# CONSIDERATIONS ON THERMAL RADIATION OF DIRECT SOLAR THERMAL POWER GENERATION SYSTEMS FOR SPACE PROPULSION

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## ABSTRACT

Recently, a concentrating solar power (CSP) system coupled to AMTEC (Alkali Metal Thermal-to-Energy Converter) units [1] has been proposed as alternative to the NASA solar electric propulsion (SEP) system, which is based on PV (photovoltaic) technology. The main advantages are related to the significant lower mass, size at launch, and robust construction. Such aspects recommend this concept as a viable solution to the PV based power systems for missions in low Earth orbit (LEO) and low medium Earth orbits (MEO), such as the proposed space tug. The present paper discusses the adaptation to space environment and the possibilities for the reduction of the radiation heat losses in the unit.

**KEYWORDS**: *AMTEC, space propulsion, CSP, heat losses, radiation*

## 1 INTRODUCTION

A solar energy system based on concentrating solar power coupled to AMTEC (Alkali Metal Thermal-to-Energy Converter) technology has been recently proposed for deep space missions [1].The system proposed consists of a primary mirror that collects the solar rays and focuses them on a secondary collector. The primary mirror consists of flexible reflective foils that are rolled at launch and deployed during operation. The advantage of such a system compared to the photovoltaic system relies primary in the mass, estimated to be ~70% lower. Further, the functionality of the mirror system is not completely destroyed in case of impact with meteoroids. The efficiency of the system is larger than for PV and can be increased using a cluster of efficient AMTEC modules.
The research activities on the AMTEC technology have been restarted at KIT in the last years, and an AMTEC test cell has been recently operated in the AMTEC test facility [2]. Long term investigations of AMTEC modules aiming material qualification and performance assessment are planned in the SOLTEC-3 facility [3].
The paper is structured as follows: in section 2 is presented the review of the thermoelectrical converters for space applications. In section 3 are presented the fundamental equations describing the processes in AMTEC converter. In section 4 are discussed the measures considered for the adaptation of the module for space applications and the analytical investigations for the reduction of the radiation heat losses. The last section summarizes the paper.

## 2 STATE-OF-THE-ART THERMOELECTRICAL CONVERTERS FOR SPACE APPLICATIONS

### 2.1 Literature overview

The first radioisotope thermoelectric generator (RTG) launched into space by the United States dates back to the 60s. Such missions include Pioneer, Voyager and Galileo. However, RTGs have efficiencies of ~7% and require large and heavy heat sources [4]. The AMTEC technology arose at the same period as a spinoff of the sodium-sulfur-battery research at the Ford Motor Company. The Jet Propulsion Laboratory in USA investigated further the technology focusing on electrical power generation for spacecraft propulsion. Extensive research programs were carried out from the 80s in

USA, Japan and Germany. Soon after several liquid anode configurations were developed, in the pursuit of larger efficiency expected at larger temperature, cells having sodium vapor anode were attained. Already from the 90s, the advantages of the AMTEC technology for space propulsion were considerable compared to the state-of-art of competitor technologies. The most important advantages were the efficiency of ~ 25 %, the flexibility towards the heat input source, the competitive power to weight ratio, the absence of moving parts and the possibility of modular configurations. Reviews of the technologies available [6-9] for direct solar thermal power generation, i.e. thermoelectric conversion (Seebeck effect), thermionic conversion, AMTEC thermoelectric conversion, magnetohydrodynamic (MHD) power generation, revealed that AMTEC technology is one of the best candidates for such applications. However, despite the extensive research programs, the technology did not attained yet a degree of maturity interesting for industrial production.

At KIT, the research on the AMTEC technology was performed in the 90s with promising results [5] but was stopped for a period due to funding and technological problems. The research activity on this topic is presently ongoing at KIT and a broad review on required technological and scientific techniques have been performed, revealing the chances for realization due to the progresses made in key technologies such as ceramic manufacturing, new materials and new manufacturing technologies.

An AMTEC test cell was recently successfully operated in the AMTEC Test Facility (ATEFA) that has been developed at the Institute for Neutron Physics and Reactor Technology (INR) at KIT. The work was focused on analytical investigations on the materials for electrodes, applicability to terrestrial CSP systems, as well as experimental tasks, e.g. development of a high temperature ceramic to metal brazing and the sputtering process for the electrode-coating of the ceramic.

Based on the general mission requirements for NASA deep space scientific missions [10], the AMTEC technology was reviewed against the Stirling conversion and thermal PV technology [9]. AMTEC technology was rated best at safety, performance (highest system efficiency and lowest system mass), spacecraft interface and operation and technology scalability. Among the issues that need further optimization are the system lifetime and the development of the technology, due to its lower TRL (technology readiness level). Based on these findings the DOE/NASA/JPL selected AMTEC as the conversion technology to be developed for ARPS (advanced radioisotope power source) missions.

Concepts of solar heated AMTEC spacecraft power systems have been proposed for more than 20 years [11]. Such a system consisted of a solar concentrator, a thermal receiver, a thermal storage system, which stores the thermal energy in a phase change material, and the AMTEC units. Compared to solar-PV system, the AMTEC system has substantial advantages for missions in high radiation environments, as well as for missions with unusually large number of charge-discharge cycles. Furthermore, the AMTEC power system would be more competitive if the receiver could be lighter and if AMTEC efficiency could be raised above 20 %, which can be easily attained with the present technology and knowledge.

The solar 1.2 kWe AMTEC power system with integrated global positioning satellite (GPS) for Delta II launch vehicle and reported in [12] demonstrates further significant advantages against solar PV systems. The system had two generator sets, each containing one rigid, parabolic concentrator with direct solar receiver that had integral LiF salt canisters for energy storage to be used during the solar eclipse cycle. Specific powers greater than 5 We/kg were anticipated for mission duration of 10-12 years in orbits with natural radiation. Compared to silicon PV-array, the size of the AMTEC system is about 60% smaller, while the mass of the system is competitive with that of the PV/battery system. Furthermore, it is argued that since the AMTEC system could be much more robust and stable, it is a viable solution to PV based power systems in low Earth orbit (LEO) and lower MEO (medium Earth orbits) missions. Furthermore, solar AMTEC power systems were proposed also in ultra-high-power spacecraft applications for MEO missions and geostationary Earth orbit (GEO) missions [13]. Different stacking designs revealed power outputs up to 50 kWe at 100 V, considering an efficiency of 25%. The system integrates a high temperature TES (thermal energy storage) or batteries for power supply during eclipses in MEO and GEO. One TES proposed is sodium-fluoride (NaF) salt that melts at 1268 K. Based on the analytical analysis it is suggested that the efficiency of the system could increase significantly if the parasitic radiation losses could be minimized, high-performance electrodes could be employed and the BASE tube area could be increased.

AMTEC systems have been proposed for Space Reactors Power (SRP) for long-time missions even to planets without solar radiation [14]. Several conceptual designs of Scalable AMTEC Integrated Reactor Space Power System (SAIRS) with a total power in the range of 100 kWe and terminal voltage of 400 V DC have been reported. For SAIRS the AMTEC units are coupled to fast-spectrum

nuclear reactors that are Na cooled and which have thermal power in the range ~400-500 kWth. The AMTEC units operate at efficiencies up to ~30 % and require a low reactor exit temperature below 1200 K. It is reported that the total mass of the SAIRS system is 27-35 % lighter than for the SP-100 system [15], which has a nominal output power ~9 % lower at a terminal voltage ~50 % lower than for SAIRS.
Another system proposed considers the heat conversion for space power applications not by a single converter type, but by coupling a thermionic (TI) converter to an AMTEC converter [16]. The advantage of the thermionic system is its compactness and its high rejection temperature is used by the AMTEC converter that has a significant larger efficiency. Besides the total efficiency estimated in 1997 up to 40 %, such a system has been proposed for both solar thermal and nuclear power system. For the solar thermal energy the system proposed consisted of Cassegrainian solar concentrator and TES possibility based on phase change material (PCM). It is argued that such a cascade TI/AMTEC system should be survivable in the van Allen belts.
The AMTEC PX (Pluto Express)-series cells were designed and developed by Advanced Modular Power Systems (AMPS) as power supply system for NASA's mission to Pluto [9,17]. Such a mission will take close to 15 years to reach Pluto and complete all objectives. Therefore long time operation tests were performed to investigate the power loss in the cells. The power loss experienced by AMTEC cells is a known issue and several studies discussed this topic [18]. Among the measures to reduce the power loss are the reduction of the chemical contamination of the BASE, avoiding the causes that affect the BASE structural integrity and considering single-crystal β-alumina instead of polycrystalline β″-alumina.

### 2.2 AMTEC technology

AMTEC cells are thermoelectric devices that rely on the special capability of ceramics such as the β″-alumina solid electrolyte (BASE), which allows the transport of alkali metals ions (such as Na+), while simultaneously being an electronic insulator. Most of the cells developed use sodium as the heat transfer and working fluid. The key process in the cell is the ionization of the working fluid at the anode. The BASE divides the cell in a hot region, characterized by temperatures in the range 600-1000 °C and pressures of ~$10^5$ Pa and a cold region characterized by temperatures below ~450°C and pressures below 100 Pa. While Na ions are forced by the thermodynamic potential through the BASE, the electrons circulate towards an electric load where the electrical work is produced. On the cathode side of the BASE, the ions recombine with the electrons to form neutral Na molecules. The vapor sodium formed is condensed and circulated back to the anode side, where the cycle can restart.
The BASE is a polycrystalline sintered ceramic having the nominal composition 10 wt% $Na_2O$- balance $Al_2O_3$ having a density of ~ 3.2 g/cm$^3$ and a melting point of ~ 2000°C. Since BASE is inherently unstable, it is commonly stabilized by doping it with lithium oxide or magnesium oxide. There are several types of ceramics, which are classified in order of increased ionic conductivity as polycrystalline β-alumina, polycrystalline β″-alumina, single crystal β-alumina and single crystal β″-alumina [19]. However, the ceramics having higher ionic conductivity degrade faster as the ceramics with low ionic conductivity. Therefore, the choice of the BASE type has to be made function of the application. Since BASE is one of the most important components of the cell, any change in the composition, structure and properties of the BASE has a significant influence on the cell. The changes suffered by the BASE during long time operation of the cell are classified as chemical contamination and thermal breakdown. The effect of these changes is a significant degradation of the electrical power delivered, due to the increase of the BASE ionic resistance. Compared to the losses generated by other components, the changes occurring in BASE contribute mostly to the overall power degradation of the cell.
In Fig. 1 is displayed the AMTEC test cell that was recently operated at KIT in the ATEFA facility [2]. The image depicts in the lower part of the cell the BASE ceramic on which the current collectors are attached. For presentation purposes the condenser in which the cell is introduced is not displayed. The test cell has been optimized based on the investigations reported by Heinzel et al. [5].The design and operational experience that was gained from these developments is used for the development of new AMTEC cells that will be operated in the SOLTEC-3 facility [3].

**Figure 1: AMTEC test cell investigated in ATEFA facility in KIT**

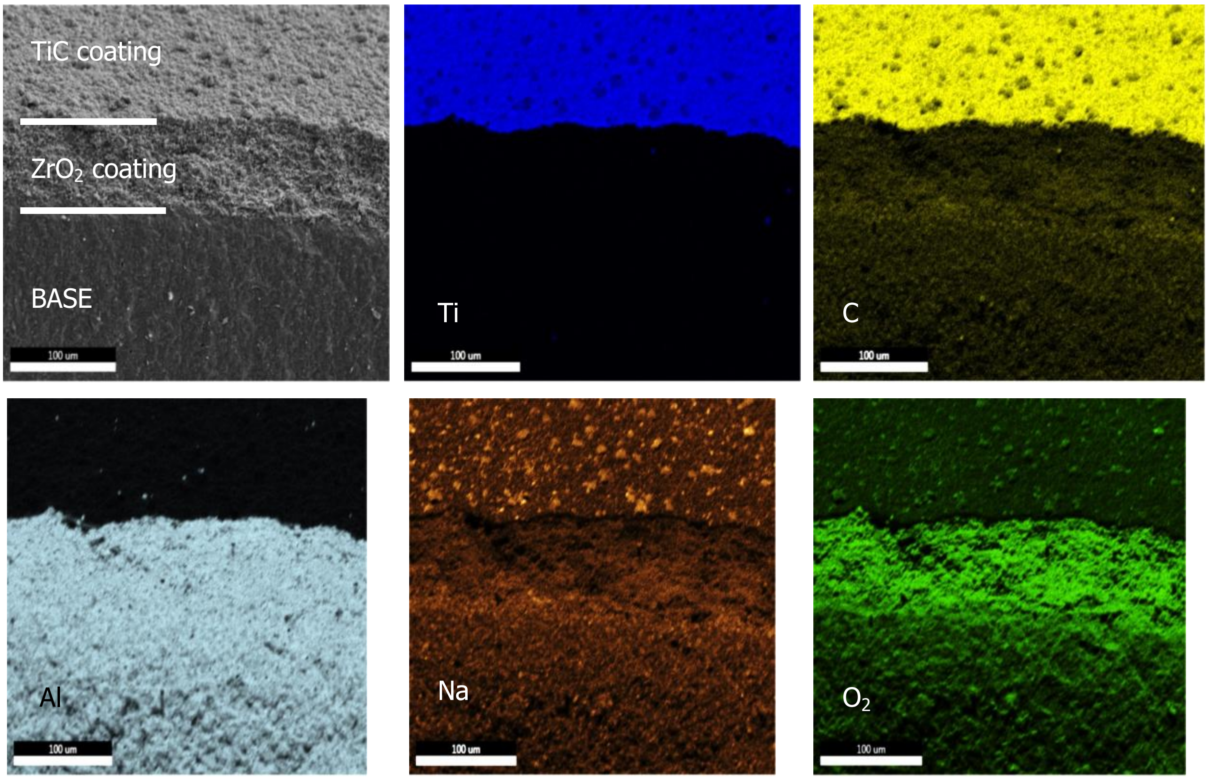



**Figure 2: EDS analysis of a TiC coating deposited on BASE**

At KIT, several coatings of titanium carbide (TiC) and titanium nitride (TiN) were deposited on BASE by reactive magnetron d.c. sputtering technique [2]. Energy-dispersive X-ray spectroscopy (EDS) was performed on TiC sample coatings prior to their use in an AMTEC cell using an SDD detector EDAX Octane Super for the chemical characterization of the TiC sputtered layer. The main components detected are Ti, C, Al, Na and $O_2$, as displayed in Figure 2. The analysis reveals that no diffusion of Ti and C occurs in the BASE. However, Na diffuses in the TiC layer and a rather similar Na concentration could be observed on the TiC layer and inside the layer. Compared to the Na signal intensity in the

BASE, the percentage difference of the intensity in the TiC layer is ~17% smaller, while on the TiC layer is ~29% smaller. The diffusion of Na in the coating has to be investigated in greater detail and minimized, since it leads to a chemical change in the BASE, affecting therefore the long time performance of the cell. Similarly, a certain share of oxygen could be observed above and in the TiC layer.

# 3 ASSESSMENT OF POWER SUPPLY

## 3.1 Energy balance

The conversion efficiency of an AMTEC cell can be calculated as [20]:

$$\eta_{AMTEC} = \frac{RI^2 - P_{pump}}{Q_{input}} = \frac{iV}{i\left[V + \frac{c_p\,\mu_0}{q}(T_{BASE} - T_{cond}) + \frac{L}{q\,\mu_0}\right] + Q_{loss}}, \tag{1}$$

where $I$ is the amperage, $V$ is the voltage, $i$ is the current density, $Q$ the heat flow, $c_p$ the molar specific heat of sodium, $L$=89 kJ/mole is the heat of vaporization, $q$ is the electrical charge and $\mu_0$ the concentration of migrating ions through the BASE.
The electrode efficiency can be calculated as [20]:

$$\eta_{electr} = \frac{iV}{i\left[V + \frac{c_p\,\mu_0}{q}(T_{BASE} - T_{cond}) + \frac{L}{q\,\mu_0}\right] + Q_{loss}}, \tag{2}$$

The voltage can be determined as:

$$V = \frac{k\,T_{BASE}}{q}\left[ln\left(\frac{q\,p_A}{\sqrt{2\,\pi\,m\,k\,T_{BASE}}}\right) - ln(i + i_\delta)\right] - i\,r, \tag{3}$$

Where $k$ is the Boltzmann constant, $m$ is the mass of a sodium ion, $p_A$ is the sodium vapor pressure, $r$ is the specific resistivity of the cell and the current density $i_\delta$ is equal to $\frac{q\,p_{cond}}{\sqrt{2\,\pi\,m\,k\,T_{BASE}}}\sqrt{\frac{T_{BASE}}{T_{cond}}}$.
In Eq. (1) the power required to circulate the sodium $P_{pump}$ can be neglected, since it is rather small in comparison to the work output [20]. The thermal heat input of the AMTEC cell can be determined as:

$$Q_{input} = P_{el} + Q_{rad}^{BASE} + Q_{cond}^{losses} + Q_{lost}^{Cool}, \tag{4}$$

where $P_{el} = RI^2$ is the electrical power generated, $Q_{rad}^{BASE}$ is the thermal heat lost by radiation through the BASE, $Q_{cond}^{losses}$ are the thermal losses by conduction and $Q_{lost}^{Cool}$ is the thermal heat required for the cooling of the cell.
The total electrical power generated is:

$$P_{el} = n_{cells} I V^{cc}, \tag{5}$$

where the closed circuit voltage is determined using Nernst equation:

$$V^{cc} = \frac{RT_{BASE}}{F}\ln\left(\frac{\mathrm{p_a^{cc}}}{\mathrm{p_c^{cc}}}\right) = V^{oc} - \zeta_a + \zeta_c, \tag{6}$$

where $\zeta_a, \zeta_c$ represent the polarization losses at the anode, respective cathode, $p_a^{cc}$ is the vapor pressure of sodium at anode in closed circuit and $p_c^{cc}$ is the vapor pressure of sodium at cathode in closed circuit. The losses at anode can be neglected since sodium has a good wetting at these temperatures.
In case of equal temperatures at anode and cathode, the open circuit voltage can be determined as [21]:

$$V^{oc} = \frac{kT_{BASE}}{q}\ln\left(\frac{\mathrm{p_a^{oc}}}{\mathrm{p_c^{oc}}}\right), \tag{7}$$

where $p_a^{oc}$ is the vapor pressure of sodium at anode in open circuit and $p_c^{oc}$ is the vapor pressure of sodium at cathode in open circuit.
Several models have been reported in literature to support the design of the cells and to evaluate its performances.

The electrical model is used to determine the electrical resistances of the current collectors, the electrical resistance of the electrodes, the electrical losses, the ionic resistance of the BASE and the total electrical current [4, 13, 22].
The electrochemical model evaluates the effective electromotive force potential per BASE using the Nernst equation. The model requires the temperatures of the BASE $T_{BASE}$ and condenser $T_{cond}$ and the pressure difference across the BASE.
The thermal model determines the heat losses by conduction and radiation in the cell. The heat losses by convection can be neglected, taking into account the small density and thermal capacity of sodium vapor [4, 13, 23].
The pressure model evaluates the sodium vapor pressure loss on the cathode side of the cell. Only a few studies are reported in literature, given the complex configuration of the cell and the fact that the sodium vapor flow regime can be transitional or free-molecular [4, 13, 23].
From all heat losses in the cell, the radiation heat losses from the BASE cylinders have the largest impact in a coaxial configuration and can be evaluated as [25]:

$$q_{rad}^{BASE} = \frac{\sigma\left(T_{BASE}^4 - T_{cond}^4\right)}{\frac{1}{\varepsilon_{BASE}} + \frac{1}{\varepsilon_{cond}} - 1 + N\left(\frac{2}{\varepsilon_{rad\,shield}} - 1\right)}, \tag{8}$$

where $\sigma$ is the Stefan-Boltzmann constant, $N$ is the number of radiation shields and ε is the emissivity.

For a coaxial arrangement of the radiation shields around cylindrical BASE tubes, which are common configurations, and if the BASE and the condenser are considered diffuse reflectors while the radiations shields are specular and considering that the shields have the same emissivity, the heat flow can be determined as [25]:

$$Q_{rad}^{BASE} = \frac{A_{BASE}\,\sigma\left(T_{BASE}^4 - T_{cond}^4\right)}{\frac{1}{\varepsilon_{BASE}} + \frac{1}{\varepsilon_{cond}} - 1 + \sum_{n=1}^{N-1}(A_{BASE}/A_n)\left(\frac{2}{\varepsilon_{rad\,shield}} - 1\right) + (A_{BASE}/A_N)\left[\frac{1}{\varepsilon_{rad\,shield}} + (A_N/A_{cond})\left(\frac{1}{\varepsilon_{cond}} - 1\right)\right]}, \tag{9}$$

# 4 AMTEC MODULES FOR SPACE APPLICATIONS

## 4.1 Adaptation to space environment

The development of AMTEC converters for space applications implies the fulfillment of several issues, such as the operational safety, low or acceptable power degradation during long-time service, autonomous maintenance, as well as a robust and stable functionality under zero gravity conditions. Regarding the safety aspects, which have such a large importance for applications on earth, they become significantly less problematic since in space neither oxygen nor steam can come into contact with sodium. Regarding the power degradation only a limited number of long term experiments are reported in literature. The power loss reported in literature, in the range of 50 % after 2.1 years of operation for the PX-3A cell [17], represents the major point of concern regarding the service of AMTEC converters for space applications. However, the longest continuous operation of an AMTEC module for more than 5 years is reported by Hunt and Rasmunssen [26]. Surprisingly, no power degradation occurred during the operation. Although the authors do not explain this achievement, it has to be underlined that this test module was operated at low temperature and very low current density, estimated to be <0.1 A/cm$^2$. A critical value of 1 A/cm$^2$ for the current density below which no power loss occurs is reported by Richman and Tennenhouse [27] for a BASE containing 0.25 wt.% $LiO_2$. However, the investigation has been performed at low operational temperature and for a short test period. Therefore, appropriate experimental research is required to validate the critical current density below which no BASE degradation can occur.
Further, to provide a stable functionality of the converter in space, the sodium flow has to be ensured for different acceleration vectors. Under zero gravity conditions, the passive draining due to gravity does not apply and the sodium flow has to be ensured for different acceleration vectors by means of a sodium pump.
Regarding the materials for the electrodes, one of the main challenges remains the operation with limited power degradation at the level of the electrodes. For operation below 800°C titanium nitride (TiN) electrodes can deliver rather good performances and are chemically inert against sodium and the BASE. However, above this temperature a large power loss is reported in literature. Molybdenum (Mo) has a smaller electrical resistivity compared to TiN, however one of its main drawback is the

chemical reactivity with sodium. Ceramic electrodes such as titanium carbine (TiC) and titanium diboride ($TiB_2$) have very interesting characteristics, such as: similar expansion coefficient with the BASE, high melting temperature and good electrical conductivity. Besides, they are also chemically inert versus sodium. However, their power loss in long time operation is not reported yet. Electrodes consisting of mixed layers of TiN (and Mo) and $TiO_2$ have been developed to enhance both the ionic and electric conductivity [28]. They are inexpensive and chemically stable in contact with sodium; however the reported power is slightly smaller than for TiN electrodes.

### 4.2 Impact of thermal radiation losses on the AMTEC cell efficiency

Considering an AMTEC cell having a thickness of 0.8 cm operated between 1175-983 K and $T_{cond}$ = 500 K, the characteristic line determined with Eq. 3 is in good agreement with the experimental data from [20], as displayed in Figure 3. The curves corresponding to the ideal case with no BASE resistance (i.e. $r$ = 0 in Eq. 2) are also displayed.
For a cell containing coated BASE tube having a diameter of 30 mm and length of 200 mm arranged in a coaxial configuration and surrounded by radiations shields, the influence of the number of radiation shields on the radiation losses function of the BASE temperature is displayed in Figure 4a.The radiation heat losses have been determined using Equations 8 and 9. For the calculations, the condenser temperature $T_{cond}$ was held at 300°C, the BASE emissivity $\varepsilon_{BASE}$ was set to 0.9, the condenser emissivity $\varepsilon_{cond}$ was set to 0.2 and the emissivity of the radiation shields $\varepsilon_{rad\ shield}$ to 0.15. The effect of the first radiation shields is largest for cells operated at high temperature. For the $\varepsilon_{rad\ shield}$ considered the first radiation shields reduces the losses by 131% compared to the case without radiation shield, while the second shield increases the reduction up to 166% and the third shield up to 173%. However, the reduction of the radiation losses by shields approaches an asymptotic limit when the number of shields is increased above 4 at temperatures below 800°C, i.e. the 8$^{th}$ shield reduces the heat losses by 183%. Adding more radiation shields will increase the vapor flow resistance between the BASE tubes and the condenser and complicate the construction. Therefore a compromise regarding these aspects has to be made.

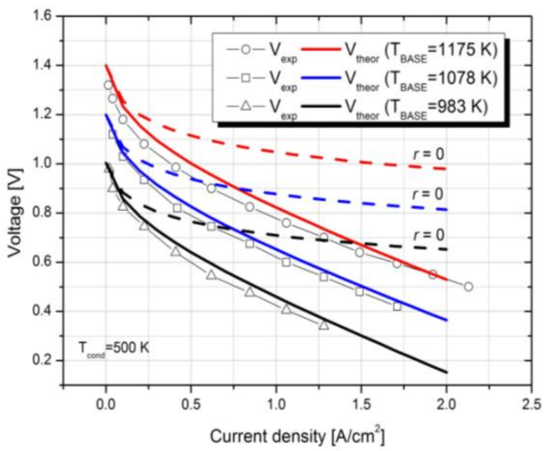



**Figure 3: Characteristic line for an AMTEC cell (experimental data from [20], theoretical values determined with Eq. 2; dashed curves correspond to the case with no BASE specific resistivity)**

The emissivity of the radiation shields has a significant influence on the reduction of radiation heat losses, especially at high temperatures, as displayed in Fig. 5. The impact of the shield emissivity is significantly influenced by the number of radiation shields. Increasing the number of shields decreases the effect of the emissivity, meaning that several shields having rather large emissivity can still be used for low heat losses. However, if the module has a small number of radiation shields, their emissivity should be very low for reduced heat losses. Polished molybdenum can reach emissivity of ~0.05 and it can be considered an appropriate candidate for both the radiation shields and the condenser.

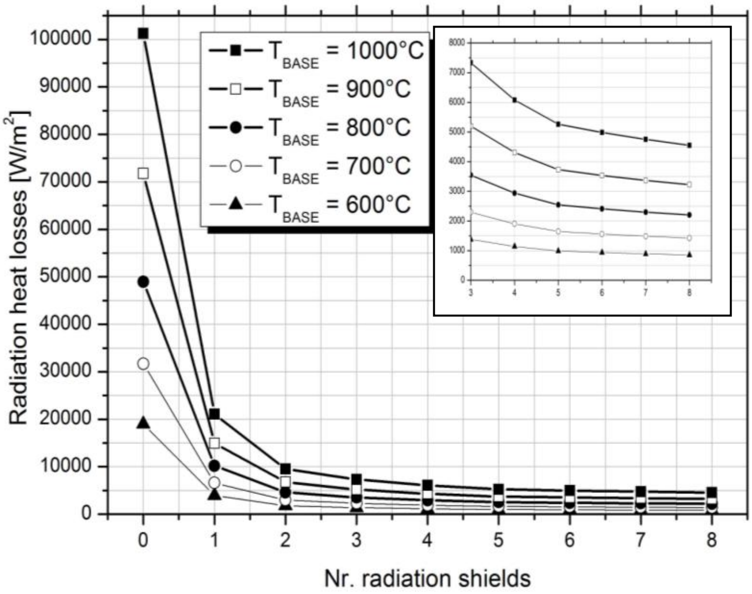



**Figure 4: Influence of number of shields on radiation losses**

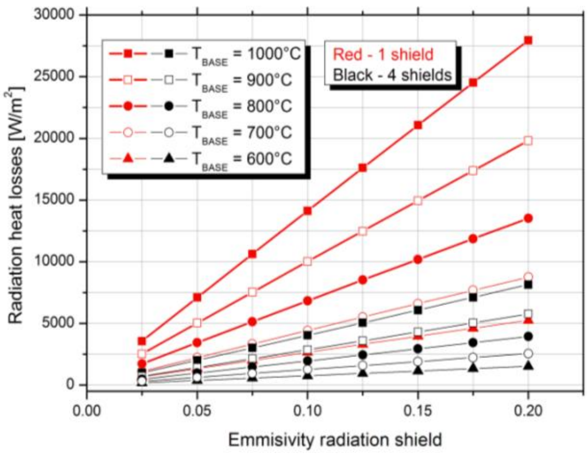
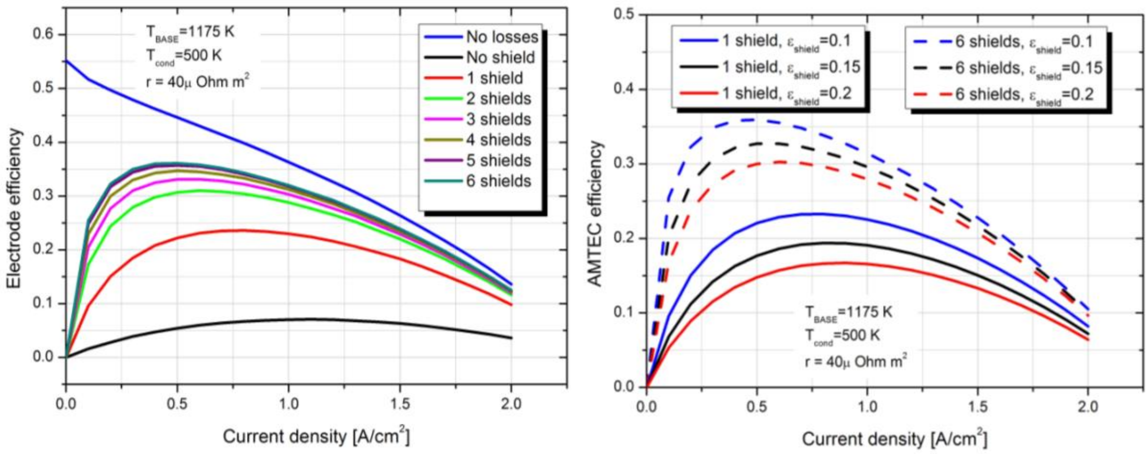



**Figure 5: Influence of radiation emissivity on radiation losses**

To estimate the impact of the radiation losses on the electrode and AMTEC efficiency, a cell has been considered that consists of a BASE tube having a diameter of 30 mm and length of 200 mm operated at $T_{BASE}$ = 1175K and $T_{cond}$ = 500K. The electrode efficiency was determined using Eq. 2 (see Fig. 6a) and the efficiency of the cell has been determined using Eq. 1 (see Fig. 6b). In both cases the heat losses have been considered either null (see Fig. 6a) or have been calculated using Eq. 8. The heat losses by conduction have been neglected, since their magnitude is design dependent. For the ideal case with no losses, the electrode efficiency exceeds 40% at low power outputs, as displayed by the blue curve in Fig. 6a. However, for the case considering radiation losses, in which no radiation shield is considered, the electrode efficiency drops below 10% (black curve in Fig. 6a), revealing the large impact of the radiation losses and consequently of the radiation shields. The electrode efficiency increases with the increase in the number of the radiation shields and reaches a peak at a current density of ~0.5 A/cm$^2$. For the parameter considered in the calculations, the electrode efficiency reaches an asymptotic peak at ~ 36% for 6 shields. Increasing further the number of radiation shields will minimally impact the electrode efficiency.
The impact of the emissivity of the radiation shields on the AMTEC efficiency is displayed in Fig. 6b for the case with one and six radiation shields. A better shield emissivity increases the efficiency of

the cell, particularly at low current density. However, as the number of radiation shields is increased, the effect of the emissivity is slightly decreased.




(a) (b)

**Figure 6: Influence of the radiation losses on the electrode efficiency (a) and AMTEC efficiency (b)**

## 5 CONCLUSIONS

AMTEC systems have been identified as one of the best technology for direct conversion of heat into electricity to be applied for space propulsion. Therefore, this technology has been proposed to be coupled with the CSP technology for solar electric propulsion in the range of 50 MW. AMTEC technology is currently in investigation for further increase of the efficiency, lifetime and power density. The present study discusses the methodology for the determination of the radiation losses and the possibilities of reducing the radiation heat losses, which are the main source of heat losses in an AMTEC unit. The main measure of reducing the radiation heat losses is the employment of radiation shields with good emissivity. However, the effect of the radiation shields approaches an asymptotic limit, which is dependent on the operational and geometrical parameter of the cell. Further, the slight increase in the vapor pressure loss on the condenser side due to the radiation shields has to be considered and compensated by the pump. If several radiation shields are used, then the effects of the radiation shield emissivity are damped. Limiting the heat losses will strongly enhance the efficiency of the module and if it is coupled with a reduced operational temperature, the lifetime of the module can be increased significantly.
Regarding the lifetime of the cell, the experimental data revealed the importance of the BASE coating, which should not affect the chemical stability of the ceramic.

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