# Direct Electricity From Heat: A Solution to Assist Aircraft Power Demands

*Jon C. Goldsby*
*Glenn Research Center, Cleveland, Ohio*

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Jon C. Goldsby
National Aeronautics and Space Administration
Glenn Research Center
Cleveland, Ohio 44135

## Abstract

A thermionic device produces an electrical current with the application of a thermal gradient whereby the temperature at one electrode provides enough thermal energy to eject electrons. The system is totally predicated on the thermal gradient and the work function of the electrode collector relative to the emitter electrode. Combined with a standard thermoelectric device high efficiencies may result, capable of providing electrical energy from the waste heat of gas turbine engines.

## Introduction: Market Drivers and Problems

Commercial aircraft users desire the most efficient vehicles possible to reduce the cost of operations and to increase market share by meeting or exceeding emission standards. As an example the Federal Aviation Administration regulations on NOx emissions has not been updated to meet more stringent international standards. Commercial aircraft engines that generate more than 27 kN of thrust will be required to reduce NOx emissions by 16 percent over the current standards (Elbir, 2008). Reductions are also required for hydrocarbon-based greenhouse gases. As an example the General Electric C. F. 3438 engine, with the thrust of 41 kN, produces 21 g of NOx for every 1 kg of fuel burned. Therefore, even this relatively new aircraft engine will be penalized for its heavy emissions (Sovde, Gauss, Isaksen, Pitari, & Marizy, 2007). Cost models consider factors such as specific fuel consumption and emissions in the determintion of an aircraft's profitability. The conclusions drawn from performance cost models are clear. The key to increasing performance and capability is to increase the power utilized while substantially reducing the weight of the engine.

### Electric Energy Conversion Devices

The use of direct thermal to electric energy conversion offers one solution to these challenges by converting the aircraft engine's waste enthalpy into usable electrical power (Lodhi & Mustafa, 2006). The purpose of this monograph is to introduce the concept and advantages of direct thermal to electrical energy conversion using solid state devices. There are two main classes of thermoelectric devices. The first type consists of two dissimilar semiconductor devices coupled electrically and thermally. A thermal gradient across the device produces a flow of current. The second type of device is thermionic (Fitzpatrick, 1981). The thermionic device produces a current by the application of a thermal gradient whereby the temperature at one electrode provides enough thermal energy to eject electrons from the metal surface. These ejected electrons are captured by a collector electrode, after which the leads are applied to an external load and hence produce electrical power. In a sense the electrons are literally boiled off of the collector electrode. There are many ways to supply the thermal gradient. Various schemes supplying the heat and necessary thermal gradients for these devices to operate include thermal nuclear, thermal radioactive, chemical combustion and solar heating as well as combinations of afore mentioned methods (Yasaka et al., 2008). While there are many types of thermoelectric devices and heating schemes the demanding environment of a gas turbine engine requires that any device used must be robust,

lightweight, and refractory in nature. In addition to device durability there are also stringent mechanical tolerances which point to the need for simplicity in concept and design.

## Thermoinics Devices Offer Advantages

The difference between a thermoelectric and a thermionic device lies in their fundamental physics of operation. The thermoelectric effect can occur when two materials differ in their work functions. The work function is that quantity of energy which is required to remove one electron from the valence band to the conduction band. The promotion of the electron into the conduction band now makes it available for electrical work. However the promoted electron moves in a diffusive manner. This random walk - type mobility leads to a current density which is smaller than its thermionic counterpart. While thermoelectrics relies upon diffusive electronic transfer, thermionics relies upon ballistic emissions of the electrons. These electrons have a much faster time of flight from the electrode through the electrolyte to the opposite electrode. In addition, the thermionics does not have a need for complicated structures. The system is totally predicated on the thermal gradient and the work function of the electrode collector relative to the electrode emitter. This greatly simplifies the construction and implementation of the device. Because the generator can be realized with standard ceramic processing techniques, a judicious selection of materials can be used to reduce electrostatic diffusive boundary layers.

Functionally graded materials can also be used to control the thermal characteristics of the various components of the thermionic device. In semiconductors, thermoelectric thermal energy contributes to lower efficiency scattering between phonons and electronic carriers in the crystal lattice, which inhibits electrical conduction and consequently charge mobility is reduced as the device is heated. The required physical properties of a thermionic device component are similar to thermal electric devices in common use today, namely high electrical conductivity and a very low thermal conductivity such that a thermal gradient can be maintained. It is likely that layered materials have phonons scattering interfaces which impede heat flow in the material. The key is to select the right electric metal or alloy that has a proper work function that can take advantage of the thermal gradient.

Some basic components of a thermionic generator consist of an emitter, a vacuum gap and a collector. Each component has a particular function. The function of the emitter is to eject electrons and serves as the high temperature leg of the system. Because of the high temperatures needed for electronic conduction, refractory material candidate electrodes include many transition metals notably, tungsten and rhenium. Ceramic carbides may also serve as electrode materials including zirconia carbide with its emission temperature of 1700 °C and boron carbide. The emitter must be heated such that the kinetic energy of the electron exceeds the surface work function of the metal or alloy yet still possess enough forward momentum to pass through a solid-state gap and into the waiting collector. Typical temperatures are near 1000 °C. Such high temperatures are necessary to exceed the material's work function. The excess thermal energy ensures a clean fire of the electrons from the surface. Only the populations of electrons which fire perpendicular to the electrode-solid vacuum gap interface contribute to the current density.

One benefit of a gas or vacuum diode is that higher thermal gradients can be used as compared to those with solid state components due to conduction carriers being removed from the system leaving only convection and radiation to carry the heat energy. The dielectric breakdown of the gas or vacuum can result in an extremely high electrical current density. Another physical aspect in the case of an energized vacuum tube, electrons are boiled off the filament transport through space of space-charged dipoles require an intermediate material to be in the vacuum. Space charged dipoles can create inefficiency in the device by inhibiting charge transport; in essence an electric double layer is created at the emitter electrode. In the case of power generation this is typically addressed by ionized gases placed in the device between the emitter and the collector plates. The ionized gas of choice contains the cesium cation. But in the case of the gas turbine engine, cyclic stresses induced by vibrations during operation along with the inclusion of a cesium ion a gas, require special consideration of containment inducing an additional level of design complexity.

For power generation in a gas turbine engine, space charges are controlled by the solid-state semi-conducting vacuum gap. As for the collector electrode while there are no particular requirements on this part of the system, the ease of manufacturing and property compatibilities with the balance of the system, will limit materials selection. The work function of the emitter must be less than the work function of the collector, with respect to the vacuum Fermi level. This requirement ensures that electrons are promoted in full to the conduction band. Typical material for the emitter can be found in the transition metal of the periodic table. Compounds that are commonly used are based on platinum or rhenium. Typical values can be seen in Table 1.

TABLE 1.—TYPICAL THERMIONIC WORK FUNCTIONS
OF VARIOUS MATERIALS (Russell, 1967)

| Material | Work function, eV |
|---|---|
| Platinum | 5.32 |
| Palladium | 4.99 |
| Tungsten | 4.52 |
| Copper | 4.47 |
| Molybdenum | 4.20 |
| Tantalum | 4.19 |
| Zirconium | 4.12 |
| Silicon carbide | 3.5 |
| Thorium | 3.4 |
| Tungsten uranium | 2.8 |
| Tungsten thorium | 2.7 |
| Cesium | 1.81 |
| Tungsten cesium | 1.5 |
| Barium strontium oxide | 1.0 |

To offset oxidation, which can hinder electrical properties, thermal protective barrier coatings are sometimes placed over these materials. It is essential that the space charge must be kept to a minimum, since they can inhibit electron flow, leading to a severe reduction in efficiency. Barriers for thin layers within the solid-state device can also be used to moderate the thermal properties of the device. Typical work functions are in the order of 1 electron volt per electron for a given surface area.

## Combined Thermionic and Thermal Electric Efficiency

It has also been found that combining both the thermal electric and thermionic can result in a much greater efficiency, nearly 40 percent direct conversion from heat to electricity. Figure 1 shows a schematic of the operation of this combined-cycle electric energy converter (Lodhi & Malka, 2006). In this schematic the heat enters a system through the thermionic emitter and electrons are ejected into the solid-state vacuum gap preceding the collector and are then siphoned off with an external load. The heat from the collector plate in turn is fed into the hot side of the thermoelectric device. A thermal gradient is established across this device producing electrical power because of the differences in the Fermi level of the PN junction of the dissimilar materials. The thermoelectric is now capable of producing additional electric power. The actual mechanisms of operation are rooted in quantum mechanics where the electrons must be ejected from the valence band across the energy gap into the conduction band where they can be used for external work. In the case of a solid state device the contact between these various elements can be an Achilles' heel. The thermal gradient, while providing the driving force for the current, also sets up thermal elastic tensions. Care must be taken when engineering these devices such that the thermal stresses do not induce fatigue failure.
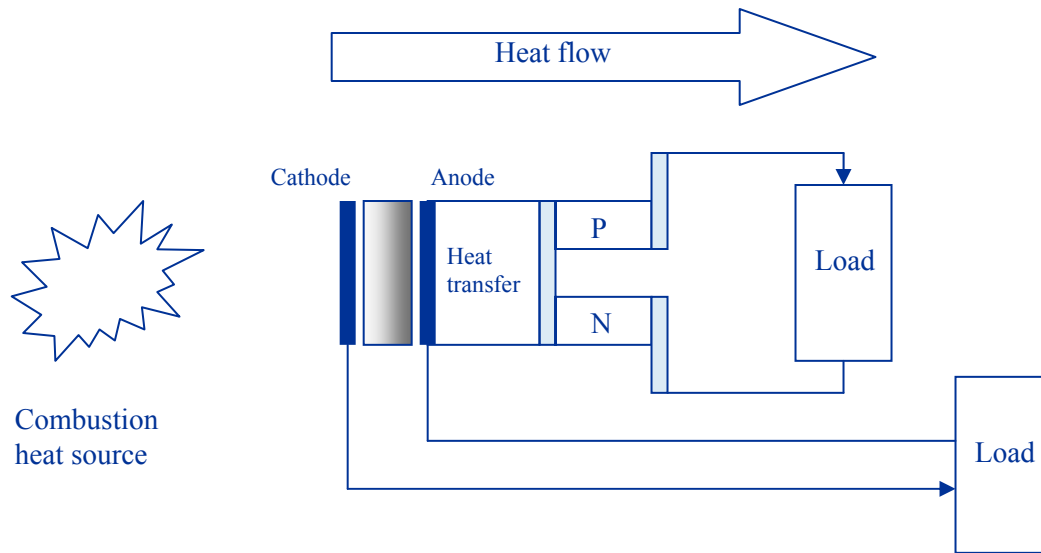
Figure 1.—Schematic diagram of a combined thermionic-thermal electric energy converter.

An electric field potential profile is created to promoting electronic excursion from the emitter to collector. These results stemmed from treating the electrons as a gaseous thermodynamic system and applying basic Carnot cycle heat engine equations of efficiency. After applying the appropriate dopants the semiconductors interface behavior can very closely approximate the same function as do the cesium cations and prevent space charge buildup by allowing the system to be relieved of dipoles and hence, eliminating the double polarizing layer of charge. In the creation of this thermionic generator a simplified system is created which is far more rugged than otherwise would be achievable. Some of the requirements for material selections include high electrical conductivity with low rates of deterioration under operating temperatures conditions. The material must also have a low emissivity to reduce heat transfer by radiation from the emitter. The system as a whole must maintain its doping composition and resist migration of components across the interface which would not interfere with device operation. Standard thermoelectric devices operate with efficiencies of less than 6 percent; however, since overall efficiency increases with increasing temperature, it is the thermionic device which will always have the highest efficiency, since it is driven at the higher temperatures to exceed the work function of the emitter material. Chief among candidate material requirements include the ability to withstand high operating temperatures, and a relatively low work function and a maximum quantity of electrons per unit cell to facilitate achieving high current densities. Possible candidates include rhenium, tungsten, tantalum, molybdenum, and carbon (Koeck & Nemanich, 2006). Yttria stabilized zirconia as the solid-state vacuum gap may be an excellent candidate material. In the case of zirconia the charge carriers are not active until at least 500 °C, however at temperatures near 1000 °C and above, it becomes electrically conductive. The actual charge carriers in the case of zirconia are not particles but charged oxygen vacancies. The oxygen vacancies being physically larger than a charged particle and may have a lower mobility within the crystal lattice. However devices such as solid oxide fuel cells commonly employ zirconia based electrolytes with no serious adverse effects on power production.

## Necessary Involvement

Current needs for fuel efficient, low emission, power sources for applications in sensor and subsystems in all-electric aircraft and on-board spacecraft has brought forth a renewed interest in this technology. When used as power harvesting devices, solid state based power harvesters have the added benefits of robustness for service in extreme environments such as gas turbine engines.

# References

T. Elbir, "Estimation of engine emissions from commercial aircraft at a midsized Turkish airport," *Journal of Environmental Engineering-Asce,* 134[3] 210–215.2008.

G.O. Fitzpatrick, "Thermionic Energy-Conversion - Its Potential and Problems," *Journal of the Electrochemical Society,* 128[3] C113-C113.1981.

F.A.M. Koeck and R.J. Nemanich, "Emission characterization from nitrogen-doped diamond with respect to energy conversion," *Diamond and Related Materials,* 15[2–3] 217–220.2006.

M.A.K. Lodhi and V. R. Malka, "Optimization of the TIEC/AMTEC cascade cell for high efficiency," *Journal of Power Sources,* 156[2] 685–691.2006.

M.A.K. Lodhi and A. Mustafa, "Use of waste heat of TIEC as the power source for AMTEC," *Journal of Power Sources,* 158[1] 740–746.2006.

C.R. Russell, "Elements of energy conversion,"). Oxford London Edinburgh New York Toronto Sydney Pergamon press. (1967).

O.A. Sovde, M. Gauss, I.S.A. Isaksen, G. Pitari, and C. Marizy, "Aircraft pollution - a futuristic view," *Atmospheric Chemistry and Physics,* 7[13] 3621–3632.2007.

Y. Yasaka, T. Yamamoto, Y. Kurumatani, H. Takeno, Y. Nakashima, T. Cho, Y. Tomita, and M. Ishikawa, "Experiment on direct energy conversion from tandem mirror plasmas by using a slanted cusp magnetic field," *Nuclear Fusion,* 48[3] -.2008.

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