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High Efficiency Vapor-Fed AMTEC System for Direct Conversion

Final Report

May 23, 1997

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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. 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. When the inside of the BASE is maintained at a higher temperature and pressure, a concentration gradient is created across the BASE. Electrons and sodium atoms cannot pass through the BASE. However, the sodium atoms are ionized, and the sodium ions move through the BASE to the lower potential (temperature) region. The electrons travel externally to the AMTEC cell, providing power.

There are a number of potential advantages to a wick-pumped, vapor-fed AMTEC system when compared with other designs. A wick-pumped system uses capillary forces to passively return liquid to the evaporator, and to distribute the liquid in the evaporator. Since the fluid return is self-regulating, multiple BASE tubes can use a single remote condenser, potentially improving efficiency in advanced AMTEC designs. Since the system is vapor-fed, sodium vapor is supplied at a uniform temperature and flux to the BASE tube, even with non-uniform heat fluxes and temperatures at the evaporator. The primary objective of the Phase II program was to develop wick-pumped AMTEC cells.

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 roughly 50 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. During Phase I of the program, a capillary pumping demonstrator was fabricated and tested to demonstrate the ability of the AMTEC wick fed cells to operate with negative pressures in the sodium. 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, demonstrating the feasibility of a wick-fed AMTEC device.

The objective of the Phase II program was to develop wick-pumped, vapor-fed AMTEC cells for use in space power applications. The AMTEC cells were designed for use with general purpose heat sources (GPHS), although the design can be easily modified for other heat sources, such as nuclear or solar.

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 very 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. 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. Since the sodium vapor pressure increases exponentially with temperature, the required pore radius to overcome the vapor pressure decreases from roughly 20 μm at 700°C to 5 μm at 800°C.

The problem with a conventional, uniform wick structure is that the permeability for flow decreases as the pore size decreases. The solution is to tailor the wick structure to maintain reasonable permeability with a high pumping capability. The cells fabricated had a range of permeabilities and pore sizes.

Two generations of AMTEC cells were fabricated. The first cell was designed to operate at 700°C, and used a state-of-the art wick. Successful testing of the 700°C cell was conducted at 600, 625, and 650°C, with a 250°C Condenser. The wick design was fully successful. Above 650°C, problems were experienced with the AMPs electrical feedthrough. This feedthrough was designed to operate at low temperatures in the condenser. The cell had roughly 3.5 grams of excess sodium. It appears that at temperatures around 650°C, the pressure in the evaporator is high enough that excess sodium is pushed from the evaporator to the condenser. The wick was fully operational, supplying the BASE with sodium from the condenser. Unfortunately, with the AMPS cold feedthrough design, a portion of the sodium condenses and shorts the electrical feedthrough.

During the program, procedures to fabricate wicks with smaller pore sizes were developed, to allow operation of an AMTEC cell at 800°C. A revised design was made for a High-Temperature, Wick-Fed AMTEC cell. In addition to the smaller wick pore size, several other changes were made to increase the cell efficiency:

- Internal artery return of condensate
- High temperature electrical feedthrough
- Separate heat pipe for providing heat to the BASE

The revised feedthrough could operate at high temperature. Any liquid sodium on this feedthrough would evaporate and travel to the colder condenser, preventing an electrical short. After fabrication, the High-Temperature Wick-Fed AMTEC cell operated successfully during the initial set of tests at AMPS. Unfortunately, the cell was damaged during shipment to Thermacore. It appears that the interface between the stainless steel artery structure and the wick structure was compromised. This interface was a mechanical one and probably separated. A very small gap is enough to impede the capillary action and reduce the sodium flow.

2.0 Introduction

The objective of the Phase II program was to develop wick-pumped, vapor-fed AMTEC cells for use in space power applications. The AMTEC cells were designed for use with general purpose heat sources (GPHS), although the design can be easily modified for other heat sources, such as nuclear or solar.

2.1 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.

There are a number of potential advantages to a wick-pumped, vapor-fed AMTEC system when compared with other designs. A wick-pumped system uses capillary forces to passively return liquid to the evaporator, and to distribute the liquid in the evaporator. Since the fluid return is self-regulating, multiple BASE tubes can use a single remote condenser, potentially improving efficiency in advanced AMTEC designs. Since the system is vapor-fed, sodium vapor is supplied at a uniform temperature and flux to the BASE tube, even with non-uniform heat fluxes and temperatures at the evaporator. The primary objective of the Phase II program was to develop wick-pumped AMTEC cells.

Figure 1. Vapor-Fed AMTEC Schematic.

2.2 Phase I Capillary Pumping Demonstrator

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, demonstrating the feasibility of a wick-fed AMTEC device.

2.2.1 Phase I Apparatus

In a vapor-fed AMTEC cell, roughly 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.

A sketch of the capillary pumping demonstrator used to simulate this sodium flow is shown in Figure 3. 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 3, the AMTEC condenser region is simulated by the secondary condenser, which is located downstream of an orifice. The demonstrator is operated with choked flow through the orifice, with the secondary condenser 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.

Figure 2. Sodium ions pass through the BASE, while electrons deliver power to an external load.

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.

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].

2.3 Capillary Pumping Demonstrator Experimental Results

After initial charging and testing, the capillary pumping demonstrator was 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 pre-warm the system. 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. During operation, temperatures were measured with a series of thermocouples in the evaporator, primary and secondary condensers, and the liquid return line. The insulation around the secondary condenser was adjusted (opened or closed) to maintain the temperature near 400°C.

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), 670°C (9340 Pa), 680°C (10,680 Pa), and 690°C (12,220 Pa). In each case, the system performed as expected. Figure 4 shows the typical temperatures in the demonstrator during operation. The evaporator operated near 690°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 5. These saturated sodium vapor pressures were calculated from a correlation in Foust [1972]:

$$P_v = \frac{101350}{\sqrt{T_K}} 10^{(6.354 - 5567/T_K)} \quad 1$$

with P_v in Pascal and T_K in Kelvin.

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.

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 45 Pa. The pressure decreases as the sodium travels to the evaporator, due to both pressure drops due to flow, and to the gravitational term:

$$\Delta P_{grav} = -\rho_L g h \quad 2$$

where h is the elevation of the evaporator above the condenser.

Figure 6 shows a schematic of the pressure in the demonstrator when the adverse elevation was increased to 22.6 cm (8.9 inches). The evaporator pressure of roughly 9000 Pa (at 670°C) is set by the evaporator temperature, since the sodium vapor is at saturated conditions. 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. 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. The minimum pressure in the system is -2430 Pa in the evaporator wick. Finally, the pressure drop is increased back to 9000 Pa by capillary forces in the wick at the vapor/liquid interface.

Figure 4. Capillary Pumping Demonstrator Evaporator and Condenser Temperatures, for an Evaporator Temperature of 690°C.

Figure 5. Capillary Pumping Demonstrator Evaporator and Condenser Pressures, for an Evaporator Temperature of 690°C.

Figure 6. Capillary Pumping Demonstrator Pressures, with an Evaporator Elevation of 22.6 cm, and a Minimum Pressure of -2430 Pa.

3.0 700°C AMTEC Cell Design

The first cell was designed to operate with an evaporator and BASE temperature near 700°C, and a condenser temperature near 400°C; see Figures 7 to 10. This wick-pumped, vapor-fed AMTEC cell was used to validate the cell design, including the evaporator and condenser designs, and the wick-fed liquid return.

Figure 7 shows the outside of the cell, while Figures 8 and 9 show cross-sections through the cell. The evaporator is covered with a sintered powder metal wick. A free-standing wick (joined to the evaporator wick) extends up into the interior of the BASE tube. The BASE tube is surrounded by a hot zone canister, which is maintained roughly at the BASE temperature, so sodium will not condense on the hot zone canister walls. Guard heaters are used to maintain the temperature during operation of a single cell. In a space power application, the canister and the evaporator would be heated by the General Purpose Heat Source (GPHS) modules.

A remote condenser, operating at a temperature near 400°C, is located above the hot zone canister. Parasitic radiation heat losses from the hot BASE to the colder condenser are minimized with a remote condenser, since the view factor is reduced. The remote condenser is coated with a sintered powder metal wick to collect the condensing sodium. As shown in Figure 7, a cable artery connects the condenser and evaporator wick. The cable artery loops around the evaporator wick to uniformly distribute the fluid, see Figure 10.

Differences from a previous wick-fed design by Hunt *et al.* [1993] include a remote condenser and a higher operating temperature. In addition, the AMTEC cell by Hunt *et al.* was heated with a electrical heater inside the BASE tube. In the current AMTEC cell design, heat is supplied to the cylindrical sides of the evaporator. The design can easily be modified to accommodate a heat source at the bottom of the evaporator. This arrangement would be required in a space power system heated with GPHS modules.

Figure 11 illustrates the heat transfer and fluid flow processes in the AMTEC cell. The evaporator operates near 700°C (14,000 Pa), while the condenser operates near 400°C (48 Pa). Heat supplied to the evaporator vaporizes liquid sodium in the evaporator wick. The sodium vapor travels up the free-standing wick inside the BASE and condenses, supplying sodium and heat to the BASE. There are two separate paths for the condensing sodium: a recirculating loop, and a power loop.

In the recirculating loop, a majority of the sodium condensate recirculates through the free-standing wick to the evaporator wick. This sodium supplies heat to the BASE. The remaining sodium travels through the BASE, generating power. This sodium vaporizes on the outside of the BASE and travels to the remote condenser, where it condenses. The sodium travels through the condenser wick to the cable artery, then returns through the artery to the evaporator wick, completing the power loop.

The AMTEC cell contains four different wicks. Each wick has different requirements and different properties:

Condenser Wick: collect the condensate, and provide flow passages to the cable artery. The condenser artery is a relatively coarse wick, with a low capillary pumping capability, and a high permeability.

Cable Artery: return condensate from condenser to evaporator. The cable artery is a flexible, high permeability cable with sufficient wick pumping capability to prime against gravity. The artery diameter is made as small as possible to reduce the parasitic heat leaks from the hot zone to the condenser, which reduce the AMTEC cell efficiency. Figure 10 shows how the cable artery is embedded in the evaporator wick.

Free-standing Wick: depending on the cell efficiency, roughly 80 to 95% of the sodium vapor delivered to the BASE is recirculated through the free-standing BASE wick. The free-standing wick has a moderate capillary pumping capability, and a moderate permeability.

Evaporator Wick: collects liquid sodium from both the free-standing and condenser wicks to the evaporator. The evaporator wick has a very high pumping capability, to pump against the pressure drops in the power loop (especially the vapor pressure difference between the evaporator and the condenser).

3.1 Capillary Pumping Equations

For the wick-pumped cell to operate, the capillary pumping capability must be greater than the sum of pressure drops as the liquid travels around the system. The pressure drops are due to fluid flow in the vapor and liquid, as well as the pressure drop in overcoming the hydrostatic head of liquid if the evaporator is located above the condenser. For the vapor-fed AMTEC cell, there are two fluid loops that must be considered: (1) the sodium recirculating in the high pressure region, and (2) the sodium that generates power as it passes through the BASE to the low pressure region.

For the recirculating loop, the capillary pumping capability of the evaporator wick must be greater than the sum of the pressure drops in the sodium:

$$\Delta P_{capillary} \geq P_{Recirc Total} = \Delta P_{Recirc Vapor} + \Delta P_{Recirc Liquid} + \Delta P_{Recirc Gravity} \quad 3$$

where the capillary pumping capability of the wick, which is the maximum capillary pressure that the wick can sustain, is given by:

$$\Delta P_{Capillary} = \frac{2 \sigma}{r_c} \quad 4$$

20/0000, 10/11/00, 07/000

Figure 7. 700°C Wick-Pumped AMTEC Cell Design: Cell Envelope.

Figure 8. 700°C Wick-Pumped AMTEC Cell Design: Section A-A.

Figure 9. 700°C Wick-Pumped AMTEC Cell Design: Section B-B.

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Figure 10. 700°C Wick-Pumped AMTEC Cell Cable Artery.

Figure 11. Heat Transfer and Fluid Flow Schematic for the 700°C Wick-Pumped AMTEC Cell.

Sodium properties were calculated from correlations in Foust [1972]. While the gravitational pressure drop can be neglected during space operation, it must be considered for ground testing:

$$\Delta P_{Recirc\ Gravity} = \rho_l g h_{BASE} \sin(\theta) \quad 5$$

For the power loop, evaporator wick pumping capability must be larger than the sum of the pressure drops:

$$\Delta P_{Capillary} \geq P_{Power\ Total} = \Delta P_{Recirc\ Vapor} + \Delta P_{BASE} + \Delta P_{Power\ Liquid} + \Delta P_{Power\ Gravity} \quad 6$$

The liquid pressure drop for the power cycle contains contributions from the condenser wick, the cable artery, and the evaporator wick:

$$\Delta P_{Power\ Liquid} = \Delta P_{Condenser\ Wick} + \Delta P_{Cable\ Artery} + \Delta P_{Evap\ Wick} \quad 7$$

The pressure difference between the high pressure vapor in the BASE and the low pressure vapor in the condenser is:

$$\Delta P_{BASE} = P_{Sat}(T_{BASE\ Interior}) - P_{Sat}(T_{Cond}) \quad 8$$

The Ditchburn-Gilmour equation was used for the sodium vapor pressure, where the vapor is assumed to be saturated, see equation 1. The gravitational pressure drop for the power cycle is:

$$\Delta P_{Power\ Gravity} = \rho_L g h_{Cond} \sin(\theta) \quad 9$$

For both the recirculating and power loop, the pressure drops for the liquid and vapor flow are calculated by the standard heat pipe equations, e.g., see Chi [1976] or Dunn and Reay [1982]. For example, the pressure drop through the cable artery is:

$$\Delta P_{cable} = \frac{\dot{m}_{cable} \mu_L L_{cable}}{K_{cable} \rho_L A_{cable}} \quad 10$$

In addition to the overall recirculating and power loop calculations, similar equations must be developed for the condenser wick, the cable artery, and the free-standing wick. Appendix A contains a derivation of all the equations for the 700°C wick system.

3.2 AMTEC Wick Design

The choice of pore structure for the condenser wick, cable artery, free-standing wick, and evaporator wick requires a trade-off between capillary pumping capability and permeability to liquid flow. Decreasing the wick pore size increases the capillary pumping capability while simultaneously decreasing the liquid permeability. A reduced liquid permeability will in turn increase the liquid pressure drop through the system.

The wick properties for the 700°C AMTEC design are shown in Table 1. The condenser wick and cable artery have relatively high permeabilities to reduce the overall pressure drop. The low wicking capability associated with the high permeability is acceptable for these wicks. On the other hand, a low pore size is required in the evaporator wick to provide sufficient wicking capability for the power loop pressure drops, as discussed below. In this AMTEC cell design, the cross-sectional area of the evaporator wick was increased to compensate for the low permeability.

Table 1. Wick Properties

	Pore Size, m	Permeability, m ²
Condenser Wick	5.5×10^{-5}	3.5×10^{-11}
Cable Artery	4.8×10^{-5}	7.3×10^{-11}
Free-Standing Wick	3.0×10^{-5}	1.5×10^{-11}
Evaporator Wick (Est.)	1.0×10^{-5}	1.0×10^{-12}

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. The evaporator wick has a smaller pore radius than the cable artery, which in turn has a smaller radius than the condenser wick. This causes the sodium in the condenser to spontaneously wick to the evaporator, giving a self-priming liquid return system.

Equations 3 - 10 above were used to calculate the pressure drops for the chosen wick design as a function of temperature, see Appendix A for details. Pressure drops are shown in Figure 12 for the power loop, and in Figure 13 for the recirculation loop in the high pressure region. Pressure drops for the condenser wick, cable artery, and free-standing wick are shown in Figure 14 to 16. It can be seen that the pressure drops for the recirculating liquid are much less than the pressure drops for the power cycle. The majority of the power loop pressure drop is the drop in vapor pressure as the sodium travels from the inside of the BASE tube to the condenser, see equation 8. As the temperature increases, the total pressure drop for the power loop also increases, until it is higher than the pumping capability of the evaporator wick. At this point, the cell would dry out and stop operating. As shown in Figure 12, the estimated maximum operating temperature for the first AMTEC cell design is 725°C.

Figure 17 shows a schematic of the pressure in the demonstrator at 700°C and the maximum adverse elevation, when the evaporator is vertical above the BASE tube. The evaporator pressure of roughly 14,000 Pa is set by the evaporator temperature, since the sodium vapor is at saturated conditions. The pressure decreases slightly when traveling from the evaporator to the BASE, due to the vapor flow losses. The pressure then decreases sharply as the sodium travels through the BASE, generating electricity. The low pressure sodium vapor condenses in the condenser at a pressure near 50 Pa. The condensed sodium then travels back to the evaporator through the cable artery and wick. 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 due to

both gravity and viscous forces. The minimum pressure in the system is -6000 Pa in the evaporator wick. Finally, the pressure is increased back to 14,000 Pa by capillary forces in the wick at the vapor/liquid interface.

3.3 Negative Pressures

In a wick-pumped AMTEC cell, the increase in pressure occurs in the evaporator at the liquid/vapor interface due to interfacial tension forces. The vapor pressure next to the wick is set by the temperature, and is roughly 14,000 Pa at 700°C. The liquid pressure in the wick is set by the *condenser* vapor pressure, and the liquid pressure drops in the condenser wick, cable artery, and evaporator wick, and the hydrostatic head:

$$P_{Evap\ Liquid} = P_{Cond} - \Delta P_{Cond\ Wick} - \Delta P_{Cable\ Artery} - \Delta P_{Evap\ Wick} - \rho_L g h_{Cond} \sin(\theta) \quad 11$$

The condenser typically operates near 50 Pa, assuming a condenser temperature of 400°C. An examination of Equation 12 and Figure 12 shows that the pressure drops in the evaporator wick are larger than the condenser vapor pressure, so that the sodium liquid in the evaporator wick can have a negative sodium pressure, with the sodium in tension. Figure 18 shows the minimum absolute pressure in the AMTEC evaporator wick for three different experimental conditions:

- (1) Gravity-aided, with the evaporator located directly below the condenser. This liquid tension is about -5000 Pa. Other test orientations will have a lower negative pressure.
- (2) Zero-Gravity, the expected minimum pressure in space, and
- (3) Adverse, with the evaporator located directly above the condenser, the minimum possible pressure.

If the superheat is too large, boiling will occur, blocking the wick with vapor, and preventing further operation of the cell. During an earlier part of this program, 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 [Anderson, 1992]. The demonstrator uses a sodium heat pipe, with a pressure and temperature difference between the evaporator and condenser maintained with a small orifice. The demonstrator successfully operated with the evaporator at 690°C (12,000 Pa), and the condenser at 380°C (40 Pa). 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.

Kemme [1968] has demonstrated negative pressures as low as -5300 Pa in a sodium heat pipe. The heat pipe was operated with sonic conditions at the evaporator exit, so that the flow was choked. The vapor temperature decreased from 695°C at the start of the evaporator (stagnation temperature) to 625°C at the end of the evaporator. The temperature decreased further in the

condenser to roughly 600°C. Finally, the temperature recovered back to 645°C at the end of the condenser. Kemme estimated that the pressure dropped from 6500 Pa at the end of the condenser to -5300 Pa at the end of the evaporator, due to the vapor pressure difference, as well as frictional losses in the heat pipe wick. Further information can be found in Anderson [1993].

3.4 Cell Design and Performance

The AMTEC cell was designed to demonstrate the feasibility of wick pumping in vapor-fed cells, not for high efficiency. However, the cell was designed with a reasonable efficiency (approximately 5 percent) and electrical power output (2.1 W). A state-of-the-art cell model was used to predict the cell performance. All of the heat and power losses are calculated with detailed thermal and electrical models. An enhanced, three-zone, vapor flow/pressure drop model derived from an existing model (Sievers and Wright, 1990) predicts the back pressure at the electrode. The thermal and flow models are combined with an electrolyte/electrode model that predicts the cell electrical power output. The predicted cell operating conditions are summarized in Table 2.

Table 2. Predicted Cell Performance

Base Temperature	973 K
Average Housing Temperature	920 K
Condenser Temperature	610 K
Feedthrough Temperature	473 K
BASE Power Density	0.35 A/cm ²
Total Cell Heat Input	40 W
Cell Voltage	0.3 V
Cell Current	7.0 A

The cell design tries to thermally decouple the hot BASE tube from the cold condenser and minimize the radiative heat transfer. The radiative heat transfer between the hot and cold regions of the cell has the most impact on the overall cell efficiency. These losses are reduced with the remote condenser, and the use of a radiation shield between the two regions. This also increases the back-pressure at the electrode, reducing the power density of the electrode. Previous studies have shown this to be an acceptable trade-off. No attempt was made to optimize the cell configuration. All of the significant heat losses are summarized in Table 3.

The cell power density depends on both the sodium vapor pressure inside the BASE tube and the actual BASE tube. These parameters are dependent on the capillary capability of the wick system. Later cells in this program used wicks capable of operating at higher temperatures, significantly enhancing performance.

Table 3. Predicted Cell Heat Losses

Radiation Losses	5.4 W
Conduction, Cell Wall	16 W
Conduction, Artery	2.1 W
Conduction, Feedthrough	7.2 W
Sensible Heat Loss	0.8 W
Latent Heat Loss	6.4 W
Total	37.9 W

Figure 12. Calculated AMTEC Power-Cycle Pressure Drop.

Figure 13. Calculated AMTEC Cell Recirculating-Loop Pressure Drop for the Evaporator Wick.

Figure 14. Calculated AMTEC Power-Cycle Pressure Drop for the Condenser Wick.

Figure 15. Calculated AMTEC Power-Cycle Pressure Drop for the Cable Wick.

Figure 16. Calculated AMTEC Cell Recirculating-Loop Pressure Drop for the Free-Standing Wick.

Figure 17. Calculated Pressure Loop for the AMTEC Power-Cycle, at 700°C with the Evaporator Vertical Above the Condenser.

Figure 18. Calculated Minimum Pressure in the AMTEC Wick.

4.0 700°C AMTEC Cell Fabrication

4.1 Experimental Set-up

The wick structure for the 700°C wick-fed AMTEC cell was fabricated at Thermacore. Complete parts drawings for the 700°C AMTEC cell are shown in Appendix B. The fabrication of the wick structure is discussed in Section 5. Figure 19 is a photograph of the cell parts.

Figures 20 and 21 shows the AMTEC cell after fabrication of the wick. The feedthrough was attached at Thermacore, and the evaporator end cap welded in place. The cell was then shipped to ERIM, where the BASE and electrodes were welded in place. The BASE tube was fabricated by Ceramatec, Inc. The BASE tube has a 1.5 cm diameter, a length of 10 cm, and a wall thickness of approximately 1 mm.

The two hot zone canisters were slid into place around the BASE tube and sealed. The cell was then charged with sodium. The set-up for charging is shown in Figure 22. Charging was conducted in several steps, to distribute the sodium in both the evaporator and condenser. First, the condenser was chilled, and the evaporator was heated, so that the initial sodium injected into the system would form a plug in the artery near the condenser, and sodium would flow into the evaporator. 16 cm³ of sodium was injected. Next the cable artery leading into the evaporator was frozen, while the condenser was heated. The remaining sodium, 5 cm³, then filled the condenser wick.

Finally, the cell was then placed in the test cell. Figure 23 shows a schematic of the test set-up. The evaporator and hot zone canisters are surrounded by heaters, then insulation to minimize the heat losses. Power to the cell is supplied by the heater around the evaporator. The guard heater around the hot zone canister is used to minimize heat losses in this region. The condenser is exposed to air, to aid in heat rejection. A heater tape is used to keep the condenser at the desired temperature. A small ceramic heater is used to control the artery temperature. A TC well is used to monitor the artery temperature.

Nine thermocouples were used on the AMTEC cell; the thermocouple locations are shown in Figure 24. Three of the thermocouples were located in small tubes. The thermocouples were moved up and down the tubes to obtain temperature profiles. Additional TC wells are used to control the guard heater.

The circuit diagram for the cell is shown in Figures 25 and 26. The voltage measurement leads are connected to the positive feed through and to the condenser (negative feed through), which is at ground potential. The leads are brought to a control panel where current and voltage values are read directly on digital panel meters. Separate cords from the panel permit the current and voltage leads to be connected to an X-Y recorder for taking current/voltage data.

Because it is often difficult to produce a smoothly variable passive load resistance at the impedance levels needed to match the internal impedance of AMTEC cells, the I-V current is

measured with a D.C. power supply. As shown in Figure 26, the power supply is connected in series with the cell so that the power supply current is "aiding" the cell output. The current and voltage are then measured on an X-Y recorder as the current is swept using the power supply controls. The current must be limited to a maximum of the "short-circuit" value, to avoid reversing the cell voltage and possibly damaging the cell.

During start-up, the cell +ve lead of the AMTEC cell is insulated, and isolated from system ground and the cell body until the system is ready to power a load. Cell output is measured between the +ve feed-through lead and the cell wall by connecting the -ve lead to the stud at the top of the cell. Open circuit voltages are monitored during start-up. When the cell temperature is above 500°C and the condenser temperature is above 200°C, the IV curves can be measured.

4.2 Experimental Results

Successful testing was conducted at 600, 625, and 650°C, with a 250°C Condenser. Current-Voltage and Current-Power curves are shown in Figures 27-28, 29-30, and 31-32 with the BASE at temperatures of 600, 625, and 650°C, respectively. Current-Voltage and Current-Power are shown in Figures 33 and 34 as a function of BASE temperature. The wick design by Thermacore was fully successful.

Above 650°C, an apparent blow-by was experienced which was indicated by a sudden rise in the temperature of the condenser, and an accompanying electrical short shown by the drop in output voltage (0.7 V to 0.2 V). The cell temperature was reduced to 550°C, with the condenser at 250°C overnight. The next morning, the cell had fully recovered. Voltage-current scans duplicated the previous data at temperatures up to 650°C.

The cell was then successfully operated at 660°C with an open circuit. However, when a load was applied, a blow-by occurred again, with shorting at about 8 amps and 0.25 V. An overnight bake-out of the system to remove the second electrical short was not successful.

The problem is caused by AMPS' electrical feed-through design, which is located in a relatively cold area of the cell. The cell had roughly 3.5 grams of excess sodium. It appears that at temperatures around 650°C, the pressure in the evaporator is high enough that excess sodium is pushed from the evaporator to the condenser. The wick was fully operational, supplying the BASE with sodium from the condenser. Unfortunately, with the AMPS cold feedthrough design, a portion of the sodium condenses and shorts the electrical feedthrough.

Amps has seen similar problems in their other cells with the same feedthrough design. The problem will always re-occur, even if the initial short is fixed. The solution to the problem is to change the electrical feed-through design and location, to increase its temperature and eliminate the shorting problems.

After the failure of the AMPS feedthrough, the cell was opened and examined. A photograph of the cell is shown in Figure 35. The BASE tube is shown in the center of the opened cell. It is covered with an electrode. A copper mesh is used to distribute the electrons that are supplied to the BASE tube from the copper cable extending from the top of the cell. The cone above the BASE cell is the radiation shielding, which minimizes the losses from the BASE to the cold condenser.

The ceramic-to-metal seal was examined, and a deposit was found in the braze area. The deposit was dull white in color, and probably sodium oxide. This deposit is consistent with leakage of sodium through the braze, causing failure of the feedthrough.

Figure 19. 700°C Wick-Pumped AMTEC cell parts.

Figure 20. Photograph of the 700°C Wick-Pumped AMTEC Cell Before Adding the BASE Tube and Hot-Zone Canister.

Figure 21. Schematic of the 700°C Wick-Pumped AMTEC Cell Before Adding the BASE Tube and Hot-Zone Canister.

Figure 22. Charging the 700° Wick Pumped Cell with Sodium.

Figure 23. Test Set-Up for the 700°C Wick-Pumped AMTEC Cell, Showing the Location of the Heaters and Insulation.

Figure 24. Thermocouple Well Locations for the 700°C Wick-Pumped AMTEC Cell.

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Figure 25. Schematic circuit diagram of cell set-up for current/voltage measurement. $R_c = 0.001 \Omega$ and typical $R_L = 0.005 \Omega$.

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Figure 26. Circuit diagram for cell connection to X-Y Recorder for current/voltage plotting.

Figure 27. Current/Voltage Curves for the 700°C AMTEC Cell, 600°C BASE, 250°C Condenser.

Figure 28. Current/Power Curves for the 700°C AMTEC Cell, 600°C BASE, 250°C Condenser.

Figure 29. Current/Voltage Curves for the 700°C AMTEC Cell, 625°C BASE, 250°C Condenser.

Figure 30. Current/Power Curves for the 700°C AMTEC Cell, 625°C BASE, 250°C Condenser.

Figure 31. Current/Voltage Curves for the 700°C AMTEC Cell, 650°C BASE, 250°C Condenser.

Figure 32. Current/Power Curves for the 700°C AMTEC Cell, 650°C BASE, 250°C Condenser.

Figure 33. Current/Voltage Curves for the 700°C AMTEC Cell, 600, 625, and 650°C BASE, 250°C Condenser.

Figure 34. Current/Power Curves for the 700°C AMTEC Cell, 600, 625, and 650°C BASE, 250°C Condenser.

Figure 35. 700°C AMTEC Cell Internals after failure of the AMPS feedthrough.

5.0 Wick Development

The Phase I capillary pumping demonstrator operated up to a temperature of 690°C. The 700°C AMTEC cell has a 10 mm pore size. The calculations discussed above indicate that this cell should operate at temperatures up to 725°C. The Task objective was to develop wicks that would 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 very 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. 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, see equation 6. The major contribution to the pressure drop is the difference in vapor pressure between the evaporator and condenser, see equation 8.

Figure 36 shows the sodium vapor pressure in the evaporator and BASE as a function of temperature. Figure 36 also includes an estimate of the required pore size which neglects all pressure drops except the vapor pressure:

$$r_c \leq \frac{2 \sigma}{P_{\text{vapor}}(T_{\text{BASE}})} \quad 12$$

where the actual pore size is *smaller* than the estimated pore size. As shown in Figure 36, the required pore radius to overcome the vapor pressure decreases from roughly 20 μm at 700°C to 5 μm at 800°C.

The problem with a conventional, uniform wick structure is that the permeability for flow decreases as the pore size decreases. Figure 37 is a plot of permeability versus pore radius for a series of wicks sintered with different sizes of nickel powder; niobium powder will have similar properties. The permeability decreases as (Pore Size)^{2.207}. A wick with a 2 μm pore size would have a permeability on the order of $4 \times 10^{-15} \text{ m}^2$. This 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. Appendix C contains the pressure drop calculations for the 800°C cell, which are used to estimate the required wick properties. Thermacore examined a series of different wick designs. The solution chosen was to use a series of wicks, with a range of permeabilities and pore sizes:

1. Condenser Wick
2. Cable Artery
3. Evaporator Wick
4. Free-Standing Wick

The choice of pore structure for the condenser wick, cable artery, free-standing wick, and evaporator wick requires a trade-off between capillary pumping capability and permeability to liquid flow. Decreasing the wick pore size increases the capillary pumping capability while simultaneously decreasing the liquid permeability. A reduced liquid permeability will in turn increase the liquid pressure drop through the system. Figure 38 shows the permeabilities and pore sizes used for the four wicks in the 700°C AMTEC cell.

A fabrication procedure was developed for the wicks. It was necessary to fabricate the wicks in stages, due to mechanical constraints and different sintering temperatures for the different wicks. As the pore size decreases, the optimum sintering temperature also decreases, so the coarser wicks were fabricated first. The first wick to be fabricated was the free-standing wick. Prototypes of the free-standing wick are shown in Figure 39.

Next, the condenser wick was sintered. The cable artery that communicates between the evaporator and the condenser was sintered into the condenser wick at the same time. The condenser/cable artery assembly is shown in Figure 40.

The evaporator has the smallest pore size, and the lowest sintering temperature, so it was fabricated last. Excessive shrinkage and cracking of the wick would occur if the evaporator wick was exposed to the temperatures required to sinter the condenser and free-standing wicks. The cable artery was inserted into the evaporator (see Figure 10), while the free-standing wick was placed above the evaporator (see Figure 21 for a schematic). A photograph of the free-standing wick sintered into the evaporator is shown in Figure 41. The cable artery is in the tube to the right of the wick. The interior of the evaporator is shown in Figure 42. The hole in the interior of the evaporator wick extends up through the free-standing wick.

For the high temperature AMTEC cell, wicks were developed with a 2 μm pore size. Figure 43 shows the pore size versus permeability for various wicks developed on this and other programs. The -200 mesh, and the 1-to-5 μm powders were developed on this program. In addition, zirconium rods were successfully implanted in the niobium wicks. These rods would act as getters, protecting the niobium wick from any oxygen in the system.

Figure 36. Maximum Allowable Pore Size Decreases as the BASE Temperature Increases.

Figure 38. Pore Size Versus Permeability for the 700°C AMTEC Cell.

Figure 39. Free-Standing Evaporator Wick for the 700°C Wick-Pumped AMTEC cell.

Figure 40. Condenser Wick and Cable Artery for the 700°C Wick-Pumped AMTEC cell.

Figure 41. Free-Standing Wick Sintered into the 700°C AMTEC Cell Evaporator.

Figure 42. Interior of the 700°C Wick-Pumped AMTEC Cell Evaporator, showing the interior of the free-standing wick.

Figure 43. Pore Size and Permeability for Niobium wicks, with a minimum pore size of 2 μm .

6.0 High Temperature Wick-Fed AMTEC Cell Design

A high-temperature, wick-fed AMTEC cell was designed, based on the results of the work discussed above. The cell was designed to operate near 800°C. A schematic of the cell is shown in Figure 44. The cell has a single β'' -alumina solid electrolyte (BASE) tube, with a sintered Niobium evaporator wick structure for distributing the sodium. The β'' -alumina tube was fabricated by Ceramtec, Inc. The BASE tube has a 1.5 cm diameter, a length of 10 cm, and a wall thickness of approximately 1 mm.

The modifications made to the High Temperature cell design include:

- Internal artery return of condensate
- High temperature electrical feedthrough
- Separate heat pipe for providing heat to the BASE

Vapor flow to the condenser and liquid return are shown in Figure 45; details of the fluid flow are shown in Figure 46. See Appendix C for the calculations. Sodium evaporates from the BASE surface, and travels to the top of the cell. The vapor travels past a series of radiation shields to a condenser, which operates near 400°C. The liquid travels to the center of the condenser, and is returned to the evaporator by a cable artery. The cable artery, surrounded by a tube to accommodate the pressure difference, passes through the pressure boundary between the low temperature condenser and the high-temperature, high-pressure BASE region. As shown in Figure 47, the artery is tied into a niobium wick structure.

As shown in Figures 44 and 46, the High-Temperature Wick-Fed cell was fabricated in two parts, the actual AMTEC cell and a separate sodium heat pipe. The separate heat pipe simplifies fabrication of the wick system.

In a space power system, power would be supplied by radiation from a General Purpose Heat Source to the bottom of the evaporator. As shown in the right half of Figure 46, heat supplied to the evaporator vaporizes sodium, which travels up to the cylindrical condenser. The sodium vapor condenses, and the latent heat is supplied to the AMTEC cell, see the left half of Figure 46. Sodium vaporizing from the niobium wick supplies sodium vapor to the BASE. A portion of the sodium travels through the BASE to provide power. The remaining sodium provides heat for the parasitic heat losses, and returns from the BASE directly to the niobium wick.

The third major change to the design was replacing the low-temperature electrical feed-through in the 700°C cell with a high temperature feedthrough. There are two advantages to the hot zone location. First, parasitic thermal losses through the feedthrough can be reduced. In addition, the hot zone location eliminates problems with sodium condensing on and shorting out the feedthrough.

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Figure 44. High Temperature Wick-Fed AMTEC Cell Schematic.

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Figure 45. Sodium passes through the BASE, condenses on the condenser at the top of the cell, and is returned by the artery.

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Figure 46. High Temperature Wick-Fed AMTEC Cell Heat and Fluid Flow Schematic.

7.0 High Temperature Wick-Fed AMTEC Cell Fabrication and Testing

7.1 Experimental Set-up

The experimental set-up for testing the High Temperature Wick-Fed AMTEC Cell is shown in Figure 48. The AMTEC cell is surrounded by a series of guard heaters, which are used to accurately measure the efficiency of the AMTEC cell. There are a total of six heaters in the test set-up:

HTR-1, Bottom Furnace Heater (115 V),
HTR-2, Top Furnace Heater (115 V),
HTR-3, Top Guard Cylinder Heater (11.4 ohms),
HTR-4, Condenser Heater (3.0 ohms),
HTR-5, Heat Pipe Heater (4.9 ohms),
HTR-6, Bottom Guard Cylinder Heater (6.2 ohms).

The Heat Pipe Heater (HTR-4) supplies the measured power to drive the cell. Two of the guard heaters (HTR-1 and HTR-2) are mounted on a stainless steel cell surrounding the AMTEC cell. These heaters are used to balance the axial heat flow. The guard heaters are used to balance the temperature profiles, so that the parasitic heat losses from the cell are accounted for, and the power supplied to the heat pipe is the input power valued used to determine the cell efficiency. The AMTEC cell with the heaters is shown in Figure 49. A close-up of the evaporator and heater is shown in Figure 50, while the condenser and guard heaters is shown in Figure 51.

An argon getter system is used to ensure a supply of oxygen-free argon to the power feed-through during elevated temperature testing. The argon is used to protect the feed-through from oxidation.

Six thermocouples were used during the testing:

TC-1, Cell Wall Thermal Well
TC-2, Guard Cylinder Thermal Well
TC-3, Heat Pipe Internal Temperature (BASE Temperature),
TC-4, Condenser Temperature
TC-5, Heat Pipe Heater Control
TC-6, Guard Cylinder Bottom Temperature.

Prior to testing, the AMTEC cell and guard heater were installed in the insulation package, see Figure 52. The thermocouples were inserted into the wells (TC-1 and TC-2). These movable TCs are used to map the temperature profiles during cell operation. The heaters were attached to separate controllers, and voltage and current were measured.

During start-up, the cell +ve lead of the AMTEC cell is insulated, and isolated from system ground and the cell body until the system is ready to power a load. Cell output is measured between the +ve feed-through lead and the cell wall by connecting the -ve lead to the stud at the top of the

cell. Open circuit voltages are monitored during start-up. When the cell temperature is above 500°C and the condenser temperature is above 200°C, the IV curves can be measured.

7.2 Experimental Results

Preliminary tests on the High Temperature Wick-Fed Cell were conducted at AMPS, as shown in Table 4 and Figure 53. These data show a normally functioning AMTEC cell. The cell was then shipped to Thermacore for further testing.

Unfortunately, the cell was damaged during shipment. As shown in Figures 54 and 55, the cell power and current were greatly reduced after shipment. Based on the measurements made before shipment, the cell and wick structure initially functioned normally. It appears that either the shipping or the cooldown process affected the ability of the artery/wick system to deliver enough sodium to the anode. The good open circuit voltages show that leakage of the sodium through the electrolyte structure is not a problem.

It appears that the interface between the stainless steel artery structure and the wick structure was compromised. This interface was a mechanical one and probably separated. A very small gap is enough to impede the capillary action and reduce the sodium flow.

Table 4. High Temperature Wick-Fed Cell Test Data, 623°C BASE, 284°C Condenser

Current, Amps	Volts	Power, Watts
0	0.55	0
1	0.478	0.478
2	0.427	0.854
3	0.383	1.149
4	0.345	1.38
5	0.308	1.54
6	0.274	1.644
7	0.24	1.688
8	0.208	1.664
9	0.175	1.575
10	0.143	1.43
11	0.113	1.243
12	0.083	0.996
13	0.053	0.689
14	0.023	0.32

Figure 48. High Temperature Wick-Fed AMTEC Cell Test Set-Up.

Figure 49. High Temperature Wick-Fed AMTEC Cell with Heaters.

Figure 50. High Temperature AMTEC Cell Evaporator with Heaters.

Figure 51. High Temperature AMTEC Cell Condenser with Guard Heaters.

Figure 52. High Temperature AMTEC Cell Test Set-Up.

Figure 53. Current/Voltage Curve for the High Temperature Wick-Fed AMTEC Cell, 623°C BASE, 284°C Condenser.

Figure 54. Current/Voltage Curves for the High Temperature Wick-Fed AMTEC Cell before and after shipping, 200°C Condenser Temperature.

Figure 55. Current/Power Curves for the High Temperature Wick-Fed AMTEC Cell before and after shipping, 200°C Condenser Temperature.

8.0 Preliminary AMTEC System Design

Thermacore developed a preliminary design for an AMTEC system powered by General Purpose Heat Source (GPHS) modules. Thermacore also identified Flat BASE systems as an area where further work is needed.

8.1 Planar Cell Design Improves AMTEC Efficiency

The efficiency of the AMTEC cell is the electrical power out ($P = IV$) divided by the thermal power in. A portion of the thermal power is required for the AMTEC cycle to operate, while the remainder replaces parasitic heat losses due to conduction, and due to radiation from the hot BASE surface to the cold condenser surface [Bankston, 1986]. The parasitic heat losses reduce the overall efficiency, and should be minimized. The parasitic thermal radiation loss from the evaporator to the condenser is:

$$Q_{rad} = A_{Evap} F_{12} \sigma_{SB} (T_{Cond}^4 - T_{Evap}^4)$$

where

Q_{rad} = radiational heat losses [W]

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

σ_{SB} = Stefan-Boltzmann constant [$\text{W}/\text{cm}^2 \text{K}^4$]

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. The overall AMTEC efficiency is strongly dependent on the parasitic heat losses due to radiation, and hence on the view factor. For example, Crowley [1991] made rough estimates of AMTEC efficiency as a function of radiation losses for a typical concentric AMTEC configuration. As the radiational 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.

Changing the BASE and condenser configuration to reduce the view factor is one attractive method of reducing the parasitic radiation losses. A schematic of the conventional AMTEC cell configuration is shown in Figure 56. 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 while Figure 56 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.

The use of multiple parallel plate BASEs in a planar AMTEC system can reduce the radiation losses, hence improve the efficiency. As shown in Figure 57, most of the BASEs would see the opposing hot BASE, rather than the colder condenser. The condenser could either be local as shown in Figure 57, or remote to further reduce radiation losses, and aid in heat rejection.

Figure 56. Conventional AMTEC cell, with the cylindrical BASE located inside a concentric condenser.

Figure 57. Multiple parallel plate BASEs, with a nearby or remote condenser. Radiation losses are reduced, because the parallel flat plates mostly view each other.

Currently, β'' -alumina is only manufactured in cylinders. While several researchers have proposed flat plate system designs, we are unaware of the fabrication of any flat plate system, due to the unavailability of planar BASE. Sievers and Cooper [1990] proposed plasma spraying β'' -alumina on a porous substrate. It was anticipated that the electrolyte coating on the porous substrate would be thinner than conventional BASE cylinder. The reduced ohmic resistance of the cell would increase the system specific power in high current density applications. The increased efficiency was expected to be 25 to 35% for packed electrolyte models. A JPL New Technology Report [1992] proposed a compact planar configuration featuring a β'' -alumina solid electrolyte tape cast onto both sides of a flat porous metal wick.

8.2 AMTEC System Design

A preliminary design was developed for an AMTEC system powered by General Purpose Heat Source (GPHS) modules. The DOE designed GPHS modules use the decay of plutonium-238 (Pu^{238}) to heat a graphite brick to approximately 1200°C [Shock, 1980]. The baseline for the design was the AMTEC system design by Sievers and Bankston (1988), modified to use the High-Temperature Wick-Fed AMTEC cell developed during the program. A schematic of the AMTEC cell is shown in Figure 58, and the Power System Concept is shown in Figure 59. Appendix D contains the calculations for the cell design.

Table 5. General Purpose Heat Source Parameters

Radioisotope	Pu-238
Half-Life	86 years
Operating Temperature	1200°C
Module Dimensions	9.97 cm x 9.4 cm x 5.38 cm
Number of Modules	18 (250 W/ module)
Thermal Power	4500 Watts

The system is powered by 18 General Purpose Heat Sources (GPHS). Properties for the GPHS are given in Table 5. Properties for the system are given in Table 6. As shown in Figure 59, the GPHS bricks are stacked, with a single column of AMTEC cells along each side of the GPHS stack. Thermal energy from the GPHS stack is radiated to the heat pipe evaporator of the AMTEC cell. Waste heat is radiated from the AMTEC condensers.

The AMTEC cells are based on the High-Temperature Vapor-Fed cells developed on the program. As shown in Figure 58, the BASE length has been lengthened from 10 cm to 13 cm to increase the overall system efficiency. The BASE was sized to use the radiation incident on the heat pipe evaporator. The condenser has also been lengthened to remove the waste heat by radiation. The remainder of the section discusses the calculated system behavior and efficiency.

Table 6. GPHS-Powered AMTEC System Characteristics

Total Thermal Power	4500 Watts
GPHS Surface Temperature	1200°C
BASE Temperature	800°C
Condenser Temperature	350°C
Module Voltage	0.530 Volt
BASE Current Density	0.429 amp/cm ²
Number of Modules	68
BASE Diameter	1.5 cm
BASE Length	13.5 cm
Net Electrical Power	940 Watt
Efficiency	21.5%
System Mass	55.7 kg
System Specific Power	16.9 Watt/kg

8.2.1 AMTEC Cell Model

The voltage-current density relation for the BASE is given by [Bankston, 1988]:

$$V_{BASE} = \left(\frac{R \cdot T_{BASE}}{F} \right) \cdot \ln \left[\frac{P_v(T_{BASE})}{P_v(T_{Cond}) \cdot \left(\frac{T_{BASE}}{T_{Cond}} \right)^{0.5} + \left(2 \cdot \pi \cdot M_{Na} \cdot T_{BASE} \right)^{0.5} \cdot \frac{J}{F} + P_d} \right] - J \cdot R_{total}$$

where:

F	Faraday constant [96,500 Coulomb/g-mole]
J	Current density [amp/cm ²]
M _{Na}	Sodium molecular weight
P _d	Pressure drop for flow through the electrode
P _v	Sodium vapor pressure at the given temperature
R	Universal gas constant
R _{total}	Resistances in the cell
T _{BASE}	Temperature of the BASE
T _{Cond}	Temperature of the condenser
V _{BASE}	Voltage across the cell

The pressure drop for flow through the electrode is:

$$P_d = \left(\frac{0.75 \cdot G \cdot J}{F} \right) \cdot \left[\frac{M_{Na} \cdot R \cdot T_{BASE}}{2 \cdot \pi} \right]^{0.5}$$

where

G Dimensionless geometry factor

The resistance to current flow is given by:

$$R_{total} = R_{BASE} + R_{Contact} + R_{Electrode} + R_{Cable}$$

Where:

R_{BASE}	BASE resistance [Ohm]
$R_{Contact}$	Contact resistance [Ohm]
$R_{Electrode}$	Electrode resistance [Ohm]
R_{Cable}	Cable resistance [Ohm]

The resistance across the BASE, R_{BASE} , is given by the following curve fit [Bankston, 1988]:

$$R_{BASE} = t_{BASE} \cdot T_{BASE} \cdot \left[4.03 \cdot 10^{-4} \cdot \exp\left(\frac{1420}{T_{BASE}}\right) + 3.24 \cdot 10^{-7} \cdot \exp\left(\frac{4725}{T_{BASE}}\right) \right]$$

where the thickness, t_{BASE} , is in cm and T_{BASE} is in Kelvin

The above equations can be used to calculate the AMTEC cell voltage, current, and power as a function of T_{BASE} and T_{Cond} . Calculations for the High-Temperature Wick-Fed cell are shown in Appendix D. Voltage as a function of current density is shown in Figure 60 for BASE temperatures of 600, 700, and 800°C. Power and voltage versus current are shown in Figure 61 for the same three BASE temperatures.

8.2.2 AMTEC Cell Efficiency

Energy must be supplied to the AMTEC cell to replace the energy used by the following mechanisms:

- Electrical energy generated in the cell
- Heating and vaporization of sodium
- Parasitic heat losses

The efficiency of the AMTEC cell is given by the ratio of the electric energy to the total heat required:

$$\eta = \frac{I_{BASE} \cdot V_{BASE}}{I_{BASE} \cdot V_{BASE} + Q_{Sodium} + Q_{Parasitic}}$$

where:

η AMTEC cell efficiency []

I_{BASE}	Cell current [amp]
Q_{sodium}	Heat required to heat and vaporize the sodium [Watt]
$Q_{Parasitic}$	Parasitic heat losses [Watt]

The heat required for the sodium has both sensible and latent heat components:

$$Q_{Sodium} = \left(\frac{I_{BASE} \cdot M_{Na}}{F} \right) \cdot [\lambda_{Na} + c_p \cdot (T_{BASE} - T_{Cond})]$$

where:

c_p	Sodium specific heat [Joule/kg K]
λ_{Na}	Sodium latent heat [Joule/kg]

The parasitic heat losses include radiation losses from the BASE and cylinder to the Condenser, and conduction through the cylinder wall and artery. Radiation between the evaporator and condenser is a major loss, and reduces the efficiency. A heat shield was inserted between the evaporator and condenser to reduce the radiation losses:

$$Q_{rad} = \frac{\sigma_{SB} \cdot A_{BASE} \cdot (T_{BASE}^4 - T_{Cond}^4)}{\left(\frac{1}{\epsilon_{BASE}} + \frac{2}{\epsilon_{Shield}} + \frac{1}{\epsilon_{Cond}} - 2 \right)}$$

where:

ϵ_{BASE}	Emissivity of the BASE and hot zone
ϵ_{Shield}	Emissivity of the shield
ϵ_{Cond}	Emissivity of the condenser

Cell efficiency for BASE temperatures of 600, 700, and 800°C is shown in Figure 62. The maximum efficiency increases from roughly 14.4% to 21.5% as the BASE temperature is increased from 600 to 800°C. Figure 63 shows the power and efficiency for a cell operating at 800°C. The maximum power of 17.7 Watt occurs at 49.1 amps (current density of 0.808 amp/cm²).

As shown in Figure 63, the current at maximum efficiency is lower than the current at maximum power. The power at maximum efficiency is 13.8 watt. The maximum efficiency of 21.5% occurs at 26.1 amps (current density of 0.429 amp/cm²).

Figure 58. High Temperature Wick-Fed AMTEC Cell Schematic for a GPHS power system.

Figure 59. GPHS Power System Concept.

Figure 60. Voltage versus current density for the High-Temperature Wick-Fed Cell at three different BASE temperatures.

Figure 61. Voltage and power versus current for the High-Temperature Wick-Fed Cell at three different BASE temperatures.

Figure 62. Efficiency versus current for the High-Temperature Wick-Fed Cell at three different BASE temperatures.

Figure 63. Maximum efficiency occurs at a lower current than the maximum power, 800°C.

9.0 Nomenclature

A_{Cable}	Cable artery cross-sectional area [m^2]
A_{evap}	Area of the BASE [m^2]
c_p	Sodium specific heat [Joule/kg K]
g	Gravitational acceleration [m/s^2]
F	Faraday constant [96,500 Coulomb/g-mole]
F_{12}	View Factor []
G	Dimensionless geometry factor []
h_{BASE}	Elevation of the evaporator above the free-standing wick [m]
$h_{\text{Condenser}}$	Elevation of the condenser above the free-standing wick [m]
I_{BASE}	Cell current [amp]
J	Current density [amp/m^2]
K_{Cable}	Cable Artery permeability [m^2]
L_{Cable}	Cable artery length [m]
m_{Cable}	Mass flow through the cable artery [kg/s]
M_{Na}	Sodium molecular weight [g/mole]
P_d	Pressure drop for flow through the electrode [Pa]
P_v	Sodium vapor pressure at the given temperature [Pa]
$\Delta P_{\text{Capillary}}$	Capillary pumping capability of the evaporator wick [Pa]
$\Delta P_{\text{Recirc vapor}}$	Pressure drop in the vapor between the evaporator and free-standing wick [Pa]
$\Delta P_{\text{Recirc liquid}}$	Pressure drop in the liquid return through the free-standing wick and the evaporator [Pa]
$\Delta P_{\text{Recirc gravity}}$	Pressure drop due to gravity [Pa]
Q_{rad}	Radiational heat losses [Watt]
Q_{sodium}	Heat required to heat and vaporize the sodium [Watt]
$Q_{\text{Parasitic}}$	Parasitic heat losses [Watt]
r_c	Radius of the pores in the wick [m]
R	Universal gas constant [Joule/g-mole K]
R_{BASE}	BASE resistance [Ohm]
R_{Contact}	Contact resistance [Ohm]
$R_{\text{Electrode}}$	Electrode resistance [Ohm]
R_{Cable}	Cable resistance [Ohm]
R_{total}	Resistances in the cell [Ohm]
t_{BASE}	BASE wall thickness [cm or m]
T	Temperature [K]
$T_{\text{evap}}, T_{\text{cond}}$	Evaporator and condenser temperature [K]
T_{BASE}	Temperature of the BASE [K]
T_{Cond}	Temperature of the condenser [K]
V_{BASE}	Voltage across the cell [Volt]
ϵ_{BASE}	Emissivity of the BASE and hot zone
ϵ_{Shield}	Emissivity of the shield
ϵ_{Cond}	Emissivity of the condenser

η	AMTEC cell efficiency []
c_p	Sodium specific heat [Joule/kg K]
ρ_L	Sodium liquid density [kg/m ³]
μ_L	Sodium liquid viscosity [kg/m s]
σ	Surface tension [N/m]
σ_{SB}	Stefan-Boltzmann constant [W/cm ² K ⁴]
θ	Angular orientation of the condenser relative to the evaporator [radians]

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