Sodium Heat Pipe Module Processing For the SAFE-100 Reactor Concept

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Abstract. To support development and hardware-based testing of various space reactor concepts, the Early Flight Fission-Test Facility (EFF-TF) team established a specialized glove box unit with ancillary systems to handle/process alkali metals. Recently, these systems have been commissioned with sodium supporting the fill of stainless steel heat pipe modules for use with a 100 kW thermal heat pipe reactor design. As part of this effort, procedures were developed and refined to govern each segment of the process covering: fill, leak check, vacuum processing, weld closeout, and final "wet in". A series of 316 stainless steel modules, used as precursors to the actual 321 stainless steel modules, were filled with 35 +/-1 grams of sodium using a known volume canister to control the dispensed mass. Each module was leak checked to <10^{-10} std cc/sec helium and vacuum conditioned at 250 °C to assist in the removal of trapped gases. A welding procedure was developed to close out the fill stem preventing external gases from entering the evacuated module. Finally the completed modules were vacuum fired at 750 °C allowing the sodium to fully wet the internal surface and wick structure of the heat pipe module.

INTRODUCTION

Ambitious exploration of the solar system and beyond will only be possible using vehicles that have extremely high specific power with associated high specific impulse and thrust to power ratios (Schmidt, 1998). Available power is of paramount importance in the design of any mission significantly affecting the flexibility of spacecraft operation/lifetime in addition to scientific capability/return. Implementing space nuclear fission systems would provide a significant advantage - permitting future missions to be performed in a power rich environment uncharacteristic of current and past space endeavors (Houts, 2001). In an effort to deploy near term nuclear systems those under consideration must be highly testable (Houts, 2003); taking maximum advantage of non-nuclear evaluations using specially designed thermal resistance devices to simulate the heat from fission (Van Dyke, 2003). By implementing this approach a significant number of system and integration issues can be identified and resolved early on, increasing the probability of success should a costly full power ground nuclear demonstration be required. In all cases, the guiding focus is to maintain a simple initial systems design, maximizing the potential for success. This success will foster the development and maintenance of infrastructure necessary to initiate development of larger more capable, powerful and sophisticated systems.

As a first step along this path, the Early Flight Fission – Test Facility (EFF-TF) is evaluating a heat pipe reactor design as one of several reactor concepts (Houts, 1996). This heat pipe system, referred to as the Safe Affordable Fission Engine (SAFE), has a family of power levels, one of which has an output of 100 kWt (SAFE-100). The SAFE-100 consists of 61 sodium/stainless steel heat pipe modules (183 fuel pins) and operates at a nominal temperature of 973K (Van Dyke, 2002). The SAFE-100A, a reduced version of the full SAFE-100 core using only 19 heat pipe modules, serves as an initial proof of process with an integrated gas heat exchanger.

The demand for alkaline metal heat pipes to support both the SAFE-100 and future programs was the impetus to establish an in-house processing capability. Key objectives of this activity include: 1) setup of hardware based infrastructure for handling/processing sodium, and 2) developing validated procedures for filling and commissioning heat pipe modules. Currently, heat pipe modules are being filled/processed onsite using a specially designed glove box system and ancillary hardware. Although these systems were specifically designed to support the SAFE-100, they can easily be modified to handle other alkaline metals such as potassium or

lithium and can accommodate filling/processing other reasonably sized hardware geometries such as liquid metal loops or core assemblies.

APPROACH

The capability to manipulate and process alkaline metals has been established by the EFF-TF team to support the rapid development and testing of prototypic hardware components (Salvail, 2003). The centerpiece of this setup is a specially modified Vacuum Atmospheres Corporation (VAC) glove box, figure 1, that is equipped with Dri-Train, Ni-Train and Dri-Kool systems to control oxygen, nitrogen, hydrogen and water vapor concentration in the internal box environment. For the work described in this report, only oxygen and water vapor were controlled with the box environment maintained at < 1 part-per-million for oxygen and < -70 °C dew point for water vapor. Currently, the focus is directed towards filling nineteen 321 stainless steel/sodium heat pipe modules to support the SAFE-100A project. As a precursor to this work, a series of 316 stainless steel/sodium modules (figure 2) were filled, pioneering the process.

During the set up and commissioning of the glove box equipment, detailed operating procedures were developed and modified as necessary. In parallel, procedures were developed to control each step of the process used to fill, condition and closeout the modules. As is typical in all hardware activities, the procedures evolved as the initial modules were processed, accounting for improvements in both hardware layouts and operations. For each heat pipe module, a detailed log (or traveler) is maintained to track all specific operations and note any pertinent observations.
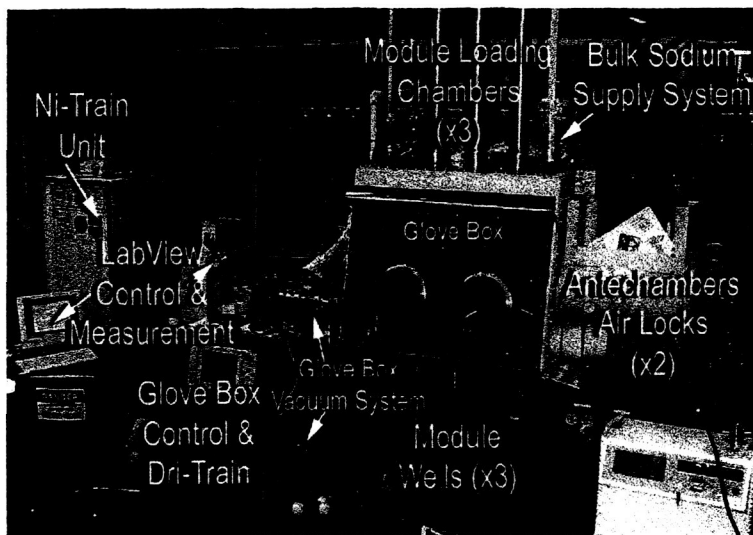

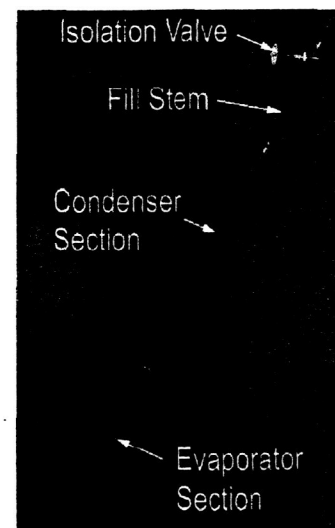**FIGURE 1.** Glove Box Setup for Heat Pipe Module Filling.

FIGURE 2. Heat Pipe Module.

HEAT PIPE MODULE FILL AND CLOSE OUT OPERATIONS

An approach was developed and successfully implemented to commission heat pipe modules. Specifically, it was tested and refined by filling/processing a series of 316 stainless steel heat pipe modules; verifying readiness to prepare nineteen 321 stainless steel modules for the SAFE-100A project. This approach consists of a set of well-defined steps:

- Dispensing a know quantity of sodium
- Transferring the known quantity of sodium to a heat pipe module
- Leak checking the heat pipe module
- Vacuum processing the heat pipe module
- Closeout welding of the heat pipe module fill stem
- Final "Wet in" of the heat pipe module

For all operations involving use of the glove box system, its argon environment was maintained at <1ppm for oxygen and < –70 °C dew point for water vapor. The following sections detail each of the steps used to process a heat pipe module.

Preparing And Filling A Known Volume Canister With Sodium

The first step of the process is to accurately meter out a specific quantity of sodium (35 +/-1grams) from the bulk storage system (approximately 3.6 kg), which can then be transferred to a heat pipe module. To control this quantity, a known volume canister was fabricated from stainless steel with dimensions consistent with the required mass of sodium. These volumes and all other connecting valves, fittings and filters were cleaned using both freon and alcohol baths and then vacuum baked at 10^{-5} torr or lower and 250 °C prior to usage (baking drives off all volatile materials such as absorbed water). As a process check, the mass of sodium transferred is verified by taking weight measurements of the known volume canister before and after a fill sequence. A number of initial trial fills were performed to determine the best combination and placement of valves, fittings and heaters to minimize components and maximize the success for transfer (optimize the parameters for production). The final glove box internal hardware setup is illustrated in figure 3.

A typical fill operation begins by heating all the sodium lines and bulk storage (external to the glove box) to a temperature of approximately 160 °C; this requires several hours due to the mass of the system and the desire to bring up the temperature in a controlled fashion. Temperatures are kept as low as possible in order to minimize the solubility of oxygen in the sodium, yet high enough to enable a successful transfer. The known volume canister is weighted and connected to the sodium dispensing station (inside the glove box). Prior to heating the internal components, the glove box high vacuum system is connected to the bottom of the known volume canister evacuating it to a pressure in the low 10^{-5} torr range; sufficient for the pressurized sodium (supplied from the bulk storage) to completely fill its volume (figure 3). After the desired vacuum is established, the isolation valve is closed and heaters are placed over the sodium fill tubing, isolation valve, filter, and known volume canister. The individual heaters (inside the glove box) are adjusted to provide a temperature gradient with the sodium inlet at the highest temperature (~200 °C) and the known volume canister at the lowest temperature (~120 °C). A 14-micron filter, located between these two extremes is heated to a target temperature of approximately 160 °C. Establishing a temperature gradient across these components provides a straightforward determination as to the success of the fill operation by observing the temperature response as illustrated in figure 4. All heater control and thermocouple measurements are processed and displayed using a customized LabVIEW interface.
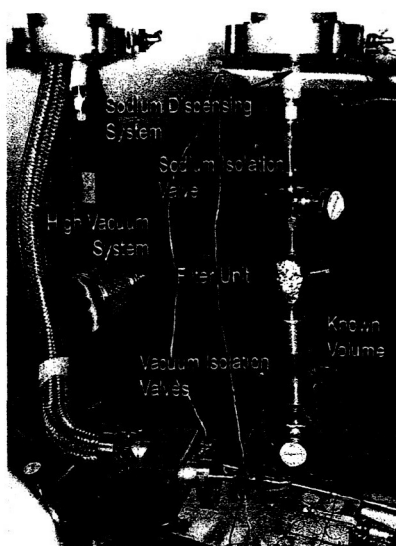

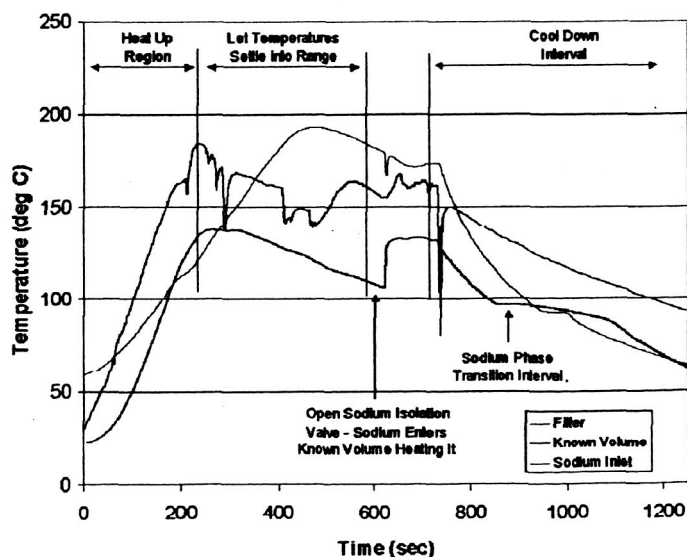**FIGURE 3.** Typical Fill Setup.

FIGURE 4. Temperature Response During A Typical Fill.

Once internal temperatures have reached required levels, the bulk sodium reservoir is pressurized to 15 psia (with high purity argon) and the sodium isolation valve inside the glove box is opened. Figure 4 illustrates the temperature response for a satisfactory transfer; there is a rapid rise in the known volume canister temperature as it fills, and a slow rise in the filter temperature as the hot sodium passes through it (the large filter mass is responsible for the slow response). Likewise, there is a momentary drop in temperature on the sodium feed line above the filter because the external manifold and reservoir are at a cooler temperature (~160° C). The known volume and other components are tapped periodically to eliminate potential voids; heat is maintained for several minutes before being shut off and the sodium isolation valve closed. Another characteristic of a successful transfer is a plateau in known volume temperature as it cools through the sodium liquid-to-solid transition region at ~100 °C (nicely illustrated in figure 4). Once the volume has cooled, it is removed, weighed and then compared to its pre-fill weight, to verify 35 +/-1 grams of sodium were transferred. The known volume canister is now ready to be connected to the heat pipe module.

Transfer Of Sodium From A Known Volume Canister To A Heat Pipe Module

Prior to connecting the known volume canister, the heat pipe module fill stem is fitted with an isolation valve so that it can be coupled to the glove box high vacuum system and evacuated. Fittings are tightened (eliminating leaks) until the module vacuum pressure reaches the low 10^{-5} torr range, sufficient to allow the sodium to freely flow into the module with glove box pressure providing the driving force. With the module evacuated, the known volume canister is attached to the module isolation valve as shown in figure 5. A thermocouple is attached to the base of the module fill stem to monitor temperature variation during the transfer procedure (indication that sodium has flowed into the module). Heaters and aluminum foil are attached to the known volume and module stem. Heaters are adjusted based on a target temperature of 180°C for the known volume and 130 °C for the module stem; setting up this temperature difference provides a visual indicator as to the success of the transfer.

Once temperatures have reached their target values, the module isolation and vent valves are opened allowing sodium to rapidly flows into the module; figure 6 illustrates the rapid increase in temperature along the stem. The module and known volume canister are tapped to assure transfer and heating is maintained for several minutes. The heaters are then shut off, isolation and vent valves closed, and the foil insulation removed resulting in a rapid temperature drop. A clear indication that all sodium has been transferred and both the canister and stem are clear is the absence of a liquid to solid phase change in the cool down. The known volume canister is removed and weighed to verify the amount of sodium transferred. The module is fitted with a new isolation valve to ensure a vacuum tight valve (e.g. eliminate the chance of residual sodium in the valve seat). The module is connected to the glove box high vacuum system and evacuated into the low 10^{-6} torr range.
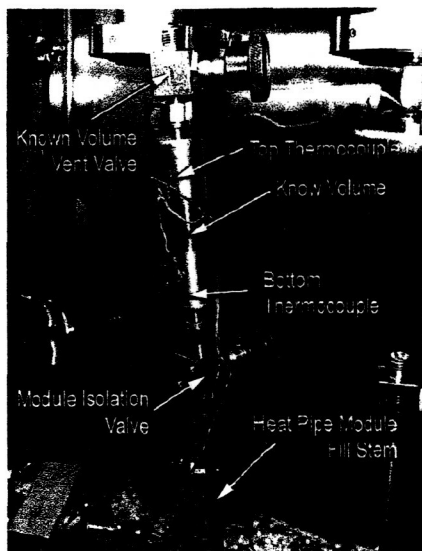

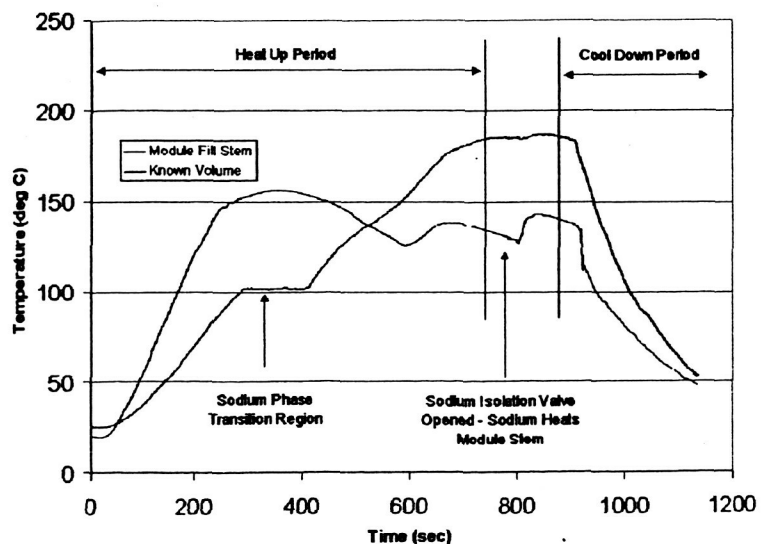**FIGURE 5.** Typical Transfer Setup.

FIGURE 6. Temperature Response During A Typical Transfer.

Leak Checking A Heat Pipe Module and Isolation Valve

With the glove box high vacuum line attached to the module isolation valve (figure 7), the unit was evacuated into the low 10^{-6} torr range in preparation for a gaseous helium leak check. This leak check serves to evaluate the integrity of the module isolation valve fittings prior to removal from the glove box environment. A Varian model 979 leak detector unit was used, and is connected to the glove box vacuum system using a secondary roughing valve as shown in figure 8.

The leak detector is allowed to self calibrate and is then brought online; the unit's baseline leak rate is typically 0.2×10^{-11} std cc/sec helium (when isolated from the system). Depending on the amount of helium already saturating the glove box system (from previous operations), the leak detector baseline will typically increase into the 10^{-9} or low 10^{-8} std cc/sec range when opened. It is very difficult to maintain a leak rate baseline $< 10^{-9}$ std cc/sec range since the glove box is a closed environment trapping the helium which easily diffuses through the vacuum system O-ring seals. However, the leak detector has a built in zeroing function, which resets the sampling range to its lowest level ($<10^{-11}$ std cc/sec subtracting out the background baseline). Helium can then be sprayed around the fittings under investigation and any increase in leak rate (produced by locally higher helium concentration introduced by a "real" leak) is readily picked up and displayed.

All fittings are systematically tested for integrity and tightened as necessary (so that the zeroed helium leak rate is $<10^{-10}$ std cc/sec). The system is allowed to stabilize for approximately 15 minutes and a final helium leak check performed on all module isolation valve fittings. As an additional checkout, the module's isolation valve is closed for several minutes (locking up the heat pipe volume). Noting the vacuum system pressure, the module isolation valve is reopened and any change in vacuum level recorded/investigated (no increase in pressure expected if leak tight). If no problems are apparent, the module is approved for removal from the glove box for further processing.
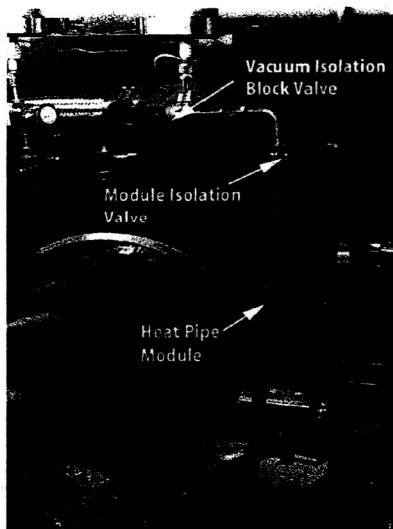
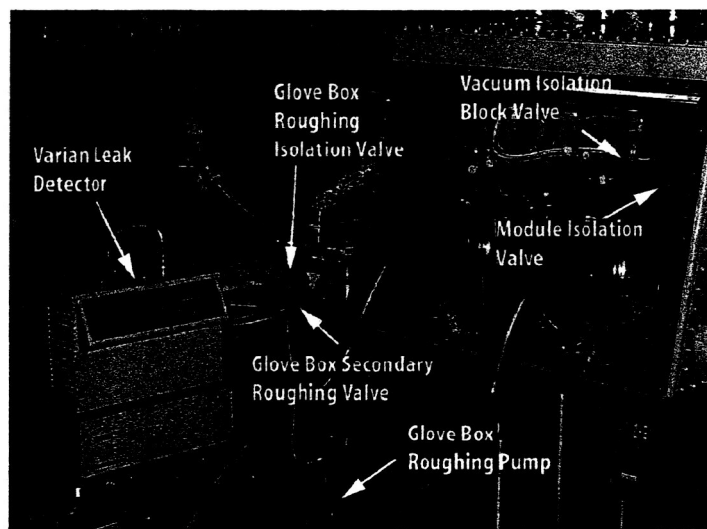

FIGURE 7. Typical Setup (Internal).   **FIGURE 8.** Typical Leak Checking Setup (External).

Vacuum Processing A Heat Pipe Module

Upon completion of the fill and leak check portions of the heat pipe module procedure, the module is transferred out of the glove box to a vacuum-processing booth. The purpose of this procedure is to remove any residual gases trapped in the module by performing a limited bake out. This operation also serves to verify the original leak check carried out in the glove box; leak detector baseline is typically lower for this setup since it is outside the self-contained and potentially helium saturated environment of the glove box. The typical configuration is illustrated in figure 9. The heat pipe module is connected to a vacuum manifold and evacuated to less then 10^{-7} torr upstream of the module isolation valve (this valve remains closed); if necessary, additional heating can be

provided for several hours to the vacuum manifold to help remove trapped water on the surface of the vacuum manifold lines.
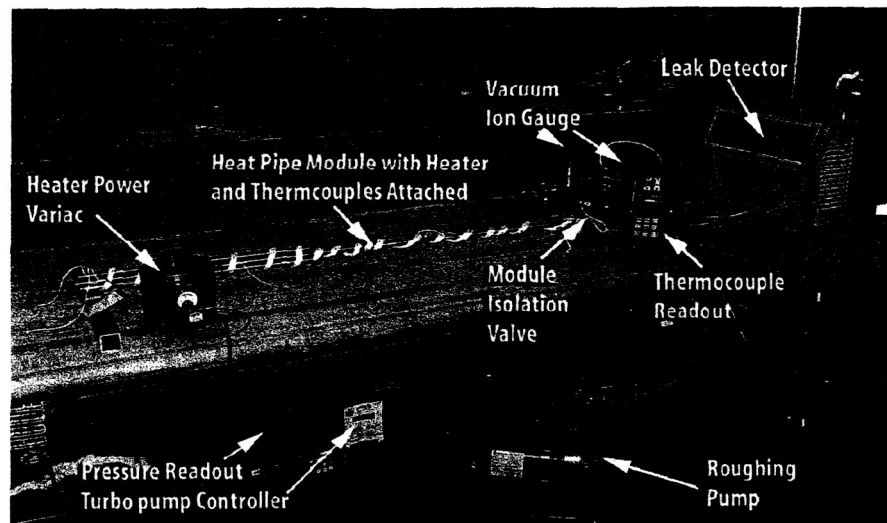
**FIGURE 9.** Typical Setup To Vacuum Process a Heat Pipe Module.

Once low pressure has been established, the leak detector can be brought online and the module isolation valve upstream fittings checked and tightened as necessary. Once it has been determined that the system is tight, the module isolation valve is opened and the pressure spike recorded. Typically, the pressure will jump into the 10^{-6} to 10^{-5} torr range before rapidly returning to the baseline. If the pressure climbs too high or takes significant time to recover, it is an indication of a potential leak or significant trapped gases (virtual leak). The isolation valve fittings and the module welded joints/surface area are checked with the leak detector. Once vacuum integrity is assured, the module is wrapped with a heating tape powered by a variable autotransformer in preparation for a low temperature bake out. Module temperatures are sampled using two type-K thermocouples attached to the module surface at the approximate midpoints of the lower module heater/evaporator section and upper module single condenser pipe section. The module is covered with two layers of aluminum foil for insulation and then heated into the 200 °C to 250 °C range. The module is maintained at this condition for approximately 2 hours and is periodically tapped (e.g. assisted in breaking up potential gas pockets trapped in the sodium); the highest pressure reached is recorded. Once the heating period has expired, the heaters are turned off and the module cooled to room temperature; final vacuum level is recorded. The module is then typically evacuated for another 30 minutes prior to closing the module isolation valve. The module can now be disconnected and readied for the next step involving pressing and welding of the fill stem.

## Close Out Welding A Heat Pipe Module Fill Stem

After successful completion of vacuum processing, the module is transferred to a hydraulic press where a 1-inch section of the fill stem (between the module and isolation valve) is flattened. Figure 10 illustrates the process showing the fill stem pressed between two stainless steel dies. The methodology for this process was established using a number of trial stem pieces that were crimped and leak checked. Typical leak rate through the crimped samples was in excess of 6.6×10^{-6} std cc/sec helium (upper limit of the detector), however, the vacuum pressure was observed to plateau (10^{-3} torr range) at a ram setting of 20-tons (no improvement with increased load); a value of 20-tons was selected to minimize wear on the dies.

The actual seal weld is performed using a TIG welder to fusion weld/cut across the center of the crimped portion (vacuum on both sides) allowing the isolation valve to fall free. This welding process prevents introduction of the external atmosphere into the module since the molten stainless steel (on the crimp) blocks a potential entry path; the low leak rate crimp prevents entrainment of molten steel back into the module. However, as an added precaution, this process is performed in an argon purged welding glove box. To qualify the fusion weld/cut off process, a number of sample pressed fill stems were used. These stems were setup inside the welding glove box

(typical oxygen content at <0.2%) and hooked to the Varian 979 leak detector (figure 11). The detector was used to monitor the leak rate while the crimped portion was closed out by fusion welding/cutting across its center, allowing the outer portion to fall away.
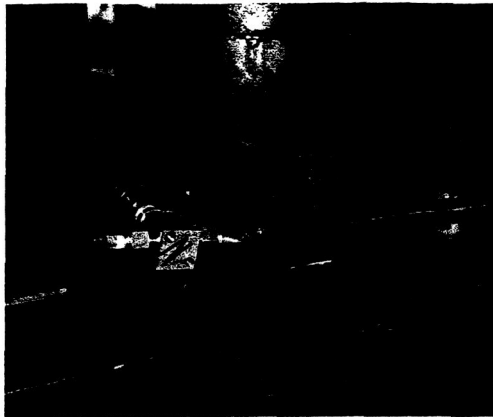

FIGURE 10. Pressing Operation On Fill Stem.
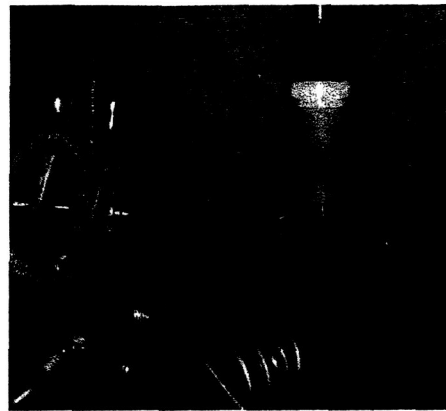
FIGURE 11. Weld Close Out of Fill Stem.

In all test cases, the molten stainless steel successfully sealed the crimped end throughout the process (no leaks were detected with the detector operating at its baseline 0.2×10^{-11} std cc/sec). The TIG welder was then used to trace back across each of these practice fusion welds providing an additional seal weld on top of the original. Throughout this process, no leaks were introduced, verifying that the welds could be touched up as necessary. Each of the actual heat pipe modules was closed off using the same procedure as the sample fill stems. However, since it was impossible to perform a leak detection in this hardware configuration, all welds could only be visually examined for pinholes, cracks or evidence of incomplete closure across the crushed seam; no readily apparent problems were found.

To complete the closeout process, a cover was welded over the fill stem stub providing protection against mechanical abuse in addition to serving as a secondary seal. The nominal length of this cap is three inches and it is the same material, diameter and thickness as that used for the module. This cap was also welded in place using the argon purged welding glove box (environment containing < 0.2% oxygen). Figure 12 illustrates the final product; a heat pipe module with the protective end cap welded in place.

Wet In For A Heat Pipe Module

The final step in processing a heat pipe requires wetting in modules at their nominal operating temperature using a vacuum furnace. This process allows the sodium to fully wet the interior of the module (contains the capillary screen structure).
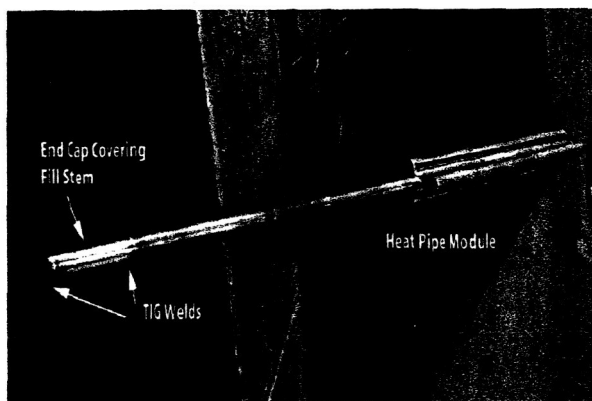
FIGURE 12. Completed Heat Pipe Module.
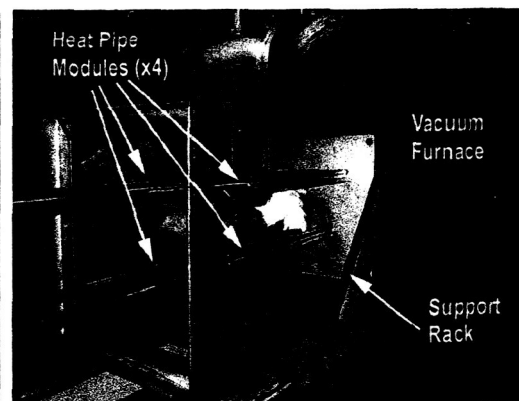
FIGURE 13. Wet In Vacuum Furnace.

A good wet in should both improve the startup characteristics of the module and reduce the potential for evaporator dry out should the module be operated at high heat flux. The modules were thoroughly cleaned using a combination of freon and alcohol wipe downs and then loaded into the furnace using a 5 slot stainless steel rack as shown in figure 13. The temperature was ramped up over a two-hour period to 750°C where it is held for 48 hours at a vacuum in the low 10^{-5} torr range. After an ambient furnace cooling cycle (several hours), the modules were removed and a final weight measurement recorded. The finished heat pipe modules were returned to the EFF-TF laboratory to be prepared for operational testing.

SUMMARY

A specially modified glove box system equipped with sodium metal dispensing hardware was successfully commissioned for filling heat pipe modules in support of the EFF-TF program. As a precursor to filling nineteen 321 stainless steel heat pipe modules for the SAFE-100A project, a series of 316 stainless steel modules were successfully filled with 35 +/-1 grams of sodium each. Additional facility and ancillary hardware was assembled or modified as necessary to complete processing of the modules. During these operations, detailed procedures were developed and refined providing a high quality heat pipe module with sufficient documentation to trace its history. The approach also paid close attention to the number of steps in the overall process, and streamlined the time required to complete a unit. This will become important in the event that a full core assembly (containing hundreds of modules) is fabricated.

ACKNOWLEDGMENTS

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