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Performance analyses of an Nb–1Zr/C-103 vapor anode multi-tube alkali-metal thermal-to-electric conversion cell

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Abstract

The results of performance analyses of a refractory Nb–1Zr/C-103 vapor anode multi-tube alkali-metal thermal-to-electric conversion (AMTEC) cell are presented and discussed. This cell could be used with a radioisotope heater unit to provide electric power from tens to a few hundreds of watts. In the tens of kilowatts electric range, the AMTEC cells could be used with a parabolic solar concentrator or a nuclear reactor heat source. The present cell measures 41.27 mm in diameter and is 125.3 mm high and has eight sodium beta″-alumina solid electrolyte (BASE) tubes, which are connected electrically in series to provide a load voltage in excess of 3 V. The hot structure of the cell, including the hot plate, the BASE tube support plate, the hot plenum wall and conduction stud, the evaporator standoff and porous wick and the side wall facing the BASE tubes, is made of Nb–1Zr. The cell's colder structure, which includes the condenser structure, the interior thermal radiation shield, the casing and wick of the liquid sodium return artery and the side wall above the BASE tubes, is made of C-103. This niobium alloy is stronger and has a lower thermal conductivity than Nb–1Zr, reducing the parasitic heat conduction losses in the cell wall, hence enhancing the cell's performance. The base cell weighs 163.4 g and delivers 7 W_e at 17% conversion efficiency and load voltage of 3.3 V (cell specific mass of 23.4 g/W_e). These performance parameters were for TiN BASE electrodes characterized by $B = 75\ \mathrm{A\,K^{1/2}/m^2\,Pa}$ and $G = 50$, assuming a BASE/electrode contact resistance of 0.06 $\Omega\,\mathrm{cm}^2$ and a BASE braze structure leakage resistance of 3 Ω. Also, the inner surfaces of the thermal radiation shield and the cell wall above the BASE tubes were covered with low emissivity rhodium. The temperatures of the BASE brazes and the evaporator were below the recommended design limits (1123 and 1023 K, respectively), and the temperature margin was $\geqslant +20$ K to avoid sodium condensation inside the BASE tube, shorting the cell. When high performance electrodes, characterized by $B = 120\ \mathrm{A\,K^{1/2}/m^2\,Pa}$ and $G = 10$, were used, the cell's electric power increased to 8.38 W_e at 3.5 V, and the efficiency increased to 18.8%, decreasing the specific mass of the cell to 19.7 g/W_e without exceeding any of the design temperature limits. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

During the last four to six years, extensive advances have been made in the fabrication, testing and performance of vapor anode multi-tube alkali-metal thermal-to-electric conversion (AMTEC) cells for potential use in space and terrestrial applications. The driving force behind the recent advances in the technology of these AMTEC cells has been to demonstrate the technology readiness for potential space missions with radioisotope heat sources. AMTEC cells have been considered for use in radioisotope power systems for spacecraft scheduled for launch in the year 2003 to explore Jupiter's moon, Europa, and the Pluto-Express (PX) flyby spacecraft to be launched in the year 2005 [1]. The power systems for these missions consist of one or two generators connected electrically in parallel. Each generator uses three to four standard general purpose heat source (GPHS) modules and 8–16 AMTEC cells connected in series in two parallel strings for redundancy. A GPHS module generates 250 and 230 W_{th} by radioactive decay of ^{238}Pu at the beginning-of-mission (BOM) and end-of-mission (EOM), respectively. Because of the long half life of ^{238}Pu (86 years), the thermal power output of a GPHS module decreases by only 11% at the end of a 10 year space mission. The radioisotope/AMTEC power systems for the Europa and PX spacecraft were designed to provide BOM electric power of 141 W_e and EOM power of 98.5 and 112 W_e, respectively [2]. The projected operation lifetime for these missions is seven years and 10–15 years, respectively.

Vapor anode multi-tube AMTEC cells could also be used in conjunction with a parabolic solar concentrator or a nuclear reactor heat source to generate tens or even hundreds of kilowatts of electric power. For these power systems, reducing the mass of the AMTEC cells and operating at a high bus voltage of 100–200 V are important considerations for reducing the mass of the power conditioning subsystem and, hence, that of the spacecraft. The relatively high operating voltage of vapor anode multi-tube cells (>3 V) is more than an order of magnitude higher than other static energy conversion options. These include thermoelectric, thermionic, thermophotovoltaic or solar photovoltaic cells.

A typical vapor anode multi-tube AMTEC cell comprises six to nine sodium beta″-alumina solid electrolyte (BASE) tubes connected electrically in series. The cell operates at typical hot and cold side temperatures of 1150–1200 and 550–620 K, respectively. The cell could provide 6–10 W_e at a load voltage >3 V and a conversion efficiency of 14–18% [3,4]. With further advances in technology, the cell's conversion efficiency can potentially reach 25–30% in the next 5–10 years, making vapor anode multi-tube AMTEC cells very attractive for a host of space and terrestrial applications.

During the last four years, several stainless steel, PX-series cells (Fig. 1), fabricated by advanced modular power systems (AMPS), have been tested in vacuum at the Air Force Research Laboratory in Albuquerque, NM. A few of these cells were fabricated of nickel and Haynes-25 to improve compatibility with the sodium working fluid and reduce heat conduction losses in the cell

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