of all five slugs was 2270.0 g, and the mass of the cladding with the spacer piece was 134.9 g. All five slugs were placed in one LTC, and the cladding with the spacer piece were placed in another LTC, as shown in Figure 23. The LTCs were removed from the glove box and transferred to ARL for quantitative analysis.

Figure 22. Post-run 1 depleted uranium slugs and cladding—during (left) and after (right) separation.

Figure 23. Loading of depleted uranium alloy slugs in LTC following MEDE run 1.

4.2.2 Run 2

Seven Fermi-1 radial blanket elements were selected for run 2 as shown in Figure 24. The wire wrap was removed from both ends of each element. Both end pieces on each element were removed with a tubing cutter. The bottom and top-end pieces exhibited varying amounts of sodium metal on the inner surfaces, as shown in Figure 25. The breached elements were weighed collectively (17051.0 g) and connected to the push rod as a bundle, as seen in Figure 26.

Figure 24. Fermi-1 radial blanket elements for MEDE run 2.

Figure 25. Bottom (upper row) and top (lower row) element end pieces for MEDE run 2.

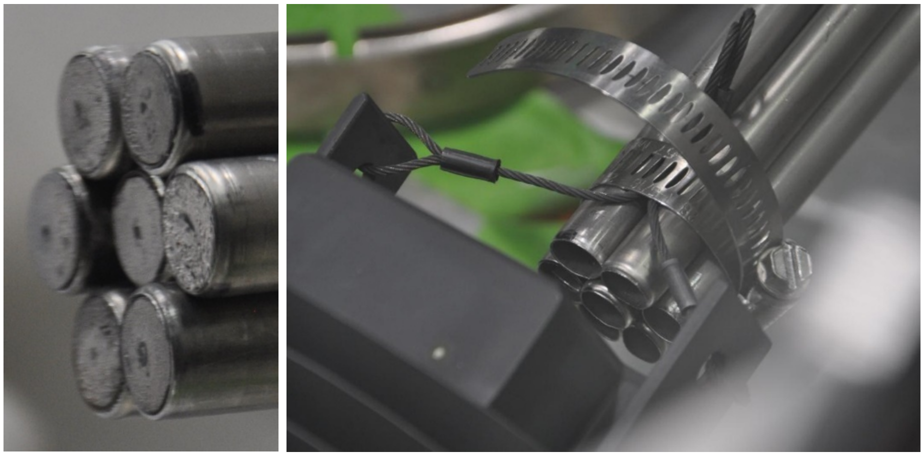

Figure 26. Bundle of Fermi-1 radial blanket elements showing cut bottom ends (left) and fitting of open plenum ends to push rod (right) prior to MEDE run 2.

The retort was assembled with the nickel funnel, moved to the MEDE furnace station, positioned vertically on the retort base with the same loaded glassy carbon crucible following run 1, and enveloped by the MEDE furnace after starting the vacuum pump and verifying a reduced pressure below 200 mTorr. The operating recipe was initiated, ramping zones 3–5 to 600°C at approximately 15 hours from the beginning of the recipe to accommodate a later run start time. A time plot of furnace temperature and retort pressure for MEDE run 2 is shown in Figure 27.

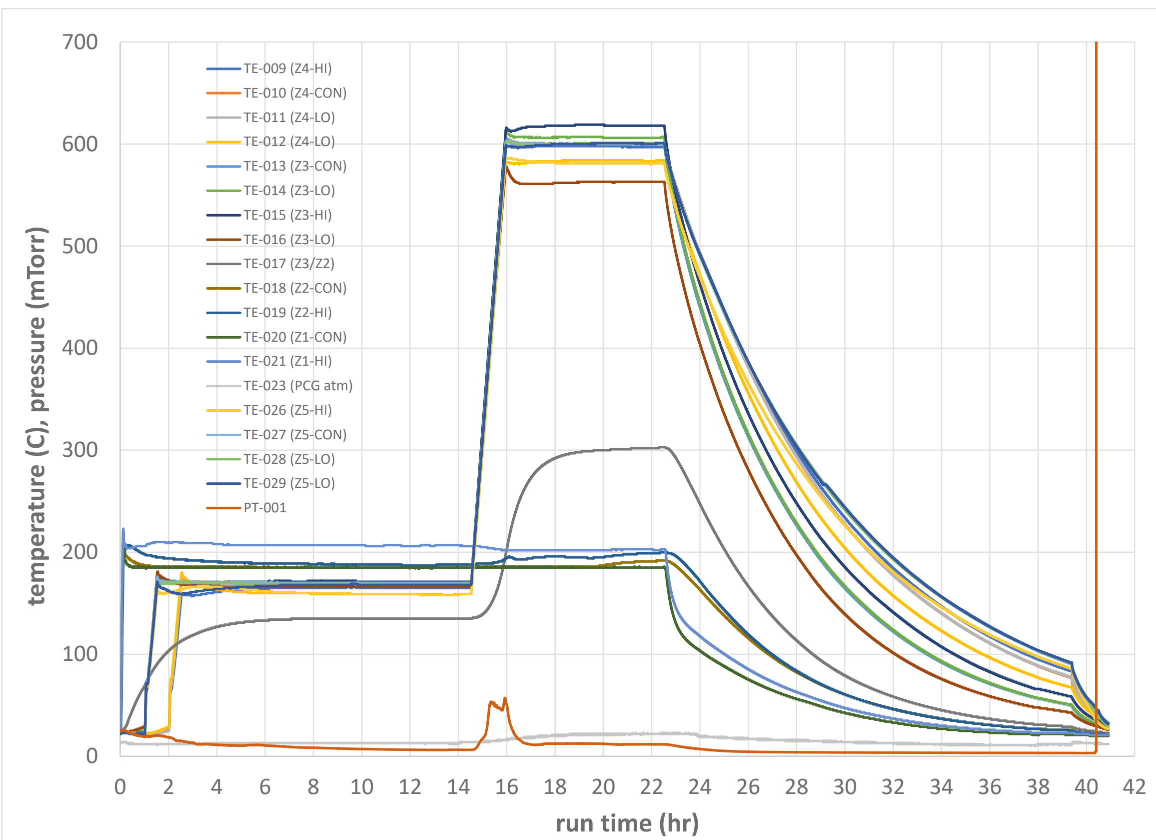

Figure 27. Time plot of furnace temperature and retort pressure for MEDE run 2.

After cooling down, the pressure in the retort was equalized. The retort was removed from its base and moved horizontally to its loading/unloading station. The glassy carbon crucible was removed, revealing an additional amount of sodium in the bottom. A significant number of small beads of sodium were observed near the bottom of the nickel funnel. Consequently, a steel tray was placed under the funnel during its disassembly from the retort body to capture loose sodium beads. After separating the nickel funnel from the retort body, fine beads of sodium metal were observed on the inside surface of the funnel. Relatively few beads of sodium were observed on the push rod (limited to the upper regions of the trefoil blade), and no sodium was observed on the elements or retort body. Pictures of sodium in the crucible, nickel funnel, and push rod are shown in Figure 28.

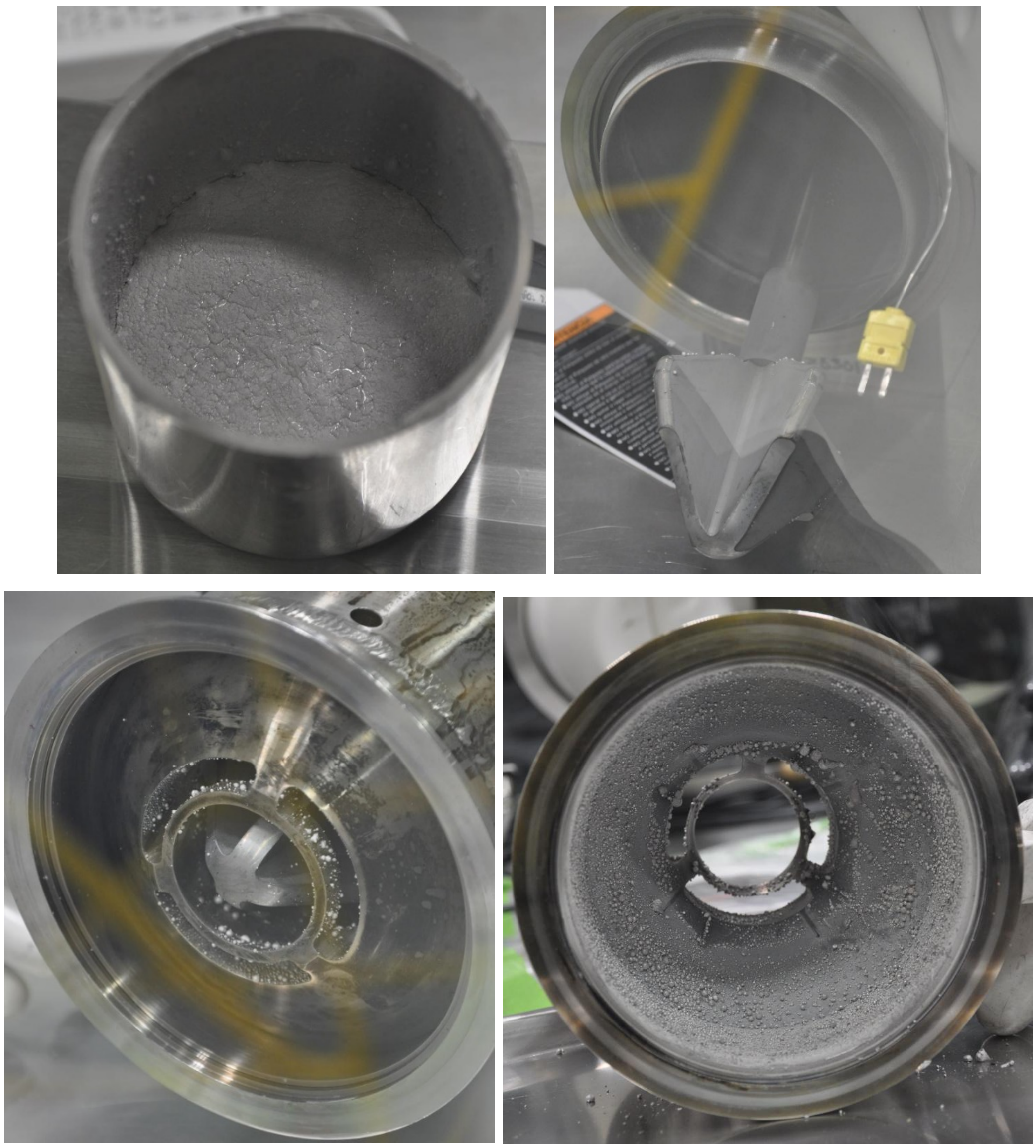

Figure 28. Post-run 2 crucible (upper left), push rod (upper right), underside of nickel funnel (lower left), and top side of nickel funnel (lower right).

Loose sodium beads on the nickel funnel and push rod were removed by lightly scraping the surface with a straight edge and collecting the dislodged beads in a steel pan. The collected beads were added to the sodium in the glassy carbon crucible, and the tray was dry wiped. Post-run masses of the retort body (42154 g), push rod (2634.6 g), nickel funnel (9183.6 g), glassy carbon crucible (390.90 g), and the bundle of elements (16,878.8 g) were obtained. The elements were unloaded into the same tray used to collect and offload the loose sodium beads after the tray was dry wiped. All the depleted uranium alloy slugs from each of the seven elements slid out of the cladding. The separated slugs and cladding from the center element and one perimeter element were set aside for future analysis. The cladding from the remaining five elements was sized to accommodate immersion in a graduated cylinder of alcohol. Pictures of the steel tray used to collect loose sodium metal beads, the unloading of elements, and the sized cladding and separated slugs from five of the seven elements in run 2 are shown in Figure 29.

Figure 29. Steel tray used to collect loose sodium metal beads (left), the unloading of elements (center), and the sized cladding and separated slugs from five of the seven elements (left) in run 2.

A 100-ml graduated cylinder was filled with ethyl alcohol, into which both ends of all 25 depleted uranium alloy slugs were individually immersed. Fine bubbles were observed emanating from one or more spots on nearly 90% of the slugs. While the spots of sodium metal were not visually apparent on the slugs before immersion, the spots became white and more readily detectable upon immersion in alcohol. At no point was the bubbling vigorous; rather, it was faint, lasting from a few seconds to half a minute depending on the size of the sodium metal spot on the slug, which was generally smaller than 1-mm in diameter. A picture of the first immersion of a depleted uranium alloy slug from run 2 in alcohol, which exhibited some bubbling and was typical of all other occurrences, is shown in Figure 30.

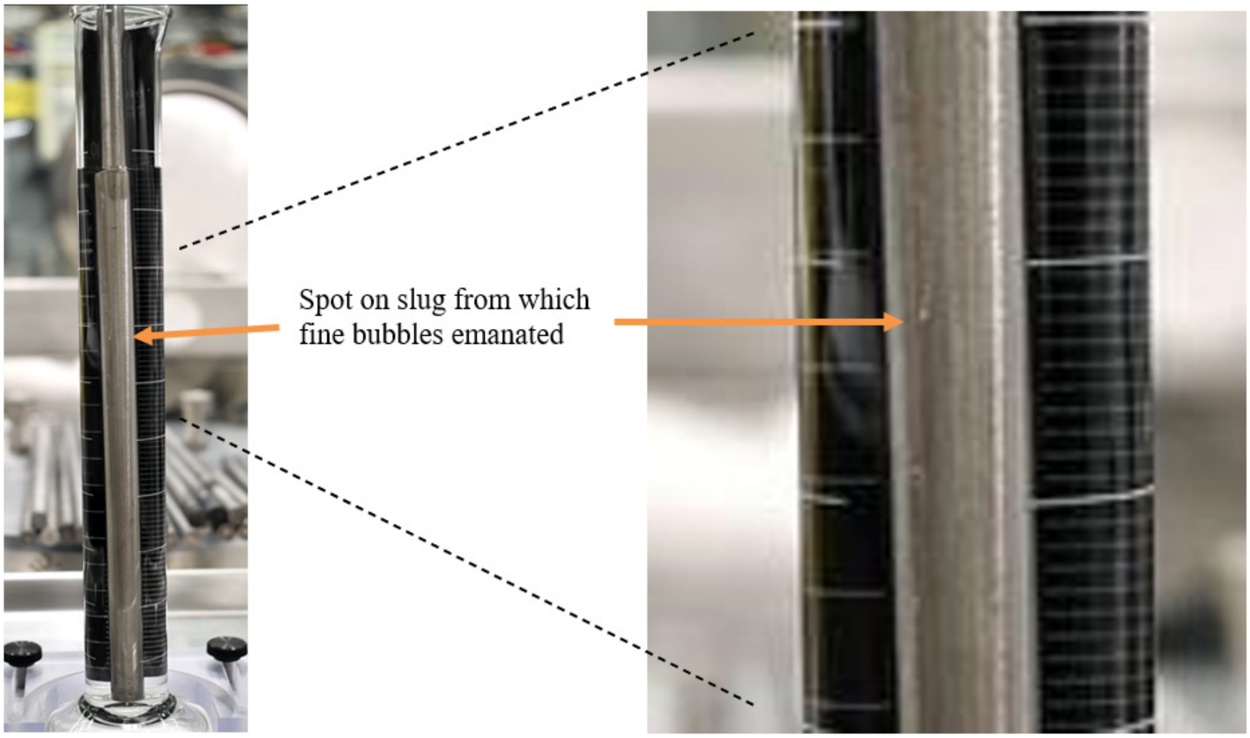

Figure 30. Immersion of depleted uranium alloy slug from run 2 in alcohol (left), expanded view (right).

While individual uranium slugs were immersed in alcohol one-half at a time due to their 14-inch length, the cladding from run 2 was sized below 8-inch lengths to facilitate complete immersion of each cladding segment in the same graduated cylinder of alcohol. After immersing over 100 cladding segments from run 2 in alcohol, fine bubbles were observed on only two segments. Furthermore, the bubbling on those two segments originated from the outside of the cladding where a corresponding white spot like those on the slugs was observed. No bubbling was observed to originate from the inside surfaces of any of the cladding segments, which would have been evidenced by bubbles exiting the top open ends of the segments. Thus, it was concluded that the sodium on the cladding and the uranium slugs originated from contacting fine sodium debris on the steel tray or other glovebox surfaces in the immediate work area. Consequently, the two elements from run 2 that were set aside for transfer to ARL were considered suspect contaminated with sodium metal and not subjected to quantitative analyses. The cladding from the suspect elements was sized and immersed in alcohol, along with the associated suspect depleted uranium metal alloy slugs, revealing similar results in terms of fine bubble formations as observed in the qualitative testing of the previous five elements.

For comparison to slug and cladding segment immersion in alcohol, one of the bottom end pieces with visible sodium metal on its inner surface was immersed in the same graduated cylinder of alcohol. It exhibited a significantly higher volume of hydrogen gas, forming bubbles that rose to the surface at much faster rates. Indeed, the bubbling action was sufficient to create a convective flow of the alcohol within the cylinder and suspend undissolved solid particles. Furthermore, complete reaction of sodium on the end piece with alcohol spanned several minutes, as opposed to seconds for incidental sodium spots on a fraction of the slugs and cladding segments. A picture of the end piece reacting in the cylinder of alcohol is shown in Figure 31.

Figure 31. Bond sodium from the inner surface of a Fermi-1 radial element bottom end piece reacting in a graduated cylinder of ethyl alcohol.

4.2.3 Run 3

The wire wrap was removed from both ends of the remaining seven loose elements. Given the favorable results of bond-sodium removal following the first two runs with both ends of each element open, and for comparison, only the plenum end pieces from three elements were removed with a tubing cutter while both end pieces on the remaining four elements were removed. The breached elements were weighed collectively (17058.3 g) and connected to the push rod as a bundle. The bundle was configured with a single open-ended element in the center, surrounded by the two additional single open-ended elements and four double open-ended elements. All elements were positioned with the open plenum ends toward the push rod.

The retort was assembled with the nickel funnel, moved to the MEDE furnace station, positioned vertically on the retort base with the same loaded glassy carbon crucible following run 2, and enveloped by the MEDE furnace after starting the vacuum pump and verifying a reduced pressure below 200 mTorr. The operating recipe was modified slightly to accommodate zone heating from a single open end of the element bundling during the melting portion of the operation. Specifically, the 1-hour hold of zones 1 and 2 at 185°C was followed by a ramp and 1-hour hold of zone 3 at 170°C, followed by the same for zone 4 and then zone 5. The vaporization portion then proceeded as before, ramping zones 3–5 to 600°C at approximately 17 hours from the beginning of the recipe. Also, in an attempt to lower the amount of sodium metal beading in the condenser, zones 1 and 2 were held at their respective temperatures until 35 and 39 hours after the recipe start time. A time plot of furnace temperature and retort pressure for MEDE run 3 is shown in Figure 32.

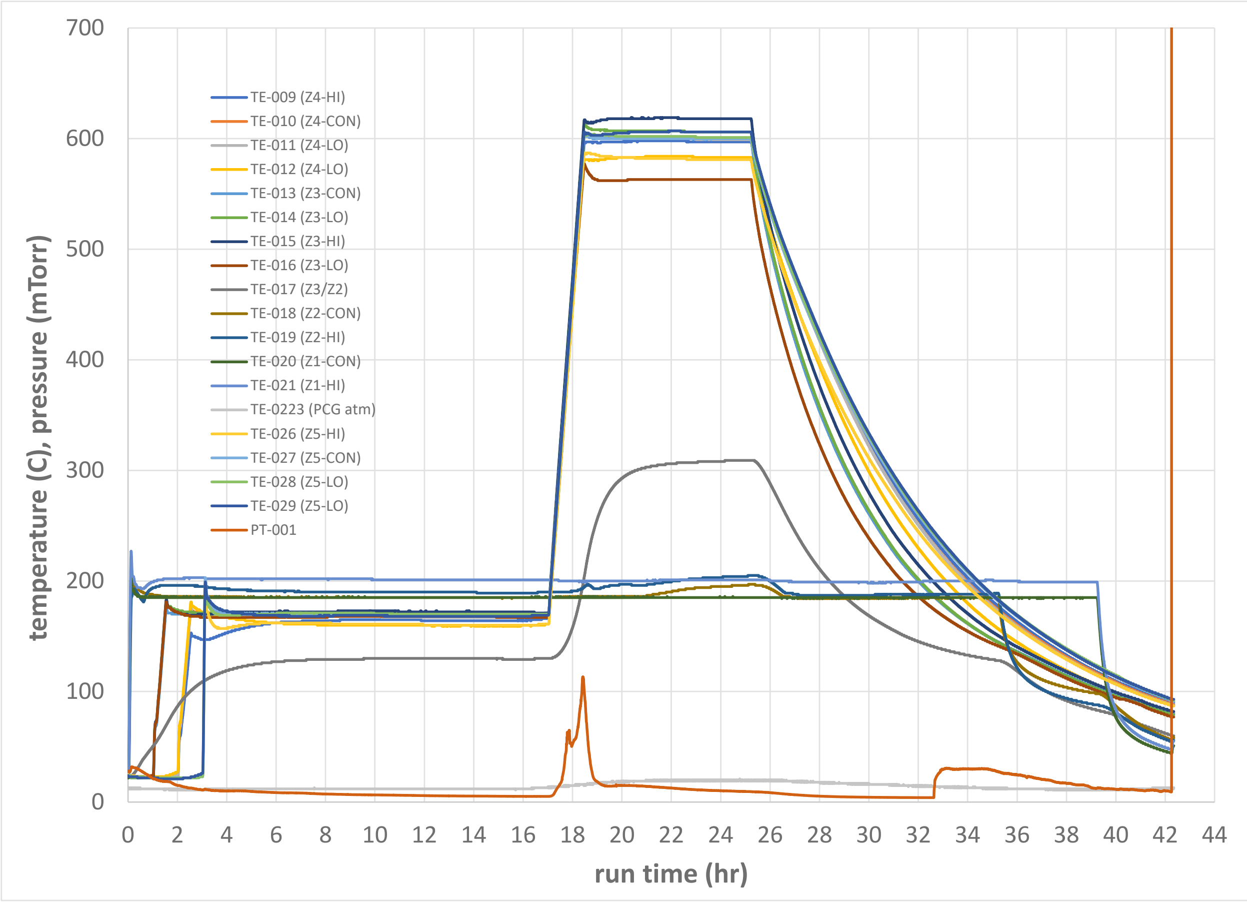

Figure 32. Time plot of furnace temperature and retort pressure for MEDE run 3.

After cooling down, the pressure in the retort was equalized. The retort was removed from its base and moved horizontally to its loading/unloading station. The glassy carbon crucible was removed, revealing an additional amount of sodium in the bottom. Small beads of sodium were observed near the bottom of the nickel funnel. A steel tray was placed under the funnel during its disassembly from the retort body to capture loose sodium beads. After separating the nickel funnel from the retort body, fine beads of sodium metal were observed on the inside surface of the funnel. Relatively few beads of sodium were observed on the push rod (limited to the upper regions of the trefoil blade), and no sodium was observed on the elements or retort body. Pictures of sodium in the crucible, nickel funnel, and push rod are shown in Figure 33.

Figure 33. Post-run 3 crucible (upper left), underside of nickel funnel (upper right), top side of nickel funnel and push rod (bottom).

Loose sodium beads on the nickel funnel and push rod were removed by lightly scraping the surface with a straight edge and collecting the dislodged beads in a steel tray. The collected beads were added to the sodium in the glassy carbon crucible. Post-run and post-scraping masses of the retort body (42162 g), push rod (2635.2 g), nickel funnel (9185.3 g), glassy carbon crucible (560.52 g), and the bundle of elements (16886.0 g) were obtained. Prior to unloading slugs from the elements, immediate work area gloves and surfaces were wiped using rags dampened with ethyl alcohol. Surfaces were allowed to dry, and the elements were unloaded onto a clean steel tray, keeping those elements that had both ends open separate from those that only had one end open. All the depleted uranium alloy slugs from each of the seven elements slid out of the cladding. Given the higher propensity for slugs to exhibit sodium on their surfaces, based on the alcohol immersion tests after MEDE run 2, only the slugs from the center element that had one open end and a perimeter element that had two open ends were transferred to ARL for quantitative analysis. The cladding from the remaining five elements was sized to accommodate immersion in a graduated cylinder of alcohol. Pictures of the element bundle upon removal from the retort and the slug samples from the center element are shown in Figure 34.

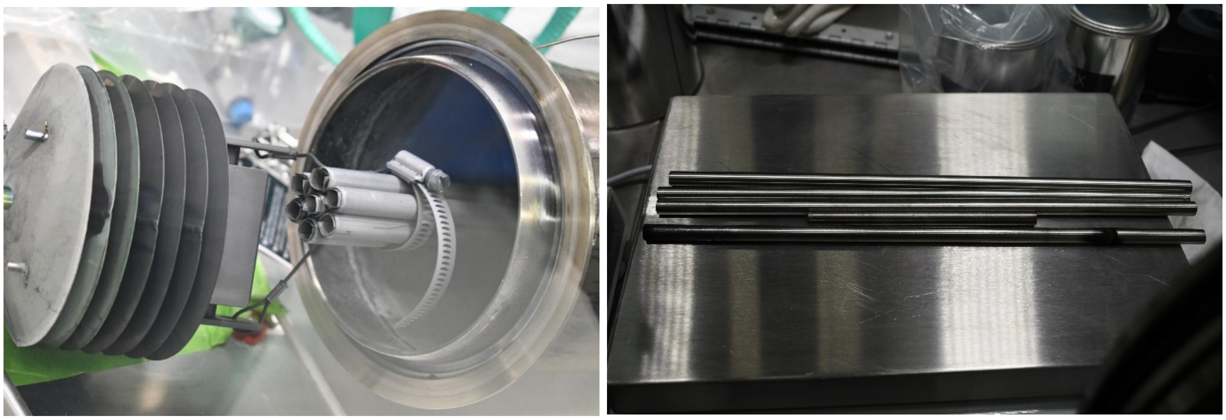

Figure 34. Element bundle upon remove from retort (left) and separated slugs from center element in the bundle following MEDE run 3.

The 15 remaining slugs from the elements with both ends open were immersed in a graduated cylinder filled with ethyl alcohol, and only two of the slugs exhibited spots emanating fine bubbles. One spot dislodged from the slug upon its immersion in the column of alcohol and rose to the surface to react. The other exhibited very faint bubbling. Nearly 50 segments of cladding from the elements with two open ends were immersed in alcohol, and only three of them exhibited faint bubbling. In every case, the bubbles emanated from external surfaces of the cladding, again suggesting they picked up sodium contamination from handling. The ten remaining slugs from the elements with one open end were immersed in alcohol, and no bubbling was observed from any of the surfaces. Nearly 30 segments of cladding from the elements with one open end were immersed in alcohol, and only one of them exhibited faint bubbling from an external surface.

4.2.4 Run 4

Three cuts were made on Fermi-1 radial blanket assembly M893 with a chop saw to prepare it for MEDE operations. The first cut was made through the middle of the bottom grid plate to remove the nozzle end, as shown in Figure 35. This operation produced significant smearing of cut metal, as seen in Figure 35, which required filing of the square duct to remove sharp edges prior to further hands-on manipulations in the glovebox.

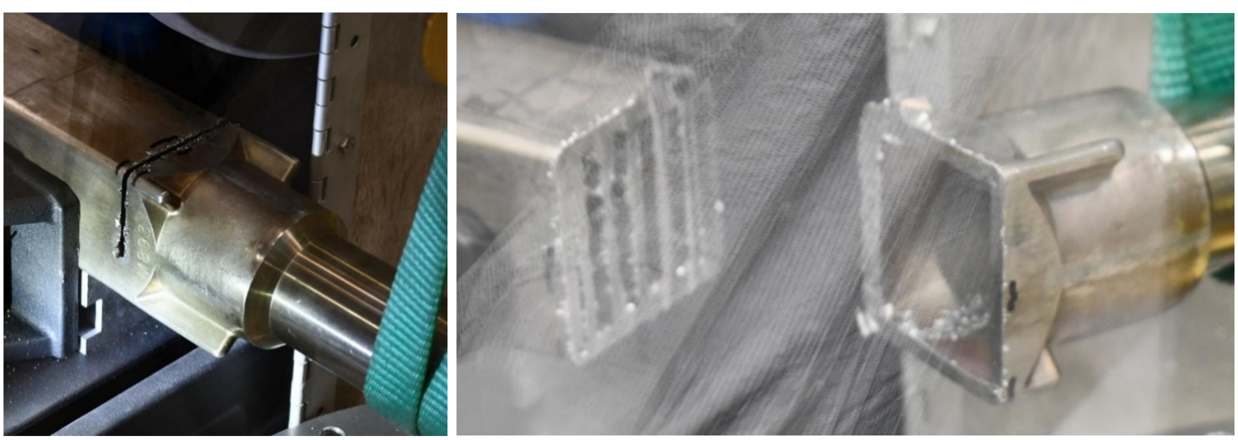

Figure 35. Cutting through bottom grid plate of Ferim-1 radial blanket assembly (left) and separated nozzle end (right).

The second cut was made through the upper grid plate adjacent to the top of the element end plugs, as shown Figure 36. This operation facilitated separation of the entire upper grid plate so that the element top-end pieces were exposed and free to fall away upon subsequent element breaching. This operation likewise produced significant smearing of the cut metal, requiring filing of the square duct to remove sharp edges.

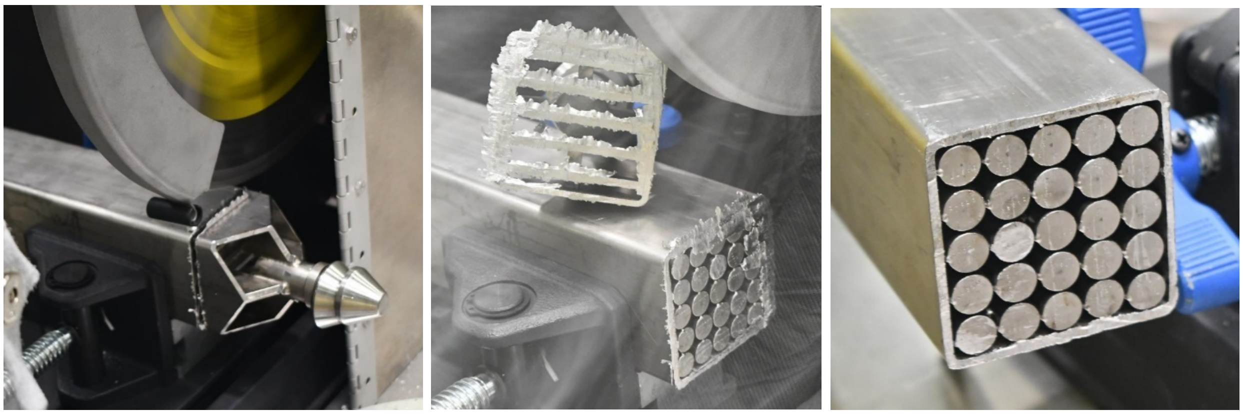

Figure 36. Cutting through the top grid plate of Fermi-1 radial blanket assembly (left), separated assembly lifting fixture (center), and filed end of square duct (right).

The third cut was through the plenum regions of the 25 elements in the assembly, as shown in Figure 37. Some aerosol, presumably from sodium metal, was observed during this operation, as some of the bond sodium in the plenum region appeared to contact the saw blade. Significant smearing of metal was observed over the cut surfaces. The square duct was filed to remove sharp edges prior to handling; however, no attempt was made to remove smeared cut metal, which varied widely, over the individual breached elements.

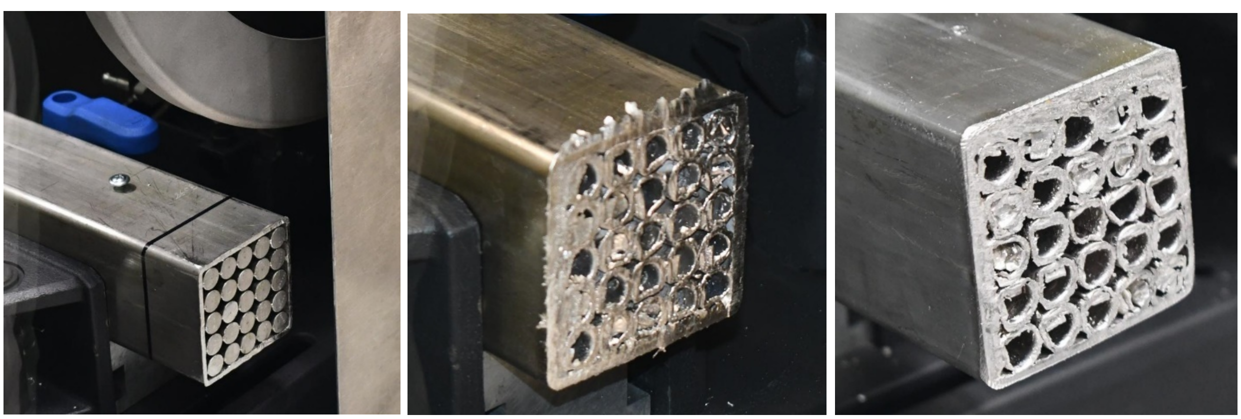

Figure 37. Cutting through the plenum region of Fermi-1 radial blanket assembly (left), cut open ends of elements in assembly before (center) and after (right) filing edges of square duct.

The breached assembly was weighed (70320 g) and connected to the push rod using two screws through opposite faces of the assembly. (Note: These screws were also in place during the third cut of the assembly to preclude rotation of the individual elements upon contact with the rotating chop saw blade.) The assembly was positioned inside the retort body with the open plenum ends of all elements toward the push rod.

The retort was assembled with the nickel funnel, moved to the MEDE furnace station, positioned vertically on the retort base with a new glassy carbon crucible (tare mass of 214.84 g) in place, and enveloped by the MEDE furnace after starting the vacuum pump and verifying a reduced pressure below 200 mTorr. The operating recipe from run 3 was used in run 4 to accommodate zone heating from a single open end of the assembly during the melting portion of the operation. However, the ramp rate of zones 3–5 to 600°C at approximately 15 hours from the beginning of the recipe was lowered to 3°C/minute (from 5°C/minute) to avoid overheating of the condenser from the substantially larger bond sodium loading in this run. Also, the extended temperature holds in zones 1 and 2 following the vaporization portion of the run were eliminated, as they did not appear to inhibit the beading of sodium on the nickel funnel during run 3. Thus, zones 1–5 were all de-energized after approximately 24 hours from the start of the recipe. A time plot of furnace temperature and retort pressure for MEDE run 4 is shown in Figure 38.

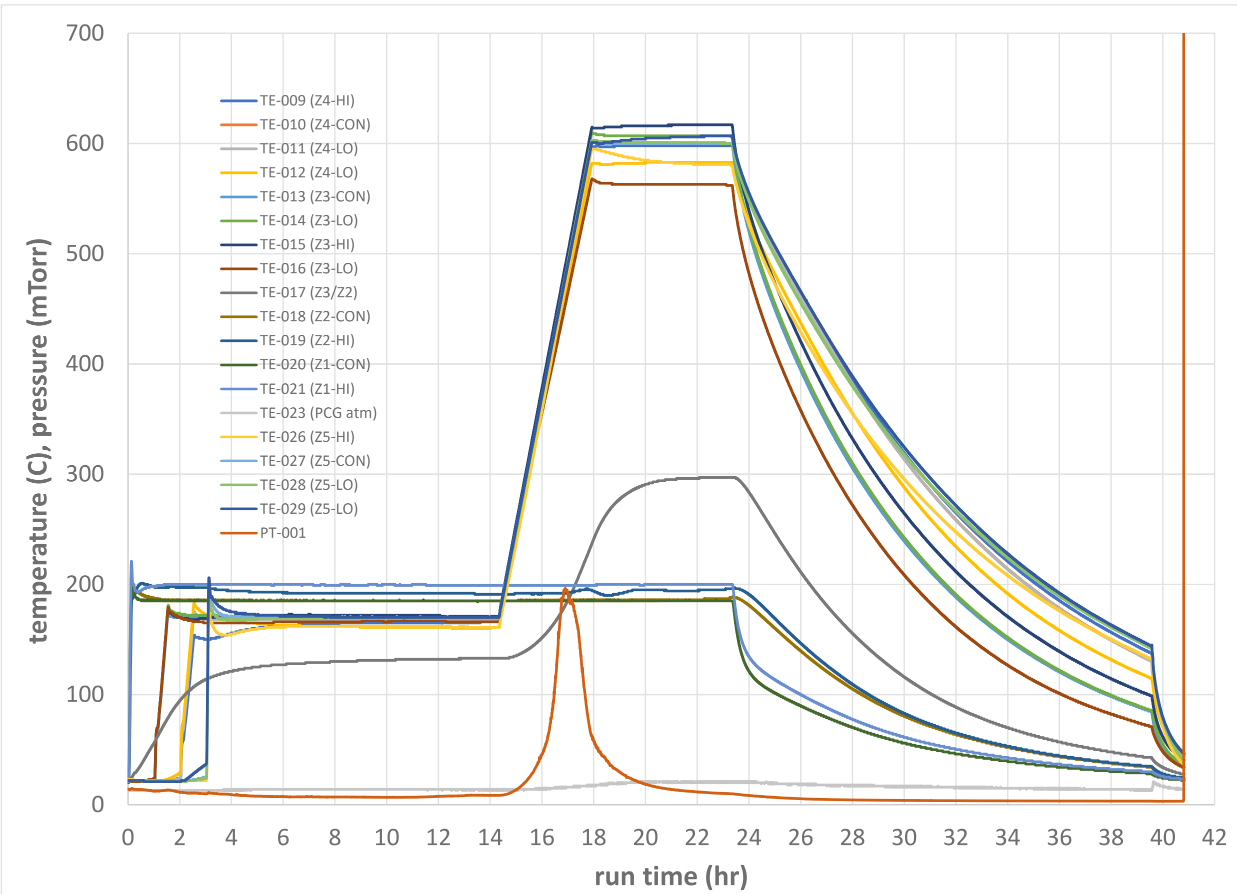

Figure 38. Time plot of furnace temperature and retort pressure for MEDE run 4.

After cooling down, the pressure in the retort was equalized. The retort was removed from its base and moved horizontally to its loading/unloading station. The glassy carbon crucible was removed, revealing a new loading of sodium in the bottom. A larger mass of sodium was observed wetting the nickel funnel. Relatively little sodium was observed on the push rod (limited to the upper regions of the trefoil blade), and no sodium was observed on the elements, assembly, or retort body. Pictures of sodium in the crucible, nickel funnel, and push rod are shown in Figure 39.

Figure 39. Post-run 4 crucible (upper left), top side of nickel funnel (upper right), and push rod (bottom).

Loose sodium beads from the nickel funnel and push rod were removed by lightly scraping the surfaces with a straight edge and collecting dislodged beads in a steel pan. The collected beads were added to the sodium in the glassy carbon crucible. Post-run and post-scraping masses of the retort body (42141 g), push rod (2635.5 g), nickel funnel (9200.2 g), glassy carbon crucible (816.67 g), and the assembly (69680 g) were obtained. Prior to unloading elements from the assembly and slugs from the elements, immediate work area gloves and surfaces were wiped using rags dampened with ethyl alcohol. Surfaces were allowed to dry, and the center element was removed from the assembly. The cladding was cut and tipped, allowing the depleted uranium alloy slugs to slide out of the cladding unto a clean steel tray. The separated slugs and cladding (from the center element in the assembly) were weighed, placed in separate LTCs, and transferred to ARL for quantitative analysis. Pictures of the post-run assembly and disassembled center element are shown in Figure 40. The slugs were likewise separated from an element adjacent to the center element and set aside along with its cladding as archive samples. The remaining 23 elements were removed from the assembly, and all the slugs slid out of the respective cladding. The cladding from the remaining 23 elements was sized to accommodate immersion in a graduated cylinder of alcohol.

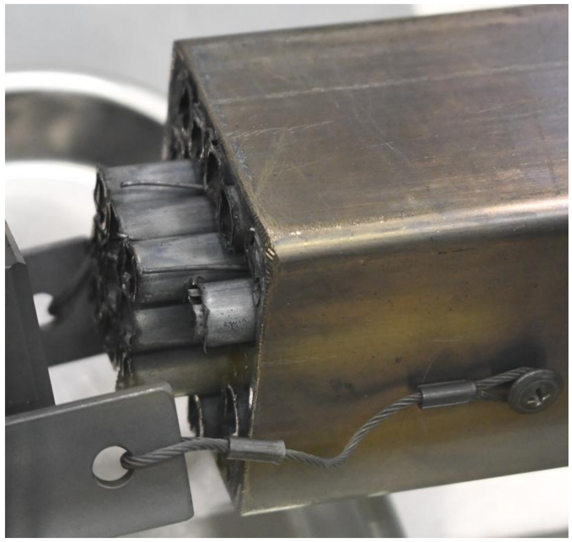

Figure 40. Removal of assembly from retort (left) and separated slugs from center element in the assembly following MEDE run 4.

The slugs from the remaining 23 elements (totaling 115) were immersed in a graduated cylinder filled with ethyl alcohol, and no slugs exhibited fine bubbles indicative of sodium metal on their surfaces. The cladding segments from the remaining 23 elements (more than 200 pieces) were likewise immersed in alcohol and no sodium metal was apparent on any of the pieces.

4.3 Sample Analysis Results

Depleted uranium alloy slugs and associated cladding from MEDE runs 1, 3, and 4 were sampled and subjected to quantitative analyses in ARL, as outlined in Table 3 and as described in section 3.4. Results of the analyses are shown in Table 5.

Table 5. Results of quantitative analysis of samples from MEDE runs 1, 3, and 4.

Run	Sample	Sodium metal (µg)	Total sodium (µg)
1	Slug column	<6	4870 ± 5%
	Cladding	30 ± 6	35700 ± 5%
3	Slug column from center element	<7	375 ± 5%
	Slug column from perimeter element	<6	1060 ± 5%
4	Slug column from center element	14 ± 3	521 ± 5%
	Cladding from center element	19 ± 4	1380 ± 5%

5. DISCUSSION

The removal of bond sodium from Fermi-1 radial blanket material using a MEDE system is based on its volatility, as shown in the sodium vaporization curve of Figure 41. Using an off-the-shelf vacuum system (i.e., a dry scroll vacuum pump), a reduced pressure in the range of 10 to 200 mTorr is readily attainable. A concurrent rise in temperature at reduced pressure drives sodium metal to first melt and then vaporize. The vaporized sodium then transports to a cooler region of a condenser, where the sodium condenses into a liquid and drains into a collection crucible. This movement of sodium is aided by gravity with top-down vaporization, condensing, and collection regions, which were incorporated into the MEDE system for this demonstration.

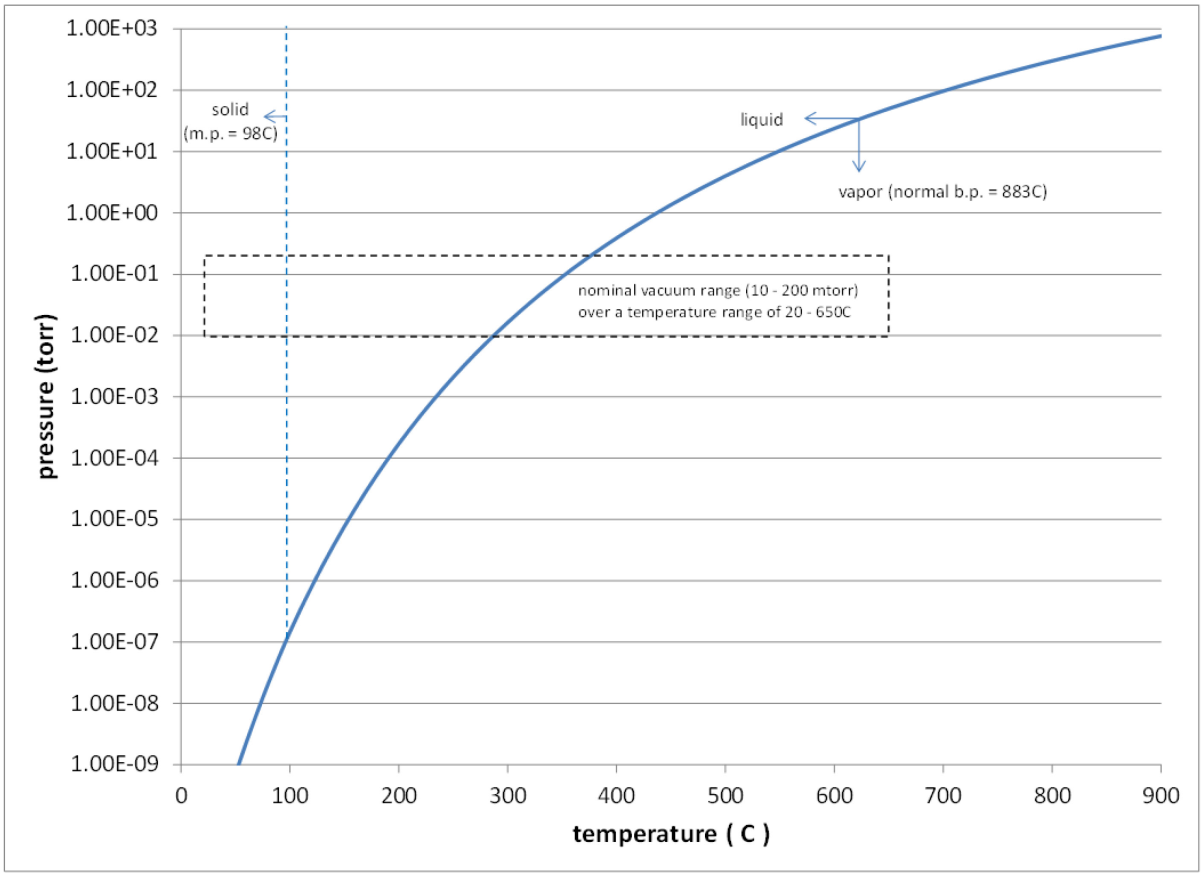

Figure 41. Sodium vaporization curve. [7]

Movement of bond sodium from Fermi-1 blanket materials was tracked over the course of the four runs in this study by weighing the primary components in the MEDE system. A summary of Fermi-1 blanket materials and MEDE component masses for runs 1 through 4 are shown in Table 6, where the sodium masses were determined by differential between sodium-containing components and their respective initial mass from run to run.

Table 6. Summary of Fermi-1 blanket materials and MEDE component masses for runs 1–4.

grams	Component	Initial mass	Post-run 1	Post-run 2	Post-run 3	Post-run 4
MEDE components	Retort body	42140	42160	42154	42162	42141
	Push rod *(Na gain from run)*	2633.4	2634.3 *(+0.9)*	2634.6 *(+0.3)*	2635.2 *(+0.6)*	2635.5 *(+0.3)*
	Nickel funnel *(Na gain from run)*	9181.6	9183.0 *(+1.4)*	9183.6 *(+0.6)*	9185.3 *(+1.7)*	9200.2 *(+14.9)*
	Crucible (runs 1-3) *(Na gain from run)*	198.66	219.53 *(+20.87)*	390.90 *(+171.37)*	560.52 *(+169.62)*	--
	Crucible (run 4) *(Na gain from run)*	214.84	--	--	--	816.67 *(+601.83)*
Fermi-1 blanket materials	Single element, 2-cuts *(net Na loss)*	2429.6	2404.9 *(-24.7)*	--	--	--
	Bundle of seven elements, 2-cuts *(net Na loss)*	17051.0	--	16878.8 *(-172.2)*	--	--
	Bundle of seven elements, 1 & 2-cuts *(net Na loss)*	17058.3	--	--	16886.0 *(-172.3)*	--
	Assembly, 1-cut *(net Na loss)*	70320	--	--	--	69680 *(-640)*

Three balances were used in the pyrochemistry glovebox with different ranges—100-kg, 16-kg, and 6-kg—to weigh the various MEDE components and Fermi-1 blanket materials. The 100-kg balance had a readout of 2 g but was not calibrated to an assigned tolerance. Thus, its measurements were considered approximate. The 16-kg had a readout of 0.1 g and was calibrated to an assigned tolerance of ± 0.4g. (Note: The 16-kg balance was used to weigh all of the elements due to their length, and the bundle of elements were weighed in two parts in order to gain a better accuracy as opposed to using the 100-kg balance.) The 6-kg balance had a readout of 0.01 g and was calibrated to an assigned tolerance of ± 0.08 g.

For runs 1–3, 24.7, 172.2, and 172.3 g of mass (i.e., sodium) were removed from the respective Fermi-1 blanket elements while 23.2, 172.3, and 171.9 g, respectively, were gained on MEDE components, accounting for 94%, 100%, and 99.8% of the mass in each of the runs. For runs 1–3, the average mass of sodium per element was remarkably consistent at 24.6 g. Extending this mass to the 25 elements of the assembly equates to 615 g, which compares well to the 617.0 g of sodium that was collected on the MEDE components for run 4. Thus, the overall balance of sodium between the Fermi-1 blanket material and the MEDE components was reasonable. Furthermore, over the course of the four runs, approximately 98% of the sodium in the MEDE components resided in the two collection crucibles, while 2% remained on the nickel funnel and push rod.

The quantitative analysis of depleted uranium slug columns and cladding from Fermi-1 radial blanket elements from runs 1, 3, and 4 revealed the substantive, if not complete, absence of sodium metal in the treated material. Analysis on three of the six samples, including the slug columns from runs 1 and 3, identified the absence of sodium metal on their surfaces. The cladding from the first run exhibited sodium metal at 30 µg, while the slug column and cladding from the fourth run exhibited sodium metal of 14 and 19 µg, respectively. Each of these detectable quantities was only marginally above a sodium detection level of ~7 µg. For perspective, the detectable mass of sodium from each of runs 1 and 4 equates to a single sodium particle size of ~300 µm, essentially a dust particle. For an average bond sodium loading of 24.6 g in a radial blanket element, the mass of detectable sodium metal from each of runs 1 and 4 equates to a 99.9998% removal efficiency, while the non-detectable sodium mass from runs 1 and 3 equates to >99.9999%. Sodium metal analysis for run 1 was performed before identifying the need to adequately clean areas where the treated elements were handled to avoid sodium contamination. After cleaning measures were applied, non-detectable levels of sodium were observed on the slugs from run 3. However, detectable levels of sodium were observed on the slug column and cladding from run 4 despite the cleaning efforts. The total sodium values provided an indication of how much oxidized sodium might have been present on the treated blanket material; however, these values have no bearing on the reactive characteristic of the material.

The results of the qualitative analyses were consistent with quantitative analyses. First, the mechanical separation of all the depleted uranium slugs from the cladding in this demonstration identified the effectual removal of the bond sodium from the treated Fermi-1 blanket materials, as very little sodium metal would be needed to preclude the free-falling separation of a slug from its cladding. Second, the immersion of all treated slugs and cladding segments in alcohol (that were not subjected to quantitative analyses) identified the substantial, and in most cases, complete absence of sodium metal in the treated elements. The reactions that were observed from the gas bubble formation were faint and short lived. At no point were vigorous reactions observed in the treated material upon alcohol immersion. Furthermore, evidence suggests that the observed faint reactions were likely due to sodium contamination from surfaces of the glovebox. When precautions were taken to clean adjacent work areas and to avoid incidental contact between the treated blanket material and surface areas contaminated with sodium, no sodium reactions were observed upon immersion of the treated materials from the radial blanket assembly in alcohol.

6. CONCLUSIONS

A progression of four MEDE runs with unirradiated Fermi-1 radial blanket elements and an intact assembly proved successful in removing their bond sodium. Collectively, qualitative and quantitative analyses of samples from the four runs revealed the effectual absence of bond sodium from the treated assembly, equating to a sodium removal efficiency of ≥99.9998%, and thereby removing the material's reactive characteristic in regard to material disposition. The results of this demonstration substantiate the use of a MEDE system for treatment and disposal of 34 MTHM of irradiated sodium-bonded Fermi-1 blanket material currently stored at INL.

7. REFERENCES

[1] MEDEC Treatment of FERMI-1 Sodium-Bonded Blanket Fuel in Preparation for Final Geologic Disposal – Final Technical Report, ANL-W Doc . No. F3640-1300-ES-00 (2003).

[2] MEDEC Treatment of FERMI-1 Sodium-Bonded Blanket Fuel in Preparation for Final Geologic Disposal – A Life-Cycle Cost Estimate and Feasibility Report, ANL-W Doc . No. F3640-1287-ES-00 (2003).

[3] Functional and Operational Requirements, MEDE System, INL Doc. No. FOR-438 (2019).

[4] Engineering Job 2972, MEDE System, Element 1 FASB Pyrochemistry Glovebox MEDE System – Furnace, Retort, Tools & Mockup.

[5] Engineering Job 2972, MEDE System, Element 2 FASB Pyrochemistry Glovebox MEDE System – PLC.

[6] Specification, FASB MEDE Furnace, INL Doc. No. SPC-2721 (2019).

[7] HSC Chemistry 7.1, Chemical Reaction and Equilibrium Software with Thermochemical Database and Simulation Module, Outotec (2011).