

An overview of advanced space/terrestrial power generation device: AMTEC

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Abstract

Alkali metal thermal electric converter (AMTEC) technology offers several advantages over conventional forms of electric generation. Some of these advantages are high efficiency, high density, reliability, absence of moving parts, and competitive manufacturing costs. These and other advantages make AMTECs ideally suited for several space, aerospace, military and domestic applications.

Current AMTEC designs suffer from some drawbacks that need to be rectified if the full potential of the technology is to be realized. These are current cell efficiencies that are still at values below the theoretically possible, and the adverse power–time characteristic of the cell. The PX-3A AMTEC cell, for instance, shows decreasing values of the maximum power output with time. Maximum power decreases from 2.54 W at the end of 172 h to 1.27 W at 18,000 h of cell operation. This latter problem, called power degradation, in particular, will preclude the use of the cell for applications that require operation of the cell for long periods of time.

This paper discusses in detail the advantages of AMTEC technology and the problems with current designs. In particular, the problem of power degradation is dealt with in some detail and some measures are suggested that will help arrest this loss of power with time. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: AMTEC; Power degradation; Ionic resistance; Solid electrolytes; Space power; Efficiency

1. Introduction

Since the start of the industrial revolution, energy consumption has been on the increase and this increase has been more pronounced in the past few decades. After the science of electric power generation was developed, electricity has been the most important source of energy to mankind. There are two main ways of electric generation, namely, dynamic conversion and static conversion, by which other forms of energy are converted to electrical energy. In the process of dynamic conversion, there is movement of machinery and machine parts as in turbines couple to conventional electromagnetic generators in the production of electricity. Static conversion, on the other hand, produces electricity without movement of parts. Examples of static converters are batteries, fuel cells and photovoltaic cells. In the early days of mass electric generation, dynamic conversion was the only

means used and it is still used extensively. However, static conversion systems are gaining importance in recent times because of newer applications of electricity like in spacecraft, hybrid-electric vehicles, military uses and domestic purposes. Of the many new static energy conversion systems that are being considered, one is the alkali metal thermal electric converter (AMTEC). It is a thermally regenerative, electrochemical device for the direct conversion of heat to electrical power. As the name suggests, this system uses an alkali metal (lithium, sodium or potassium) in its process. The electrochemical process involved in the working of the AMTEC is the ionization of the alkali metal atoms at the interface of the electrode and the electrolyte. The electrons produced as a result flow through the external load thus doing work, and finally recombine with the sodium ions at the cathode.

The history of AMTEC technology can be said to date back to 1916 when Rankin and Merwin [1] discovered a new compound, which they named β -alumina because it resembled α -alumina. Later work established the presence of sodium in the structure, and in 1936 Ridgway et al. [2] determined that it is a sodium aluminate. Yamaguchi and Suzuki [3] discovered a closely related compound in 1943 that they named β' -alumina. In 1967, Yao and Kummer [3]

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reported that β -alumina exhibited rapid sodium ion diffusion and high ionic conductivity. Their work was critical in focusing interest in high ionic conductivity electrolytes and to the subsequent development of energy batteries using β -alumina as (solid) electrolyte. Though many solid electrolytes have been investigated, interest in β -aluminas has endured principally because of one characteristic that is virtually unique to the β -alumina family: their ability to undergo ion exchange. AMTEC technology was first conceived at Ford Scientific Laboratory in Dearborn, Michigan in 1968 with the development of a converter called the sodium heat engine. The technology used the β -alumina ceramic as electrolyte. In the early 1980s, Jet Propulsion Laboratory, Pasadena, CA started studies on this technology to determine its possible use in spacecraft. Research, since then, has focused primarily on space applications of AMTEC technology. In the recent past, a number of programs at the Jet Propulsion Laboratory, Electrotechnical Laboratory and Kyushu University in Japan, Advanced Modular Power Systems and the Environmental Research Institute of Michigan have focused on developing AMTEC technology and improving its performance characteristics. Work is also underway at many institutions and companies like Air Force Research Laboratories, Advanced Modular Power Systems, Orbital Sciences Corporation, and Texas Technical University to improve current designs and performance of AMTEC cells. Continuous development and

improvements in the technology have greatly enhanced the performance of AMTECs, and today, AMTECs have approximately the size and configuration of regular D-sized batteries. AMTEC has several versions based on the number of tubes—single or multiple. One such multiple tube AMTEC model with a configuration of five tubes is PX-3A. It weighs less than 150 g and occupies a volume of just 80 cm³. Fig. 1 shows the cross-section of the PX-3A cell, and the geometry and materials used in the various parts are given in Table 1.

2. Working principle of the AMTEC

All AMTEC cycles involve the use of β -aluminas as solid electrolyte to produce electron flow. The two sides of the β -alumina electrolyte are connected to electrodes and the two electrodes are electrically connected through an external load. Alkali metal atoms ionize at the interface of the electrode and electrolyte. While the alkali metal ions pass through the electrolyte, free electrons flow from the anode, through the external load thus doing work and return to the cathode where they recombine with the alkali metal ions that have passed through the electrolyte. There are two main types of AMTEC cycles namely, liquid-anode cycle and vapor-anode cycle. The first is so named because the working fluid (liquid sodium) is in direct contact with one side of

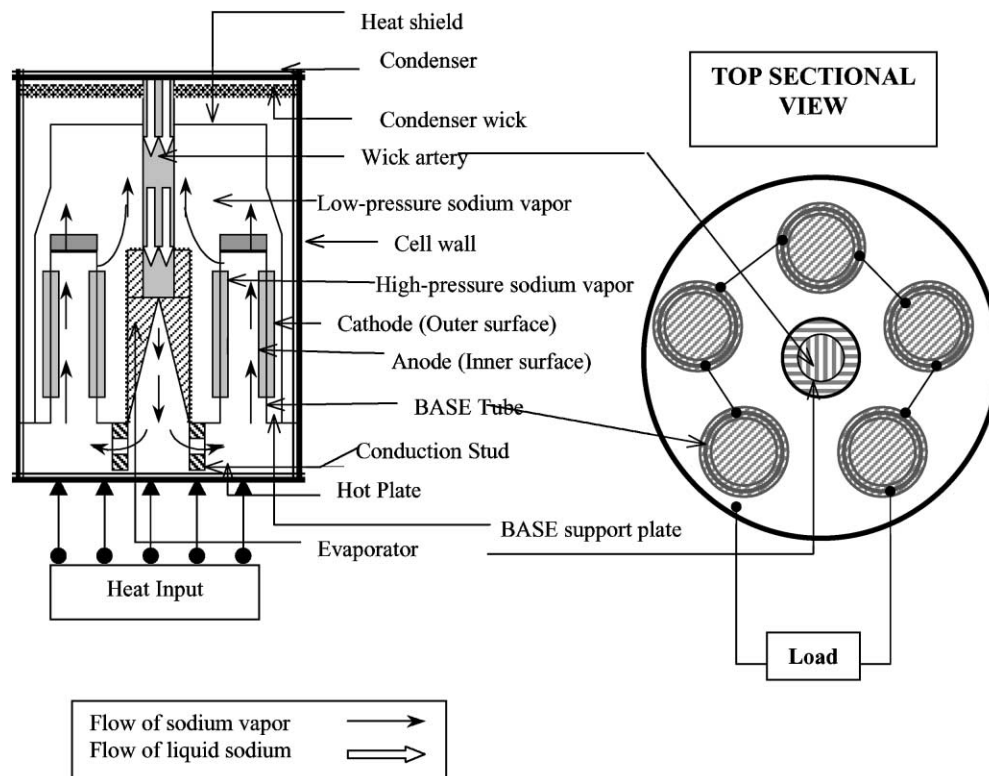


Fig. 1. Side and top sectional views of the PX-3A cell. The top sectional view also shows the electrical circuit also.

Table 1
Dimensions of various parts used in the PX-3A and their material specifications

Component	Material	Dimensions
Cell wall	Stainless steel	Diameter: 317.5 mm
Hot plate	Stainless steel	Thickness: 1.2 mm
Evaporator	Stainless steel	Outside diameter: 11.56 mm, thickness: 3.33 mm, inner height: 8.66 mm
Thermal rings	Nickel	Number of rings: 5, outside diameter: 19.42 mm, thickness: 1.1 mm
BASE tubes	β'' -Alumina	Height: 31.75 mm, thickness: 0.51 mm, outside diameter: 7.62 mm
BASE support plate	Stainless steel	Thickness: 2.54 mm
Electrodes	Titanium nitride	Height: 25.4 mm, thickness: 5 μ
Heat shield	Stainless steel	Diameter: 24 mm, thickness: 0.025 mm
Condenser	Stainless steel (micromachined surface)	Thickness: 6 mm

the β -alumina electrolyte and thus, also acts as one of the electrodes. In the vapor-anode cycle, though, both sides of the electrolyte are covered with solid electrodes and are both in contact with sodium in the vapor state.

The liquid-anode cycle is briefly explained here. Fig. 2 shows schematically how it works. The working fluid used is liquid sodium. One side of the β'' -alumina solid electrolyte (BASE) is covered with a porous electrode while the other side is in contact with liquid sodium which also acts as an electrode. The porous electrode is in contact with sodium vapor. When the electrodes are electrically connected through an external load, metallic sodium is ionized at the liquid sodium/BASE interface allowing sodium ions to enter the BASE, which is a conductor of positive ions but an insulator to electrons. The electrons pass through the external load performing work and then recombine with sodium ions at the electrode on the low-pressure side of the BASE. The sodium, in vapor form, passes through the electrode traverses the vapor space and condenses. The

liquid sodium is then collected from the condenser and recycled to the hot sodium reservoir by an electromagnetic pump or other appropriate method [4,5].

Another scheme for the AMTEC is the vapor-fed AMTEC cycle. This is the scheme used in current PX-3A AMTEC technology with which we will be concerned in this paper. A schematic diagram depicting this cycle is shown in Fig. 3. There are many differences between this and the scheme described earlier. These include the use of electrodes, and the existence of sodium vapor, on both sides of the β'' -alumina. The working principle of this cycle is described below [6–8].

The BASE separates two regions of sodium vapor. On one side of the BASE is sodium vapor at high temperature and high pressure; on the other, is sodium vapor at low pressure and low temperature. The side of the BASE in contact with high-pressure sodium vapor is also in contact with the anode, the anode being situated between the vapor and the BASE. The other side of the BASE is in contact with the cathode

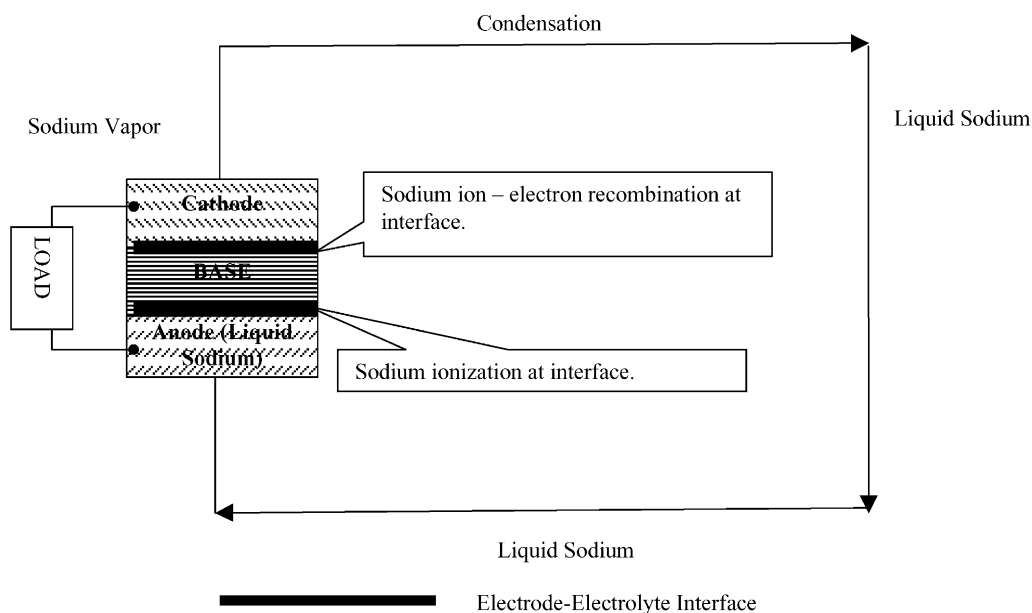


Fig. 2. Schematic diagram of the liquid-anode AMTEC cycle.

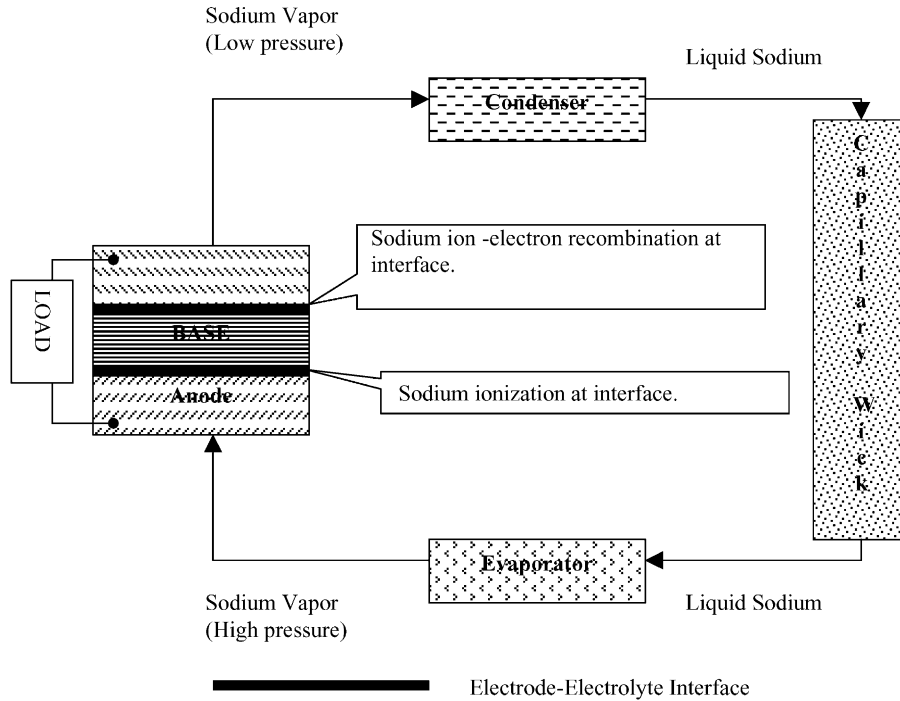


Fig. 3. Schematic diagram of the vapor-fed AMTEC cycle.

that is similarly situated between the BASE and the vapor. The high pressure is in the order of kPa (usually greater than 20 kPa) while the low pressure is in the order of Pa (less than 100 Pa). The pressure of sodium vapor at the anode/BASE interface (the high-pressure side) is equal to the saturation pressure at the evaporator temperature. The pressure at the BASE/cathode interface is given by [9]

$$P_c = P_c^{oc} + \Delta P = P_c^{oc} + \sqrt{\frac{2\pi R_g T_B}{M} \left(\frac{3G}{8\pi}\right) \frac{MJ}{F}} \quad (1)$$

where ΔP is the pressure loss through the electrode, R_g the universal gas constant (8.314 J/mol K), T_B the temperature of the BASE, G the geometric factor for pressure losses, M the molecular weight of sodium (23 g/mol), J the electrode current density (A/m^2), F Faraday's constant (96,485 C/mol), and P_c^{oc} is the sodium vapor pressure at the BASE/cathode interface in open-circuit condition is given by

$$P_c^{oc} = P_{cond} \sqrt{\frac{T_B}{T_{cond}}} \quad (2)$$

This pressure differential between the two sides of the BASE is associated with potential energy, which can be converted to useful work. As a result of the high pressure, sodium vapor tries to expand. However, β'' -alumina is impermeable to neutral atoms as also to electrons. Thus, the only way for the pressure energy to be released, in other words, for the vapor to expand, is for neutral sodium atoms to ionize. The sodium atoms, hence, ionize and sodium cations and free electrons are produced. The BASE permits the sodium ions

to pass through its material and the pressure differential causes this movement of the ions. Thus, positive sodium ions accumulate on the low-pressure side and electrons collect on the high-pressure side resulting in an electrical potential, which balances the pressure differential and prevents further flow of sodium ions. The effective electromotive force V_0 of the cell is given by [9]

$$V_0 = V^{oc} - \zeta^a + \zeta^c \quad (3)$$

where V^{oc} is the open-circuit voltage given by

$$V^{oc} = \frac{R_g T_B}{F} \ln\left(\frac{P_a}{P_c^{oc}}\right) = \frac{1}{f_B} \ln\left(\frac{P_a}{P_c^{oc}}\right) \quad (4)$$

where P_a is the sodium vapor pressure at the anode/BASE interface and is equal to the saturation vapor pressure at the evaporator temperature, and f_B defined as $F/R_g T_B$.

The charge-exchange polarization overpotentials at the anode (ζ^a) and at the cathode (ζ^c) used in Eq. (3) are calculated using the following expression in which, the 'x' in the subscripts may be substituted by either 'a' for anode or 'c' for cathode

$$\zeta_x = -\frac{2}{f_B} \ln \left\{ \frac{1}{2} \left[\left(\frac{J_x}{J_x^0} \right)^2 + 4 \frac{P_x}{P_c^{oc}} \right]^{1/2} + \frac{1}{2} \frac{J_x}{J_x^0} \right\} \quad (5)$$

where $J_c = J$ at the cathode and $J_a = -J$ at the anode, and J_x^0 is the exchange current density and is a measure of the nature of the contact at the BASE/electrode interface and is related to the saturation equilibrium exchange current

density as

$$J_x^0 = J_0^0 \left[\frac{P_x^{\text{oc}}}{P_{\text{sat}}(T_B)} \right]^z \quad (6)$$

J_0^0 in Eq. (6) is a function of the BASE temperature and of the type of electrode. It can be expressed as

$$J_0^0 = B \frac{P_{\text{sat}}(T_B)}{\sqrt{T_B}} \quad (7)$$

where B is the temperature-independent exchange current ($\text{A K}^{1/2}/\text{Pa m}^2$), and P_{sat} is the saturation pressure of sodium vapor at BASE temperature.

With appropriate electrodes, this electrical potential can be utilized to drive an electrical current through a load. While the sodium ions flow through the BASE, the electrons flow from the anode through the lead and the external load, to the cathode on the other side of the BASE. Sodium ions that have passed through the BASE reach the interface between the BASE and the cathode where they recombine with the electrons to form neutral sodium atoms. The sodium atoms escape from the interface and the cathode to form sodium vapor at low pressure on the other side. The low-pressure sodium vapor goes to the condenser where it condenses to the liquid state. After condensation it goes to the high-pressure region where it is converted to high-pressure vapor at the evaporator. This way the sodium continues to re-circulate.

3. Advantages and uses of AMTEC cells

AMTECs convert the work done during the nearly isothermal expansion of sodium vapor to produce a high current and low voltage electron flow. Due to its principle of working it has many inherent advantages over other conventional generators. These are discussed in detail below.

3.1. High efficiency

This, probably, is one of the most important advantages of AMTECs. These devices are capable of achieving high efficiencies at relatively low operating temperatures. For instance, an optimized AMTEC can potentially provide a theoretical conversion efficiency between 20 and 40% when operated at hot-side temperatures in the range of 1000–1300 K and a cold-side temperature between 400 and 700 K. Other conventional devices cannot achieve such high efficiencies as close to Carnot efficiency [10–13].

3.2. High power density

AMTECs inherently have high power densities. Power densities of up to 1 W/cm^2 were achieved as early as 1978 [14]. This means that the size of the cell will be small relative to power output. This attribute is closely related to efficiency. Some designs of AMTEC cells have calculated energy

conversion efficiencies of up to 23.5% with power densities of 19.8 W/kg [15]. This value can go as high as 0.5 kW/kg of system mass in AMTECs with optimized design [15].

3.3. Closed-loop design

There is no transfer or flow of matter either into or outside of the cell system. As a result, there are no problems of leakage, malfunctioning of valves, meters, flow regulating devices, etc. that are possible if the working fluid flows into and out of the system.

3.4. Absence of moving parts

This is an important characteristic of AMTECs though some other converters like thermocouples also have this feature. Absence of moving parts eliminates several associated problems. Moving parts are invariably associated with problems of wear and tear, and friction. While these can be reduced with proper lubrication, there is virtually no way they can be eliminated. Moreover, lubrication comes with its attendant problems like oil leaks, sealant problems, and possibly undesirable chemical interaction with other components. Besides, moving parts and lubricant movement (if liquid) will give rise to problems related to the dynamic stability of the structure especially if it is a spacecraft. Noise and vibration are virtually nonexistent.

3.5. Reliability

AMTECs are extremely reliable partly because of the absence of moving parts and the basic functional technology — AMTEC technology does not involve chemical reactions between different substances thus avoiding any unpredictable failure of the chemical reactions. It only involves an electrochemical reaction (ionization) of a single element.

3.6. Maintenance-free operation

This is a result of many of the features that have been discussed with respect to its working principle. Once the system is started and a steady state is reached, no further external intervention is required. The cell will run for a very long time without requiring any maintenance work. This feature too makes AMTECs well suited for long duration space and terrestrial applications.

3.7. Competitive production costs

AMTEC technology utilizes materials that are commonly or easily available for most of its components. Even the critical solid electrode can be produced at competitive costs. Fabrication of the cell, including deposition of electrodes on the solid electrolyte and wick manufacturing, can be achieved at very economical costs. Manufacture of AMTEC cells is thus a very economically viable venture.

3.8. Working temperatures

AMTECs have relatively high heat-rejection temperature (about 600 K) and low heat source temperature (about 1200 K). The heat-rejection temperature has to be kept at a level above the phase change temperature (371 K) of sodium in order to maintain sodium in liquid state. Besides, for the optimum performance of the cell the temperature of the condenser is kept at that level. The low heat source temperature of the AMTEC allows it to be coupled with converters like the thermionic energy converter (TIEC) that reject heat at high temperatures. Such an arrangement, called cascading, involves thermally connecting the heat-rejecting end of the other device with the source end of the AMTEC [16].

3.9. Flexibility of heat source

Heat input to AMTEC cells can be from many different sources (nuclear, combustion, solar). This flexibility allows AMTEC technology to be applied to many fields like space, military, terrestrial and domestic/residential uses.

3.10. Modular design

AMTECs are amenable to a modular design. AMTECs typically generate high current (thousands of amperes) at low voltage (hundreds of millivolts) due to the use of large electrode areas in electrical parallel rather than in series. Therefore, the modular feature of AMTECs means that powerful systems can be built by simply connecting smaller cells in series together [17,18].

Because of these advantages, AMTECs find many applications ranging from space and military to domestic uses. AMTECs can be used for hybrid electric vehicle systems, independent and portable power generation units for military uses, micro-cogeneration, residential power generation either in conjunction with or independent of the electric grid, power generation for recreational vehicles, power for air-conditioning and lighting in cross country transportation, charging rechargeable batteries and residential self-powered furnaces. However, it is in space applications that this technology may find the greatest use and importance. It offers a viable alternative to current energy conversion systems for use in spacecraft with significant advantages. For instance, a coupled general purpose heat source (GPHS) (that would provide the heat energy for power generation) and AMTEC system at 15–20% efficiency will require only one-fourth the mass of the radioisotope (plutonium-238) heat sources as the present thermoelectric conversion approach at 4% efficiency, resulting in large savings in mass, fuel, and cost.

4. Problems with current AMTEC designs

In spite of the many advantages of AMTEC technology, current designs suffer from two significant drawbacks. One

is with respect to steady-state efficiency and the other is regarding time-dependent performance.

AMTECs can theoretically perform at efficiencies close to Carnot efficiency. However, in practice, designs have only given efficiencies in the range of 10–15% [19]. This indicates that current designs have not yet taken care of high parasitic losses and that further improvements are necessary.

The other problem is with the power versus time characteristic of the AMTEC cell which has been observed experimentally in the PX-3A model cell [20]. Fig. 4 shows the power–time characteristic of the PX-3A cell. As can be seen, maximum power output decreases with time from 2.45 W at 172 h to 1.27 W at 18,000 h. The drop in power output also means that the efficiency of the cell also decreases. This characteristic will preclude the use of the cell for many applications that require operation of the cell for long durations of time unless it is corrected. Since both these problems cause the cell to give a reduced performance, it is interesting to look for their causes.

5. The BASE and power degradation

The BASE undergoes several changes as a result of the working temperature at about 1000 K and the action of high-pressure, high-temperature sodium vapor, which is highly caustic. These changes can be broadly classified as chemical contamination, and thermal breakdown. In the case of chemical contamination, products of chemical reactions between the sodium vapor and the materials of the container, like stainless steel may deposit on the surface of the BASE and block the pores [18–24]. They may also enter the material structure and deposit on the grain boundaries increasing grain boundary resistance to ionic motion, or replace some Na^+ ions in the structure [25]. All of these will increase the ionic resistance of the BASE. Thermal breakdown manifests itself in the form of loss of sodium from the BASE, formation of molten dendrites in the BASE, crack formation or changes in the microstructure. Loss of sodium from the BASE can increase its ionic resistance [26]. Molten sodium dendrites that have propagated through the entire thickness of the BASE can create an electrical short causing electrons freed at the anode/BASE interface to flow through the dendrite to the BASE/cathode interface directly and without flowing through the external load, thus reducing output power [2]. Cracks in the BASE material can propagate through the entire thickness causing high-pressure sodium to flow to the low-pressure side without having ionized at the anode/BASE interface. This will reduce the number of electrons, produced as a result of ionization, that are available to the external load causing a decrease in the power output [2]. Changes in the microstructure, especially grain growth, will increase resistance to ions flowing through the material. We can thus see that changes in the properties and/or structure of the BASE can significantly affect power output.

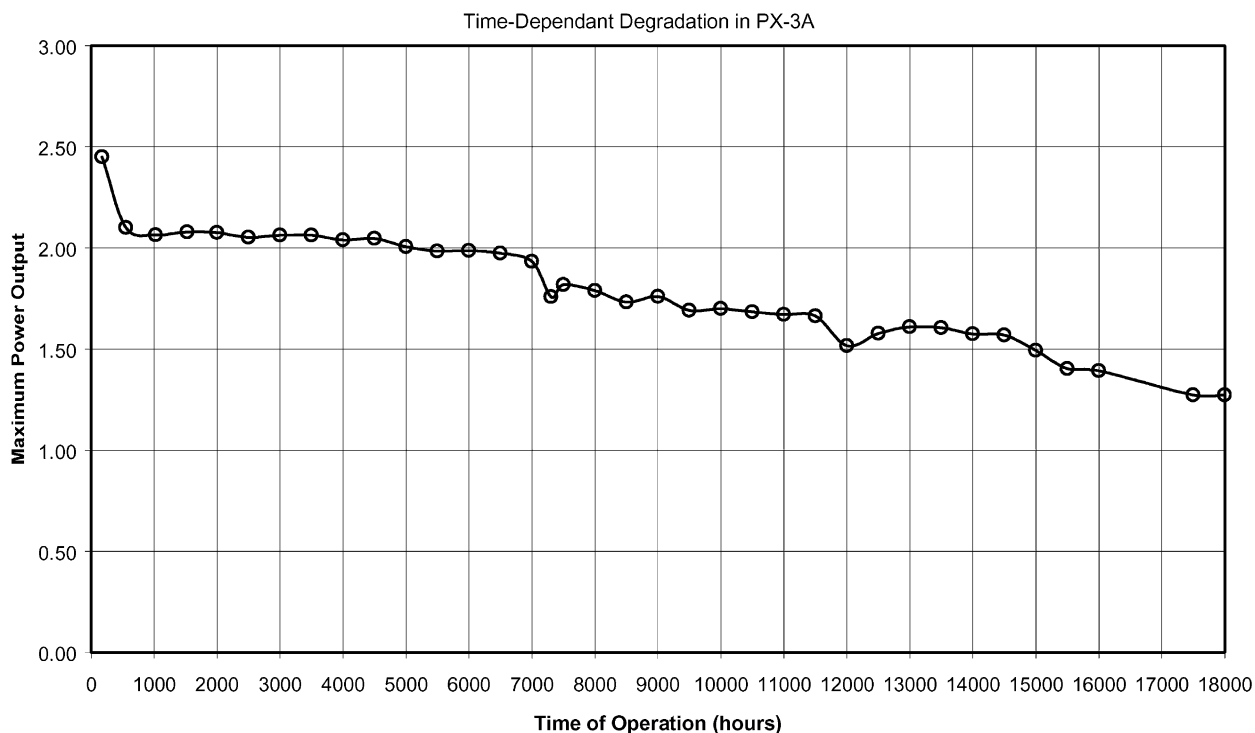


Fig. 4. Power degradation in the PX-3A AMTEC cell.

6. Further improvements

Some further ideas to be discussed that will help improve the time-dependent power characteristic of the PX-3A cell seem to be in order. These ideas deal primarily with the changes in the BASE and the contamination of the BASE discussed in the previous section [27,28].

The contamination of the BASE by products of reactions between the sodium vapor at high temperature and stainless steel in the cell can adversely affect the properties of the BASE. As a means to reduce this contamination, an ionic or other kinds of filters may be used. In this manner, contamination may be reduced or the contaminants may even be prevented from reaching the BASE to affect its performance efficiently. This may be feasible certainly for terrestrial applications of AMTEC technology where the filter can be replaced as and when needed. The use of filters, however, is not feasible for space applications where frequent replacement of filter is not practical. For that and also terrestrial purposes as well we should look at the problem from a different angle, the use of different material.

The next three suggestions deal with the structural stability of the BASE. Polycrystalline β'' -alumina is used as the solid electrolyte in the PX-3A because it has higher ionic conductivity than polycrystalline β -alumina. β'' -Alumina is inherently unstable and is stabilized by doping it with lithium or magnesium oxides. However, these dopants are detrimental to electrolyte's life. Since, doping cannot be avoided, if β'' -alumina is used, the single-crystal β -alumina may be used instead for better conductivity and stability than

polycrystalline β'' -alumina though it costs much more. Single-crystal β -alumina is stable even without doping and has higher ionic conductivity than polycrystalline β'' -alumina. Polycrystalline β -alumina may also be used rather than single-crystal β -alumina when compared in terms of economy and quality control. Its conductivity can be increased by a process of sintering and annealing [2]. The order of materials in terms of increasing ionic conductivity is polycrystalline β -alumina, polycrystalline β'' -alumina, single crystal β -alumina and single crystal β'' -alumina. However, the high performance materials degrade more rapidly than the low performance materials. Thus, for long use with limited access to the electrolyte, the choice of material has to be optimized with respect to these parameters for a specific requirement.

Current density can affect BASE degradation. There is a critical value of current density below which no degradation will occur [2,29]. This critical value depends on the amount of Li_2O content in the BASE. Therefore, the current density in the BASE should be kept below the critical value to eliminate degradation due to current density. The higher the current density above the critical value, the higher is the rate of degradation. If it is not possible to maintain the current density below the critical value, it should be kept as close to that value as possible to reduce the rate of degradation [2,29].

Loss of sodium from the BASE as sodium oxide affects not only its ionic conductivity but also the stability of the BASE. The range of sodium oxide content for which the BASE is stable is dependent on its stabilizer content.

Accordingly, the stabilizer's contents should be adjusted so that the anticipated loss of sodium oxide during the operating life of the cell still maintains the sodium oxide content within the range of stability corresponding to that stabilizer level [2]. Although there can be several metal stabilizer for the BASE like magnesium, lithium, etc. lithium stabilization is more common.

7. Concluding remarks

The drawbacks discussed can be said to be more a problem of design than that of the technology. However, current designs have demonstrated reasonably good performance in terms of efficiency and power density. As the work in improving the performance of AMTECs is in progress, it is likely to become more efficient in not too distant future. For that, concentrated effort needs to be directed to improve the BASE performance. The BASE is responsible to a significant degree for the power degradation in the PX-3A. In a recent analysis, the power degradation due to the BASE alone is 76% of the initial value at the end of 100,000 h while total degradation as observed experimentally is 92% of the initial value [28]. Reducing the contamination of the BASE, possible use of β -alumina instead of β'' -alumina, and controlling the current density in the BASE and the stabilizer content in β'' -alumina would likely help to improve the power–time characteristic of the PX-3A AMTEC cell. Despite some aforementioned problems associated with current designs, AMTEC technology is promising and has a lot of potential for use in many applications.

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