

THE ALKALI METAL THERMAL-TO-ELECTRIC CONVERTER FOR SOLAR SYSTEM EXPLORATION

M. A. Ryan
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena CA 91109
mryan@jpl.nasa.gov

Abstract

AMTEC, the Alkali Metal Thermal to Electric Converter, is a direct thermal to electric energy conversion device; it has been demonstrated to perform at high power densities, with open circuit voltages in single electrochemical cells up to 1.6 V and current densities up to 2.0 A/cm². It is a sodium concentration cell which uses a β "-alumina solid electrolyte (BASE) tube as a separator between a high pressure region containing liquid sodium at 900 - 1300 K and a low pressure region containing a condenser at 400 - 700 K. As a power system, AMTEC is expected to deliver ~ 20 W/kg with a 15-20 % thermal to electric conversion efficiency. AMTEC has been baselined as the power conversion system for the Ice and Fire missions in NASA's X2000 Program and is being developed as part of the NASA/DoE Advanced Radioisotope Power Systems Program. This paper will discuss the basic operating principles of AMTEC as well as the evolution of design and materials selection for power converters for spacecraft in the X2000 program. Life and degradation studies of AMTEC cells and converters are underway at JPL and will be considered in this paper.

Introduction

AMTEC, the Alkali Metal Thermal to Electric Converter, is a direct energy conversion device capable of near-Carnot efficiencies; it has been demonstrated to perform at high power densities, with open circuit voltages in single electrochemical cells up to 1.6 V and current densities up to 2.0 A/cm² [1-3]. Cell conversion efficiencies as high as 19% have been demonstrated in the laboratory [4]. The fundamental principles of AMTEC were developed and investigated by Drs. J. Kummer and N. Weber at the Ford Motor Company in the 1960's; the device was patented as the Sodium Heat Engine [5]. Further work on AMTEC was carried out at Ford in following years [4, 6], and the more general name of AMTEC came into use, particularly as the possibility of using other alkali metals as working fluids became evident.

As a power system, AMTEC is expected to operate with a specific power of ~ 15 W/kg at ~18% efficiency. Current work on AMTEC is primarily funded by the Advanced Radioisotope Power Systems program and includes system design and test, device improvement studies and life studies of cells, cell components and systems. The work at JPL which will be described in this paper is part of a program of life studies to develop AMTEC technology for use as the power converter in NASA's Deep Space Systems Technology Program Ice and Fire Missions.

The Deep Space Systems Technology Program (also called X2000) is a technology development and spacecraft delivery program which has as its rationale the use of multi-mission technology development. Several small missions are designed to use a basic spacecraft so that technology is developed which can be applied to more than one mission. Within the X2000 program, the Ice and Fire missions are designed to use a single spacecraft design with an Advanced Radioisotope Power System (ARPS). AMTEC is a power converter under development for the Ice and Fire Missions. Ice and Fire consists of three missions: a Europa Orbiter to study the moon of Jupiter with a planned launch in 2003, Pluto-Kuiper Express to fly by Pluto and study the Pluto-Charon system and the Kuiper belt with a planned launch in 2004, and Solar Probe to study the corona of the sun with a planned launch in 2007. The spacecraft for these missions have a mass of 100 - 200 kg and require 150-200 W of electric power; thus the power system is constrained to 10 - 15 kg on the spacecraft. Because the time to reach Pluto is 8-14 years, depending on the launch vehicle used, the power converter used in ARPS must have an operating lifetime of at least 15 years.

Principles of Operation

In AMTEC devices now being studied for inclusion on spacecraft for solar system exploration, the working fluid is sodium metal, although it is possible to use potassium as the working fluid (*vide infra*). The device is a sodium concentration cell which uses a ceramic, polycrystalline β "-alumina solid electrolyte (BASE), as a separator between a high pressure region containing sodium vapor at 900 - 1300 K and a low pressure region containing a condenser for liquid sodium at 400 - 700 K. The β "-alumina solid electrolyte is the critical material in operating AMTEC devices. It is an ionic conductor for the alkali metal with which it is made; for sodium BASE, the nominal composition is Na₅LiAl₃₂O₅₁. The electrolyte is fabricated as a polycrystalline sintered ceramic stabilized with Li.

In an AMTEC cell, BASE is used as the separator between high and low pressure sides, and the ceramic is coated on both sides with thin film, porous metal electrodes. Vapor phase sodium atoms are oxidized at the high pressure sodium/electrode/BASE interface and sodium ions are conducted through the BASE to the low pressure side. Electrons are collected in the porous electrode on the high pressure side and travel through an external load to recombine with sodium ions at the BASE/electrode interface on the low pressure side of the BASE. After recombination of electrons and sodium ions, sodium vapor travels through the porous

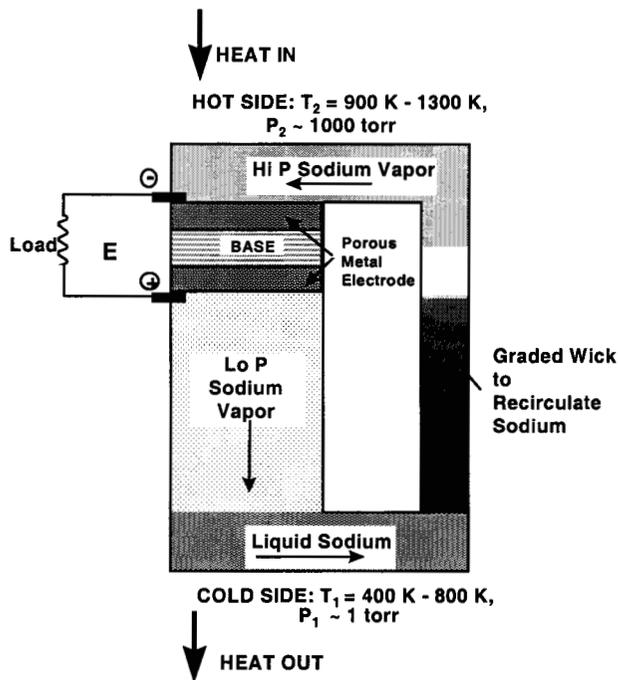


Figure 1: Schematic of a recirculating AMTEC cell.

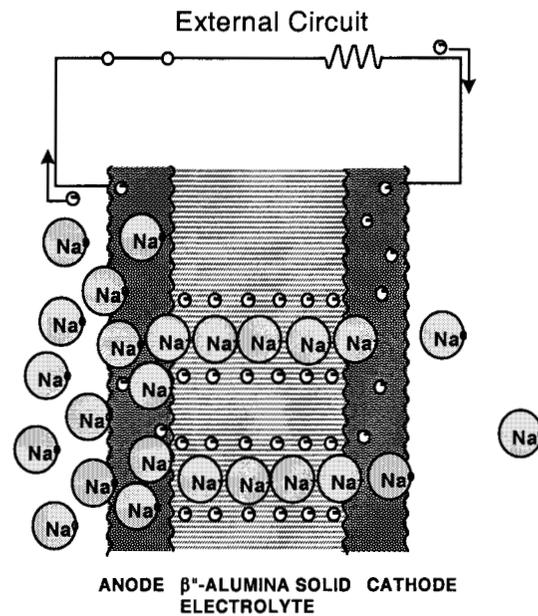


Figure 2: Detail of the processes at the electrode/electrolyte interfaces in an AMTEC cell.

electrode, leaves the electrode as vapor and is collected on a cold condenser, from which it can be recirculated as a liquid to the hot, high pressure side of the BASE [1, 2]. In current designs of AMTEC devices, recirculation is accomplished using capillary pumps, or wick systems. Figure 1 shows a diagram of the overall system in a recirculating AMTEC cell, and Figure 2 shows a detail of the processes at the interfaces between the electrolyte (BASE) and the electrodes.

In the AMTEC cycle, liquid sodium at T_1 is pumped into the hot zone by the capillary wick where it absorbs thermal energy and reaches T_2 . Sodium evaporates from the pump and comes into contact with the anode on the high pressure side of the BASE and the sodium ionizes. The pressure difference between the anode and cathode sides of the BASE drives Na^+ across the separator and the electrons travel through the load. At open circuit, Na^+ is driven toward the low pressure side by thermal kinetic energy, and a potential difference is created by charge build-up on the cathode side. The open circuit potential E_{OC} may be calculated from the Nernst equation as

$$E_{OC} = RT_2/F \ln(P_2/P_3) \quad (1)$$

where R is the gas constant, P_2 is the vapor pressure of sodium at T_2 (hot side temperature), and P_3 is the vapor pressure of sodium at the cathode/BASE interface. P_3 is related to the sodium vapor pressure at T_1 , the condenser temperature, as

$$P_{3(i=0)} = P_1 (T_2/T_1)^{1/2} \quad (2)$$

In principal, an AMTEC device can operate with near-Carnot efficiency; the reversible thermodynamic cycle is inherently efficient and relatively insensitive to losses related to pressurizing and heating the liquid sodium and cooling and condensing the low pressure vapor. The high efficiency is the result of the large entropy change associated with the change in state from liquid to vapor phase sodium and the incompressible nature of the liquid phase [7].

Earlier versions of AMTEC cells used liquid sodium on the anode side of the BASE, and the liquid sodium acted both as the source of sodium for the reaction and as the anode, as the liquid sodium metal was in intimate contact with the BASE [1, 3]. Recirculation of the sodium was accomplished in that case using an electromagnetic pump. This cell was generally referred to as a "liquid anode cell." In the early 1990's, the concept of using vapor-phase sodium on both sides of the electrolyte was explored, and the utility of this approach demonstrated [8, 9]. This cell has been referred to as a "vapor-vapor cell"; such an AMTEC cell is desirable because AMTEC is a low-voltage high-current device. The voltage can be raised by connecting cells in series, but in liquid anode cells, series connection will require that each cell have an individual reservoir, making series connection somewhat complex. In a vapor-vapor cell, several electrochemical cells can share a sodium reservoir and still be connected in series, reducing the complexity of fabrication [10].

The earliest version of a vapor-vapor cell is shown in Figure 3 [8, 11]. This cell consisted of three sections of BASE brazed together to make a tube. Porous metal electrodes were deposited on each side of the BASE, and series connection was made through the metallic braze joints. Sodium vapor was provided to the tube from a boiler. The open circuit voltage for this cell was 2.5 V; somewhat lower than 3 times the open circuit voltage of a single, liquid anode cell. The decreased open circuit voltage was attributed to the number of brazed joints; there is always some vapor and electrical loss through the joint (*vide infra*).

Current ARPS designs include 5 - 8 electrochemical cells connected in series in a single container with a single recirculation system; a cutaway view of a six tube design from Advance Modular Power Systems, Inc. (AMPS) is shown in Figure 4 [12].

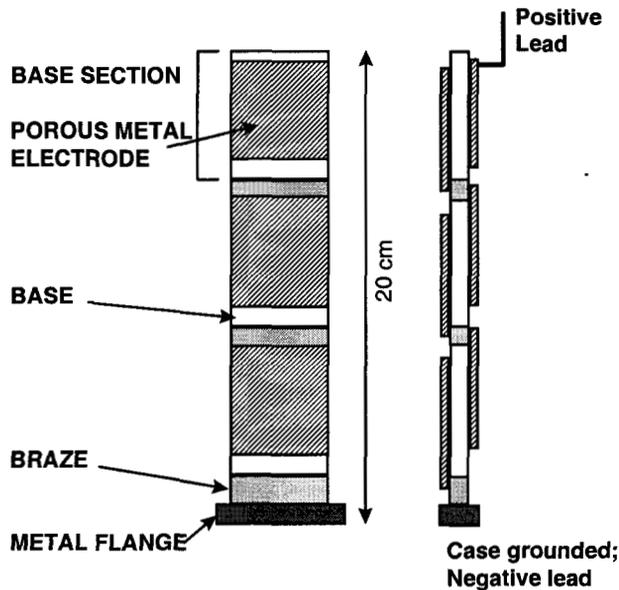


Figure 3: JPL AMTEC vapor-vapor cell; three joined, series connected electrochemical cells share a common vapor source.

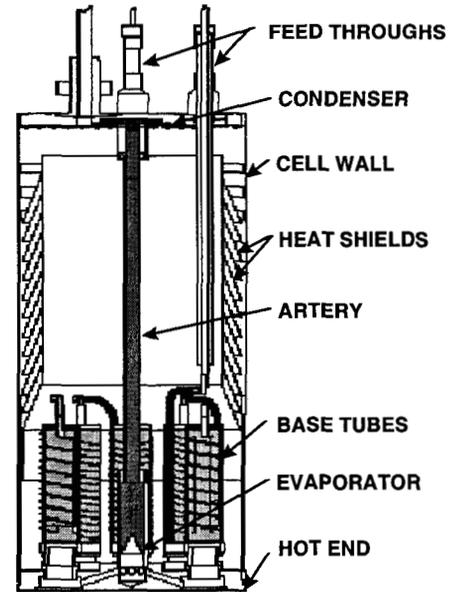


Figure 4: AMPS AMTEC vapor-vapor cell; six series connected BASE tubes (each an electrochemical cell) share a common vapor source [12].

AMTEC Cell Operation

BASE is generally available commercially in tubular form; systems efforts have incorporated BASE into the design as tubes to avoid the necessity of special orders of the ceramic. An AMTEC electrochemical cell in the configurations used at AMPS today consists of a single tube with an anode deposited on the inside and a cathode deposited on the outside of the tube. What is generally referred to as an "AMTEC cell" is a group of 5-8 electrochemical cells connected in series within a single housing. The remainder of the cell consists of the capillary pump and condenser system, electrical leads, and thermal design features such as heat shields to diminish thermal losses to the cold end of the cell.

Sources of Loss in Operating AMTEC Cells

Electrochemical Losses

There are several sources of loss in a real AMTEC device. There are electrochemical, thermal and electrical losses, as well as losses owing to degradation of components such as the electrodes and the electrolyte over time. The primary focus of research efforts through the 1980's and 1990's has been on understanding the sources of loss and improvement of the efficiency of those processes; system design efforts during this time have focused on designing systems which are low mass and capable of delivering 150 W of power at 28 V for incorporation into spacecraft without major power conditioning devices.

The open circuit voltage of a single electrochemical cell can reach as high as 1.6 V at a BASE temperature of 1120 K. A typical open circuit voltage in a cell with a single BASE tube is 1.2 - 1.4 V. Open circuit voltage is impacted by the hermeticity of the seal between the high pressure and low pressure sides and by pressure losses from the high to low pressure side caused by "leakage current" or sodium ion conduction accompanied by electronic conduction through the BASE.

A model describing the electrochemical processes in an AMTEC cell has been developed [8, 13-14] and discussed in detail for application to current model cells in several publications [15-17]. The primary electrochemical factor which must be taken into account in modeling the electrochemical behavior of an AMTEC cell is the overpotential, η , which is the deviation of the cell potential from its equilibrium value. It is related to the current density and dependent on the kinetics of the reversible reaction. The current-overpotential equation for an AMTEC electrochemical cell assumes no concentration polarization in the BASE and can be expressed as:

$$j_b = j_b^0 \left[e^{-\alpha f \eta_b} - \left(1 + \frac{K_b j_b}{P_b} \right) e^{(1-\alpha) f \eta_b} \right] \quad (3)$$

where

j_b = electrode current (b = a for anode, c for cathode), A/m²

j_b^0 = exchange current density, A/m²

α = electrochemical transfer coefficient (0.5)

f = F/RT_2 , V⁻¹

F = the Faraday, 96,485 C/mol

R = gas constant, 8.314 J/(K mol)

T_2 = electrode temperature, K

K_b = mass transfer loss coefficient, Pa m²/A

P_b = vapor pressure of Na at T_2 (no current flow), Pa

The derivation of this equation and its application to operating cells are discussed in detail in publications from JPL [8, 13-14].

In an AMTEC cell, the overpotential at the anode is insignificant compared with that at the cathode. The overpotential at the cathode is influenced by the exchange current at the electrode/electrolyte interface (a measure of the efficiency with which sodium ions are reduced by electrons

entering from the cathode) and by the mass transfer loss coefficient, which can be translated into a morphological parameter, G , a measure of the resistance to sodium atom flow from the electrode/electrolyte interface to the outside surface of the cathode, where it can enter the vapor space. Experimentally, these two parameters, the exchange current and the morphological parameter, are derived from current-voltage curves and interfacial impedance measurements, and are used to evaluate the performance of electrodes.

Ohmic losses in the cell are also important; these losses consist primarily of sheet resistance in the cathode, contact resistance between current collecting screens and the cathode, contact resistance between the screen and the lead, and lead resistance.

Another source of loss in the current-voltage characteristics of an AMTEC cell is in leakage between the high and low pressure sides of the BASE. Any leak in sodium pressure between the high pressure side and the low pressure side will result in a depressed open-circuit voltage, which will depress the entire iV curve. Sodium leaks may be caused by non-hermeticity in the seals where the BASE is joined to the cell assembly, and by any source of "leakage current". "Leakage current" may be attributed to electronic conductivity in the BASE, where electrons as well as sodium ions are conducted through the BASE, and to electronic conduction in the braze seal, where electrons and Na ions are conducted side-by-side through the braze and BASE, respectively. Both processes will reduce the pressure difference between the anode (high pressure) and cathode (low pressure) sides of the BASE. The sum of the two "leakage currents" is ~ 40 mA, which will result in a decrease in open circuit voltage of ~ 0.1 . Non-hermeticity is a much more significant source of loss in AMTEC cells than losses owing to "leakage current."

Figure 5 shows how the current-voltage curve of an AMTEC cell changes when the overpotential of both the anode and cathode, ohmic losses in the cell, and open circuit voltage loss are taken into consideration.

Most of the electrochemical losses discussed above can be minimized, although not eliminated, by choice of electrode and current collection network material and improvement in joining technology. Selection of electrode and current collection network material will be discussed in the *Component* section, below.

Thermal Losses

Thermal losses in an AMTEC cell consist primarily of radiative losses, and some conductive loss. Conductive loss is thermal loss in the containment of the cell, which results in a condenser temperature higher than is optimum. In state-of-the-art AMTEC cells, conductive losses have been minimized by using thin cell walls.

Radiative loss is found in several places in the cell. Use of multiple tubes in a single containment not only decreases the complexity of an AMTEC system, it also reduces the radiative thermal losses from BASE to cell walls; the tubes in a multi-tube cell radiate to each other. An ideal cell design would be one in which there is no radiative heat loss to the interior cell walls, or in which the interior cell walls re-radiate heat back to the BASE tubes. This situation is difficult to achieve, as low-

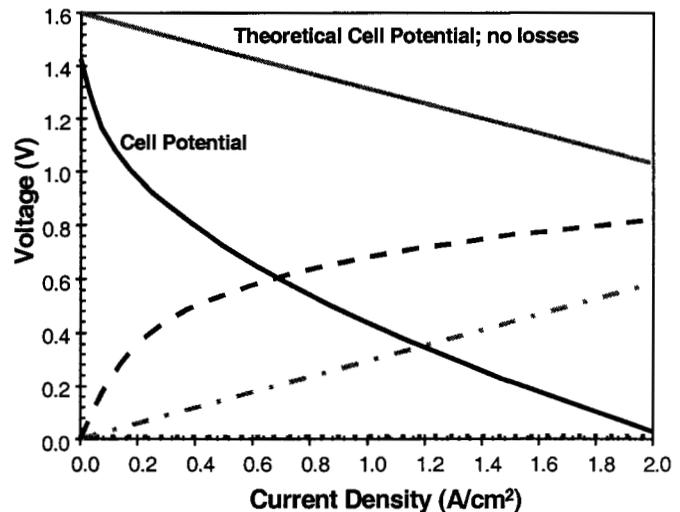


Figure 5: Theoretical Cell Potential and actual cell potential, showing losses. Dashed line - cathode overpotential, dotted line - anode overpotential, dot-dash - ohmic losses

emissivity cell wall coatings tend to corrode in the sodium vapor atmosphere or diffuse in the high temperature, sodium vapor atmosphere, raising the emissivity by roughening the surface in a few hundred hours. This thermal loss is not entirely avoidable, but exterior insulation is helpful.

Radiative heat loss from the BASE tubes to the condenser has been minimized in the cell using reflective heat shields in the region between the tubes and the condenser (see Figure 4) and a reflective condenser [18]. The condenser itself is designed to coat with liquid sodium, which has been calculated to have a very low emissivity (~ 0.5). The sodium coating on the condenser reflects heat back to the BASE tube.

Lifetime of an AMTEC Cell

The lifetime of an AMTEC power converter is determined by the degradation characteristics of the fuel, the system and the components in the cells. The degradation characteristics of the fuel are well known, and cannot be affected by system design. The degradation characteristics of the system are affected primarily by the fastest-degrading components and by any interactions between and among components. Life modeling work at JPL has focused primarily on the components of the electrochemical cell, with attention to interaction with the components of the AMTEC cell. Work at JPL has not focused on the overall generator.

Degradation of Components

Degradation of Electrode Performance

As can be seen in Figure 5, the overpotential in the anode is insignificant compared with the overpotential in the cathode and ohmic losses in the electrochemical cell. Thus, electrode development and degradation studies have focused on the cathode. While improvement in anode performance will be helpful to overall performance, improvement in cathode performance will have a more dramatic effect on cell performance.

As discussed above, there are two primary performance parameter that are derived from experimental iV and impedance

measurements, the exchange current and the morphology factor. The exchange current is a measure of the efficiency with which sodium ions and electrons combine at the electrode-electrolyte interface. It is a balanced, reversible current where the reaction



takes place at the interface. There is an exchange current at both the anode and the cathode, but it is the cathode performance which determines the cell performance.

The exchange current is a function of the resistance to charge transfer across the interface, and its magnitude is related to the size of the reaction area. In a simple model of electrode performance, the electrode is considered to be electronically conducting only, and can be thought of as grains sitting on the electrolyte surface. Reaction can take place only at the perimeter of grains where they contact the electrolyte; thus, the smaller the grains, the larger the size of the total reaction zone.

The morphology factor is a measure of the electrode resistance to sodium atom removal from the interface and electrode after sodium ions are reduced. In an electrode in which sodium atom transport is accomplished only by mass flow, the morphology factor is related to the size and number of pores in the electrode which allow sodium transport [14]. Most electrode materials, however, have alternative methods for sodium transport. The most common is an activated transport method such as grain boundary diffusion, but some electrodes may have some degree of conductivity toward sodium ions, and thus remove Na^+ from the interface before it is reduced by electrons in the cathode [19, 20]. Sodium molybdate, Na_2MoO_4 , is such a compound, and it can be formed in Mo electrodes, but its melting point is too low for AMTEC operating temperatures (960 K); it evaporates in a few hundred hours of AMTEC operation [21]. NaTi_2O_4 is another such compound which can be included in TiN electrodes. It is under study for use in mixed conducting AMTEC electrodes [22].

Both the exchange current and the morphology factor change over time as the electrode is exposed to sodium vapor at 1120 K. Exchange current decreases as grains grow together by diffusion of atoms, and the total grain perimeter decreases, decreasing the size of the reaction zone. The process of grain growth should open voids in the electrode as grains coalesce, improving transport of sodium by mass flow. The morphology factor does not always improve with time, especially in electrodes where sodium transport proceeds by a process other than mass flow.

The best performing electrodes tested so far are alloys of the noble metals rhodium and platinum with tungsten. The grains start out small, and grain growth rates are slow. Models of grain growth in RhW electrodes have predicted that overall power density will decrease < 5% in the 15 year lifetime of a Pluto mission [23]. A model of TiN grain growth [24] has been used to predict that power density in TiN electrodes will decrease 30% in 15 years [25].

The grain growth rate of electrodes can be significantly altered by exposure to materials from other components in the cell. Rh_xW , Pt_xW , ($x=1-3$) and TiN electrodes will all react with elements which may be present in small quantities or as impurities in other components. The grain growth rate of

tungsten alloy electrodes is significantly increased upon exposure to trace quantities of Mn, making them inadequate for use as electrodes in long term (15 year) AMTEC cells [26]. Mn is present in many grades of stainless steel and other iron-alloy materials. Mn also reacts with TiN in AMTEC operating conditions, but the extent to which the reaction influences the performance of TiN as an AMTEC cathode is not yet clear.

The cathode is contacted by wrapping it in a Mo screen, and tying the screen with Mo wire to make intimate contact with the electrode. The lead from the electrode to make connection with the next tube in the cell, or with the outside of the cell, is a bundle of Mo wires tied onto the screen with the same tie wires. Over time at 1120 K, Mo will diffuse from the screen over the cathode surface, changing the characteristics of the electrode. The initial stages of diffusion will increase the performance of the electrode as the contact resistance between the screen and the electrode is lowered, but eventually, Mo will cover the entire electrode surface and it will form Mo crystals. The diffusion rate of Mo on itself in low pressure sodium has been measured [23]. Calculation of the extent of Mo coverage on the surface of the cathode at 1120 K shows that in 15 years, Mo will not advance more than 100 μm from the contact point, posing no threat to electrode performance. However, operation at 1170 K will result in covering the half the surface with Mo in ~ 12 years, and substantially increasing the grain growth rate. The process of Mo diffusion across the electrode sets the upper operating temperature of AMTEC electrochemical cells at 1120 K unless alternative contacting methods are used. There has been some work in embedding current collecting grids in AMTEC electrodes to improve the sheet resistance of the electrode [27]; with embedded grids of the same material as the electrode, it may be possible to eliminate the need for contacting screens.

Degradation of Ionic Conductivity of BASE

Sodium β'' -alumina ceramic is the solid electrolyte used in AMTEC cells. This component is bought from a supplier (Ionotec, Inc.) and used as-received. The nominal conductivity for sodium β'' -alumina ceramic at 1120 K in low pressure sodium vapor has been measured at JPL to be 0.54 S/cm [28]. Most samples of as received BASE have an ionic conductivity within a few percent of this value.

While BASE has been well characterized at temperatures < 700 K, the kinetics of slow degradation reactions at AMTEC operating temperatures have not been well studied. Modeling has predicted slow and highly activated loss of Na_2O into Na and O_2 vapor, but substantial degradation of BASE conductivity has not been observed in AMTEC cells run up to several thousands of hours [28, 29]. In both Na- and K-BASE, AMTEC cells have shown a small (<5%) initial decrease in conductivity followed by several thousands of hours of unchanging conductivity. Conversion of β'' -phase to β - or α -phase alumina have also been predicted, but has been observed only at temperatures above 1273 K in dynamic vacuum [29].

BASE conductivity can be influenced by other materials found in an AMTEC cell. Experiments with trace amounts of Mn, Cr and Fe in vacuum at 1273 K and 1373 K showed that the reactive metals Mn and Cr will evaporate onto BASE and cause decomposition of the β'' -phase by forming MnAl_2O_4 and

Cr₂O /Al₂O₃ [29]. These reactions at temperatures as low as 1273 led to discontinuation of the use of stainless steel anywhere in an AMTEC cell. The cell containment in current AMPS cells is Nb-1%Zr, and all other metal parts are Mo. Experiments in Nb-1%Zr containers have shown no decrease in ionic conductivity of BASE after 3000 hours in low pressure Na at 1170 K.

BASE conductivity can be also be degraded by exposure to impurities in the sodium operating fluid. Any K or Ca in the sodium can replace Na in the electrolyte lattice structure, decreasing the BASE ionic conductivity to sodium. Sodium can be cleaned by electrolyzing it through β"-alumina; impurities will be left in the electrolyzing BASE.

Degradation of capillary pumping system

A component of an AMTEC cell which has not yet been well tested or characterized is the capillary pumping system. It has been shown that such a system can work at close-to-AMTEC temperatures (900 K) for periods as long as 16,000 hours using stainless steel wicks and arteries [30]. There is no reason to expect that a system made from Mo will perform differently. Possible degradation modes include corrosion of the wicks by hot liquid sodium, resulting in increased pore size and decreased pumping capability, and deposition of corroded materials in the wick, resulting in plugging in the pores. Wick pores may also be plugged with Na₂O formed in the cell from oxygen and sodium.

AMTEC Cell Performance History

Since its initial development at Ford Motor Company, AMTEC cells have been made primarily at JPL and AMPS, although there are (or have been) other researchers in the field, including the Electrotechnical Laboratory in Japan, Kyushu University, Thermacore, Inc. and Asea Brown Boveri, among others. Some AMPS cells have been run at the Air Force Research Laboratory (AFRL) in Albuquerque NM.

The maximum efficiency achieved in an AMTEC cell has been 18-19% (P_{el}/P_{th}) [4]. AMPS cells similar to that shown in Figure 4 and run at AFRL have routinely been started with efficiencies of ~ 16% [30]. However, because of limitations on temperature mandated by the use of a TiNi braze, which melts at ~ 1200 K, those cells have not been run at a BASE temperature of 1120 K, but at T<1000 K.

Under the ARPS program, full cells are being made by AMPS and run by JPL, AMPS and AFRL. The longest running cells run under the ARPS program have been those at AFRL which have been operating >16,000 hours. Performance in those cells has been somewhat less than expected and has degraded more rapidly than initially expected. However, understanding of the influence of Mn and Cr found in stainless steel on BASE has been developed since those cells were put on test, and may be a major factor in the cell performance degradation.

Cells have performed at ~ 70% of expected power (Maximum power at 1044 K was 4.95 W, as opposed to an expected power at 1050 K of 7 W) [31]. This lower performance can be addressed by replacing the stainless steel elements with refractory metal elements, changing the TiN cathode for a RhW electrode and improving the ceramic to

metal seal. The capillary pumping system is under test to determine its efficiency. The expected power at 1120 K for a six-tube AMTEC cell is 10-11 W; the cells will run at ~ 3 V (0.5 V/tube) and 3 - 4 A. Using RhW electrodes and all refractory materials, the expected efficiency of an AMTEC cell is 18-20%. Degradation should be caused primarily by electrode grain growth if the sodium is clean and the wick structure does not corrode significantly.

AMTEC Generators

AMTEC generators for use on Ice and Fire spacecraft have been designed by AMPS, the University of New Mexico and by Orbital Sciences Corporation (OSC). An OSC design for an 8 cell generator using two General Purpose Heat source (GPHS) bricks is shown in Figure 6 [32]. A generator would produce 88 W_{el} at the beginning of life; with two generators, the power system would produce 176 W_{el}.

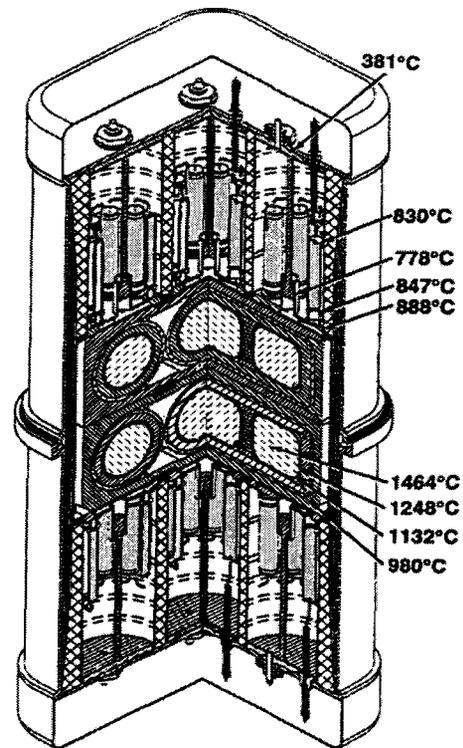


Figure 6: Cutaway view of an AMTEC generator design using 2 GPHS bricks and 8 6-tube AMTEC cells [32].

**ARPS - AMTEC Generator
2 GPHS Modules/Generator - 2 Generator System**

	Cell	Generator	System
Efficiency (%)	20		18.4
Voltage (V)	3.5	14	28
Power (W _{el})	11	88	176
Mass (kg)	0.2	6.55	13.10
Specific Power			13.44 W/kg

Alternative materials - Potassium AMTEC

Most discussions of AMTEC focus on sodium AMTECs because that is the most commonly used operating fluid. It is, however, possible to use other operating fluids. Potassium has been used in at least two experiments [33, 34], and offers a great deal of promise for improved AMTEC cells.

Potassium is desirable as an operating fluid because the saturated vapor pressure of K is higher than that of Na at the same temperature. Because the open circuit voltage, and consequently operating performance, of an AMTEC is a function of the ratio of the high and low pressures, the same open circuit voltage can be reached in a K-AMTEC at a temperature 100 K lower than in a Na-AMTEC.

The advantages of using potassium are several. With a lower operating temperature, components will degrade at a much slower rate, there will be decreased thermal losses, and it will be possible to use materials not available for $T > 1100$ K, such as Mo electrodes. Mo is a high performing electrode which cannot be used above 1100 K because it diffuses too quickly in an alkali metal vapor atmosphere to make a long lived electrode [25]. Overall performance of a K-AMTEC may be better than performance in Na-AMTEC because K transport through the cathode may be more efficient (higher surface mobility) and higher volatility. Finally, the viscosity of potassium is greater than that of Na at 1100 K, which will lead to better wicking in the capillary pump.

There are, however, a few disadvantages to using K-AMTECs, which diminish but do not cancel the advantages. The primary disadvantage is that the ionic conductivity of K-BASE is somewhat lower than that of Na-BASE, 0.36 S/cm [34]. K-BASE has not generally been available, although it has recently been available for purchase from Ionotec. Finally, the surface free energy of K is lower than of Na, which requires smaller pore diameters in the hottest part of the capillary pump.

K-AMTEC cells have been operated at JPL and at AMPS. A liquid anode cell at JPL operated at 825 K at 3% efficiency, demonstrating that K-BASE can be made and K-AMTECs operating [33, 9]. A liquid anode K-AMTEC cell has been

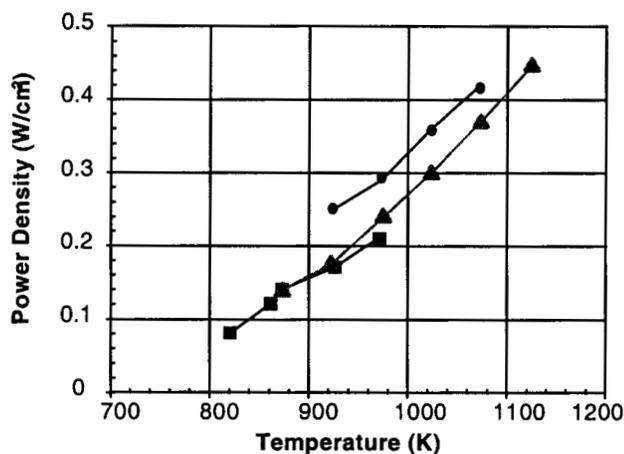


Figure 7: Power Density vs. T for liquid anode K-AMTEC (circles) and liquid anode (triangles) and vapor-vapor (squares) Na-AMTEC cells [Barkan 1998].

operated at AMPS at 820 - 1073 K and compared to a similar Na-AMTEC cell. Power data from that cell are shown in Figure 7. The internal resistance of AMPS' K-AMTEC was greater than internal resistance for similar Na-AMTEC cells, supporting the conclusion that the improved performance was caused by use of potassium in the cell [34].

Future of AMTEC in Solar System Exploration

Until August, 1999, AMTEC was baselined as the power converter for ARPS, to be used in all three Ice and Fire Missions. The first Ice and Fire Mission, Europa Orbiter, is scheduled to launch in 2003, and the ARPS program determined in late August, 1999 that it was unlikely that AMTEC would be ready for launch in 2003. Use of AMTEC in ARPS has been postponed to the Solar Probe mission, which is scheduled to launch in 2007. The ARPS program will continue a technology development program for AMTEC in support of the Solar Probe Mission. The technology development program will continue to address the issues identified above as possibly contributing to losses in the cell, and life testing will continue.

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