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Mechanisms Engineering Test Loop (METL) Operations and Testing Report - FY2022

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1 EXECUTIVE SUMMARY

This report documents the operations, testing, maintenance, and improvements that were performed at the Mechanisms Engineering Test Loop (METL) during FY2022. The METL facility had a very successful fourth year of operations and went through some new experiences such as taking the facility from its frozen state in October 2021 and thawing the facility and also recovering from an oxide plug in one of the cold trap lines. After the facility was fully thawed, the METL staff maintained the facility in a continuous molten state – either flowing sodium or a static flow condition. METL facility continued supporting the Gear Test Assembly (GTA) testing and hosted its first 28” test vessel experiment, called the Thermal Hydraulic Experimental Test Article (THETA) which was inserted into Test Vessel 4. Work to accommodate two additional experiments, a gripper test article (GrTA) and a flow sensor test article (F-STAr) continued as they are expected to make their debut in FY2023. In addition, the steam piping for the B308 scrubber unit was replaced with stainless steel piping and controls and new parts for the scrubber were purchased – such as a new pump, new storage tank, and new blower and motor. These components will ultimately replace the existing scrubber components when those 1970’s era require replacement.

1.1 Purpose & Background

The METL facility has the capability to test small to intermediate-scale components and systems for advanced liquid metal technology development. Testing various components in METL is essential for the future of advanced fast reactors as it will provide invaluable performance data and reduce the risk of failures during plant operation.

METL continues to provide development opportunities for younger scientists, engineers, and designers who will ultimately lead the advancement of U.S. liquid metal technologies. The hands-on experience with METL, both successes and perceived failures; will ultimately lead to better liquid metal technology programs that can support the commercialization of advanced reactors.

Some examples of technologies that can be tested in METL include:

1. Components of an advanced fuel handling system – Fuel handling systems are used for the insertion and removal of core assemblies located within the reactor vessel. Undoubtedly, these components are essential to the successful operation of fast reactors. For liquid metal applications, fuel handling systems need to work inside the primary vessel and typically penetrate through the cover gas of the primary system. As a result, fuel handling systems must address issues associated with ‘sodium-frost’ buildup.

2. Mechanisms for self-actuated control and shutdown systems – These components have been conceived by various designers to provide added defense-in-depth for reducing the consequences of beyond-design-basis accidents. These self-actuated control and shutdown mechanisms include devices such as curie-point magnets and fusible linkages.

3. Advanced sensors and instrumentation – Advanced fast reactors contain sensors and instrumentation for monitoring the condition of the plant. Sometimes these components are required to work while immersed in the primary coolant. This category includes but is not limited to, sensors for the rapid detection of hydrogen presence in sodium (which is indicative of a leak), the detection of impurities in the coolant (i.e., improvement of
plugging meters or oxygen sensors), alternative methods of leak detection, improved sensors for level measurement (1) and other advanced sensors or instrumentation that improve the overall performance of the advanced reactor system.

4. *In-service inspection and repair technologies* – These systems include visualization sensors for immersed coolant applications and technologies for the welding and repair of structures in contact with the primary coolant.

5. *Health Monitoring of METL systems and components* – The development of sensors and prognostic techniques for deployment that can monitor and quantify materials degradation in liquid metal-cooled fast reactor primary systems. Technologies that detect degradation early, can survive in typical liquid metal-cooled fast reactor environments over extended periods of time, and can be embedded in/on structural materials to enable structural health monitoring (e.g., nondestructive examination techniques, remote or automated inspection techniques including visualization in optically opaque coolants) can be tested in METL.

6. *Thermal hydraulic testing in prototypic sodium environment* – A thermal hydraulic test loop could be used to acquire distributed temperature data in the cold and hot pools of a small-scale sodium fast reactor during simulated nominal and protected/unprotected loss of flow accidents. This testing could allow for the articulation of the heated region in the core to allow for a parametric study of IHX/core outlet height difference and its effect on thermal stratification of sodium in the hot pool. Ultimately this data will be used for validating CFD and systems level code.

7. *Human Machine Interface Technology* – Technologies for improving the ability of operators to understand what is happening inside the sodium environment. One example would be the ability to provide a refueling system operator to see in-vessel refueling in a virtual environment during in-vessel refueling.

As shown below in Figure 1, the design of the METL facility consists of test vessels connected in parallel to a main sodium loop. The different vessels share an expansion tank, purification system, and several electromagnetic (EM) pumps and flowmeters. This flexible, consolidated design minimizes infrastructure requirements and allows multiple experiments to be performed simultaneously.
Figure 1 – A 3D model of the Mechanisms Engineering Test Loop showing Phase I and four additional test vessels.
1.2 METL Operational Year 3 Accomplishments

The METL facility and team had a successful fourth year of operations that involved validating level sensing equipment and operating the GTA. The METL team remained productive during supporting facility renovations by progressing on experimental designs, upgrading/repairing METL components and supporting industry/academia needs. The following list is the significant accomplishments during the past reporting period:

- METL has maintained its sodium in a molten state (either flowing or static) for almost 3.5 years, since September 19, 2018, and drained the facility on April 20, 2021.
- The METL team brought METL out of a cold and frozen state for the very first time.
- The METL team removed an oxide plug from the inlet cold trap line for the very first time by heating the line to maximum temperature and using an argon push to dislodge the oxide plug.
- Multiple sodium flowing and purification ‘batch’ campaigns were performed.
- The METL team has continued to confirm the functionality of the sodium purification cold trapping system and has purified the METL sodium down to 5 ppm oxygen (150°C).
- Refurbishing of building 308’s superheated steam system was completed.
- The 28-inch flexicask was assembled, but not yet tested.
- Maintained alkali metal program support equipment (Building 308 Scrubber, Superheated Steam System, 18-inch & 28-inch Flexi-Casks, Carbonation System, Glovebox and Qualifying Stations)
- Performed the fourth test article extraction using the 18-inch flexicask from Test Vessel 1 (GTA extraction from Test Vessel 1) to the carbonation vessel
- Performed the fourth cleaning using moist carbon dioxide followed cleaning with ethanol and water, and by disassembly of the GTA on the 18-inch test stand
- Performed the fifth test article extraction using the 18-inch flexicask from Test Vessel 1 (GTA extraction from Test Vessel 1) to the carbonation vessel
- Performed the fifth cleaning using moist carbon dioxide followed cleaning with ethanol and water, and by disassembly of the GTA on the 18-inch test stand
- Continued demonstration of level sensor technologies (using an inductive level sensor, a differential pressure sensor, and a thermophysical property probe).
- Modified two of the three flow meters from hall-effect sensor flow meters to permanent magnet flowmeters.
- Worked with Virginia Tech professor to test an optical fiber-based flow sensor as part of a NEUP award.
- Purchased and obtained a replacement B308 scrubber water pump, water storage tank, and blower/motor for the 1970’s era B308 scrubber. METL cannot operate without a functional oxide scrubbing system.
• Initiated the design of an extension of the METL platform to increase the usable floor space for METL operations and maintenance.

1.3 Plans for FY2023 at METL Phase II
The METL facility will continue with molten sodium operations in FY2023. During FY2023, we expect to be reconditioning the Gear Test Assembly (6th time) which was tested in FY2019-2022 and retesting the test assembly in Test Vessel 1 with new bearing blocks and bearings. The THETA experiment primary system will continue with its testing and the project will install the secondary system to allow for the rejection of the heat generated by the THETA primary core. The secondary system will be filled with sodium. The THETA primary and secondary system will be operated as unit for thermal hydraulic code validation. We will be operating the inductive and thermal property probe level sensors and installing an ultrasonic heat monitoring system on the Test Vessel 6 primary piping system, system will be operated, and Test Vessel 6 will be installed in METL. Test Vessel 6 piping is nearly 80% complete and will then be equipped with heaters, instrumentation, and insulation. We initiated the design of an extension to the METL platform to increase the usable space for METL work. We will continue to collaborate with industry and support the nuclear energy university program calls for experimentation in METL.

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The authors are also very grateful to the former Argonne personnel who worked on EBR-II and sodium technology in the former Components Technology Division.
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2 Background and Objectives

The successful operation of sodium-cooled fast reactors will largely depend on how well their components work within a sodium environment. Therefore, the mission of the Mechanisms Engineering Test Loop (METL) is to provide the infrastructure and technical expertise required to test advanced technologies in a high-temperature sodium environment. In turn, the results gleaned from experiments performed in METL will help to develop state-of-the-art advanced reactors.

2.1 Design Overview

The layout of METL follows the characteristic design of a sodium test facility. The facility consists of multiple test loops in which tanks/vessels, valves, and other components are interconnected via piping and tubing. The system is designed to handle both static and flowing sodium which permits each test vessel to provide the environment suitable for the specific needs of an experiment. During operation, the sodium is purified by passing it through the METL cold trap. Impurity levels can be continuously monitored using the plugging meter. The general design temperature of the facility is 1000 [°F] but the maximum design temperature of a 28” test vessel is 1,200 [°F] (Figure 2).
3 METL Operations

METL is a unique U.S. facility within the Department of Energy complex as it provides opportunity for researchers to test small to intermediate scale sodium components but also acts as an experiment itself. METL’s infrastructure promotes flexible operations to accommodate virtually any device that fits within the volume of the Test Vessels but also has open mezzanine area and (3) inlet/outlet ports available to demonstrate larger or loop-type tests. In addition, METL’s 20+ year operational life will garner information and experience essential for SFR commercialization that small/benchtop test apparatus which are periodically operated cannot supply.

METL’s resemblance of a liquid metal reactors (LMRs) intermediate heat transport system yields data directly applicable to operations and maintenance of LMR systems and components. METL’s configuration, scale, and years of continuous operation establishes a proving ground not only for SFR equipment but also supporting equipment and operational methods.

3.1 Thaw

In the FY2021 METL report, the need to freeze METL to accommodate repairs on the alkali metal scrubber was described. A strategic thaw process was conceptualized in FY2021 to ensure sufficient expansion volume as the sodium undergoes a phase change. Post scrubber repair, this thaw process procedure was performed to melt METLs sodium so that its’ mission could continue. The general process of thawing METL involved heating the argon service portion of METL above sodium’s melting point first, then proceeding to melt its’ adjacent sodium service zone and continuing this process through the piping network until the entire facility was molten. The molten section of sodium expands due to a density decrease from a temperature increase. If the expanding sodium is constrained by a closed valve or frozen sodium, the result could be a ruptured pipe or fractured vessel; hence, the scrutiny behind the thaw procedure.

The thawing process is straight forward for most of the facility as each vessel/tank has a vapor space (argon service zone) to which the heating can originate, and majority of the components were empty. However, the Cold Trap and Plugging Meter (diagnostic loop) portions could not be drained prior to freezing, presenting a challenge to melting this section. An attempt to illustrate the complexity associated with thawing this portion of METL is provided by the steps taken to change the set point of heater zones found in this subsection of METL (see Table 1). Special care had to be taken when thawing the sodium near the piping Tees, valves and other piping junctions.
Table 1. Cold Trap and Plugging Meter Thaw Sequence of Operation

| Zone                  | Current Temp | Step 1 | Step 2 | Step 3 | Step 4 | Step 4.5 | Step 5 | Step 6 | Step 7 | Step 8 | Step 9 | Step 10 | Step 11 | Step 12 | Step 13 | Step 14 | Step 15 |
|-----------------------|--------------|--------|--------|--------|--------|----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| CT EM PUMP to CT OUT (26) | 56 | 85 | 92 | 120 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| PM EM PUMP to PM IN (28) | 62 | 85 | 92 | 120 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| PM OUTLET TO PM OUT TOP (32) | 64 | 85 | 92 | 120 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| Pipe Zone 38: FM TO EM PUMP (CT) | 58 | 85 | 92 | 120 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| Valve CT OUT / PM IN | 52 | 85 | 92 | 120 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
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| Cash Traps (Pumps) | 60 | 60 | 60 | 85 | 92 | 120 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| Econo to EMFM | 60 | 60 | 60 | 60 | 85 | 92 | 120 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| Econo tot Ex Top (14) | 60 | 85 | 92 | 120 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| Econo to Econ Top (14) | 60 | 85 | 92 | 120 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| Econo to Ex Top (14) | 60 | 85 | 92 | 120 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| Econo to Ex Top (14) | 60 | 85 | 92 | 120 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| Econo to Ex Top (14) | 60 | 85 | 92 | 120 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| Econo to Ex Top (14) | 60 | 85 | 92 | 120 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| Econo to Ex Top (14) | 60 | 85 | 92 | 120 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
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| Econo to Ex Top (14) | 60 | 85 | 92 | 120 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
| Econo to Ex Top (14) | 60 | 85 | 92 | 120 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 150 |
3.2 Plug

Upon thawing and reaching METL’s normal operating temperature of roughly 300°C, a sodium purification operation was conducted for two business weeks to remove any sodium oxides that may have been generated during METL’s downtime. The METL team was able to successfully carry out this preventative maintenance measure and proceeded to refill test vessels to resume experimentation.

When sodium is transferred from the Dump Tank to another portion of METL, it undergoes a purification operation to ensure its components and experiments have an acceptable level of sodium oxides. It was during the purification after refilling test vessels that an issue arose as no sodium flow was developing. The Cold Trap (purification) pump was activated, and its’ operation was verified by measuring the coil’s current draw. All valves in the system were physically inspected to verify they were in the correct position and the temperatures of all the heater zones were well above the freezing point of sodium, thus, suggesting there was a sodium oxide plug somewhere in the system.

3.2.1 Diagnosis of Plug

Utilizing the Plugging Meter electromagnetic pump and flowmeter, sections of METLs piping network could be verified clear of major obstructions by reconfiguring the valve positions. An example of this is illustrated below in Figure 4. The plugging meter pump was energized (yellow electrical sign) to move sodium through the plugging meter and over towards the cold trap. The plugging meter flowmeter indicated a positive flow rate thus proving these zones were clear.

![Figure 4. Example of determining unobstructed lines](image-url)
Sections that could not be tested using the methodology illustrated in Figure 4 were determined to be clear by utilizing two pressure transducers mounted to the inlet and outlet of the cold trap. Both pressure transducers indicated high pressure values when sodium was pumped backwards through the cold trap but remained steady state when pumped in the forward direction, proving the plug was not the pump itself as a pressure was generated and its’ relative location was between the cold trap pump outlet and cold trap inlet pressure transducer.

Three components remained suspect; the cold traps newly renovated flowmeter, the economizer and an ultrasonic flow meter installed between the economizer and the cold trap inlet pressure transducer. The flow meter had fans operating to keep its’ magnets cool but this in turn cooled the duct. The fans were shut off, the duct was allowed to reach near 250°C and the pump was energized. This resulted in a slight oscillating flow signal, providing credible evidence the plug was elsewhere.

The economizer is effectively a tube in pipe heat exchanger to pre-cool and pre-heat incoming and outgoing cold trap sodium, respectively. Accounting for the diameter of the helix wound turbolator, the distance between the inner ¾” tube and 1-1/2” schedule 10 outer pipe is 0.421”. The size of the annulus and inner tube cross-sections coupled with the fact the economizer maintained a steady temperature and was well insulated with vermiculate deemed a plug in the economizer to be unlikely, shifting focus to the ultrasonic flowmeter.

### 3.2.1 Root Cause of the Plug

Two ultrasonic flowmeters were installed in FY2021 during METLs frozen period; one on the primary loop, downstream of its electromagnetic flowmeter and the other was installed between the cold trap inlet and economizer. The primary loop was free of obstructions as sodium was able to flow freely though all its zones, but a combination of factors led team members to believe the plug existed at the cold traps’ ultrasonic flowmeter installation location due to the following:

- Installation requires the ultrasonic transmitters to protrude from the insulation to prevent overheating, increasing heat loss.
- Flowmeter was distant from process control thermocouples, omitting this disturbance from the control loop and in turn inadequate heat input.
- Location was after the economizer; sodium was pre-cooled prior to flowing through the flowmeter
- The sodium inventory was purified for 10 consecutive business days followed by a couple weeks of no flow while maintaining the facility in a molten state stand-by state.

In summary, the cold trap’s ultrasonic flowmeter installation’s insufficient heat input plus additional heat loss created a ‘cold spot’. The location was at a lower temperature than the cold trapping process. It is believed during the two-week purification, sodium oxide was deposited in the ultrasonics flowmeter conduit cold spot instead of the cold trap, ultimately forming a plug.
3.2.2 Clearing of the Plug

When the general location of the plug was identified, attempts to reestablish flow were made. Firstly, additional insulation was added to verify that it was indeed a sodium oxide plug and not a frozen section of sodium. Temperatures were increased well beyond the melting point of sodium and still no flow was generated, confirming the existence of excessive sodium oxide. The melting point of sodium oxide is 1,132°C, well above the maximum operating temperature of METL. Excluding replacing the plugged section of pipe, increasing the pressure to “push” the plug out and into the cold trap was the only option to remediate the issue.

METL’s valves were arranged to drain the expansion tanks’ sodium through the cold trap and into the dump tank (Figure 5). This allowed METL operators to increase the pressure in the expansion tank to assist in removing the plug in the cold trap inlet line. Pressures were increased to the actuation point of the pressure relief valves (20psig) and valve ‘L-OUT’ was opened to initiate the expansion tank drain/plug removal.
Several iterations of draining/refilling the expansion tank with this configuration were conducted. Only a small flow rate was achieved, and it did not clear the line to the extent the electromagnetic pump could generate a differential pressure which could overcome the resistance. A majority of METL is code stamped for 200psig at 1000°F, the lowest pressure rating being the cold trap at 100psig at 1000°F. The expansion tank’s original pressure relief valve (PRV) was exchanged for one that actuated at 100psi, enabling the pressure to increase to 80psig (the PRV begins to slowly leak at 80% of its’ actuation rating). Pursuing the argon pressure ‘push’ at 80psig cleared the sodium oxide plug in the cold trap inlet line as sufficient flow rate was achieved. The cold trap pump was energized and was able to produce sodium flow through the cold trap. Clearing of the sodium oxide plug allowed for periodic purification operations to resume and METL to continue its mission.
3.3 Experimental Campaigns

In FY2022 the METL team supported two active experiments, the Gear Test Assembly (GTA) and the Thermal Hydraulic Experimental Test Apparatus (THETA) in addition to a future experiment, the Flow-Sensor Test Article (F-STAr). Investments and modifications to METL to support experimental programs will continue, assuring researchers have resources to perform a successful demonstration of their technology or quality data for code validation.

3.3.1 GTA Continuation

The Gear Test Assembly (GTA) is equipped with servo-motor driven gears to evaluate fuel handling equipment for SFRs. The METL team provided purified sodium for two test iterations of the GTA in FY2022. Combining the two test runs, the GTA (Figure 6, left) completed 3,682 fuel assembly insertions and removals while installed in METL. A full report on GTA FY2022 progress is provided in the reference section (2).

3.3.2 THETA

THETA (Figure 6, right) is METL’s flagship thermal hydraulic experiment which has a myriad of test applications such as instrumentation calibration/demonstration, thermohydraulic phenomena investigation and equipment/material evaluation. METL team members filled and proceeded to purify sodium in test vessel 4 for conducting THETA’s inaugural test matrix. During the fiscal year METL performed periodic sodium purification operations to maintain sodium quality in test vessel 4. In FY2022, THETA’s data acquisition system was integrated with the METL ecosystem’s VLAN, enabling communication between METL and THETA. Further details regarding THETA and results from its test matrix were captured in its yearly report (3).
The Flow Sensor Test Article (F-STA) is a test article currently under construction for the Mechanisms Engineering Test Loop (METL). F-STA was designed to provide high sodium flowrate capabilities for sensor calibration, component testing, and fluid studies. Figure 7 shows two solid model views of the new test article. F-STA includes a high-capacity pump that can provide a nominal flowrate of 120 GPM; a test section support structure that can accommodate a wide array of sub-test articles and their instrumentation; and finally, a heating and cooling system to aid in controlling the testing environment.
The status report for F-STAr is reported in the Flow Sensor Test Article (F-STAr) – Design and Fabrication Status Report, August 2022. The reference selection provides direction to a report on F-STAr’s status as of FY2022. (4)

3.4 Extended Research and Outreach
Repeating earlier discussions, METL’s primary mission is to support experiments to advance SFR development but the facility is also an experiment itself. The later statement continues to hold true as various uses of METL and data generated have translated to research activities which weren’t initially considered. In addition to pursuing cross-cutting initiatives, the METL team has assisted internal and external collaborators with understanding METL/data generated, were co-applicants on numerous NEUP proposals and provided presentations at industry conferences and forums.
4 Continuous Improvement

METLs success throughout the years has demanded the facility perpetually investigate and pursue emerging and cutting-edge technologies concurrently with increasing system efficiencies, maintaining existing capabilities and improving ease of access for various experimenters.

4.1 Instrumentation and Control

Modern industrial plants have an increasing reliance on instrumentation and control (I&C) and cyber-security systems required to protect them, nuclear power plants are no exception. METLs mission expands past providing an in-situ SFR environment for experimentation to evaluating analogous I&C and processes with the intent to accelerate adoption/approval at advanced reactors.

4.1.1 Flow Meter Calibration

In FY2021, two of three electro-magnetic flow meters underwent a transition from utilizing hall-effect sensors to a permanent magnet flowmeter; full details on this work are found in the previous FY METL report (5). OEM hall-effect sensors measured the magnetic field shift induced by flowing sodium whereas ANL modified the existing flowmeter hardware so that the electromotive force generated across two electrodes welded orthogonal with respect to the magnetic field and sodium flow direction could be measured with a standard voltage input data acquisition module. The result of this was a stable and reliable indication of sodium flow but required calibration which is subsequently explained.

Leveraging sodium level sensors developed and installed at ANL enabled online electromagnetic flowmeter (EMFM) calibration. METL’s expansion tank was filled with sodium while test vessel 2 was empty. Valves were set to the positions shown in Figure 8 to force flow through the cold trap and plugging meter flow meters once valve ‘V2 OUT’ was opened. A tank blanketing and back pressure regulator ensured a relatively constant pressure differential between the expansion tank and vessel 2 during the sodium transfer. Level sensor and EMFM voltage outputs were recorded during the transfer, given the internal geometry of the expansion tank, the volumetric flow rate versus EMFM voltage. The process was repeated to increase confidence in the calibration.
4.1.2 CMI Heater Consolidation

In the preceding section, the commercial off the shelf flowmeters were converted and thus most of their support hardware (DC power supplies, PACs, transformers, etc.) are no longer needed. The only remaining components in use were the controls to maintain a molten temperature on their respective conduits and on the ALIP, cooling fans. The ease of transitioning this responsibility to spare METL heater zone process loop controllers and the premium space the aforementioned equipment was occupying provided the momentum to generate a consolidation plan, which is outlined below.

Like METLs heaters, the conduit heaters are 1Φ-240VAC and the largest conduit heater draws 1.875A. METLs Power Enclosure 3 (PE 3) has the most power available (75 spare 8A heater zones) so this was selected as the source for all the conduit heaters. Consequently, PE3 already has the spare conductors routed so once de-energized, only source and load termination connections need to be made.

Process loop controller, Eurotherm Mini-8 #8 has zero active loops so this device will be used to monitor/control the conduit heater zones. Mini-8 #8 is in Control Enclosure 1 which has 21 thermocouple umbilical cables routed throughout METL. Thermocouple umbilical #12 was selected as it has a sufficient vacancy for the additional heater zones and is within reasonable proximity of the heaters. In summary, upon identifying an appropriate time to LOTO METLs power enclosures, the consolidation should require minimal modifications and translate into easier operations and decongest METLs mezzanine.

4.1.3 cDAQ Replacement

Over the past FYs, METLs control system has been systematically converted from a centralized-monolithic control scheme to a decentralized and modular architecture. New
hardware installed consisted of real-time Linux operating systems, but some original data acquisition chassis could only be commanded from a Windows operating system. This fact combined with the manufacturer’s notification that these chassis would no longer be supported in the coming years required their replacement.

Figure 9. Obsolete (left) and New (right) Chassis

The new chassis which allow for a Linux master, were slightly larger, requiring new enclosures and the critical values they obtained (pressures and valve positions) demanded a prompt replacement as well as a standardized design. In FY2022, the chassis, enclosures and terminal blocks were received. These components were assembled in their enclosures and wired on a bench top to the extent possible, minimizing ‘down-time’. All (8) data acquisition enclosure/chassis were successfully installed and integrated with the METL control program with no downtime to METL.

4.1.4 Air Conditioners

The brain of METL is in a control room, consisting of a Linux Real-Time Industrial Controller and two enterprise grade managed network switches. The room is cooled with a 2-ton minisplit to protect METLs I&C. Similarly, room C-102 in B308 is equipped with a 3-ton minisplit which removes heat from four power enclosures (discussed in the following paragraph). Due to the importance of these minisplits, a MODBUS RTU to TCP converter was installed to communicate with an IR AC interface gateway, adding to METLs I&C capabilities.
The heart of METL is composed of four electrical enclosures which control hundreds of electric resistance heater circuits. Each has an input of 150kVA, requiring dedicated enclosure air conditioners to remove heat generated inside of the panel. Maintaining adequate temperature and humidity levels is essential to METL’s operation and longevity. Four IIoT interfaces and IoT adapters for interfacing with the legacy air conditioners were installed in FY2022 (Figure 10). This hardware provides the use of a web-based portal for manipulating and configuring the equipment but also enables the METL control program to monitor and adjust these air conditioners. Adding the seemingly trivial components to METL’s I&C is relatively consequential as now the root cause of a heater zone component or networking device malfunction may be determined or avoid a failure altogether.

4.1.5 Acoustic Emission

Advancing non-destructive examination (NDE) technologies is extremely beneficial for numerous industries. NDE and continuous monitoring of piping networks is of particular interest for the nuclear energy industry as it may lead to economic designs, increased automation, reduced inspection intervals and accelerated licensing/renewal. Commercially available acoustic emission (AE) software and hardware was procured in FY2022 and is on-site (Figure 11).
Waveguides are welded onto the piping which allow the sensors to ‘listen’ for acoustic signals emitted from a high temperature system. The continuous monitoring and regular post analysis of elastic waves traversing METLs piping segments during normal operating conditions will enable the team to detect a plastic deformation prior to it escalating to a failure as the energy generated from this irreversible change will be in the form of a stress wave which is able to be captured by the AE instrumentation. Equipping METL with this technology not only provides the potential detection of a degrading piping section, avoiding a sodium breach and reducing resulting downtime but also provides a baseline from a cost, installation, use and accuracy perspective for newly developed systems. The addition of an AE system is expected to compliment two Nuclear Energy University Programs (NEUP) which plan to demonstrate structural health monitoring (SHM) technologies. These include NEUP Projects 21-24162 and CFA-22-27082.

4.2 Information Technology
Integration of information technology (IT) into operational technology (OT) has continued to increase and this merger is expected to only become more critical especially as the 4th Industrial Revolution evolves. Placing METL in a position to apply emerging trends required the reevaluation of its network topology. Presently, METLs network has dozens of controllers which communicate with a single server and a virtual machine to act as a bastion host.
Increasing METLs capabilities has resulted in adding responsibilities to the aforementioned devices. The METL team expects to deploy extended reality applications in FY2023, to counteract this increased workload on the existing infrastructure, a new IT topology (Figure 12) was conceptualized and will be online in FY2023. The changes include acquiring (2) new servers, (1) development PC for hosting/generating extended reality content and moving services such as the website to a virtual machine.

**Figure 12. New METL IT Topology**

### 4.2.1 Web Service

METLs webservice was conceptualized as an OS and IDE agnostic method to securely obtain live data for METL users and affiliates to create any application conceivable. The data is separated by read-only and read-write, allowing developers to gather all information pertaining to METLs status. Demonstrated uses include:

- **Quantum Key Distribution** (6)
  - METL health broadcast data was encrypted, transmitted via webservice and the client decrypted the data via key distributed by a simulated quantum computing network

- **Anomaly Detection**
  - During METLs purification process, a component was deenergized and historical data was import into a long short-term memory (LSTM) neural network for evaluating its ability to detect the failure. The process was...
repeated to verify LSTM to discover the anomaly real-time using the webservice.

- Web-Based Graphical User Interface (GUI)
  - A web-based GUI was developed utilizing the webservice on the back end to display data to virtually any device, including two kiosks on ANLs campus.

![METL Data View](image)

**Figure 13. METLs Web-based GUI (left) and Touch-Screen Kiosk in Building 208 Lobby (right).**

The uses of the METL webservice and its associated data are expected to grow as future applications have already been in development. These include browser-based control, creation of a tool to swiftly obtain historical data, transmitting data to extended reality devices and assisting in evolution of machine learning and artificial intelligence techniques related to SFR/advanced reactor operations and maintenance.

### 4.2.2 Intranet

Developing a facility-specific intranet is an effective way to ensure designers, engineers, technicians, and experimenters can rapidly view/edit commonly accessed documents, live data feeds and other resources. Presently, the METL intranet provides quick access to a virtual tour of METL, two live data feeds (system and asset perspectives), links to frequently accessed files (e.g., torque patterns, sodium properties, drawings, etc.) for download or viewing and a placeholder to incorporate web-based control of key METL and support equipment operations. Future capabilities may also include a digital logbook and historian to swiftly obtain read-write and read-only data logged to disk.
Figure 14. METL Intranet
5 Building 308 Investments

Constructed in the late 1950s, Building 308 (B308) was built to conduct alkali metal research and it continues to support this mission today. Previous fiscal years efforts included replacing the roof, painting the siding, increasing the electrical capacity of the power coming into the building from 1,000KVA to 2,000KVA, high-bay air conditioning and renovating the alkali metal scrubber. During FY2022, Building 308 again saw major investments by ANL. Expenditures included rehabilitating the superheated steam system, replacing B308’s 100kW redundant power supply, improving the B308 alkali metal scrubber (AMS) and removing historical equipment.

5.1 Superheated Steam System Rehabilitation

The B308 superheated steam system is used for alkali metal decontamination. Its’ simple function increases the temperature of utility saturated steam until it reaches a superheated state. A wand is then used to direct superheated steam at surfaces coated with alkali metals. The superheated steam method is an effective way to have a slow reaction rate between water and alkali metals as the superheated steam is effectively water at a very low density. The original system was constructed of two superheaters connected in parallel with carbon steel piping. During design reviews, it was determined the redundancy was not needed as the system layout allows for easy isolation and swapping of heating elements.
Figure 15. New Superheated Steam System

The newly built superheated steam system is built from stainless steel piping and is equipped with modern instrumentation and control which is integrated with the B308-AMS PAC and HMI. Pressure measurements in conjunction with the density value from the steam flow meter allows operators to know the level at which the steam is superheated.

5.2 Redundant Power Update

B308 was originally equipped with a 100kW diesel generator which fed an automatic transfer switch (ATS) to energize a panelboard in the event B308s’ substation A lost power. Allowing sensitive loads throughout the building to remain powered during substation A failure or maintenance. The eventual failure of this diesel generator and generation of electrical equipment prompted their removal to accommodate a modern replacement.
The new redundant power scheme involves two automatic transfer switches, a manual transfer switch (MTS), 100kW stationary diesel generator and connections to each of B308s’ substations (A & B). The generator is connected to an MTS that allows a mobile generator to be connected in lieu of the stationary generator. This allows a mobile generator to provide redundancy during stationary generator repair/replacement. The MTS then feeds each ATS which are powered by a substation during normal operation. The substation A ATS provides power to building loads (lighting, garage door opener, etc.) and substation B ATS electrifies predominately programmatic facilities (METL control room included).

![Image of new power scheme](image)

**Figure 16. New 480-3Φ Panelboards (left), Support Enclosures & Disconnects (center) and 100kW diesel generator (right).**

### 5.3 Alkali Metal Scrubber

The use of an Alkali Metal Scrubber dates back to the original construction of the building in the 1950s. In the late 1970s, a larger 30,000 CFM system replaced the original. The 30,000 alkali metal scrubber is operational today a considerable portion of it was replaced in the previous FY. Alkali metal scrubber improvements in FY2022 revolved around increasing the instrumentation and ordering replacement components.

#### 5.3.1 *Increased Instrumentation and Control*

The original alkali metal scrubber was equipped with instrumentation that degraded or failed during its tenure. A water tank which acts as a buffer to caustic water generated from alkali metal scrubbing process was equipped with a modern pH meter, differential pressure level sensor and multi-junction thermocouple probe. The pH meter provides feedback to ensure bulk water pH does not become too basic while the differential pressure level sensor provides verification to operators on the tanks water inventory. A multi-junction thermocouple probe provides redundant temperature input to a steam valve which is actuated to feed a sparger located at the bottom of the tank, preventing freezing during winter months. The alkali metal scrubber I&C is on METLs VLAN, enabling remote manipulation and monitoring as well as an articulating HMI near the burn stall.
Figure 17. AMS HMI Mounted to Articulating Arm Near Burn Stall.

5.3.2 Hardware Procurement

The vital function and age of the scrubber coupled with ever challenging supply chain disruptions motivated the METL team to procure components critical to alkali metal scrubber operation. In FY2021, a replacement pump and motor were ordered which was received in FY2022. In FY2022, a new 350HP motor, coupling, pillow block bearings, lubricators and underground water storage tank were purchased and delivered. The replacement blower is expected to arrive mid FY2023.
Figure 18. New water pump with 7.5 HP motor (left) and 350HP blower motor (right)
Figure 19 - New Scrubber Tank Arriving at B308
Figure 20 - Scrubber Tank being Offloaded by Argonne Riggers
5.4 Space Repurposing

Maintaining METL’s standing as a valuable asset within the nuclear energy community has compelled plans for ongoing expansion. Areas capable of supporting alkali metal research are at a premium and scarce, therefore recovering areas of B308 that housed legacy liquid metal experiments was initiated. The Steam Generator Test Facility (SGTF) is a four-story structure located in the high bay of B308. Its original mission was to conduct critical heat flux tests on sodium-water heat exchangers for use in the Clinch River Breeder Reactor project and follow-on large scale demonstration projects. Although most of its’ hardware is past its’ remaining useful life, the facility is located in prime high-bay space and it consumes about 25% of the highbay square footage, so the decommissioning and demolition of the SGTF was pursued in FY22.
Figure 22. Point Cloud of SGTF (orange and maroon structures) in B308 High Bay.
Figure 23 – Picture of the Steam Generator Test Facility – Piping System and Test Article (silver item in the center of the piping) – Picture taken looking North in the B308 highbay
Space reclaimed for METL expansion is illustrated by the point cloud of B308 above in Figure 22. The SGTF spans from two below grade pits to the entire four stories of the orange structure. Originally, the crane bridge had barriers installed to prevent its’ collision with the SGTF, limiting the useful range of the overhead crane. Included in the SGTF D&D was cutting the support structure and frame down to three stories, allowing the crane bridge to traverse to its western most point. The D&D of the SGTF will further enable the expansion of METL and allow for better utilization of the B308 overhead crane.
6 Summary
The preceding fiscal year report provided a summary for the status of the METL facility as of September 2021. A tremendous amount of effort has gone into demonstrating METL’s capabilities for another year, continuing with experimentation in METL, deploying a preventative maintenance/corrective action program, building upon current functions, and supporting future experimenters. The METL crew continues to work on expanding METL into Phase II, grow Argonne’s alkali metal capabilities, developing and qualifying potential Sodium Fast Reactor technologies, and working to ensure METL remains a state-of-the-art testing facility by investing in new talent, components, and methods.

In conclusion, METL is a high-temperature sodium test facility, designed with an emphasis on testing flexibility to support near endless designs for experimental apparatus and has proven its ability to demonstrate Sodium Fast Reactor and other alkali metal technologies as well as further the understanding of associated phenomena.
7 Bibliography

Appendix A

The following is the procedure used for the thawing of the METL facility including the undrainable portions of the purification and diagnostic system. This procedure is included because it was a major operating evolution performed during FY2022 and a lot of thought and effort went into developing this procedure.

Argonne National Laboratory
PROCEDURE TO THAW METL

Revision 7 – August 17, 2021

Prepared by: ___________________________________________ Date: ____________________

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Reviewed by: ___________________________________________ Date: ____________________

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Reviewed by: ___________________________________________ Date: ____________________

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Approved by: ___________________________________________ Date: ____________________

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Approved by: ___________________________________________ Date: ____________________

Christopher Grandy, METL Program Manager
1. BACKGROUND

1.1. Introduction

The following procedure describes steps required to bring METL from a cold standby back to a hot standby (melting all frozen sodium).

The linear thermal expansion coefficient of solid sodium is defined as Eq. (1)$^1$

\[ \alpha_{Na} = 6.84 \times 10^{-5} / ^\circ C \]  \hspace{1cm} (1)

Whereas the linear thermal expansion coefficient of 316 stainless steel is defined as Eq. (2)$^2$

\[ \alpha_{SS} = 1.60 \times 10^{-5} / ^\circ C \]  \hspace{1cm} (2)

As can be seen the thermal expansion coefficient of sodium is over 4X larger than stainless steel, the material which makes up the piping, vessel and delicate bellows materials in METL. In addition, the phase change from solid to liquid sodium results in a volume change of +2.71%$^3$ at 1 atm pressure. This disparity in thermal expansion and the sudden reduction in sodium density upon melting can create extremely large expansion forces that can critically damage the stainless-steel components in a sodium system. Therefore, as is historically practiced, to fully thaw the system- the components will be heated from the known open gas space downwards in a systematic approach. Only when a zone that is nearer to the known open gas space has melted will the next zone’s heater be activated. A temperature of at least 120 °C (~250 °F) is required to ensure sodium in a particular component is sufficiently molten.$^4$

The procedure begins by melting the dump tank (which is 80% filled with sodium) as it is important to have a molten, high-volume vessel of sodium to facilitate dumping the loop at any time. The procedure then moves on to melt the expansion tank and vessels starting with the expansion tank and vessel heaters from top to bottom and then the piping from top to bottom. The primary loop is then thawed starting with each vessel and expansion tank valve in/out, then working around the piping consecutively. The dump tank lines are now free to melt as all (residual) sodium in the primary loop is molten, the dump tank lines are melted from the top down, ending with the piping heaters just past L-IN and L-OUT, before the dump tank nozzles. Note that all sodium in the L-IN dip tube will have melted during the dump tank melt. The procedure then ends by melting the diagnostic loop, paying close attention to melting the economizer from the top down to eliminate the risk of the expansion of the trapped sodium volume.

1.2. Scope

This procedure governs the operations required to bring the METL facility safely and effectively from a cold standby state where all sodium is frozen in the system, to hot standby, where all sodium has been thawed in a strategic manner to prevent trapped sodium volumes from thermally expanding, putting undue stress on system components.

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3 P. Bridgman, The Physics of High Pressure, G. Bell & Sons Ltd., London, 1931
This work and procedure are covered by WCD No. 67195.0–Mechanisms Engineering Test Loop (METL) Operations 2020-2023

1.3. Prerequisites and Assumptions

☐ This procedure relies on the METL facility being in a cold and drained state because of the implementing METL-OP-070 – Procedure to Put METL into Cold Standby Rev. 14.

☐ The facility will be drained of sodium except for the cold trap system, diagnostic system below the mixing tees and of course the dump tank. All other systems, expansion tank, test vessels, piping system will have residual sodium in their respective systems.

☐ This procedure relies on the DT Sample Valve being tied into the existing manifold that ties together EXP, V1 and V2 Sample Valves to facilitate tying all the system gas spaces together during draining operations.

☐ The selected heat-up rates will be such that the heating will not place undue thermal stresses onto the system.

☐ The thawing procedure for a test vessel will be performed in a manner to limit the temperature differential across the entire vessel to ≤ 20 °C

☐ The METL 1000 L high-purity argon micro bulk is plumbed into and valved into METL gas system; the reading is greater than 25 units? < this is either % or inH2O

☐ Appropriate personnel protective equipment will be available for implementing this procedure

☐ The B308 scrubber unit is available for emergency operations, if necessary, when the sodium in the piping, test vessels, expansion tank, purification and diagnostic system is molten.

☐ Sodium is expected to go through a phase transformation from solid to liquid at about 97°C

1.4. Precautions and Limitations

☐ This procedure needs to be reviewed by all METL personnel who are involved with this evolution

☐ Building 308 personnel will be notified of this evolution prior to its performance

☐ The facility will be monitored for leaks during the thawing (the phase transformation process from frozen sodium to liquid sodium) process

  o There will be at least one trained METL operator wearing the personal protective equipment specified in Section 3 Error! Reference source not found. of this document and another METL operator available. They will be monitoring for the extremely unlikely scenario that there is a leak during this process. If a leak occurs the operator will engage the scrubber, utilize class D
and LITH-X fire extinguishers to contain the leak/fire if necessary. A METL operator not containing the leak will notify the Argonne Fire Department and will serve as the liaison with the fire department to ensure the possible alkali metal fire is dealt with appropriately.

☐ The correct valve lineup will be established with appropriate valves fixed in open position before freezing occurs to protect the valves and ensure the system can be readily thawed and re-charged with sodium.

☐ The position of valves will not be changed until their temperature is at least 300 °C to ensure that any residual sodium on the valves has had time to become molten.

2. ACCEPTANCE CRITERIA

The acceptance criteria for this procedure to put METL into in molten hot standby state are as follows:

The Lead Operator or designee(s) has/have primary responsibility to ensure that these Acceptance Criteria are met as part of this procedure. The Lead Operator or designee(s) should initial next to each step to signify successful completion. Should additional steps not mentioned in this Standard Operating Procedure (SOP) be deemed necessary, or existing steps unnecessary, then detailed notes should be taken and the SOP be updated prior to the following test. The Lead Operator shall sign off on this document if the steps were properly performed and METL was successfully put into cold standby.

Lead Operator or designee name: ________________________________
Lead Operator or designee signature: _____________________________ Date: _____________
3. PERSONAL PROTECTIVE EQUIPMENT

If at any time an operator must access components under the mezzanine, over the catch pan, the following personal protective equipment (PPE) shall be worn:

- Flame resistant (FR) pants
- Long-sleeve FR shirt
- FR coveralls
- Leather boots with leather spats to cover laces
- Leather gloves
- Safety glasses
- Fiberglass hardhat with face shield

If at any time an operator must access an electrical cabinet or disconnect the appropriate PPE should be worn according to the requirements dictated by the most recent revision of the Argonne Electrical Safety Manual
4. PROCEDURE

4.1. Preliminary Steps

1. Ensure that the DT Sample Valve is tied into the existing manifold that ties together EXP, V1 and V2 Sample Valves.
2. ENSURE Dump Tank Blanketing Regulator (TBR) is providing pressure between 3-6 PSIG by opening and then closing EXP VENT valve and watching the sample pressure gauge go to zero and climb to between 3-6 PSIG
3. Open EXP GAS to ensure the Sample Back Pressure Regulator (SBPR) is relieving at 8±1 PSIG. Adjust SBPR accordingly to ensure pressure is being relieved during system heat up.
4. Verify the valve lineup is in the correct configuration before starting

4.2. Dump Tank

5. Thaw the dump tank using the following steps and reference Table 1. For vessel heaters USE a heat up rate limit of 0.02 °C/min.
   5.1. Close breakers CB-001 through CB-006 in PE 1₅ to activate dump tank heaters zones 1-6.
   5.2. SET Zones 1-6 to the respective set points in step 1 of Table 1. DO NOT PROCEED until Zone 1 set point reached (±2°C)
   5.3. SET Zones 1-6 to the respective set points in step 2 of Table 1. DO NOT PROCEED until Zone 2 and 3 set point reached (±2°C)
   5.4. SET Zones 1-6 to the respective set points in step 3 of Table 1. DO NOT PROCEED until Zone 4 and 5 set point reached (±2°C)
   5.5. SET Zones 1-6 to the respective set points in step 4 of Table 1. DO NOT PROCEED until Zone 6 set point reached (±2°C)
   5.6. SET Zones 1-6 to the respective set points in step 5 of Table 1. DO NOT PROCEED until Zone 1-6 set point reached (±2°C)

Table 2: Dump tank temperature set points, values in degrees Celsius

<table>
<thead>
<tr>
<th>Step</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 1</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>270</td>
</tr>
<tr>
<td>Zone 2</td>
<td>80</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>270</td>
</tr>
<tr>
<td>Zone 3</td>
<td>80</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>270</td>
</tr>
<tr>
<td>Zone 4</td>
<td>75</td>
<td>80</td>
<td>120</td>
<td>120</td>
<td>270</td>
</tr>
<tr>
<td>Zone 5</td>
<td>75</td>
<td>80</td>
<td>120</td>
<td>120</td>
<td>270</td>
</tr>
<tr>
<td>Zone 6</td>
<td>75</td>
<td>75</td>
<td>80</td>
<td>120</td>
<td>270</td>
</tr>
</tbody>
</table>
The following sections, 4.3, 4.4, and 4.5 can be performed in parallel with one another. DO NOT proceed to section Error! Reference source not found. until Vessel 1, Vessel 2 and the Expansion Tank components are all at a temperature above 150 °C.

4.3. Vessel 1 Heat up

6. CLOSE the respective heater circuit breaker and SET the following Vessel 1 set points, these sub-steps may be entered concurrently. For vessel heaters USE a heat up rate limit of 0.02 °C/min. DO NOT EXCEED A TEMPERATURE VARIATION OF XX °C ACROSS THE ENTIRE VESSEL (ADJUST PID CONTROL TO ACHIEVE)

6.1. CLOSE breaker PE2 CB-019 SET Zone 1 to 300°C, PROCEED
6.2. CLOSE breaker PE2 CB-024 SET Zone 2 to 300°C, PROCEED
6.3. CLOSE breaker PE2 CB-025 SET Zone 3 to 300°C, PROCEED
6.4. CLOSE breaker PE2 CB-026 SET Zone 4 to 300°C, PROCEED
6.5. MONITOR process control and measurement thermocouples to ensure we do not exceed 40 °C temperature differential across vessel

FIG 1: Dump tank heater zones
7. CLOSE the respective heater circuit breaker and SET the following heater set points. For piping and valves USE a heat up rate limit of 0.1 °C/min.

7.1. CLOSE breaker PE3 CB-147 SET V1 OF VALVE to 300°C, PROCEED

7.2. CLOSE breaker PE4 CB-286 & CB-287 SET V1 SUPPLY TO V1 IN ISO to 300°C, PROCEED

7.3. CLOSE breaker PE4 CB-283 SET V1 RETURN TO TEE to 300°C, PROCEED

7.4. CLOSE breaker PE4 CB-269 SET TEE TO V1 OUT ISO to 300°C, PROCEED

7.5. CLOSE breaker PE4 CB-268 SET TEE TO V1 DUMP to 300°C, PROCEED

7.6. CLOSE breaker PE3 CB-149 SET V1 DUMP to 300°C, PROCEED

7.7. CLOSE breaker PE4 CB-281 SET V1 DUMP TO V1 OF to 300°C, PROCEED

7.8. CLOSE breaker PE4 CB-277, CB-278 & CB-279 SET V1 DUMP/OF TEE TO DT to 300°C, PROCEED
4.4. Vessel 2 Heat up

_8. CLOSE the respective heater circuit breaker and SET the following Vessel 2 set points, these sub-steps may be entered concurrently. For vessel heaters USE a heat up rate limit of 0.02 °C/min. DO NOT EXCEED A TEMPERATURE VARIATION OF XX °C ACROSS THE ENTIRE VESSEL (ADJUST PID CONTROL TO ACHIEVE)_

_8.1. CLOSE breaker PE2 CB-015 SET Zone 1 to 300°C, PROCEED_
_8.2. CLOSE breaker PE2 CB-016 SET Zone 2 to 300°C, PROCEED_
_8.3. CLOSE breaker PE2 CB-017 SET Zone 3 to 300°C, PROCEED_
_8.4. CLOSE breaker PE2 CB-018 SET Zone 4 to 300°C, PROCEED_
_8.5. MONITOR process control and measurement thermocouples to ensure we do not exceed XX °C temperature differential across vessel_

_9. CLOSE the respective heater circuit breaker and SET the following heater set points. For piping and valves USE a heat up rate limit of 0.1 °C/min._

_9.1. CLOSE breaker PE4 CB-298, CB-299, CB-300 SET V2 OF TO V2 OVERFLOW to 300°C, PROCEED_
_9.2. CLOSE breaker PE3 CB-152 SET V2 OF VALVE to 300°C, PROCEED_
_9.3. CLOSE breaker PE4 CB-301 & CB-302 SET V2 SUPPLY TO V2 IN ISO to 300°C, PROCEED_
_9.4. CLOSE breaker PE4 CB-297 SET V2 RETURN TO TEE to 300°C, PROCEED_
_9.5. CLOSE breaker PE4 CB-271 SET TEE TO V2 OUT ISO to 300°C, PROCEED
_9.6. CLOSE breaker PE4 CB-270 SET TEE TO V2 DUMP to 300°C, PROCEED
_9.7. CLOSE breaker PE3 CB-154 SET V2 DUMP to 300°C, PROCEED
_9.8. CLOSE breaker PE4 CB-291 SET V2 DUMP TO V2 OF to 300°C, PROCEED
_9.9. CLOSE breaker PE4 CB-292, CB-293 & CB-294 SET V2 DUMP/OF TEE TO DT to 300°C, PROCEED

4.5. Expansion Tank Heat up

_10. CLOSE the respective heater circuit breaker and SET the following Expansion Tank heater set points, these may be entered concurrently. For expansion tank vessel heaters USE a heat up rate limit of 0.1 °C/min.
_10.1. CLOSE breaker PE1 CB-035 SET Zone 1 to 300°C, PROCEED
_10.2. CLOSE breaker PE1 CB-036 SET Zone 2 to 300°C, PROCEED
_10.3. CLOSE breaker PE1 CB-037 SET Zone 3 to 300°C, PROCEED

_11. CLOSE the respective heater circuit breaker and SET the following heater set points.
   For piping and valves USE a heat up rate limit of 0.1 °C/min.
_11.1. CLOSE breaker PE3 CB-146 SET the EXP IN valve to 300°C, PROCEED-D
_11.2. CLOSE breaker PE4 CB-235, CB-236 & CB-237 SET EXP TO EXP IN Pipe Zone 29 to 300°C, PROCEED
_11.3. CLOSE breaker PE3 CB-054 SET the EXP OUT Valve to 300°C, PROCEED
_11.4. CLOSE breaker PE4 CB-258 SET Pipe Zone 56 to 300°C, PROCEED

4.6. Primary Loop Heat up

_12. CLOSE the respective heater circuit breaker and SET the following heater set points.
   For piping and valves USE a heat up rate limit of 0.1 °C/min.
_12.1. CLOSE breaker PE3 CB-151 SET Valve V1 IN ISO to 300°C, PROCEED
_12.2. CLOSE breaker PE3 CB-150 SET Valve V1 OUT ISO to 300°C, PROCEED
_12.3. CLOSE breaker PE3 CB-156 SET Valve V2 IN ISO to 300°C, PROCEED
_12.4. CLOSE breaker PE3 CB-155 SET Valve V2 OUT ISO to 300°C, PROCEED

_13. CLOSE the respective heater circuit breaker and SET the following heater set points.
   For piping and valves USE a heat up rate limit of 0.1 °C/min.
_13.1. CLOSE breaker PE4 CB-280 SET Pipe Zone 78 to 300 °C, PROCEED
_13.2. CLOSE breaker PE4 CB-282 SET Pipe Zone 80 to 300 °C, PROCEED
_13.3. CLOSE breaker PE4 CB-295 SET Pipe Zone 93 to 300 °C, PROCEED
_13.4. CLOSE breaker PE4 CB-296 SET Pipe Zone 94 to 300 °C, PROCEED
_13.5. CLOSE breaker PE4 CB-231 SET Pipe Zone 29 to 300 °C, PROCEED
_13.6. CLOSE breaker PE4 CB-258 SET Pipe Zone 56 to 300 °C, PROCEED

_14. CLOSE the respective heater circuit breaker and SET the following heater set points.
   For piping and valves USE a heat up rate limit of 0.1 °C/min.
14.1. CLOSE breaker PE4 CB-257 SET Pipe Zone 55 to 300 °C, PROCEED
14.2. CLOSE breaker PE4 CB-265 SET Pipe Zone 63 to 300 °C, PROCEED
14.3. CLOSE breaker PE4 CB-263 SET Pipe Zone 61 to 300 °C, PROCEED
14.4. CLOSE breaker PE4 CB-266 SET Pipe Zone 64 to 300 °C, PROCEED
14.5. CLOSE breaker PE4 CB-245 SET Pipe Zone 43 to 300 °C, PROCEED
14.6. CLOSE breaker PE3 CB-142 SET Valve Zone L-V Bypass to 300 °C, PROCEED
14.7. CLOSE breaker PE4 CB-264 SET Pipe Zone 62 to 300 °C, PROCEED
14.8. CLOSE breaker PE4 CB-262 SET Pipe Zone 60 to 300 °C, PROCEED
14.9. CLOSE breaker PE4 CB-261 SET Pipe Zone 59 to 300 °C, PROCEED
14.10. CLOSE breaker PE4 CB-246 SET Pipe Zone 44 to 300 °C, PROCEED
14.11. CLOSE breaker PE4 CB-248 SET Pipe Zone 46 to 300 °C, PROCEED
14.12. CLOSE breaker PE4 CB-242 SET Pipe Zone 40 to 300 °C, PROCEED
15.1. SET EMFM Primary to 300 °C, PROCEED
15.2. CLOSE breaker PE4 CB-241 SET Pipe Zone 39 to 300 °C, PROCEED
15.3. CLOSE breaker PE4 CB-229 SET Pipe Zone 27 to 300 °C, PROCEED
15.4. SET ALIP to 300 °C, PROCEED
15.5. CLOSE breaker PE4 CB-247 SET Pipe Zone 45 to 300 °C, PROCEED
15.6. CLOSE breaker PE4 CB-260 SET Pipe Zone 58 to 300 °C, PROCEED
15.7. CLOSE breaker PE4 CB-139 SET Valve Zone L-CT Bypass to 300 °C, PROCEED
15.8. CLOSE breaker PE4 CB-259 SET Pipe Zone 57 to 300 °C, PROCEED
16.1. CLOSE breaker PE4 CB-311 SET Pipe Zone 109 to 300 °C, PROCEED
16.2. CLOSE breaker PE4 CB-317 SET Pipe Zone 115 to 300 °C, PROCEED
16.3. CLOSE breaker PE4 CB-329 SET Pipe Zone 127 to 300 °C, PROCEED
16.4. CLOSE breaker PE4 CB-330 SET Pipe Zone 128 to 300 °C, PROCEED
16.5. CLOSE breaker PE4 CB-331 SET Pipe Zone 129 to 300 °C, PROCEED
16.6. CLOSE breaker PE4 CB-332 SET Pipe Zone 130 to 300 °C, PROCEED
16.7. CLOSE breaker PE4 CB-333 SET Pipe Zone 131 to 300 °C, PROCEED
16.8. CLOSE breaker PE4 CB-334 SET Pipe Zone 132 to 300 °C, PROCEED
16.9. CLOSE breaker PE4 CB-335 SET Pipe Zone 133 to 300 °C, PROCEED
16.10. CLOSE the respective heater circuit breaker and SET the following heater set points.

For piping and valves USE a heat up rate limit of 0.1 °C/min.
16.11. CLOSE breaker PE3 CB-133 SET V3 OUT ISO to 300°C, PROCEED
16.12. CLOSE breaker PE3 CB-137 SET V4 OUT ISO to 300°C, PROCEED
16.13. CLOSE breaker PE3 CB-159 SET V5 IN ISO to 300°C, PROCEED
16.14. CLOSE breaker PE3 CB-160 SET V5 OUT ISO to 300°C, PROCEED
16.15. CLOSE breaker PE3 CB-161 SET V6 IN ISO to 300°C, PROCEED
16.6. CLOSE breaker PE3 CB-162 SET V6 OUT ISO to 300°C, PROCEED
16.7. CLOSE breaker PE3 CB-163 SET V7 IN ISO to 300°C, PROCEED
16.8. CLOSE breaker PE3 CB-164 SET V7 OUT ISO to 300°C, PROCEED
16.9. CLOSE breaker PE3 CB-165 SET V8 IN ISO to 300°C, PROCEED
16.10. CLOSE breaker PE3 CB-166 SET V8 OUT ISO to 300°C, PROCEED

17. CLOSE the respective heater circuit breaker and SET the following heater set points.
   For piping and valves USE a heat up rate limit of 0.1 °C/min.
17.1. CLOSE breaker PE4 CB-244 SET Pipe Zone 42 to 300 °C, PROCEED
17.2. CLOSE breaker PE4 CB-267 SET Pipe Zone 65 to 300 °C, PROCEED
17.3. CLOSE breaker PE4 CB-310 SET Pipe Zone 108 to 300 °C, PROCEED
17.4. CLOSE breaker PE4 CB-316 SET Pipe Zone 114 to 300 °C, PROCEED
17.5. CLOSE breaker PE3 CB-134 SET Valve V3 IN to 300 °C, PROCEED
17.6. CLOSE breaker PE3 CB-138 SET Valve V4 IN to 300 °C, PROCEED
17.7. CLOSE breaker PE4 CB-243 SET Pipe Zone 41 to 300 °C, PROCEED

FIG 4: Primary loop heater zones

18. DO NOT proceed to Section 4.7 until Primary Loop and the Expansion Tank components are all at a temperature above 150 °C

4.7. Dump Tank Line
Perform below steps __19 and Error! Reference source not found. in parallel if desired
__19. WAIT for the following zones to reach 120 °C. AFTER the zone reaches 120 °C via conduction from the preceding zone: CLOSE the respective circuit breaker and SET the zone to 300 °C. For piping and valves USE a heat up rate limit of 0.1 °C/min.

__19.1. Port 8 / Nozzle A to L-OUT, breaker PE4 CB-256

__19.2. Valve L-OUT, breaker PE3 CB-140

__20. WAIT for the following zones to reach 120 °C. AFTER the zone reaches 120 °C via conduction from the preceding zone: CLOSE the respective circuit breaker and SET the zone to 300 °C. For piping and valves USE a heat up rate limit of 0.1 °C/min.

__20.1. Valve L-IN, breaker PE3 CB-141

__21. WAIT for the following zones to reach 120 °C. AFTER the zone reaches 120 °C via conduction from the preceding zone: CLOSE the respective circuit breaker and SET the zone to 300 °C. For piping and valves USE a heat up rate limit of 0.1 °C/min.

__21.1. Port 5 / Nozzle B to L-IN, breaker PE4 CB-255

4.8. Purification and Diagnostic Loop

__22. PAUSE. Discuss general progress in METL heating. The following steps will be heating up the piping system with all components 100% full of solid sodium. Thus, a conservative heat up approach is required to ensure no undue stress is imposed on the system due to a differential of thermal expansion between the sodium and piping. The following approach will strategically melt sections of piping that possess an expansion region in argon gas space. Once these regions melt (a process temperature of >120 °C) the heater zones in that melted region will be set to a temperature of 300 °C, this will serve to provide process heat to the next solidified sodium zone, directionally melting from a region of liquid sodium into the region of solid sodium via thermal conduction to ensure the volumetric expansion of solidified sodium upon heat up and phase change is accommodated. If a temperature of 300 °C is not adequate to bring the consecutive zone to a melting temperature of 120 °C, the Lead Operator shall confer with the other METL Engineers and the Program Manager to determine a suitable course of either raising the preceding zone to a set point greater than 300 °C or by beginning to slowly apply process heat to the consecutive zone to begin melting.

__23. UNLESS OTHERWISE SPECIFIED, use a heat up rate limit of 0.1 °C/min for the following piping and valves in this section.

__24. SET the following heater set points.

__24.1. CLOSE breaker PE4 CB-204 SET Pipe Zone 2 to 120 °C, PROCEED

__24.2. CLOSE breaker PE4 CB-207 SET Pipe Zone 5 to 120 °C, PROCEED

__24.3. CLOSE breaker PE4 CB-250 SET Pipe Zone 48 to 120 °C, PROCEED

__24.4. CLOSE breaker PE4 CB-252 SET Pipe Zone 50 to 120 °C, PAUSE

__25. PAUSE until Pipe Zones 2, 5, 48 and 50 have reached 120 °C

__26. SET Pipe Zone 2 to 300 °C, PROCEED (piping zone to CT IN)

__27. SET Pipe Zone 5 to 300 °C, PROCEED (piping zone to CT OUT)

__28. SET Pipe Zone 48 to 300 °C, PROCEED (piping zone to PM IN)
29. SET Pipe Zone 50 to 300 °C, PROCEED (piping zone to PM OUT)

30. WAIT for the following valve zones to reach 120 °C. AFTER the zone reaches 120 °C via conduction from the preceding zone: CLOSE the respective circuit breaker and SET the zone to 300 °C (these valves are all locked open)

   30.1. Valve CT IN, circuit breaker PE3 CB-169
   30.2. Valve CT OUT, circuit breaker PE3 CB-168
   30.3. Valve PM IN, circuit breaker PE3 CB-170
   30.4. Valve PM OUT, circuit breaker PE3 CB-171

31. WAIT for the following zones to reach 120 °C. AFTER the zone(s) reaches 120 °C via conduction from the preceding zone: CLOSE the respective circuit breaker and SET the zone to 300 °C.

   31.1. Pipe Zone 26, circuit breaker PE4 CB-228 (CT IN to CT Pump)
   31.2. Pipe Zone 11, circuit breaker PE4 CB-213 AND Pipe Zone 7, circuit breaker PE4 CB-209 (CT OUT to CT/PM SERIES)
   31.3. Pipe Zone 28, circuit breaker PE4 CB-230 AND Pipe Zone 6, circuit breaker PE4 CB-208 (PM IN to PM Pump)
   31.4. Pipe Zone 52, circuit breaker PE4 CB-254 AND Pipe Zone 8, circuit breaker PE4 CB-210 (PM OUT to PM)

32. WAIT for the following zones to reach 120 °C. AFTER the zone reaches 120 °C via conduction from the preceding zone: CLOSE the respective circuit breaker and SET the zone to 300 °C.

   32.1. CT EM Pump
   32.2. PM EM Pump

33. WAIT for the following zones to reach 120 °C. AFTER the zone reaches 120 °C via conduction from the preceding zone: CLOSE the respective circuit breaker and SET the zone to 300 °C.

   33.1. Pipe Zone 38, circuit breaker PE4 CB-240
   33.2. Pipe Zone 37, circuit breaker PE CB-239
   33.3. Valve CT OUT/ PM IN, circuit breaker PE3 CB-174
   33.4. Valve CT/PM SERIES, circuit breaker PE3 CB-173

34. WAIT for the following zones to reach 120 °C. AFTER the zone reaches 120 °C via conduction from the preceding zone: CLOSE the respective circuit breaker and SET the zone to 300 °C.

   34.1. CT EMFM, circuit breaker XX
   34.2. PM EMFM, circuit breaker XX
   34.3. Valve CT OUT/ PM OUT, circuit breaker PE3 CB-172

35. WAIT for the following zones to reach 120 °C. AFTER both the zones reach 120 °C via conduction from the preceding zone: CLOSE the respective circuit breakers and SET the zones to 300 °C
35.1. Pipe Zone 21, circuit breaker PE4 CB-223 AND Pipe Zone 12, circuit breaker PE4 CB-214

36. WAIT for the following zones to reach 120 °C. AFTER both zones reach 120 °C via conduction from the preceding zone: CLOSE the respective circuit breaker and SET the zone to 300 °C.

36.1. Pipe Zone 51, circuit breaker PE4 CB-253 AND Pipe Zone 49, circuit breaker PE4 CB-251

37. WAIT for the following pair of zones to reach 120 °C. AFTER both zones reach 120 °C via conduction from the preceding zones: CLOSE the respective circuit breakers and SET the zones to 300 °C.

37.1. Pipe Zone 19, circuit breaker PE4 CB-221 AND Pipe Zone 20, circuit breaker PE4 CB-222

38. WAIT for the following zone to reach 120 °C via conduction from the preceding zone. AFTER the zone reaches 120 °C via conduction from the preceding zone: CLOSE the respective circuit breaker and SET the zone to 300 °C:

38.1. Pipe Zone 22, circuit breaker PE4 CB-224

39. WAIT for the following zone to reach 120 °C. AFTER the zone reaches 120 °C via conduction from the preceding zone: CLOSE the respective circuit breaker and SET the zone to 300 °C:

39.1. Pipe Zone 23, circuit breaker PE4 CB-225

40. WAIT for the following zone to reach 120 °C. AFTER the zone reaches 120 °C via conduction from the preceding zone: CLOSE the respective circuit breaker and SET the zone to 300 °C:

40.1. Pipe Zone 24, circuit breaker PE4 CB-226

41. WAIT for the following zone to reach 120 °C AFTER the zone reaches 120 °C via conduction from the preceding zone: CLOSE the respective circuit breaker and SET the zone to 300 °C:

41.1. Pipe Zone 25, circuit breaker PE4 CB-227

42. WAIT for the following zones to reach 120 °C. AFTER both the zone reach 120 °C via conduction from the preceding zones: CLOSE the respective circuit breakers and SET the zones to 300 °C.

42.1. Pipe Zone 4, circuit breaker PE4 CB-206 AND Pipe Zone 10, circuit breaker PE4 CB-212

43. WAIT for the following zones to reach 120 °C. AFTER the zone reaches 120 °C via conduction from the preceding zone: CLOSE the respective circuit breaker and SET the zone to 300 °C.

43.1. Pipe Zone 3, circuit breaker PE4 CB-205

43.2. Pipe Zone 9, circuit breaker PE4 CB-211

44. Hold point to discuss progress in METL heating of the diagnostic and purification system.
The following sections 4.9 and 4.10 may be performed in parallel. DO NOT PROCEED UNTIL pipe zones 3, 9, 49, and 51 from the previous section are at a temperature ≥150 °C

4.9. CT Vessel

__45. SET the following heater set points to thaw the Cold Trap. For Cold Trap vessel USE a heat up rate limit of 0.02 °C/min.

__45.1. CLOSE breaker PE4 CB-203, SET Cold Trap vessel zone 1 to 120 °C, PAUSE until zone 1 reaches 120 °C

__45.2. CLOSE breaker XXX, SET Cold Trap vessel zone 1 to 168 °C, PROCEED
__45.3.  CLOSE breaker PE1 CB-033, SET Cold Trap vessel zone 2 to 120 °C, PAUSE until zone 2 reaches 120 °C
__45.4.  CLOSE breaker XXX, SET Cold Trap vessel zone 2 to 168 °C, PROCEED
__45.5.  CLOSE breaker PE1 CB-034, SET Cold Trap vessel zone 3 to 120 °C, PAUSE until zone 3 reaches 120 °C
__45.6.  CLOSE breaker XXX, SET Cold Trap vessel zone 3 to 168 °C, PROCEED

4.10. Plugging Meter
__46. SET the following heater set points to thaw the Plugging Meter. For plugging meter
    USE a heat up rate limit of 0.1 °C/min.
__46.1.  CLOSE breaker PE4 CB-249, SET Plugging Meter vessel zone 1 to 120 °C,
         PAUSE until zone 1 reaches 120 °C
__46.2.  SET Plugging Meter vessel zone 1 to 300 °C, PROCEED
__46.3.  WAIT until vessel zone 2 reaches a temperature of 120 °C via conduction from
         zone 1
__46.4.  CLOSE breaker PE2 CB-129, SET Plugging Meter vessel zone 2 to 300 °C,
         PROCEED
FIG 7: Plugging Meter vessel heaters
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