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THERMACORE, INC.

LANCASTER, PENNSYLVANIA

HIGH EFFICIENCY VAPOR-FED AMTEC SYSTEM FOR DIRECT CONVERSION

FINAL REPORT

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Prepared For:

U.S. DEPARTMENT OF ENERGY
WASHINGTON, D.C. 20585

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1.0 EXECUTIVE SUMMARY

The Alkali Metal Thermal to Electric Converter (AMTEC) is a high temperature, high efficiency system for converting thermal to electrical energy, with no moving parts. Published conceptual design studies on AMTEC space power systems show that AMTEC technology offers significant advantages over other energy conversion technologies. Current AMTEC research concentrates on high efficiency cells, and β " alumina and electrode development. Evaporator design for interfacing with general purpose heat source (GPHS) modules and fluid management in zero gravity have been given low priority. The Phase I and Phase II programs discussed here will develop the technology required for zero-gravity operation. AMTEC cells based on this technology can then be used in space power systems.

The Phase I program examined the integration of capillary pumping into a vapor-fed AMTEC device for eventual use in a space power application. A capillary pumping demonstrator was fabricated and tested to demonstrate a wick design that can return liquid sodium against the pressure difference between the low pressure condenser and the high pressure evaporator in the AMTEC cell. The operating goals for the demonstrator were 630°C (5230 Pa) in the evaporator, and 400°C (47 Pa) in the condenser. The demonstrator successfully performed in excess of the operating goals. The evaporator operated at 690°C (12,000 Pa) with the condenser at 380°C (40 Pa).

In an AMTEC cell, the pressure in the condenser is very low, typically less than 100 Pa. In a wick-pumped AMTEC cell, pressure drops in the wick can reduce the pressure in the sodium below zero, placing the sodium in tension. Some members of the AMTEC community had expressed concern that the sodium would boil in the wick, preventing the wick from operating as designed. The demonstrator was designed to operate with a negative liquid pressure in the liquid return line, and successfully sustained negative pressures (tensions) as low as -2430 Pa.

The zero-gravity fluid return system contains the following elements (1) a high reflectivity condenser, (2) drainage holes to remove the condensate, (3) arteries to transport the condensate back to the evaporator, and (4) an evaporator wick that sustains the pressure difference between the evaporator and condenser. In Phase I, an evaporator wick and artery design was successfully demonstrated. The design is self-priming, increasing reliability. The condenser design and drainage holes will be developed in Phase II. The condenser surface will be designed to maintain a smooth film of liquid sodium, which is highly reflective. High reflectivity is desirable, because it reduces parasitic thermal radiation losses, and increases efficiency.

The capillary pumping demonstrator operated at 690°C. A minor alteration in wick properties would be required for an AMTEC cell operating at 700°C. An innovative, high performance wick structure would be required to allow operation of the wick-pumped AMTEC cell at temperatures above 800°C. AMTEC cell efficiency and sodium vapor pressure both increase as the evaporator temperature is increased. A high pumping capability wick is required, with small pores, to wick the sodium against the higher vapor pressure. Conventional wicks with the required pore size have a flow capacity that is too low for AMTEC operation. Thermacore has developed a number of wick structure concepts, with small pore size and good flow capacity. These concepts will be developed in the proposed Phase II program.

2.0 INTRODUCTION

2.1 OBJECTIVES

The Phase I program objective was to examine the integration of capillary pumping into a vapor-fed AMTEC device for eventual use in a space power application. A capillary pumping demonstrator was fabricated and tested to demonstrate a wick design that can return liquid sodium against the pressure difference between the low pressure condenser and the high pressure evaporator. The operating goals for the demonstrator were 630°C (5230 Pa) in the evaporator, and 400°C (47 Pa) in the condenser. The demonstrator successfully performed in excess of the operating goals. The evaporator operated at 690°C (12,000 Pa) with the condenser at 380°C (40 Pa). The wick sustained a pressure difference of 14,000 Pa (larger than 12,000 Pa due to the gravitational and liquid flow pressure drops, as explained below).

With a wick-fed system, the sodium enters the wick in the condenser with a low pressure, and is consequently in a superheated state. Since the pressure in the condenser is only 47 Pa, pressure drops in the wick can reduce the pressure in the sodium below zero, placing the sodium in tension. Some members of the AMTEC community had expressed concern that sodium would boil in the wick, preventing the wick from operating as designed. Thermacore's previous experience with liquid metal heat pipes indicated that boiling would not be a problem. The demonstrator was designed to operate with a negative liquid pressure in the liquid return line, and successfully sustained negative pressures (tension) up to -2430 Pa.

2.2 BACKGROUND

The Alkali Metal Thermal to Electric Converter (AMTEC) is a high temperature, high efficiency system for converting thermal to electrical energy, with no moving parts. AMTEC can best be described as a thermally regenerative electrochemical cell. It is based on the unique properties of β "-alumina solid electrolyte (BASE), which is an excellent conductor of sodium ions, but an extremely poor conductor of electrons. A schematic of an AMTEC system is shown in Figure 1. High temperature and high pressure sodium are located on one side of the BASE, while the other side of the BASE is in contact with low temperature and low pressure sodium vapor.

The pressure and temperature gradients across the BASE create a concentration gradient. Electrons and sodium atoms cannot pass through the BASE. However, as shown in Figure 2, the sodium atoms ionize, and the sodium ions move through the BASE to the lower potential (temperature) region. The electrons travel externally to the AMTEC cell, providing power. They are then transported through a porous electrode on the low temperature side of the BASE, where they recombine with the sodium ions, forming sodium atoms. To maintain the concentration gradient, the sodium atoms are vaporized, and travel as a vapor to the low temperature condenser region. These sodium atoms are then returned to the high pressure, high temperature region using electromagnetic or capillary forces. Thermal energy is supplied to the high temperature side to replace the extracted electrical energy and the non-recoverable heat losses. Heat is removed from the condenser to maintain a low temperature and pressure and allow additional sodium atoms to evaporate from the BASE, which maintains the concentration gradient across the BASE.

A vapor-fed AMTEC cell is shown in Figure 3a, with a heat and fluid flow diagram shown in Figure 3b. The BASE is in the form of a pressed and sintered tube with one closed end. The open end of the BASE is joined to a refractory metal tube to be operated as an evaporator. The interior of the

FIGURE 1. AMTEC SCHEMATIC

BASE and the evaporator tube is maintained at a high pressure (15 - 150 kPa) and temperature (970 - 1200 K). The high pressure region contains a sodium filled wick lining the evaporator tube and BASE, and a central vapor core. Thermal energy input (Q_{in}) into the evaporator causes the liquid in the inner wick to evaporate. The resulting vapor flows to the BASE region, where it condenses and deposits thermal energy from the heat source. This energy is either converted directly to electrical energy, or is lost as a parasitic heat loss (Q_p) to the cooler condenser. An advantage of the vapor-fed design is that it simplifies the interface with the heat source.

The exterior of the BASE tube between BASE and the condenser is the low pressure (5 - 100 Pa) region. The low pressure is produced by cooling the condenser to 600 - 700 K and removing the condensing vapor. This type of cell will provide 5 to 500 W of power. Most of the condensing sodium (80%) returns to the evaporator through the inner wick. A portion of the sodium (1 gram/hour/amp), however, ionizes and passes through the BASE. Free electrons on the inside of the BASE are conducted along the sodium-filled wick to the outer surface of the cell evaporator and through the EM pump, as shown in Figure 3b. Electrons are returned to the cell through the lead to a grid that distributes the electrons to the electrode with minimal ohmic losses. Sodium ions and the electrons are recombined at the BASE-electrode interface. The neutral sodium atoms move through the electrode in either solid state or gas phase diffusion, absorbing the heat of vaporization during the process, and into the vapor space inside the condenser wall. The vaporized sodium atoms pass through the porous heat shield and condense on the wick of the low temperature condenser wall.

Liquid sodium in the low temperature/pressure condenser region moves through the wick annulus to the inlet of liquid return line. The available head to move the liquid to the inlet is approximately 10 to 100 Pa. Since the flow rate (approximately 1 gram/hour/amp) is also very low, this head is adequate to move the fluid under zero-g conditions. The low pressure liquid in the condenser must be returned to the evaporator, which operates at 15,000 to 150,000 Pa, depending on the BASE temperature. The liquid sodium can be returned by (1) an EM pump powered by the electronic current leaving the cell, (2) capillary forces generated in a porous wick structure, or (3) a hybrid wick/EM pump device. As discussed in more detail below, this project will examine the tradeoffs between the different methods.

Current AMTEC research concentrates on high efficiency cells, and β " alumina and electrode development. Fluid recirculation and condenser design have been given low priority. Most current cells are research devices, with once-through flow for sodium. Very little work has been done on fluid recirculation in zero gravity. This program was designed to examine the requirements for zero-g operation.

C:\AR11\12\1806\FIG4.DWG &LST

FIGURE 2. SODIUM IONS PASS THROUGH THE BASE, WHILE ELECTRONS DELIVER POWER TO AN EXTERNAL LOAD.

C:\AR11\12\1806\FIG14.DWG &LST

FIGURE 3. (a) VAPOR-FED "AMTEC" CELL. (b) VAPOR-FED "AMTEC" HEAT AND FLUID FLOW.

3.0 PHASE I PROGRAM RESULTS

3.1 TASK 1. DESIGN REQUIREMENTS

In Task 1, Thermacore consulted with Westinghouse to update the design and performance requirements for a vapor-fed AMTEC design. The information supplied by Westinghouse to Thermacore on their current vapor-fed design included:

- Plans and dimensions
- Evaporator heat flux
- Source temperature
- Vapor space temperature
- Condenser temperature
- Condenser heat fluxes
- Radiator interface requirements
- Electrical power generation, voltage and amperage
- Sodium flow rates, both through the BASE, and recirculating
- Heat loss information

Westinghouse informed Thermacore that a typical sodium flow rate through the BASE in a vapor-fed AMTEC cell is roughly 6×10^{-6} kg/s, and the condenser temperature is typically around 400°C, giving a vapor pressure in the condenser of roughly 50 Pa. This information was used to design the capillary pumping demonstrator in Task 2.

3.2 TASK 2. CAPILLARY PUMPING DEMONSTRATION

The Task 2 objective was to demonstrate capillary pumping in a sodium capillary pumped loop that uses a wick to return liquid sodium from the low pressure condenser to the high pressure evaporator. The operating goals were 630°C (5230 Pa) in the evaporator, and 400°C (47 Pa) in the condenser. The demonstrator was designed to operate with a negative liquid pressure in the liquid return line, to demonstrate that boiling will not cause problems in the high temperature, low pressure (superheat) regions of the AMTEC cell. These requirements were met and exceeded in the program. The system successfully operated between 690°C (12,000 Pa) and 380°C (40 Pa), with the wick sustaining a pressure difference of 14,000 Pa. Negative liquid pressures (tension) in the sodium of up to -2430 Pa were achieved, demonstrating the feasibility of a wick-fed AMTEC device.

Capillary Pumping Demonstrator Design

In a vapor-fed AMTEC cell, roughly 6×10^{-6} kg/s (20 percent) of the liquid sodium condensing on the BASE passes through the electrolyte and generates electricity. The remaining sodium, which is required to deliver sufficient thermal energy to the conversion process, is recirculated. The liquid return from the inside of the BASE to the evaporator is accomplished by the capillary action of the wick. From the point of view of the sodium flow, the vapor-fed AMTEC cell acts like a "leaky" heat pipe, with a portion of the fluid recirculating outside the main heat pipe to a lower temperature condenser region.

C:\AR11\12\1806\FIG5.DWG & LST

FIGURE 4. CAPILLARY PUMPING DEMONSTRATOR.

A sketch of the capillary pumping demonstrator is shown in Figure 4. Design calculations are located in Appendix A, while Appendix B contains the fabrication drawings. The system contains an evaporator, a primary condenser, a flow restricting orifice simulating the pressure drop across the base, and a secondary condenser. The evaporator and primary condenser are connected with a wick. Heat is supplied to the evaporator, generating sodium vapor. Most of the sodium vapor condenses in the primary condenser, and is returned through the wick. This is similar in behavior to the flow of fluids in the evaporator of a vapor-fed AMTEC cell, where 80 percent of the sodium supplies heat to the BASE, then is recirculated to the evaporator.

In an AMTEC cell, the remaining sodium generates electricity as it passes through the BASE to the low pressure condenser region. In the test apparatus shown in Figure 4, the AMTEC condenser region is simulated by the secondary condenser, which is located downstream of an orifice. At temperatures near 900 K, it is possible to operate this system so that sodium vapor flow through the orifice is choked, and the secondary condenser is at a significantly lower temperature and pressure than the evaporator.

Once sodium condenses in the secondary condenser, it falls to the bottom, forming a pool. Note that since the secondary evaporator does not contain a wick, this sodium is not available to the system until it is returned by capillary forces through the liquid return line. This system was designed to demonstrate the capability of a wick-pumped AMTEC cell to return liquid from the evaporator to the condenser against a significant temperature and pressure differential. The system was also designed to demonstrate the ability of the liquid return line to return liquid, without problems caused by vapor formation in the return line.

The liquid return line is a cable artery, which consists of a stainless steel cable mounted in a stainless steel tube. The use of a cable artery simplifies system operation, and improves reliability. If a bare tube (conventional artery) was used, the liquid line would require priming before the system could operate. If prime was lost, the system would have to be re-primed before operation could continue. In a cable artery, the liquid travels between the individual wires in the cable. The thin gaps between the wire provide a capillary pumping capability, so that the cable artery is self-priming. A cable artery was chosen, rather than a sintered or screen wick, because it is flexible, and can easily be bent inside the pipe.

Differences between the Demonstrator and an AMTEC Cell

The objective of the capillary pumping demonstrator was to demonstrate that a wick can be used to pump sodium from the condenser to the evaporator of an AMTEC cell. The design flow rate to the secondary condenser was 2×10^{-5} kg/s, which is over three times the typical flow rate in the vapor fed AMTEC cell. While the liquid flow rate simulates the AMTEC flow rate, the remainder of the system was sized differently than the AMTEC system for the following reasons:

1. **Gravity Collection of the Sodium** - In an AMTEC design for space applications, capillary forces would collect the fluid in the condenser into the liquid return system. Condenser design was not considered in the capillary pumping demonstrator, due to the difference in flow patterns between the two systems. In an AMTEC cell, sodium vapor is uniformly deposited on the condenser surface. On the other hand, the capillary pumping demonstrator has a vapor jet through the orifice, so the fluid condensation rates and flow patterns are very non-uniform. Since it was not possible to simulate the AMTEC condenser, gravity collection of fluid was used to simplify the condenser design. Locating the condenser below the evaporator also allowed the liquid sodium to be put

into tension (negative pressure) in the liquid return line (This is explained in more detail below).

2. **Demonstrator Size and Power** - The demonstrator is larger than a typical vapor-fed AMTEC cell, and up to 2000 W will be supplied to the evaporator. No attempt was made to match the recirculating sodium flow in an actual vapor-fed AMTEC reactor. In the demonstrator, the flow to the secondary condenser is set by choked flow through an orifice. The size and power of the demonstrator were set large enough so that compressible flow effects would be unimportant in the high temperature half of the demonstrator.

Design Operating Conditions

In the Phase I proposal, the demonstrator operating goals were 630°C (5230 Pa) in the evaporator, and 400°C (47 Pa) in the condenser. For the wick to return sodium from the secondary condenser to the evaporator, the demonstrator was designed so that the wick pumping capability was greater than the sum of the pressure drops in the loop:

$$\Delta P_{\text{capillary}} \geq \Delta P_{\text{total}} = \Delta P_{\text{vapor}} + \Delta P_{\text{cable artery}} + \Delta P_{\text{wick}} + \Delta P_{\text{gravity}} \quad (1)$$

where:

ΔP_{total} is the sum of the pressure drops in the system,

ΔP_{vapor} is the pressure difference between the evaporator and condenser,

$\Delta P_{\text{cable artery}}$ is the pressure drop in the liquid return line,

ΔP_{wick} is the pressure drop in the wick, and

$\Delta P_{\text{gravity}}$ is the gravitational head (zero in space)

The capillary pumping capability depends inversely on the pore radius:

$$\Delta P_{\text{capillary}} = 2\sigma/r_c \quad (2)$$

where:

σ is the surface tension, and

r_c is the pore radius.

Calculated pressure drops in the system are shown in Figure 5 as a function of evaporator temperature, assuming single phase liquid flow in the wick. As the evaporator temperature and vapor pressure increase, the pressure drop also increases, for two reasons. First, ΔP_{vapor} increases, since the vapor pressure in the evaporator increases, while the vapor pressure in the condenser remains the same. Second, the flow rate through the orifice increases as the vapor pressure increases. The pressure drops in the wick and cable artery are linearly dependent on flow rate. Prior to testing, the maximum operating temperature of the demonstrator was estimated to be around 650 °C, based on single phase flow.

Capillary Pumping Demonstrator
Secondary Condenser Pressure Drops
 $T_{\text{Condenser}} = 400^{\circ}\text{C}$ Elevation = 5.9 inches

Figure 5. Calculated Pressure Drops as a Function of Evaporator Temperature for the Capillary Pumping Demonstrator

The wick used in the capillary pumping demonstrator was chosen for two reasons: (1) a wide pore size distribution, and (2) a very high porosity, typically 70 percent. Each powder particle is a cluster formed from a large number of smaller particles. A wide pore size distribution increases the pumping capability above the single phase capability, since liquid is wicked to the evaporator through the smaller pores, while vapor is vented through the larger pores. The high porosity provides storage for the sodium, increasing the inventory available during start-up.

The capillary pumping demonstrator operates with choked flow across the orifice. A thick, square-edged orifice is used (plate thickness greater than orifice diameter), since choking does not occur with thin orifices [Miller, 1983]. The flow through the orifice is given by:

$$\dot{m} = \rho^* A^* c^* \quad (3)$$

where:

ρ^* = vapor density at sonic conditions

A^* = minimum area of the flow

c^* = sound speed

For a thick orifice, $A^* = 0.839 A$, where A is the orifice area [Miller, 1983]. Mass flow rates through the orifice are shown in Figure 6, assuming adiabatic flow of a perfect gas through the orifice. This assumption has previously given good results for calculating flows in sodium heat pipes [Levy, 1968].

One difference between the capillary pumping demonstrator and ordinary heat pipes is that the demonstrator is designed to operate with negative liquid pressure. In the AMTEC cell, the vapor pressure in the condenser is very low, typically about 50 Pa. In a wick-fed design, negative absolute pressures could exist in the liquid return line and wick. The capillary pumping demonstrator demonstrated that it is possible to operate in this regime.

A schematic of the pressure in the various parts of the heat pipe is shown in Figure 7, for an evaporator temperature of 650°C, and a condenser temperature of 400°C. The evaporator pressure of 7030 Pa is set by the evaporator temperature, since the sodium is at saturated conditions. The sodium vapor travels through the orifice to the secondary condenser, where the temperature is 400°C, and the pressure is 47 Pa. As the liquid travels through the cable artery, the absolute pressure goes negative, so that the liquid is in tension. The pressure continues to drop as the liquid travels through the evaporator wick. Finally, the pressure drop is increased back to 7030 Pa by capillary forces in the wick at the vapor/liquid interface.

Demonstrator Results

After fabrication, the demonstrator was charged with sodium. Argon was used to push sodium through the valve and into the top of the cable artery. The entire demonstrator was heated above 100°C, the melting temperature of sodium. After about one-third of the sodium charge entered the system, the liquid return line was frozen, then the remaining sodium was pushed into the system. The liquid line was frozen to force the remaining sodium into the wick, rather than allowing it to enter the secondary condenser sump.

Capillary Pumping Demonstrator
Calculated Mass Flow Rate Through Orifice
 $T_{\text{Condenser}} = 400^{\circ}\text{C}$ Elevation = 5.9 inches

Figure 6. Calculated Flow Rate Through the Orifice to the Secondary Condenser as a Function of Temperature.

Capillary Pumping Demonstrator Calculated Secondary Condenser Pressure Drops $T_{\text{Evaporator}} = 650^{\circ}\text{C}$ $T_{\text{Condenser}} = 400^{\circ}\text{C}$

Figure 7. Calculated Pressures in the Demonstrator for an Evaporator Temperature of 650°C .

Initially, the entire demonstrator was operated near 700°C. The evaporator was heated with a radio frequency (RF) coil, while electrical resistance heaters were used to raise the temperature of the secondary condenser. This assured that the sodium wet the wick properly.

The system was then operated with a large temperature difference between the evaporator and secondary condenser. Initially, electrical resistance heaters and the RF coil were used to melt the sodium, and warm the system up. The resistance heaters in the secondary condenser were then shut off, and insulation opened up on the secondary condenser, to maintain the temperature near 400°C. Note that a small amount of electrical resistance heat was supplied to the liquid return line. The flow rates are small enough that the isolated liquid line chosen for this test would cool down without supplemental heat. The evaporator temperature was initially operated near 650°C (7030 Pa vapor pressure). After several days of operation, the evaporator temperature was raised to 660°C (8120 Pa), then to 670°C (9340 Pa). In each case, the system performed as expected.

During operation, temperatures were measured at the thermocouple locations shown in Figure 8. Thermocouple 1 gives the temperature of the evaporator, while thermocouple 3 gives the temperature of the primary (high temperature) condenser. The temperature of the low temperature (secondary) condenser is measured by thermocouple 7. During operation, the insulation around the secondary condenser was adjusted to maintain the temperature near 400°C.

Figure 9 shows the typical temperatures in the demonstrator during operation. The evaporator operated near 670°C, while the secondary condenser operated near 400°C. These data represent part of a run that lasted about 8 hours. Pressures in the evaporator and secondary condenser are shown in Figure 10. These saturated sodium vapor pressures were calculated from a correlation in Foust [1972]:

$$P_v = \frac{101350}{\sqrt{T_K}} 10^{(6.354 - 5567/T_K)} \quad (4)$$

with P_v in Pascal and T_K in Kelvin.

The minimum pressure in the system is determined by the elevation of the evaporator above the secondary condenser. A pool of sodium covers the cable artery in the secondary condenser, with a pressure of roughly 40 to 50 Pa. The pressure decreases as the sodium travels to the evaporator, due to both pressure drops due to flow, and to the gravitational term

$$P_{g\Delta v} = -\rho_L g h \quad (5)$$

where h is the elevation of the evaporator above the condenser. The data shown in Figures 9 and 10 were taken with an evaporator elevation of 5.9 inches. Figure 11 shows a schematic of the pressure in the demonstrator when the elevation was increased to 8.9 inches. The pressure in the evaporator is about 9000 Pa. The pressure decreases slightly when traveling from the evaporator to the primary condenser, due to the fluid flow losses. The pressure then decreases sharply as the sodium vapor travels through the orifice, to about 40 Pa. The condensed sodium then travels back to the evaporator through the cable artery and wick. The minimum pressure in the system is -2430 Pa in the evaporator.

FIGURE 8. CAPILLARY PUMPING DEMONSTRATOR - THERMOCOUPLE LOCATIONS

AMTEC Capillary Pumping Demonstrator Jan7B: Evaporator and Condenser Temperatures

Figure 9. Evaporator and Condenser Temperatures, for an Evaporator Temperature of 670°C.

AMTEC Capillary Pumping Demonstrator Jan7B: Evaporator and Condenser Pressures

Figure 10. Evaporator and Condenser Pressures, for an Evaporator Temperature of 670°C.

Capillary Pumping Demonstrator: January 22
Secondary Condenser Pressure Drops, $P_{\min} = -2430$ Pa
 $T_{\text{Evap}} = 668^{\circ}\text{C}$ $T_{\text{Cond}} = 397^{\circ}\text{C}$ Elevation = 8.9 in.

Figure 11. Capillary Pumping Demonstrator Pressures, with an Evaporator Elevation of 8.9 Inches, and a Minimum Pressure of -2430 Pa.

After operating successfully at 670°C, the evaporator temperature was first increased to 680, and then 690°C. Figures 12 and 13 show evaporator and condenser temperatures and pressures. A schematic of the pressure loop in the system is shown in Figure 14. The maximum pressure was roughly 12,000 Pa, and the minimum pressure was near -2000 Pa, so the wick pumped liquid back to the evaporator against a roughly 14,000 Pa pressure difference.

Dryout occurred when the evaporator was operated at 700°C, as shown in Figure 15. A small hot spot formed at the top of the RF coil near the cable artery, indicating that the cable artery could no longer pump sodium. After dryout, the heat flux into the evaporator was reduced, then gradually increased again, so that the system operated with an evaporator temperature near 690°C for the remainder of the day. The vapor pressure at dryout was 13,700 Pa, and the total pumping pressure required was about 15,700 Pa, due to the elevation of the evaporator above the condenser. It is possible that the system could operate at 700°C, if the gravitational pressure drop was reduced.

Figure 5 shows the calculated pressure drops in the system as a function of temperature. The wick pumping capability is also shown, assuming that the wick is completely saturated with sodium. Figure 5 indicates that the system should have operated up to about 670°C, when it actually operated up to 690°C.

The wick pumping capability is determined by the surface tension and the capillary radius of the active pores:

$$P_{wick} = \frac{2 \sigma}{r_c} \quad (6)$$

The calculations shown in Figure 5 are based on the largest pores in the wick, and underestimate the actual capillary pumping capability. During operation, the largest pores are filled with venting vapor. The liquid is in smaller pores, and the wicking capability is higher than the single-phase calculations.

The wick used in the capillary pumping demonstrator was chosen for two reasons: (1) a wide pore size distribution, and (2) a very high porosity, typically 70 percent. The wick pore size distribution increased the pumping capability above the single phase calculated capability. The liquid is wicked to the evaporator through smaller pores, while vapor is vented through the larger pores.

3.3 TASK 3. ZERO-G FLUIDS HANDLING

Once the liquid sodium is collected in the AMTEC condenser, it must be pumped back up to the high pressure evaporator. The Task 3 objective was to examine alternate methods for liquid return in zero gravity. The methods for returning sodium from the low pressure condenser to the high pressure BASE include:

- Electromagnetic (EM) pump
- Capillary pumping with a sintered wick
- Hybrid EM pump/wick system

AMTEC Capillary Pumping Demonstrator Jan30B: Evaporator and Condenser Temperatures

Figure 12. Evaporator and Condenser Temperatures for an Evaporator Temperature of 690°C

AMTEC Capillary Pumping Demonstrator Jan30B: Evaporator and Condenser Pressures

Figure 13. Evaporator and Condenser Pressures, for an Evaporator Temperature of 690°C

Capillary Pumping Demonstrator: January 30
Secondary Condenser Pressure Drops, $P_{\min} = -2060$ Pa
 $T_{\text{Evap}} = 690^{\circ}\text{C}$ $T_{\text{Cond}} = 380^{\circ}\text{C}$ Elevation = 5.9 in.

Figure 14. Capillary Pumping Demonstrator Pressures for an Evaporator Temperature of 690°C

AMTEC Capillary Pumping Demonstrator Limits

$T_{\text{Dryout}} = 698^{\circ}\text{C}$ $P_{\text{Dryout}} = 13.7 \text{ kPa}$, Elevation = 4.9 in.

Figure 15. Dryout at a Temperature of 698°C and a Total Pressure Difference Across the Wick of 15.7 kPa

The EM pump is the method used in most current AMTEC designs. It requires electrical energy from the cell, reducing efficiency. One advantage of this technology is that it is well understood, and requires minimal technology development. A disadvantage is that the pump controls and power supply are active components subject to failure. In addition, the magnets on the pump have to be kept below the Curie temperature, so the heat losses are increased. This can cause the pump to plug with oxides, because of cold trapping resulting from the need to cool the magnets.

A second method of returning the fluid is to use a sintered porous metal wick that uses capillary forces to passively return liquid to the evaporator, and to distribute the liquid in the evaporator. This design would be similar to the capillary pumping demonstrator. The capillary pump has demonstrated operation at 690°C. A relatively minor change in the wick pore size is required for operation at 700°C. Wick development to achieve 800°C and higher temperatures will be carried out in Phase II. This can be achieved by using a smaller powder particle size to increase the wick pumping capability. AMTEC cells with a 700°C evaporator might be suitable to terrestrial applications. Elimination of the EM pump would reduce parasitic electrical and heat losses, improving efficiency and reliability. In Phase II, wicks will be fabricated with greater pumping capabilities for operation at higher temperatures.

An advantage of a wick is that it is completely passive, requiring none of the electrical output of the cell to drive an EM pump. In addition, the amount of liquid fed to the evaporator is self-regulating. As fluid is evaporated, the increase in surface tension forces at the interface pulls more fluid to the surface. The evaporator cannot flood, since the capillary pumping ability of the wick reduces to zero when excess liquid accumulates in the evaporator.

The wick-fed system has a number of advantages over an EM-pumped system, including increased efficiency, and passive regulation of the fluid returned from the condenser. In addition, the wick-fed system can be integrated with the wick used to supply sodium vapor from the evaporator to the BASE. However, the maximum BASE temperature for a wick-fed system is currently near 700°C.

A hybrid combination of EM pump and wick offers one solution for operation at higher temperature. The EM pump would pump the liquid from the condenser to an intermediate pressure, with a wick providing the remaining increase in pressure. This hybrid system would also passively feed liquid back to multiple BASEs. However, Thermacore believes that a hybrid system is not required. As discussed below in the Phase II tasks, wicks can be developed to pump the fluid at higher temperatures and pressures, eliminating the need for an EM pump. For this reason, the work in Task 3 has concentrated on a wick-pumped system.

There are four main elements to the fluid return design:

1. A series of grooves on the condenser surface to collect sodium, while maintaining a reflective sodium film.
2. Drainage holes to remove the condensate.
3. Arteries to transport the condensate
4. An evaporator wick that sustains the temperature difference between the evaporator and condenser.

One design criterion for the liquid return system is that the capillary radius decreases from one section of the fluid return system to the next, as sodium flows from the condenser to the evaporator. This causes the sodium in the condenser to spontaneously wick to the evaporator, giving a self-priming liquid return system.

A schematic of the liquid return system is shown in Figure 16. Sodium vapor condenses on the condenser surface, and the liquid sodium is drawn by capillary forces into the centers of the Gregorig grooves. The sodium then flows through the drainage hole, into a cable artery. Sodium then travels along the cable artery to the evaporator wick, where it is vaporized to supply the BASE. The wick has a smaller pore radius than the cable artery, which in turn has a smaller radius than the drainage holes, so sodium is wicked from the condenser to the evaporator.

The basic outline of the liquid return system is similar to the capillary pumping demonstrator, which is shown in Figure 4. Liquid is wicked from a liquid pool through a cable artery to the evaporator. The demonstrator experiments verified that this design can tolerate negative liquid pressures, and high sodium superheats, without experiencing any problems.

The remainder of this task will discuss the following sections of the liquid return system:

1. Wick Design for higher temperature and pressure operation
2. Evaporator Design
3. Condenser Design

Wick Design

The Phase I capillary pumping demonstrator operated up to a temperature of 690°C. Only a slight reduction in pore size is required to operate AMTEC cells at temperatures near 700°C. One objective of the Phase II program is to develop wicks that will allow the cells to operate with as high a temperature as possible. The near-term goal for long-life AMTEC cells is to operate at temperatures near 800°C. Above this temperature, problems with materials tend to limit the AMTEC cell life.

Higher operating temperatures are desirable, since AMTEC cell efficiency increases dramatically as the evaporator temperature is increased from 900 to 1200 K. For example, calculated efficiencies increase from 8 percent to 24 percent for one cell design, as shown in Figure 17. However, as the operating temperature increases, the sodium vapor pressure in the BASE also increases. For the wick to return sodium to the evaporator, the wick pumping capability must be greater than the sum of the pressure drops in the loop:

$$\Delta P_{\text{capillary}} \geq \Delta P_{\text{vapor}} + \Delta P_{\text{liquid}} + \Delta P_{\text{gravity}}$$

where: ΔP_{vapor} is the pressure difference between the evaporator and condenser (essentially the vapor pressure, since the condenser pressure is effectively zero),

ΔP_{liquid} is the pressure drop in the liquid return line and wick, and

$\Delta P_{\text{gravity}}$ is the gravitational head (zero in space)

FIGURE 16. WICK PUMPED FLUID RETURN SYSTEM SCHEMATIC.

Figure 17. Pore Size and Cell Efficiency versus Operating Temperatures

The capillary pumping capability depends inversely on the pore radius:

$$P_{\text{capillary}} = 2\sigma/r_c$$

As the operating temperature increases, the vapor pressure increases, and the required pore radius decreases, as shown in Figure 17. The required pore size to overcome the vapor pressure decreases from 50 μm at 900 K to around 2 μm when the evaporator is operating at 1200 K. Powders are available commercially which Thermacore believes could be used to manufacture a wick with a 2 μm pore size.

The problem with a conventional, uniform wick structure is that the permeability for flow decreases as the pore size decreases. Figure 18 is a plot of permeability versus pore radius for a series of wicks sintered with different sizes of nickel powder. A wick with a 2 μm pore size would have a very low permeability. The wick would have insufficient flow capacity to return sodium to the evaporator.

The solution is to tailor the wick structure to maintain reasonable permeability with a high pumping capability. Possible fabrication methods include the use of wicks with a wide pore size distribution, the creation of mini-arteries, the use of sacrificial particles during fabrication, or the use of multi-layer wicks. For example, the Phase I program used a wick with a wide pore size distribution. In areas away from the evaporator, the entire wick is filled with liquid, so the permeability for fluid flow is relatively high, minimizing the pressure drop. In the evaporator wick, the large pores contain vapor, while the smaller pores supply liquid to the system. The wick pumping capability is increased, since the pore size of the active pores in the evaporator is smaller than the pore size for single phase flow.

As a second example, the mini-artery concept will be briefly discussed here, as a second concept for developing the required wick structure. In this concept, the wick contains a series of miniature arteries embedded in the wick. The arteries, with a diameter of roughly $2.54 \times 10^{-4}\text{m}$ (0.010"), provide the required wick flow capacity. The surrounding wick has a pore radius of roughly 2 μm . Since the arteries are completely embedded in the wick, they do not reduce the wick pumping capability. One method of forming the arteries would be to sinter the wick with a series of wires embedded in the wick, then remove the wires. As shown in Figure 19, a series of wires is placed in the desired location for the arteries. The space around the wires is filled with metal powder, which is sintered into a porous wick. After the wick is sintered, the wires are removed, leaving behind small arteries that increase the liquid permeability. One possible wire material would be copper. Copper wires would be removed by etching with acid. A second possible wire material is oxidized stainless steel. The oxidation layer prevents the wire from sintering to the powder, allowing the wires to be removed.

Thermacore has fabricated this type of wick structure in plastic-bonded aluminum wick samples. A series of 0.005" diameter molybdenum wires were inserted in a -70+80 mesh aluminum powder. The powder also contained a small amount of plastic, which was used to bond the wick for the intended low temperature application. After sintering, the molybdenum wires were removed by pulling them out of the sample.

Figure 18. Permeability versus Pore Radius for Spherical Nickel Powders.

FIGURE 19. WIRE MANDRELS FOR A MINI-ARTERY WICK, WITH HIGH PUMPING CAPABILITY AND HIGH PERMEABILITY.

Evaporator Design

The evaporator design must be considered for the vapor-fed AMTEC cell, in addition to the liquid return system. One heat source is a series of General Purpose Heat Source (GPHS) modules. The general purpose heat source (GPHS) is a radio-isotope heat source for use in space power systems (Schock, 1980). Approximately 250 W of thermal energy are supplied by each GPHS module through the decay of plutonium-238 (Pu^{238}). The modules can be stacked together for higher power systems, allowing general purpose heat sources to be used for a wide range of power levels. The operating temperature of the modules is typically around 1200°C. A schematic of an AMTEC cell and GPHS is shown in Figure 20.

Heat and sodium flow for an AMTEC cell are shown in Figure 21. Radiant thermal energy from the GPHS evaporates sodium in the evaporator. The vapor flows to the BASE region where it condenses. A portion of the liquid flows back inside the BASE. The remaining sodium passes through the BASE, generates electricity, and condenses. This sodium is then wicked back into the high pressure region.

One factor that must be considered in evaporator design is start-up of the system. While the AMTEC cells will operate continuously once the GPHS modules are installed, they will be started up from room temperature a number of times during testing. Two-phase alkali metal systems tend to have significant thermal gradients during start-up, due to their very low vapor pressure. Compressible flow effects limit the heat that can be transferred along the flow axis during start-up. During start-up, most of the condensation takes place in a relatively narrow zone, which travels down the system. For example, Figure 22 shows axial temperature profiles at different times during the start-up of a long, narrow sodium heat pipe [Ponnappan et al., 1989].

Temperature gradients during start-up of the AMTEC cell must be minimized, to avoid cracking the β "-alumina from thermal stresses. In Phase II, Thermacore will examine the different options to minimize start-up stresses. For example, increasing the diameter of the system relative to the length reduces the severity of the thermal front.

A separate option that will be examined more thoroughly in Phase II is to supply heat with a heat pipe inside the BASE. This concept is shown in Figure 23. Heat supplied from the GPHS is transferred to the condenser of the internal heat pipe. The exterior of the heat pipe is covered with a wick, which is connected to the wick on the inside of the BASE at a number of points. Sodium evaporating off the exterior of the internal heat pipe travels radially to supply heat to the BASE. The condensed liquid is wicked back to the heat pipe through the wick "bridges".

The internal heat pipe reduces the thermal gradients during start-up. First, the heat pipe can use potassium rather than sodium. The vapor pressure of potassium is higher than sodium, reducing the compressible flow effects, and the thermal gradient. During start-up, the temperature front travels down the axis of the internal heat pipe. However, the thermal gradient in the BASE is minimized, since the temperature will be low enough that very little sodium will flow radially to the BASE. The BASE will warm up more slowly, due to radiation from the heat pipe. After the potassium heat pipe has a uniform temperature, the entire heat pipe will warm up. Sodium will flow radially to the BASE, warming the entire BASE at the same time, and minimizing thermal gradients.

FIGURE 20. "AMTEC" CELLS POWERED BY THERMAL RADIATION FROM A "GPHS" HEAT SOURCE MODULE, WITH WASTE HEAT REJECTED TO SPACE.

C:\AR11\12-1806\FIG16A.DWG &.LST

FIGURE 21. WICK-PUMPED, VAPOR-FED "AMTEC" CELL POWERED BY THERMAL RADIATION FROM A "GPHS" MODULE.

Figure 22. Axial Temperatures Profiles During Start-up of a Long, Sodium Heat Pipe [Ponnappan et al., 1989]

C:\AR11\12-1800\FIG15A.DWG & LST

FIGURE 23. WICK-PUMPED, VAPOR-FED, "AMTEC" CELL WITH AN INTERIOR HEAT PIPE TO MINIMIZE STRESSES ON THE β'' -ALUMINA DURING START-UP.

Condenser Design

The self-regulating nature of the wick-fed design is especially important in advanced AMTEC designs, which can have multiple BASES with a single condenser. These designs increase the overall AMTEC efficiency, by reducing parasitic radiation heat transfer losses from the BASEs to the condenser.

The efficiency of an AMTEC cell is the electrical power out ($P = IV$) divided by the thermal power in. The relation for AMTEC efficiency is approximately: [Bankston, 1986]

$$\eta = \frac{IV}{IV + [I/F] [\lambda_{fg} + C_p (T_{evap} - T_{cond})] + Q_c + Q_{rad}} \quad (7)$$

The heat input into the system consists of five terms:

- (1) Thermal energy equal to the electrical power input (IV)
- (2) Heat required to vaporize sodium from the low pressure side of the BASE, $(I/F)\lambda_{fg}$, where F is a conversion factor from the electron current to the sodium mass flow rate, and λ_{fg} is the latent heat of vaporization.
- (3) Heat required to raise the sodium temperature from the condenser temperature to the evaporator temperature, $(I/F)(C_p)(T_{evap} - T_{cond})$.
- (4) Parasitic heat losses due to conduction through the output current leads and the supporting structure for the BASE, Q_c .
- (5) Parasitic heat losses due to radiation from the hot BASE surface to the cold condenser surface, Q_{rad} .

The first three terms are required for the AMTEC cycle to operate, while the parasitic heat losses reduce the overall efficiency.

The overall AMTEC efficiency is strongly dependent on the parasitic heat losses due to radiation. For example, Crowley [1991] made rough estimates of AMTEC efficiency as a function of radiation losses for a typical concentric AMTEC configuration. As the radiation losses approached zero, the overall AMTEC efficiency approached 40 percent, which is close to the Carnot efficiency. On the other hand, assuming that the surfaces behaved as black bodies lowered the efficiency to less than 10 percent.

The parasitic thermal radiation losses from the evaporator to the condenser are:

$$Q_{rad} = A_{evap} F_{12} \sigma (T_{evap}^4 - T_{cond}^4) \quad (8)$$

where

Q_{rad} = radiation heat losses [W]

A_{evap} = area of the BASE [cm^2]

σ = Stefan-Boltzmann constant [$5.62 \times 10^{-12} \text{ W/cm}^2 \text{ K}^4$]

T_{evap}, T_{cond} = evaporator and condenser temperature [K]

F_{12} is a view factor that depends on the geometry, and the emissivities of the two surfaces. For example, the view factor for infinite (neglect end effects) concentric cylinders is:[Kern]

$$F_{12} = \frac{1}{\frac{1}{\epsilon_{evap}} + \frac{A_{evap}}{A_{cond}} \left(\frac{1}{\epsilon_{cond}} - 1 \right)} \quad (9)$$

where

A_{evap} , A_{cond} are the evaporator and condenser surface areas, and ϵ_{evap} , ϵ_{cond} are the emissivities of the two (gray) surfaces.

There are three ways to reduce the radiation losses: (1) reduce the condenser emissivity, (2) add radiation shields, and (3) change the system geometry. Changes in system geometry will first be discussed to explain why multiple BASEs in a condenser are desirable. A schematic of the conventional AMTEC cell configuration is shown in Figure 24. The sealed inner cylinder contains high pressure sodium. Sodium ions travel across the BASE, generating power. The sodium vapor then flows to a concentric cylindrical condenser. Thermal radiation travels in the same path as the sodium. Note that this figure shows a cut-away through the high pressure sodium region; this region is actually sealed off from the low pressure condenser, so sodium can only travel through the BASE.

Figure 25 is a modification of Figure 24, with multiple BASEs inside a single cylindrical condenser. Sodium from the inner cylinders flows around the outer cylinders. As shown in Figure 25, radiation losses are reduced, because the outer cylinders shield the inner cylinders. For example, the center cylinder in Figure 25 only sees the high temperature surfaces of the surrounding cylinders, and has no radiation losses. Similarly, the use of multiple parallel plate BASEs could also reduce the radiation losses, since most of the BASEs would see the opposing hot BASE, see Figure 26.

When enough BASEs are located in a single cylindrical condenser, it will be difficult to radiate the waste heat from the condenser to space, and a remote condenser must be used. In Figure 27, the configuration is modified so that the surface surrounding the BASEs is insulated, and the sodium vapor flows to a remote condenser. Radiation losses are greatly reduced, because the high temperature β'' -alumina surfaces have no direct view of the cold condensing surface.

In these AMTEC configurations, vapor from multiple BASEs is collected in a single condenser. The sodium flow rate from the condenser to each BASE must be regulated to return the liquid that travels through the BASE. An important advantage of a wick-fed system is that this regulation is automatic, and is controlled by the interfacial curvature between the sodium liquid and vapor in each wick. If the liquid flow is too low, the interfacial curvature increases. In turn, this increases the available pressure drop to draw fluid into the wick. If too much liquid is supplied, the interfacial curvature decreases, decreasing the fluid flow.

A reduction in condenser emissivity is also important in reducing radiation losses. As shown in the equation (9), the view factor is reduced when the condenser emissivity is reduced. This occurs because a reduction in the condenser emissivity is equivalent to an increase in the condenser reflectivity. When the condenser reflectivity is increased, more of the radiation emitted from the BASE is reflected back, reducing the radiation heat losses. The condenser reflectivity is increased by forming a smooth film of sodium (which is highly reflective) on the condenser surface. There have been some theoretical studies

C:\AR11\12\1806\FIG20A.DWG & .LST

FIGURE 24. CONVENTIONAL "AMTEC" CELL, WITH THE "BASE" LOCATED
INSIDE A CONCENTRIC CONDENSER.

C:\AR11\12\1806\FIG21A.DWG & LST

FIGURE 25. MULTIPLE "BASEs" INSIDE A CYLINDRICAL CONDENSER. RADIATION LOSSES ARE REDUCED BECAUSE THE OUTER CYLINDERS SHIELD THE INNER CYLINDERS.

C:\AR11\12\1806\FIG22A.DWG & LST

FIGURE 26. MULTIPLE PARALLEL PLATE "BASEs". WITH A NEARBY OR REMOTE CONDENSER. RADIATION LOSSES ARE REDUCED, BECAUSE THE FLAT PLATES MOSTLY SEE EACH OTHER.

C:\AR11\12\1806\FIG19A.DWG & LST

FIGURE 27. MULTIPLE "BASEs" WITH A REMOTE CONDENSER. RADIATION LOSSES ARE REDUCED BECAUSE THERE IS NO DIRECT PATH BETWEEN THE "BASEs" AND THE CONDENSER

on tailoring the condenser surface to form a smooth sodium film [Crowley, 1991], but we are not aware of any experimental verification. Crowley suggests the use of Gregorig grooves to collect the sodium from the condenser surface, while maintaining a smooth liquid film.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The Phase I program examined the integration of capillary pumping into a vapor-fed AMTEC device for eventual use in a space power application. A capillary pumping demonstrator was fabricated and tested to demonstrate a wick design that can return liquid sodium against the pressure difference between the low pressure condenser and the high pressure evaporator in the AMTEC cell. The operating goals for the demonstrator were 630°C (5230 Pa) in the evaporator, and 400°C (47 Pa) in the condenser. The demonstrator successfully performed in excess of the operating goals. The evaporator operated at 690°C (12,000 Pa) with the condenser at 380°C (40 Pa). Thus all Phase I goals were met and exceeded.

In an AMTEC cell, the pressure in the condenser is very low, typically less than 100 Pa. In a wick-pumped AMTEC cell, pressure drops in the wick can reduce the pressure in the sodium below zero, placing the sodium in tension. Some members of the AMTEC community had expressed concern that the sodium would boil in the wick, preventing the wick from operating as designed. The demonstrator was designed to operate with a negative liquid pressure in the liquid return line, and successfully sustained negative pressures (tensions) as low as -2430 Pa.

There are four main elements to the fluid return design: (1) A series of grooves on the condenser surface to collect sodium, while maintaining a reflective sodium film, (2) Drainage holes to remove the condensate, (3) Arteries to transport the condensate, and (4) An evaporator wick that sustains the temperature difference between the evaporator and condenser. In Phase I, an evaporator wick and artery design was demonstrated, which verified that the design can tolerate negative liquid pressures, and high sodium superheats, without experiencing any problems. The design is self-priming, increasing reliability. The condenser design and drainage holes will be developed in Phase II.

5.0 ACKNOWLEDGMENTS

The work in this document was performed by Thermacore, Inc., Lancaster, PA, under Contract DE-FG05-91ER81233 for the Department of Energy. The technical monitor was William Barnett, and the project manager at Thermacore was William Anderson. The capillary pumping demonstrator was fabricated and tested at Thermacore by Terry Duncan. Information on AMTEC and EM pumps was supplied by Constance Smith at Westinghouse.

6.0 REFERENCES

1. Bankston, C. P., "Alkali Metal Thermoelectric Conversion (AMTEC) Technology Status Review," *Space Nuclear Power Systems 1986*, ed. M. S El-Genk and M. D Hoover, Orbit Book Co., Malabar, FL, 1987.
 2. Chi, S. W., *Heat Pipe Theory and Practice*, McGraw Hill, New York, New York, 1976.
- Cole, T. (1983) "Thermoelectric Energy Conversion with Solid Electrolytes," *Science*, 221(4614):915-920.

3. Crowley, C. J., "Condenser Design for AMTEC Power Conversion," Proc., 25th Annual IECEC, Vol. 5, pp. 456-462, Boston, MA, August 4-9, 1991.
4. Foust, O. J., *Sodium-NaK Engineering Handbook: Sodium Chemistry and Physical Properties*, Vol. 1., Gordon and Breach, New York, New York, 1972.
5. Kemme, J. E., "Ultimate Heat Pipe Performance," IEEE Conference Record of 1968 Thermionic Conversion Specialist Conference, pp. 266-271, Framingham, MA, October 21-23, 1968, IEEE No. 68C58-ED.
6. Kern, D. Q., *Process Heat Transfer*, pp. 80-82 McGraw Hill Book Company, New York, New York, 1950.
7. Levy, E. K., "Theoretical Investigation of Heat Pipes Operating at Low Vapor Pressures," J. Engineering for Industry (Trans. ASME), pp. 547-552, November 1968.
8. Miller, R. W., *Flow Measurement Handbook*, McGraw Hill, New York, New York, 1983.
9. Ponnappan, R., L. I. Boehman, and E. T. Mahefkey, "Transient Characteristics of a Gas Loaded Liquid Metal Heat Pipe with Long Adiabatic Section," paper IAF-ICOSP89-5-6, 1989.
10. Schock, A., "Design Evolution and Verification of the *General Purpose Heat Source*," Proc., 17th Intersociety Energy Conversion Engineering Conference, Seattle, WA, August 18-22, 1980.
11. Shapiro, A. H., *Compressible Fluid Flow*, Vol. 1, Ronald Press, 1953.
12. Shaubach, R. M., and N. J. Gernert, "Sodium Heat Pipe with Sintered Wick and Artery: Effects of Noncondensable Gas on Performance," Ninth Symposium on Space Nuclear Power Systems, Albuquerque, New Mexico, January 12-16, 1992.
13. Sievers, R. K. and C. P. Bankston (1988) "Radioisotope Powered Alkali Metal Thermoelectric Converter Design for Space Systems," Proc. 23rd Intersociety Energy Conversion Engineering Conference, Vol. 3, American Society of Mechanical Engineers, Denver, CO, pp. 159-167.

SECTION A-A

(1) =	ENVELOPE 2" SCHEDULE 80 PIPE (2.355" O.D. x .218" WALL)	(8) =	CABLE TUBE-5/16" O.D. x .028" WALL S.S
(2) =	EXTENSION 2" SCHEDULE 80 PIPE (2.355" O.D. x .218" WALL) NUMBER 1	(9) =	ARTERY CABLE - 1/4" O.D.
(3) =	EXTENSION 2" SCHEDULE 80 PIPE (2.355" O.D. x .218" WALL) NUMBER 2	(10) =	R.F. COIL
(4) =	ELBOW 2" SCHEDULE 80 PIPE (2.355" O.D. x .218" WALL)	(11) =	WICK
(5) =	ORIFICE PLATE WITH APROX. .060" ϕ HOLE ON CENTERS	(12) =	Na LIQUID
(6) =	END CAP - .125" THK.	(13) =	VALVE WITH 1/4" S.S TUBE
(7) =	END CAP - .125" THK.		

APPENDIX A

CAPILLARY PUMPING DEMONSTRATOR CALCULATIONS

Title: AMTEC Design
Capillary Pumping Demonstrator

Calculated by: V. Anderson Date: 10/29/91
 Checked by: J. W. Ryd Date: _____
 Reviewed by: _____ Date: _____

Project: _____

Page 1 of _____

Objective: Design a capillary pumping demonstrator that will pump sodium against a significant pressure gradient.

Background:

In a vapor-fed Amtec system, heat is supplied to an Evaporator. Sodium evaporates, and travels to the wick inside the BASE. Roughly 80% of the sodium supplies heat, then recirculates in the high temperature region.

The remaining 20% of the sodium travels through the BASE, generating electricity. The sodium ions recombine with electrons at the exterior of the BASE. The atoms then evaporate and travel to a condenser in a low temperature region.

The sodium in the condenser must be pumped back to the evaporator. Current designs use an EM pump. In this Phase 1

SBIR, Thermacore is examining the use of wick pumped, or hybrid EM/wick systems. Task 2 is the fabrication of a capillary pumping demonstrator. This will be a high temperature heat pipe, with an orifice allowing a small amount of sodium to flow to a lower temperature region. The flow rate of sodium is roughly 0.006 g/s for a typical Westinghouse AMTEC design.

Title: Capillary Pumping Demonstrator

Calculated by: W. Anderson

Date: 10/29/91

Checked by: J. L. Ruffolo

Date: _____

Reviewed by: _____

Date: _____

Project: _____

Page 3 of _____

Physical Properties

Ref: Fluprop. Bas, "Sodium-NaK Engineering Handbook," by Foost.

Sodium Properties	400° C	500° C	600° C	700° C
Latent Heat, J/kg	4.37×10^6	4.27×10^6	4.17×10^6	4.06×10^6
Liquid Density, kg/m ³	856	832	808	784
Vapor Density, kg/m ³	0.0002	0.0017	0.0096	0.0407
Liquid Thermal Conductivity, W/mC	70.4	66.5	63.0	60.0
Liquid Viscosity, kg/m-s	3.03×10^{-4}	2.45×10^{-4}	2.08×10^{-4}	1.81×10^{-4}
Vapor Viscosity, kg/m-s	1.64×10^{-5}	1.78×10^{-5}	1.91×10^{-5}	2.04×10^{-5}
Vapor Pressure, Pa	47	518	3254	13940
Surface Tension, N/m	0.167	0.157	0.147	0.137

flow rate of 0.006 g/s sodium = 6×10^{-6} kg/s
equivalent to a heat transfer rate of:

$$Q_{\text{low}} = \dot{m} = (4.17 \times 10^6) (6 \times 10^{-6}) \frac{\text{J}}{\text{kg}} \frac{\text{kg}}{\text{s}}$$

$$= 25 \text{ W}$$

Candidate Evaporator Wicks - Sintered Nickel wicks

-200 + 325

$$K = 5 \times 10^{-12} \text{ m}^2$$

$$r_c = 2 \times 10^{-5} \text{ m}$$

-100 + 150

$$K = 1.5 \times 10^{-11} \text{ m}^2$$

$$r_c = 3.9 \times 10^{-5} \text{ m}$$

-50 + 100

$$K = 3.8 \times 10^{-11} \text{ m}^2$$

$$r_c = 5.5 \times 10^{-5} \text{ m}$$

Cluster wick

$$K = 2 \times 10^{-11} \text{ m}^2$$

$$r_c = 2.5 \times 10^{-5} \text{ m}$$

Permeability versus Pore Radius for Spherical Nickel Powders

Dry H₂, 1000°C, 90 min.

WICK PHYSICAL PROPERTY DATA

①

C. J. Wick

NICKEL P/M SAMPLE

MESH SIZE -100+140

DIAMETER .48 IN.

LENGTH .933 IN.

MASS 7.57 GR.

DENSITY 2.736234 GR./CM³

POROSITY .692903 %

CAPILLARY RADIUS 1.921376E-03 CM

PERMEABILITY 1.86521E-07 CM²

WICK PHYSICAL PROPERTY DATA

(Z)

cluster
wick

NICKEL P/M SAMPLE

MESH SIZE -100+140

DIAMETER .485 IN.

LENGTH .945 IN.

MASS 6.61 GR.

DENSITY 2.310509 GR./CM³

POROSITY .7406836 %

CAPILLARY RADIUS 2.607581E-03 CM

PERMEABILITY 9.177726E-07 CM²

Title: Capillary Pumping Demonstrator

Calculated by: V. Anderson

Date: 10/29/91

Checked by: J. W. Ruffolo

Date: _____

Reviewed by: _____

Date: _____

Project: _____

Page 7 of _____

Wick Pumping Capabilities, Pa

	Max Temp. °C	400°C	500°C	600°C	700°C
-200 + 325	698	16,670	15670	14670	13670
-100 + 150	652	8550	8040	7523	7010
-50 + 100	629	6060	5700	5334	4970
Cluster Wick	682	13,300	12,536	11,736	10,936

$$P_c = \frac{2\sigma}{r_c}$$

-200 + 325 wick at 700°C $P_c = \frac{(2)(.137)}{2 \times 10^{-5}} \frac{N}{mm} = 13700$

To get a very rough idea of maximum operating temperature,

Calculate the maximum possible operating temperature for each wick, assuming that vapor pressure difference is the only pressure drop

calculate temperature at which $P_{vapor} = \frac{2\sigma}{r_c}$

It would be desirable to fabricate the wick from -200+325 or cluster powder, to maximize the pressure difference. Using a wick with a small pore size is also closer to the pore size required for an actual Amtec cell.

Title: Capillary Pumping Demonstrator

 Calculated by: H. Anderson

 Date: 10/27/91

 Checked by: J. K. H. H.

Date: _____

Reviewed by: _____

Date: _____

Project: _____

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Approach

1. Design the primary heat pipe, assuming that all of the fluid recirculates
2. Design the liquid return system from the secondary condenser
3. Size the orifice between the two condensers.

Primary Heat Pipe

Assume that 1½" pipe is used for the heat pipe envelope. This is larger than the BASE diameter. However, using a larger diameter will help assure that the sonic limit is not reached in the primary heat pipe, complicating the design of the system.

1½" Schedule 10 pipe

$$D_o = 1.900" = 4.826 \text{ cm}$$

$$D_i = 1.682" = 4.272$$

$$\text{emissivity } \epsilon \approx 0.8$$

$$\text{Thermal Expansion } \alpha_{ss} = 9 \times 10^{-6} \frac{\text{in}}{\text{in } ^\circ\text{F}} = 16.2 \times 10^{-6} \frac{\text{cm}}{\text{cm } ^\circ\text{C}}$$

$$\text{Thermal Conductivity } K_{ss} =$$

$$\text{Stefan-Boltzmann Constant } \sigma = 5.67 \times 10^{-12} \frac{\text{W}}{\text{cm}^2 \text{ K}^4}$$

Title: Capillary Pumping Demonstrator

Calculated by: W. Anderson

Date: 10/29/91

Checked by: g. H. H. H.

Date: _____

Reviewed by: _____

Date: _____

Project: _____

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Assume that the primary heat pipe is 12" long

$L_{\text{evap}} = 3"$, located 1" from end of pipe

$L_{\text{condenser}} = 8"$

What would losses be at 700°C , if the entire pipe is uninsulated. Neglect radiation directly under the RF coil, since this energy never enters the heat pipe.

$$T_{\text{amb}} = 25^\circ\text{C} = 298$$

$$T_H = 700 + 273 = 973$$

$$T_{\text{cool}} = 400 + 273 = 673$$

exposed Area

$$\text{cylinder } A_{\text{cyl}} \pi D L = (\pi)(1.9)(9)(2.54)^2 = 347 \text{ cm}^2$$

$$\text{End plate } A_p \frac{\pi D^2}{4} = \frac{(\pi)(1.9)^2(2.54)^2}{4} = 18.2 \text{ cm}^2$$

$$Q_{\text{Rad}} = \sigma \epsilon (A_{\text{cyl}} (T_H^4 - T_{\text{amb}}^4) + A_p (T_H^4 - T_{\text{amb}}^4) + \underbrace{A_p (T_H^4 - T_{\text{cool}}^4)}_{\text{orifice plate}})$$

$$= (5.67 \times 10^{-12})(0.8) [(347 + 18.2)(973^4 - 298^4) + 18.2(973^4 - 673^4)]$$

$$\frac{\text{W}}{\text{cm}^2 \text{K}^4} \quad \text{cm}^2 \text{K}^4$$

$$= 1528 \text{ W}$$

Title: AMTEC Design
Capillary Pumping Demonstration

Calculated by: H. Anderson Date: 10/29/91
 Checked by: J. H. Date: _____
 Reviewed by: _____ Date: _____

Project: _____

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Natural Convection

$$D^3 \Delta T = \left(\frac{1.9}{12} \right)^3 (700 - 25) \left(\frac{9}{5} \right) = 6.7 \text{ ft}^3 \frac{^\circ\text{F}}{^\circ\text{C}}$$

$$h = 0.25 \left(\frac{\Delta T}{D} \right)^{1/4} \quad \Delta T \text{ in } ^\circ\text{F}, \quad D \text{ in ft}, \quad h \text{ in } \frac{\text{Btu}}{\text{hr ft}^2 ^\circ\text{F}}$$

ref: Rohsenow and Choi, pg 206

$$h = (0.25) \left[\frac{(700 - 25) \left(\frac{9}{5} \right)}{\frac{1.9}{12}} \right]^{1/4} = 2.34 \frac{\text{Btu}}{\text{hr ft}^2 ^\circ\text{F}}$$

$$= 2.34 \frac{\text{Btu}}{\text{hr ft}^2 ^\circ\text{F}} \times \frac{1 \text{ W}}{3.171 \text{ Btu/hr}} \times \frac{9012}{500} \frac{\text{cm}^2}{\text{m}^2} = 1.33 \times 10^{-3} \frac{\text{W}}{\text{cm}^2 ^\circ\text{C}}$$

$$= 1.33 \times 10^{-3} \frac{\text{W}}{\text{cm}^2 ^\circ\text{C}}$$

$$Q = A h \Delta T = (365) (1.33 \times 10^{-3}) (675) = 327 \text{ W}$$

$$Q_{\text{Total}} = 1527 + 327 = 1854$$

Title: Capillary Pumping Demonstration

Calculated by: W. Anderson

Date: 10/29/51

Checked by: g. h. v.

Date: _____

Reviewed by: _____

Date: _____

Project: _____

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Assume that we insulate the system, so that the total loss is 1500 W. Can a heat pipe be fabricated with a slab wick that will carry this power.

First, estimate wick thickness

$$\dot{m} = \frac{Q}{\lambda} = \frac{1500}{4.06 \times 10^6} \frac{\text{J}}{\text{kg}} = 367 \times 10^{-4} \frac{\text{kg}}{\text{s}}$$

$$L_{\text{eff}} = \frac{L_{\text{evap}}}{2} + \frac{L_{\text{condense}}}{2} = \frac{3}{2} + \frac{8}{2} = 5\frac{1}{2} \text{ m} = 13.97 \text{ cm} = 0.14 \text{ m}$$

$$\dot{m} = \frac{k_p A}{\mu} \frac{dP}{dx}$$

$$A = \frac{\dot{m} \mu L_{\text{eff}}}{k_p \Delta P} \quad \text{required Area for a given } \Delta P$$

assume $\Delta P = \frac{1}{3}$ of wick pumping capability

700°	Clutter	$\Delta P = 4445$	$A = 1.9 \times 10^{-4} \text{ m}^2$	$t = .057''$
-	200 + 325 wick	$\Delta P = 4556$	$A = 6.02 \times 10^{-4} \text{ m}^2$	$t = .200''$
-	100 + 150	$\Delta P = 2336$	$= 3.91 \times 10^{-4} \text{ m}^2$	$= .124''$
-	50 + 100	$\Delta P = 1656$	$= 2.18 \times 10^{-4} \text{ m}^2$	$= 0.066''$

$$-200 \quad \Delta P = \frac{(3.69 \times 10^{-4})(2.08 \times 10^{-4})(.14)}{(5 \times 10^{-12})(784)(4556)} \quad \frac{\text{kg} \cdot \text{m} \cdot \text{m}^2}{\text{s} \cdot \text{m}^2 \cdot \text{kg} \cdot \text{m}^2}$$

$$6.02 \times 10^{-4} \text{ m}^2$$

Title: Capillary Pumping DemonstrationCalculated by: V. AndersonDate: 10/29/91Checked by: gib

Date: _____

Reviewed by: _____

Date: _____

Project: _____

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$$A = \frac{\pi}{4} (D_i^2 - D_o^2)$$

$$D_i = 1.9" =$$

$$D_o^2 = D_i^2 - \frac{A(4)}{\pi}$$

$$D_o = \sqrt{D_i^2 - \frac{A(4)}{\pi}} = \sqrt{1.9^2 - \frac{(4.272^2 - 3.255^2)(4)}{\pi}} = \sqrt{3.61 - \frac{(4)(6.02)}{\pi}} = \sqrt{3.61 - 7.68} = \sqrt{-4.07}$$

$$D_o = 3.255 \text{ cm} = 1.281"$$

$$t = \frac{D_i - D_o}{2} = \frac{4.272 - 3.255}{2} = 0.509 \text{ cm} = 0.200"$$

We would like to use -200+325 powder to maximize pumping capability. It would be desirable to have a slightly larger vapor space, and a larger wick to provide a greater margin of safety.

1 1/2", Schedule 10	1.9" O.D.	by .109 wall	1.682" I.D.	.116
2", Schedule 80	2.355" O.D.	by 0.218" wall	1.939" I.D.	.245
2", Schedule 40	2.375" O.D.	by 0.154" wall	2.067" I.D.	.309

Thick, 1.45" nominal

Choose a 1.45" Diameter vapor space, which will allow the use of existing sintering fixtures.

$$2", \text{ Schedule 40 } t_{\text{wick}} = (2.067 - 1.45) / 2 = \underline{\underline{0.309"}}$$

$$D_{\text{vapor}} = 1.45" = 3.68 \text{ cm}$$

Title: Capillary Pumping DemonstrationCalculated by: W. AndersonDate: 12/31/91Checked by: J. W.

Date: _____

Reviewed by: _____

Date: _____

Project: _____

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Gravitational pressure drop.

$$\Delta P = \rho g (D_i + h_{\text{primary}})$$

 h_{primary} = elevation of evaporator over primary condenser.

Assume a 3" elevation

$$3 + 2067 \text{ "} = 5.067 \text{ "} = 12.87 \text{ cm } 2 \text{ " pipe}$$

$$\Delta P_{\text{grav}} = \underset{\substack{\text{kg/m}^3 \\ \frac{\text{m}}{\text{s}^2}}}{(832)(9.8)(.129)} = \underline{\underline{1052 \text{ Pa}}}$$

Upper Pressure Drop

For now, ignore compressibility

$$Re = \frac{\rho V D}{\mu}$$

$$\rho_{600^\circ\text{C}} = 0.0096 \text{ kg/m}^3 @ 600^\circ\text{C}$$

$$A = \frac{\pi}{4} D^2 = \frac{\pi}{4} (3.68)^2 \frac{\text{cm}^2 \text{ m}^2}{10^4 \text{ cm}^2}$$

$$= 1.07 \times 10^{-3} \text{ m}^2$$

$$\dot{m} = \rho V A \quad \rho V = \frac{\dot{m}}{A} = \frac{3.67 \times 10^{-4} \text{ kg}}{1.07 \times 10^{-3} \text{ s m}^2} = 0.346 \frac{\text{kg}}{\text{m}^2 \text{ s}}$$

$$V = \frac{\rho V}{\rho} = \frac{0.346}{0.0096} = \underline{\underline{36 \frac{\text{m}}{\text{s}}}}$$

Title: Capillary Pumping DemonstratorCalculated by: W. AndersonDate: 10/31/91Checked by: glt

Date: _____

Reviewed by: _____

Date: _____

Project: _____

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$$Re = \frac{\rho V D}{\mu} = \frac{(0.346)(3.68 \times 10^{-2})}{1.91 \times 10^{-5}} = 667 \text{ laminar} @ 600^\circ\text{C}$$

$$\frac{\text{Kg m-s/m}}{\text{m-s Kg}}$$

Evaluate pressure drop in vapor - Laminar, Incompressible flow,
Complete Pressure Recovery.

$$\Delta P = \frac{32 L_e \mu V}{D_{\text{vapor}}^2}$$

$$L_e = \frac{3+8}{2} = 5.5'' = .14 \text{ m}$$

$$= \frac{(32)(.14)(1.91 \times 10^{-5})(36)}{(0.0368)^2} \approx \underline{\underline{2 \text{ Pa}}}$$

$$\frac{\text{m Kg m}}{\text{m-s s m}^2}$$

Calculate The sonic limit at The exit to The evaporator
as a function of temperature, to estimate roughly when
compressibility effects become important.

Title: Amtec Capillary Pumping Demonstrator

Calculated by: W. Anderson

Date: 10/31/91

Checked by: JHR

Date: _____

Reviewed by: _____

Date: _____

Project: _____

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Sonic Limit

Assumptions

1. Flow choked at the evaporator exit, due to vapor addition
2. Neglect frictional effects
3. Neglect heat transfer
4. Sodium behaves as a perfect gas.

References:

- S.W. Chi, Heat Pipe Theory and Practice, pp 79-86, McGraw H, 1976
 A.H. Shapiro, Compressible Fluid Flow, Vol 1, Ronald Press, 1953
 E.K. Levy, "Theoretical Investigation of Heat Pipes operating at Low Vapor Pressures, J. Engineering for Industry (Trans. ASME) pp 547-552, Nov. 1968.

for frictionless flow with mass addition

$$\frac{\dot{m}_{axial}}{A} = \frac{P_0 C_0}{\sqrt{2(1+\gamma)}}$$

$$\dot{q}_{Axial} = \frac{P_0 C_0 \lambda A}{\sqrt{2(1+\gamma)}}$$

eq. 3-10, Chi

$$C_0 = \sqrt{\gamma R T_0}$$

Capillary Pumping Demonstrator Evaporator Sonic Limit, 1.45" Vapor Diameter

Reviewed by: _____ Date: _____

Page 13 of
$$P_c = 640 P_a$$

Title: Amtec Design
Liquid Return Line

Calculated by: W. Anderson

Date: 4/1/91

Checked by: J. H. K.

Date: _____

Reviewed by: _____

Date: _____

Project: _____

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$$P_c = \frac{2\sigma}{r_c}, \quad r_c = \frac{2\sigma}{P_c}$$

$$\sigma_{701^\circ\text{C}} = .137 \text{ N/m}$$

$$r_c = \frac{(2)(.137) \text{ N}}{(-640) \text{ m}^2\text{N}} = 4.29 \times 10^{-4} \text{ m} = \underline{\underline{4.29 \times 10^{-2} \text{ cm}}}$$

$$\dot{m}_{\text{LOW}} = 6 \times 10^{-6} \text{ kg/s}$$

for now, design for $2 \times 10^{-5} \text{ kg/s}$

$$L = 24" = .610 \text{ m}$$

Thermacore already has one cable suitable for a cable criteria

$$r_c = 1.825 \times 10^{-2} \text{ cm}$$

$$K = 6.86 \times 10^{-10} \text{ m}^2$$

$$\frac{Q}{A} = \frac{K}{m} \frac{dP}{dx}, \quad \dot{m} = \frac{K \rho A}{m} \frac{dP}{dx}$$

$$\frac{dP}{dx} = \frac{\dot{m} m}{K \rho A}$$

$$D = .25" = 6.35 \times 10^{-3} \text{ m}$$

$$A = \frac{\pi}{4} D^2 = 3.17 \times 10^{-5} \text{ m}^2$$

$$\Delta P_{\text{cable}} = \frac{\dot{m} m}{K \rho A} L$$

$$\mu = 3.03 \times 10^{-4} \text{ kg/m-s} @ 400^\circ\text{C}$$

$$\Delta P_{\text{cable}} = \frac{(3.03 \times 10^{-4})(2 \times 10^{-5})(.61)}{(6.86 \times 10^{-10})(856)(3.17 \times 10^{-5})}$$

$$\rho = 856 \text{ kg/m}^3 @ 400$$

$$K = 344 \times 10^{-10}$$

$$\Delta P_{\text{cable}} = \underline{\underline{400 P_a}}$$

$$= \underline{\underline{200 P_a}} \quad \text{may be suitable, make additional measurements}$$

Title: Amtec Design
Capillary Pumping Demonstrator
Orifice
 Project: _____

Calculated by: Pat Anderson Date: 4/1/91
 Checked by: 2/PL Date: _____
 Reviewed by: _____ Date: _____

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The primary and secondary condensers are separated by an orifice. This orifice must be sized to let about 6×10^{-6} kg/s of sodium pass from the high pressure to the low pressure side.

For now, assume the following

1. Sodium behaves as an ideal gas
2. Neglect compressible effects in the primary heat pipe, i.e., low pressure drop for sodium vapor flow, Not near the sonic limit.

Reference: R. W. Miller, Flow Measurement Handbook,
 McGraw Hill, NY, NY, 1983

PP 13-23 - 13-28

Thick Square Edge orifice

$$\beta = d/D < 0.5$$

There is no choked flow for a thin orifice.
 For choked flow, a Thick orifice is required. When the flow is choked,

$$C_D = 0.839$$

$$d \leq t \leq 6D$$

Title: Amtec Design
OrificeCalculated by: W. Amatore Date: 11/1/91Checked by: JM Date: _____

Reviewed by: _____ Date: _____

Project: _____

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For compressible flow neglecting friction, (area change only),
and for a thick orifice, isentropic flow, no phase change.

$$\frac{P_t^*}{P_o} = \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma}{\gamma - 1}}$$

$$= 0.4867$$

$$\gamma = 1.67$$

Estimate the required orifice size, assuming isentropic, adiabatic flow.

$$\dot{m} = \rho^* A^* c^*$$

where ρ^* and c^* are the density and sound velocity
at the minimum area.

Ref. A. H. Shapiro, The Dynamics and Thermodynamics of Compressible Fluid Flow,
Ronald Press, NY, 1953.

Choked Flow Through a Thick Orifice Saturated Sodium Vapor

Choked Flow Through a Thick Orifice Saturated Sodium Vapor

Title: Amtec Design
Orifice

 Calculated by: W. Anderson Date: 11/4/91
 Checked by: JHR Date: _____
 Reviewed by: _____ Date: _____

 Project: _____

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For isentropic flow of a perfect gas,

$$\frac{C^*}{C_0} = \frac{T^*}{T_0} = \frac{2}{\gamma+1} \quad \frac{P^*}{P_0} = \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \quad \frac{\rho^*}{\rho_0} = \left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}}$$

$$\gamma = 1.67$$

$$C^* = \sqrt{\gamma R T^*} = \sqrt{\frac{2\gamma}{\gamma+1} R T_0}$$

$$\rho^* = \left(\frac{2}{\gamma+1}\right)^{\frac{1}{\gamma-1}} \rho_0$$

 $A^* = A$ for now, neglect vena contracta

$$\dot{m} = \rho^* C^* A, \quad A = \frac{\dot{m}}{\rho^* C^*}$$

$$\dot{m} = 2 \times 10^{-5} \text{ kg/s}$$

$$\text{let } T_0 = 650^\circ\text{C} = 923 \text{ K}$$

$$N = 22.9 \text{ mole weight}$$

$$R = 8314 \text{ J/kg-mole } ^\circ\text{K}$$

$$R = \frac{8314}{22.9} = 363 \text{ J/kg } ^\circ\text{K}$$

$$C_0 = \sqrt{\gamma R T_0} = \sqrt{(1.67)(363)(923)} = 748 \text{ m/s}$$

$\frac{\text{J}}{\text{kg } ^\circ\text{K}} \times \text{K} = \frac{\text{kg } ^2 \text{ m}^2}{\text{s}^2} = \text{m/s}$

$$C^* = \sqrt{\frac{2\gamma}{\gamma+1} R T} = \sqrt{\frac{(2)(1.67)}{(2.67)} (363)(923)} = 647 \text{ m/s}$$

Title: Antec Design
OfficeCalculated by: R. Anderson Date: 11/4/91Checked by: gln Date: _____

Reviewed by: _____ Date: _____

Project: _____
_____Page 18 of _____

$$\rho_0 = 2.05 \times 10^{-2} \text{ kg/m}^3$$

$$\rho^* = \left(\frac{2}{8+1}\right)^{1/8-1} \rho_0 = \left(\frac{2}{2.67}\right)^{1/67} (2.05 \times 10^{-2}) = .013 \text{ kg/m}^3$$

$$A = \frac{\dot{m}}{\rho^* c_a} = \frac{2.05 \times 10^{-5}}{(.013)(647)} \frac{\text{kg m}^3 \text{ s}^{-1}}{\text{kg m}^3 \text{ s}^{-1}}$$

$$= 2.33 \times 10^{-6} \text{ m}^2$$

$$A = \frac{\pi}{4} d^2 \quad d^2 = \left(\sqrt{\frac{4}{\pi} A} \right) \cdot 100 \frac{\text{cm}}{1 \text{ m}}$$

$$d = \sqrt{\frac{4}{\pi} (2.33 \times 10^{-6})} \cdot 100 = .172 \text{ cm} = .068''$$

for a .070" hole

$$\dot{m} = 2.13 \times 10^{-5} \text{ kg/s at } 650$$

$$= .9 \times 10^{-5} \text{ kg/s at } 600$$

Capillary Pumping Demonstrator

Secondary Condenser Pressure Drops

$T_{\text{Condenser}} = 400^{\circ}\text{C}$

Capillary Pumping Demonstrator

Secondary Condenser Cable Pressure Drops

$T_{\text{Condenser}} = 400^{\circ}\text{C}$

Title: Orifice CalculationsCalculated by: W. Ambrose Date: _____Checked by: g/m Date: _____

Reviewed by: _____ Date: _____

Project: _____

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Pressure Drop to remove liquid drops

$$\Delta P = \frac{4\sigma}{r_c} = \frac{2\sigma}{D} \quad (2 \text{ surfaces})$$

$$\text{at } 650^\circ, \quad \sigma = .142 \text{ N/m}$$

$$D = 1.78 \times 10^{-3} \text{ m}$$

$$\Delta P = \frac{(2 \times .142)}{1.78 \times 10^{-3}}$$

$$\frac{\text{N}}{\text{m}^2} = \underline{\underline{159 \text{ Pa}}}$$

Title: Amtec DesignCalculated by: W. AndersonDate: 11/12/87

Checked by: _____

Date: _____

Reviewed by: _____

Date: _____

Project: _____

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The Amtec design has been revised so that the cable passes through the evaporator - Estimate the pressure drop in the wick

$$\dot{m} = 2 \times 10^{-5} \text{ kg/s}$$

$$L_{eff} = 3" = (3)(2.54) / 100 = 0.0762 \text{ m}$$

$$D_c = 1.919"$$

$$D_w = 1.45"$$

$$\Delta P = \frac{\mu \dot{m} L}{K \rho A}$$

$$A = \frac{\pi}{4} (D_c^2 - D_w^2) = \frac{\pi}{4} (1.919^2 - 1.45^2) (2.54^2) / 10^4 = 8.01 \times 10^{-4} \text{ m}^2$$

$$\Delta P = \frac{(3.03 \times 10^{-4})(2 \times 10^{-5})(0.076)}{(5 \times 10^{-12})(856)(8.01 \times 10^{-4})} = \underline{\underline{134 \text{ Pa}}} \quad \underline{\underline{OK}}$$

Title: Wick Volume - RevisedCalculated by: W. AndersonDate: 11/12/91

Checked by: _____

Date: _____

Reviewed by: _____

Date: _____

Project: _____

Page 1 of _____

Wick Thickness has increased - calculate revised volume

wick:

$$D_o = 2.355 - 2(0.218)$$

$$= 1.919$$

$$\frac{\pi}{4} (D_o^2 - D_i^2) (L) = \frac{\pi}{4} (1.919^2 - 1.45^2) (13)$$

$$= 16.1 \text{ in}^3$$

$$\text{end } \frac{\pi D^2 h}{4} = \left(\frac{\pi}{4} \right) (1.919)^2 (0.575) = 1.66 \text{ in}^3$$

$$V = V_1 + V_2 = 16.1 + 1.66 = \underline{\underline{17.8 \text{ in}^3}}$$

$$1 \text{ pint} \approx 30 \text{ in}^3$$

Capillary Pumping Demonstrator

Secondary Condenser Cable Pressure Drops

$T_{\text{Condenser}} = 400^{\circ}\text{C}$ $t_{\text{wick}} = .24''$

Capillary Pumping Demonstrator

Secondary Condenser Pressure Drops

$T_{\text{Condenser}} = 400^{\circ}\text{C}$ $t_{\text{wick}} = .24''$

APPENDIX B

CAPILLARY PUMPING DEMONSTRATOR DRAWINGS

NO	DESCRIPTION	DRAWING NO.
1	ENVELOPE	B-11-1140-2
2	ELBOW 2" SCH.80S 316L SS	
3	ENVELOPE EXTENSION #1	A-11-1140-3
4	ENVELOPE EXTENSION #2	A-11-1140-4
5	END CAP #1	A-11-1140-6
6	MANDREL PIN	
7	END CAP #2	A-11-1140-7
8	ORIFACE PLATE	A-11-1140-9
9	ARTERY CABLE TUBE	
10	THERMOCOUPLE TUBE	
11	VALVE TUBE #1	
12	VALVE TUBE #2	
13	ARTERY CABLE	
14	WICK	

REVISIONS			
LTR.	DESCRIPTION	DATE	APPROVED

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES		
DECIMALS	ANGULAR	
.XX=+.015 -.015	+30' -30'	
.XXX=+.005 -.005	DO NOT SCALE DRAWING	
TREATMENT		
FINISH		
SIMILAR TO	ACT. WT.	CALC. WT.

CONTRACT NO.	
DRAWN	EHD
CHECKED	
APPROVED	
APPROVED	
CUSTOMER	

THERMACORE, INC. HEAT TRANSFER SPECIALISTS		
TITLE CAPILLARY PUMP DEMONSTRATOR - ASSEMBLY		
SIZE B	DWG. NO. B-11-1140-1	
SCALE	RELEASE DATE	SHEET

STOCK
2" SCH 80 S.S. PIPE
(2.355" O.D. x .218" WALL = 1.919" I.D.)

REVISIONS				UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES DECIMALS ANGULAR XXX=+.015 -.015 +30° -30° XXX=+.005 -.005 DO NOT SCALE DRAWING			CONTRACT NO.		THERMACORE, INC. HEAT TRANSFER SPECIALISTS	
LTR.	DESCRIPTION	DATE	APPROVED	TREATMENT	DRAWN	EHD	CHECKED	TITLE ENVELOPE		
				FINISH	APPROVED	V. Anderson		SIZE	B	DWG. NO. B-11-1140-2
				SIMILAR TO	ACT. WT.	CALC. WT.	CUSTOMER	SCALE	RELEASE DATE	SHEET

SECTION A-A

STOCK
2" SCH 80 S.S. PIPE
(2.355" O.D. x .218" WALL = 1.919" I.D.)

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES DECIMALS ANGULAR .XX=+.015 -.015 +30' -30' .XXX=+.005 -.005 DO NOT SCALE DRAWING			CONTRACT NO.		THERMACORE, INC. HEAT TRANSFER SPECIALISTS		
			DRAWN EHD 11/14/91				
TREATMENT			CHECKED		TITLE ENVELOPE EXTENSION #1		
			APPROVED <i>W. Anderson</i> 11/14/91				
FINISH			APPROVED		SIZE A DWG. NO. A-11-1140-3		
			CUSTOMER		SCALE _____ RELEASE DATE _____ SHEET _____		
SIMILAR TO	ACT. WT.	CALC. WT.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES DECIMALS ANGULAR .XX=+.015 -.015 +30' -30' .XXX=+.005 -.005 DO NOT SCALE DRAWING			CONTRACT NO.		THERMACORE, INC. HEAT TRANSFER SPECIALISTS	
			DRAWN EHD	11/15/91		
TREATMENT			CHECKED		TITLE ENVELOPE EXTENSION #2	
			APPROVED <i>V. Anderson</i>	11/14/91		
FINISH			APPROVED		SIZE A	DWG. NO. A-11-1140-4
			CUSTOMER		SCALE _____	RELEASE DATE _____
SIMILAR TO	ACT. WT.	CALC. WT.			SHEET

MATERIAL: 304 OR 316L STAINLESS STEEL

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES DECIMALS ANGULAR .XX=+.015 -.015 +30' -30' .XXX=+.005 -.005 DO NOT SCALE DRAWING			CONTRACT NO.		THERMACORE, INC. HEAT TRANSFER SPECIALISTS		
			DRAWN	EHD	11/21/91		
TREATMENT			CHECKED			TITLE END CAP #1	
			APPROVED	V. Anderson	11/21/91		
FINISH			APPROVED			SIZE A	
			CUSTOMER			DWG. NO. A-11-1140-6	
SIMILAR TO	ACT. WT.	CALC. WT.			SCALE	RELEASE DATE	SHEET

MATERIAL: 304 OR 316L STAINLESS STEEL

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES DECIMALS ANGULAR .XX=+.015 -.015 +30' -30' .XXX=+.005 -.005 DO NOT SCALE DRAWING			CONTRACT NO.		THERMACORE, INC. HEAT TRANSFER SPECIALISTS	
DRAWN EHD		DATE 11/21/91		TITLE END CAP #2		
CHECKED						
APPROVED <i>W. Anderson</i>		11/21/91		SIZE A DWG. NO. A-11-1140-7		
APPROVED						
TREATMENT			CUSTOMER		SCALE _____	
FINISH					RELEASE DATE	
SIMILAR TO		ACT. WT.	CALC. WT.			SHEET

MATERIAL: 304 OR 316L STAINLESS STEEL

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES DECIMALS ANGULAR .XX=+.015 -.015 +30° -30° .XXX=+.005 -.005 DO NOT SCALE DRAWING			CONTRACT NO.		THERMACORE, INC. HEAT TRANSFER SPECIALISTS		
			DRAWN	EHD	DATE	11/21/91	
TREATMENT			CHECKED		TITLE ORIFACE PLATE		
			APPROVED	V. Anderson	DATE	11/21/91	
FINISH			APPROVED		SIZE	A	DWG. NO.
			CUSTOMER				A-11-1140-9
SIMILAR TO	ACT. WT.	CALC. WT.			SCALE	RELEASE DATE	SHEET

CAPILLARY PUMP DEMONSTRATOR -
THERMOCOUPLE LOCATIONS

APPENDIX C

WESTINGHOUSE FINAL REPORT

ESE:92:030

AMTEC SUMMARY REPORT

May 1992

Westinghouse Electric Corporation
Advanced Programs
PO Box 158
Madison, PA 15663-0158

The Westinghouse AMTEC cell design is quite simple in its basic design. The simplicity of the design is intended to provide improved reliability. The design discussed here is for a single cell; individual cells may be arranged in series, in parallel, or in series/parallel combination groups to provide the desired system power and the desired degree of system redundancy. This system is based on use with a radioisotopic general purpose heat source (GPHS). The details of the GPHS will not be addressed in this context except to provide the temperature at which heat is input to the evaporator.

This model was developed based on a high temperature of 1200°K, a low temperature of 600°K, and a minimum vapor pressure of 5 Pa in the condenser. The electrode and current collector are assumed to be molybdenum, as are the inner wick, evaporator, and current leads. The outer wick shell, liner, and insulation are assumed to be titanium. Electrode and current collector porosity is assumed to be 0.5, and the desired current density is 0.55, which is achievable with current technology electrodes. Wick porosity is assumed to be 0.6. Other assumptions will be noted as they become important to the discussion. The dimensions for the AMTEC cell discussed in this document are as listed in Table 1 and the model is illustrated in Figure 1.

The electrode is a key component of the AMTEC cell. It must provide the electronic path from the outer current collector grid to the sodium ions emerging from the BASE without substantially impeding the flow of these sodium ions. The optimization of these generally opposing characteristics occupies a substantial portion of the development effort at JPL, Ford, and Ceramatec. The electrode is typically applied to the outside of the BASE by sputtering, which produces a thin, porous layer of electrode material tightly bound to the BASE. Ceramatec is also investigating some simplified approaches to electrode application that would not require a vacuum environment. Electrode materials which appear to be the most promising are titanium nitride and molybdenum. JPL is also investigating some other refractory materials.

The outer current collector provides the electronic path from the module electrical leads to the electrode on the BASE in an efficient manner so as to minimize the ohmic power losses and the mass, without impeding the sodium vapor flow. Since a large fraction of the current flows in the axial direction toward the leads at each end of the cell, the collector should also be preferentially oriented in the axial direction. Further it must be designed to maintain a uniform current density in the BASE to achieve maximum overall BASE power density.

It can be observed from the above discussion that many of the current collector requirements are the same as those for the electrode. Both components, for example, must allow nearly unrestricted radial sodium flow. They both must also provide adequate electronic current flow along the surface of the BASE. By addressing the design of both the electrode and current collector components as a coupled system, significant performance advancements can be realized. If the electrode thickness is reduced while the current collector electrode contact points and coverage is increased, the sodium radial flow impedance can be reduced without significant penalty on the circumferential electronic flow. Research at Ford has shown that even a current collector coverage of 65% (over the BASE) will not impede the sodium flow. Recent modeling and experimental work at the Jet Propulsion Laboratory (JPL) has also addressed the issue of coupled current collector and electrode

performance. JPL has found that thin electrodes (less than 1 micron), coupled with a sprayed metal grid have performed well, with even further performance improvements expected.

Drawing on the experience at both Ford and JPL, a sprayed metal grid, has been proposed for use in this concept. This grid is nearly identical to that already used in JPL tests, except that the grid proposed here will have a slightly tighter pitch to provide sufficient axial conductivity so that the entire cell current flow can be accommodated through this grid structure. This will eliminate the need for independent bus wires along the grid, and result in a low mass collector.

Electrical leads are attached to both the transition pieces and to the outer current collector grid.

Table I AMTEC Module Design Parameters for Modelling

DIMENSION	NOMENCLATURE	VALUE
Effective Length of Condenser	L_{cond}	14.0 cm
Effective Length of Evaporator	L_{evap}	1.8 cm
Length of BASE Tube, Excluding Evaporator	L_{BASE}	10.0 cm
Middle Diameter of Inner Wick	$D_{\text{wick 1}}$	1.27 cm
Thickness of Inner Wick	$t_{\text{wick 1}}$	.15 cm
Middle Diameter of BASE	D_{BASE}	1.5 cm
Thickness of BASE	t_{BASE}	.08 cm
Middle Diameter of Electrode	D_{elect}	1.73 cm
Thickness of Current Collector	t_{col}	.15 cm
Length of electrical lead	L_{lead}	.3 cm
Diameter of electrical lead	D_{lead}	2 cm
Middle Diameter of Shell Liner	D_{liner}	2.82 cm
Thickness of Shell Liner	t_{liner}	.01 cm
Length of Shell Liner	L_{liner}	6.0 cm
Number of Liner Layers	N_{liner}	1
Middle Diameter of Space	D_{space}	2.88 cm
Thickness of Space	t_{space}	1.0 cm
Middle Diameter of Outer Wick	$D_{\text{wick 2}}$	3.93 cm
Thickness of Outer Wick	$t_{\text{wick 2}}$	.05 cm
Middle Diameter of Shell	D_{shell}	4.06 cm
Thickness of Shell	t_{shell}	.08 cm
Total length of Shell	L_{shell}	20 cm

The first cell characteristics which must be defined are the high and low pressures of the system. The pressure, P_c , at the inlet to the electromotive pump must be maintained at a minimum of the saturation pressure for the condenser temperature, T_c , or 4.69 Pa for a condenser temperature of 600°K. The pressure, P_2 , at the BASE/liquid sodium interface is the saturation pressure at the BASE temperature, T_b , which is 119.1 kPa at 1200°K. The other pressures of interest can be found from the following relationships.

$$P_1 = P_c \left(\frac{T_b}{T_c} \right)^{.5} + \frac{j (2\pi MRT_b)^{.5}}{F} + P_d$$

where

P_1 = Pressure at the BASE/electrode interface

and

j = Current density = 0.55 A/cm²

M = Molecular weight of sodium = 23 g/mole

F = Faraday's constant = 96,500 coulombs/mole

R = Universal gas constant = 8.314 J/mole-°K

with

P_d = Pressure drop due to diffusion across the electrode

$$P_d = \frac{0.75Gj}{F} \left(\frac{MRT_b}{2\pi} \right)^{.5}$$

where

G = Dimensionless pore geometry factor = 40

as determined from electrode testing.

Substituting, these equations give values of

$$P_d = 3.27 \times 10^{-2} \text{ Pa}$$

and

$$P_1 = 6.67 \text{ Pa}$$

From these pressures, the BASE voltage can be established, using the equation

$$V_{\text{BASE}} = \left(\frac{RT_B}{F} \right) \left(\ln \left(\frac{P_2}{P_1} \right) \right) - jR_T$$

where

R_T = Total ohmic resistance

$R_T = R_B + R_S$

with

R_B = Ionic resistance of BASE

R_S = Other system resistance

The resistance of the BASE is given by the equation

$$R_B = t_B T_B [(4.03 \times 10^{-4}) (e^{1420/T_B}) + [(3.24 \times 10^{-7}) (e^{4725/T_B})]]$$

giving a value of

$$R_B = 0.1279 \, \Omega\text{-cm}^2$$

and electrode testing has provided a value of

$$R_S = 0.14 \, \Omega\text{-cm}^2$$

for a combined value of

$$R_T = R_B + R_S$$

$$R_T = 0.1279 + 0.14 = 0.2679 \, \Omega\text{-cm}^2$$

Substituting, the voltage is then

$$V = 0.865 \text{ volts}$$

For a cell with the characteristics shown above, the required heat input to the evaporator to achieve the desired current density is given by the following:

$$Q_{\text{evap}} = Q_{\text{cell}} + Q_{\text{cond}} + Q_{\text{losses}}$$

where

Q_{cell} = Cell power output

which is defined by

$$Q_{\text{cell}} = Q_{\text{BASE}} - Q_{\text{col}} - Q_{\text{lead}} - Q_{\text{shell}}$$

with Q_{BASE} given by

$$Q_{\text{BASE}} = V_{\text{BASE}} \times j$$

$$Q_{\text{BASE}} = (0.865 \text{ volts}) (0.55 \text{ A/cm}^2) = 0.475 \text{ Watts/cm}^2$$

and

$$Q_{\text{col}} = \text{Current collector electrical loss}$$

$$Q_{\text{col}} = (jL_{\text{BASE}})^2 \left(\frac{R_1}{t_{\text{wick1}}} + \frac{R_0}{t_{\text{col}}(1-P_{\text{col}})} \right)$$

where

$$P_{\text{col}} = \text{Current collector porosity} = 0.5$$

$$R_1 = \text{Inner electrode resistivity} = 5 \times 10^{-4} \Omega\text{-cm}$$

$$R_0 = \text{Outer electrode resistivity} = 3 \times 10^{-4} \Omega\text{-cm}$$

giving

$$Q_{\text{col}} = 0.0074 \text{ Watts/cm}^2$$

and

$$Q_{\text{lead}} = \text{Electrical lead electrical loss}$$

$$Q_{\text{lead}} = \frac{4D_{\text{BASE}}L_{\text{BASE}}L_{\text{lead}}R_{\text{lead}}j^2}{D_{\text{lead}}^2}$$

where

$$R_{\text{lead}} = \text{Resistivity of electrical lead} = 4 \times 10^{-4} \Omega\text{-cm}$$

giving

$$Q_{\text{lead}} = 0.016 \text{ Watts/cm}^2$$

Also,

Q_{shell} = Electrical loss in shell

$$Q_{\text{shell}} = \frac{D_{\text{BASE}} L_{\text{BASE}} L_{\text{liner}} R_{\text{liner}} j^2}{D_{\text{liner}} t_{\text{liner}}}$$

where

R_{liner} = Shell liner resistivity = $4 \times 10^{-4} \Omega\text{-cm}$

giving

$$Q_{\text{shell}} = 0.015 \text{ Watts/cm}^2$$

Summing the terms

$$Q_{\text{cell}} = 0.475 - 0.0074 - 0.016 - 0.015 = 0.4366 \text{ Watts/cm}^2$$

Q_{cond} = Heat transfer from base to condenser

Further, the heat transfer to the condenser can be found from the equation

$$Q_{\text{cond}} = Q_{\text{latent}} + Q_{\text{sensible}} + Q_{\text{vapor}} + Q_{\text{rad}}$$

where

Q_{latent} = Latent heat
= Heat input for vaporization for Sodium

$$Q_{\text{latent}} = \frac{j L_{\text{Na}}}{F}$$

with

j = Current density = 0.55 A/cm^2

L = Latent heat of Sodium = 89,000 Joules/mole

F = Faraday's constant = 96,500 coulombs/mole

and

Q_{sensible} = Sensible heat input to Sodium

$$Q_{\text{sensible}} = \frac{j C_p (T_{\text{Base}} - T_{\text{cond}})}{F}$$

with

$$C_p = \text{Specific heat of sodium} = 30 \text{ Joules/mole-}^\circ\text{K}$$

$$T_{\text{BASE}} = \text{BASE temperature} = 1200^\circ\text{K}$$

$$T_{\text{cond}} = \text{Condenser temperature}$$

$$= \text{Evaporator inlet temperature} = 600^\circ\text{K}$$

Substitution of values into the preceding equations gives

$$Q_{\text{latent}} = \frac{(0.55\text{A/cm}^2) (89000\text{Joules/mole})}{96500\text{coulombs/mole}}$$

which solves to

$$Q_{\text{latent}} = 0.507 \text{ Joules/sec-cm}^2 = 0.507 \text{ Watts/cm}^2$$

and

$$Q_{\text{sensible}} = \frac{(0.55\text{A/cm}^2) (30\text{Joules/mole-}^\circ\text{K}) (1200^\circ\text{K}-600^\circ\text{K})}{96500\text{coulombs/mole}}$$

which solves to

$$Q_{\text{sensible}} = 0.103 \text{ Watts/cm}^2$$

The heat loss through vapor conduction is given by the equation

$$Q_{\text{vapor}} = \frac{K_{\text{Na}} (T_{\text{BASE}} - T_{\text{cond}})}{t_{\text{space}}}$$

with

$$K_{\text{Na}} = \text{Thermal conductivity of sodium vapor}$$

$$= 1.7 \times 10^{-4} \text{ Watts/cm-}^\circ\text{K}$$

which solves to give a value of

$$Q_{\text{vapor}} = 0.102 \text{ Watts/cm}^2$$

The heat loss through radiation to the condenser is given by

$$Q_{\text{rad}} = \frac{\sigma (T_{\text{BASE}}^4 - T_{\text{cond}}^4)}{Z}$$

where

$$\sigma = \text{Stefan-Boltzmann constant} = 5.67 \times 10^{-8} \text{ Watts/m}^2\text{-}^\circ\text{K}^4$$

and Z is a radiation reduction factor defined by the equation

$$Z = 1 + \left(\frac{1}{\epsilon_{\text{elec}}} - 1 \right) + \left[\left(\frac{D_{\text{BASE}}}{D_{\text{liner}}} \right) \times \left(\frac{2}{\epsilon_{\text{liner}}} - 1 \right) \right] + \left[\left(\frac{D_{\text{BASE}}}{D_{\text{shell}}} \right) \times \left(\frac{1}{\epsilon_{\text{NaL}}} - 1 \right) \right]$$

where

$$\epsilon_{\text{elec}} = \text{Emissivity of electrode} = 0.7$$

$$\epsilon_{\text{liner}} = \text{Emissivity of shell liner} = .2$$

$$\epsilon_{\text{NaL}} = \text{Emissivity of liquid sodium on condenser} = 0.02$$

and diameters are as given in Table 1. Substitution into these equations gives

$$Z = 1 + \left(\frac{1}{0.7} - 1 \right) + \left[\left(\frac{1.5}{2.82} \right) \times \left(\frac{2}{.2} - 1 \right) \right] + \left[\left(\frac{1.5}{4.06} \right) \times \left(\frac{1}{0.02} - 1 \right) \right]$$

with a value of

$$Z = 24.32$$

and

$$Q_{\text{rad}} = \frac{5.67 \times 10^{-8} \text{ Watts/m}^2\text{-}^\circ\text{K}^4 [(1200^\circ\text{K})^4 - (600^\circ\text{K})^4]}{24.32}$$

with a value of

$$Q_{\text{rad}} = 0.453 \text{ Watts/cm}^2$$

giving a total heat transfer from the evaporator to the condenser of

$$Q_{\text{cond}} = 0.507 + 0.103 + 0.102 + 0.453 = 1.165 \text{ Watts/cm}^2$$

An accurate estimate of the required heat input to the evaporator can be gained by accounting for other system losses, which can be approximated as follows.

The conductive loss to the shell liner is given by

$$Q_{c-shell} = \frac{K_{shell} D_{liner} t_{liner} (T_B - T_c)}{L_{liner} D_{BASE} I_{BASE}}$$

where

$$K_{shell} = \text{Thermal conductivity of the shell liner} \\ = 60 \text{ Watts/m-}^{\circ}\text{K}$$

giving

$$Q_{c-shell} = 0.286 \text{ Watts/cm}^2$$

The conductive loss through the electrical lead is given by

$$Q_{c-lead} = \frac{K_{lead} D_{lead}^2 (T_B - T_c)}{4 L_{lead} D_{BASE} I_{BASE}}$$

where

$$K_{lead} = \text{Thermal conductivity of the electrical lead} \\ = 60 \text{ Watts/m-}^{\circ}\text{K}$$

giving

$$Q_{c-lead} = 0.27 \text{ Watts/cm}^2$$

In summary the total heat input to the evaporator is

$$Q_{evap} = Q_{cell} + Q_{cond} + Q_{c-shell} + Q_{c-lead}$$

which evaluates to

$$Q_{evap} = 0.4366 + 1.165 + 0.286 + 0.27 = 2.1576 \text{ Watts/cm}^2$$

From this we can find the required heat transfer temperature for the heat source (GPHS), for an evaporator diameter equal to the BASE diameter, using the relationship

$$Q_{\text{total}} = \sigma \epsilon_{\text{evap}} (T_s^4 - T_B^4) (\pi D_{\text{BASE}} L_{\text{evap}})$$

where

$$\epsilon_{\text{evap}} = \text{Emissivity of evaporator} = 0.8$$

Solving for the source temperature, T_s , gives

$$T_s = 1263^\circ\text{K}$$

The cell electric power can be found from the equation

$$Q_{\text{elec}} = Q_{\text{cell}} (\pi D_{\text{BASE}} L_{\text{BASE}})$$

$$Q_{\text{elec}} = (.4366 \text{ Watts/cm}^2) \pi (1.5 \text{ cm}) (10 \text{ cm}) = 20.58 \text{ Watts}$$

The cell current can be found from

$$I_{\text{cell}} = j (\pi D_{\text{BASE}} L_{\text{BASE}})$$

$$I_{\text{cell}} = (0.55 \text{ A/cm}^2) \pi (1.5 \text{ cm}) (10 \text{ cm}) = 25.92 \text{ Amperes}$$

The total mass flow of sodium can be evaluated using the previously determined relationship for latent heat

$$Q_{\text{latent}} = \frac{j I_{\text{Na}}}{F}$$

with

$$L = \text{Latent heat of Sodium} = 89,000 \text{ Joules/mole}$$

The total latent heat is

$$Q_{\text{lat-tot}} = Q_{\text{latent}} (\pi D_{\text{BASE}} L_{\text{BASE}})$$

$$Q_{\text{lat-tot}} = (0.507 \text{ Watts/cm}^2) (\pi) (1.5 \text{ cm}) (10 \text{ cm})$$

$$Q_{\text{lat-tot}} = 23.89 \text{ Watts}$$

It is also known that

$$Q_{\text{lat-tot}} = \frac{\dot{m} \times L}{M}$$

Solving this equation for the mass flow rate gives

$$\dot{m} = 6.17 \times 10^{-4} \text{ g/sec}$$

If it is assumed that approximately 10% of the system sodium passes through the pump, the pump mass flow is

$$\dot{m}_{\text{pump}} = 6.17 \times 10^{-5} \text{ g/sec}$$