KAPL-P-000180
(K97072)
CONF-970701--

DESIGN AND CONSTRUCTION OF A THERMOPHOTOVOLTAIC GENERATOR USING TURBINE COMBUSTION GAS

G. Nichols, T. A. Erickson, et. al.

July 1997

KAPL ATOMIC POWER LABORATORY SCHENECTADY, NEW YORK 10701

Operated for the U. S. Department of Energy
by KAPL, Inc. a Lockheed Martin company

DISCLAIMER

97201

DESIGN AND CONSTRUCTION OF A THERMOPHOTOVOLTAIC GENERATOR USING TURBINE COMBUSTION GAS

Timothy A. Erickson
Keith W. Lindler
Mark J. Harper
U.S. Naval Academy
Department of Naval Architecture, Ocean, and Marine Engineering
590 Holloway Rd
Annapolis, MD 21402

ABSTRACT:

This U.S. Naval Academy project involves the development of a prototype thermophotovoltaic (TPV) generator that uses a General Electric T-58 helicopter gas turbine as the heat source. The goals of this project were to demonstrate the viability of using TPV and external combustion gases to generate electricity, and develop a system which could also be used for materials testing. The generator was modularly designed so that different materials could be tested at a later date.

The combustion gas was tapped from the T-58's combustor through one of the two ignitor ports and extracted through a silicon carbide matrix ceramic composite tube into a similarly constructed ceramic composite radiant emitter. The ceramic radiant emitter is heated by the combustion gas via convection, and then serves the TPV generator by radiating the heat outwards where it can be absorbed by thermophotovoltaic cells and converted directly into electricity. The gas turbine and generator module are monitored by a data acquisition system that performs both data collection and control functions. This paper details the design of the TPV generator. It also gives results of initial tests with the gas turbine.

INTRODUCTION TO TPV

Thermophotovoltaics is a relatively new science that utilizes previous experience and technology from solar photovoltaics to convert heat energy directly into electricity (1). The technology provides the advantage of having a higher power density than other types of power generation systems currently in use (2). It also offers a distinct advantage of generating electricity with no moving parts that are subjected to wear, cause vibration and noise, or are prone to breakdown. Unlike solar photovoltaics, almost any high temperature heat source can provide energy for thermophotovoltaic cells (3).

EMITTER SIZE

The initial design of the thermophotovoltaic generator started simply as a device that would hold an outer emitter tube and an inner gas extraction tube.

The emitter is designed to radiate heat energy outward onto thermophotovoltaic cells, which convert this energy directly into electricity. However, if the radiated heat is not at the correct wavelength, it will be reflected back, unusable to the cells. Therefore, it is of the utmost importance that the emitter temperature is uniform in order to emit at the appropriate wavelength. The inner gas tube is the component primarily responsible for ensuring the even temperature distribution.

To ensure an even temperature distribution, the generator has a non-porous gas tube and a turning vane at the end to redirect the gas in the opposite direction. This method directs the hottest gases to the upper end of the generator. At the bottom of the gas tube, where the inside gas temperature is greatest, emitted radiation helps heat the lower portions of the emitter. The radiation makes up for the cooler gas at the bottom of the emitter, which traveled both up and down the generator. This design was intensively modeled with a Quattro Pro spreadsheet (4), and selected for the actual generator design.

Based on choked flow calculations for the maximum velocity of the gas exiting the combustor, a ¼ inch inner diameter tube would allow a gas flow rate of 305 lb/hr. However, due to pressure drops and frictional losses from the inside tube surfaces, the actual flow rate will be less. The actual mass flow rate was estimated to be about 200 lb/hr. This flow rate, combined with a specific heat capacity (c_p) value of 0.3 Btu/lb_m °F for high temperature air, and an estimated air temperature drop of 300°F across the generator, yields 18,000 Btu/hr of energy released by the combustion gases to heat the emitter. The central core of the generator, the radiant emitter, radiates energy proportionally to its surface area. For steady state operation, the emitter must radiate at approximately 18,000 Btu/hr. Assuming an emissivity of 0.9 and an emitter temperature of 2400°F results in a surface area of 0.1744 ft^2. Based on a cylindrical geometry and a height of 8 inches, the corresponding outer diameter of the emitter was found to be about 1 inch.

MOUNTING SYSTEM

In order to reduce heat loss, it was decided that the TPV generator would be mounted directly on the gas turbine. A set of brackets was designed that could be bolted to the existing flanges that separate the combustor section from the compressor and turbine sections of the gas turbine.

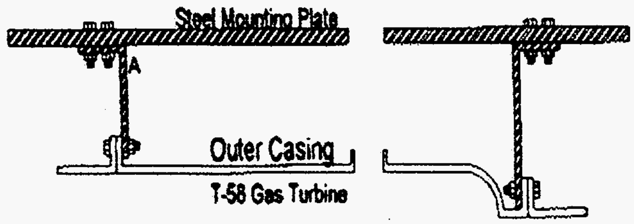

Figure 1. Mounting Plate Installation

These flanges are of different diameters and have different bolt patterns. This required individual design of each of the four brackets that would attach the flat mounting plate to the cylindrical gas turbine. These brackets were then cut from 3/16 inch low carbon steel. Each bracket was bent so that the folded edges would form a parallel surface at the correct plane to provide a flat mounting surface for the TPV module.

The mounting plate itself was cut from the same type of low carbon steel. The mounting plate was ¼ inch thick, 15 inches wide and 20 inches long, large as compared to the initial footprint of the TPV generator, but necessary to accommodate the edges of the four brackets. The oversize also provides a workstation area that could be used for future emitter/TPV experiments. A ¾ inch hole was drilled into the mounting plate to accommodate the gas extraction tube. These components were then assembled on the operating T-58 gas turbine, as shown in Figure 1. The completed generator design is shown in Figure 2.

THREADED RODS

The next components in the assembly of the thermophotovoltaic generator are four threaded ½ inch x 13 stainless steel rods. These rods are the support structure for the entire generator. They are bolted above and below the mounting plate for strength and stability.

The threaded rods keep the emitter tube under compression. The initial design had the emitter sandwiched between two ceramic blocks, held in compression by nuts on the threaded rods. However, it was determined that the compressive stress associated with resisting the emitter's thermal expansion was a fracture risk. If the stainless steel was to accommodate this expansion, it would have to undergo a tensile stress of 32,000 psi, assuming a silicon carbide matrix composite material for the emitter. To eliminate the tensile stress applied to the threaded rods and the compressive stress applied to the emitter, springs have been incorporated into the final design to absorb the expansion of the emitter.

LOWER STEEL PLATE

The lower stainless steel plate (Part C in Figure 2) acts as the base of the thermophotovoltaic generator. Structurally, it is the bottom piece of the generator assembly and applies one side of the compressive force that sandwiches the generator together. The lower steel plate is shielded from the hot combustion gases by a ceramic block.

The lower steel plate is 5 x 5 x ½ inches of type 304 stainless steel. The piece rests atop the four nuts securing the threaded rods to the top of the mounting plate. The plate has four ½ inch holes for the threaded rods. The center has a ¾ inch diameter hole through which the ½ inch outer diameter extraction tube passes.

CERAMIC BLOCK

The ceramic block (Part D of Figure 2) holds both the extraction tube and the emitter, and contains the exhaust passage. It is in thermal contact with the high temperature emitter and extraction tube. A 5 x 5 x 1.5 inch block, was machined to hold the extraction tube and the emitter. This was accomplished by drilling concentric holes of varying diameters at different depths as shown in Figure 3. The center hole was ½ inch in diameter to hold the extraction tube. This hole went completely through the block. Next a ¾ inch hole was drilled into the block to a depth of 5/8 inches. This hole collects and redirects the exhaust gases out of the block through a ½ inch hole drilled from the side of the block. Finally, a 1 inch hole was drilled in the center of the block, extending down ¼ inch. This cut holds the emitter tube.

Due to the complex design of the ceramic block, material selection became extremely important. The material must be able to withstand high temperatures without being adversely affected, yet retain some ability to be machined. When working with ceramics, this seems to be almost a mutually exclusive parameter. The material must also have a small thermal conductivity to limit the heat conducted to the stainless steel components. It must also have a low thermal expansion rate. As the block heats up it will expand, but it cannot expand more than the steel plates that hold it.

The machinable ceramic aluminum silicate was selected. Aluminum silicate is temperature tolerant and will not sublime in an oxidizing environment. It has almost no thermal expansion—after being fired. The alumina silicate, referred to as a "green" ceramic, is easily machined before it has been fired. The block was machined to specifications and then fired. The firing process hardens the ceramic and causes a 2% expansion in size.

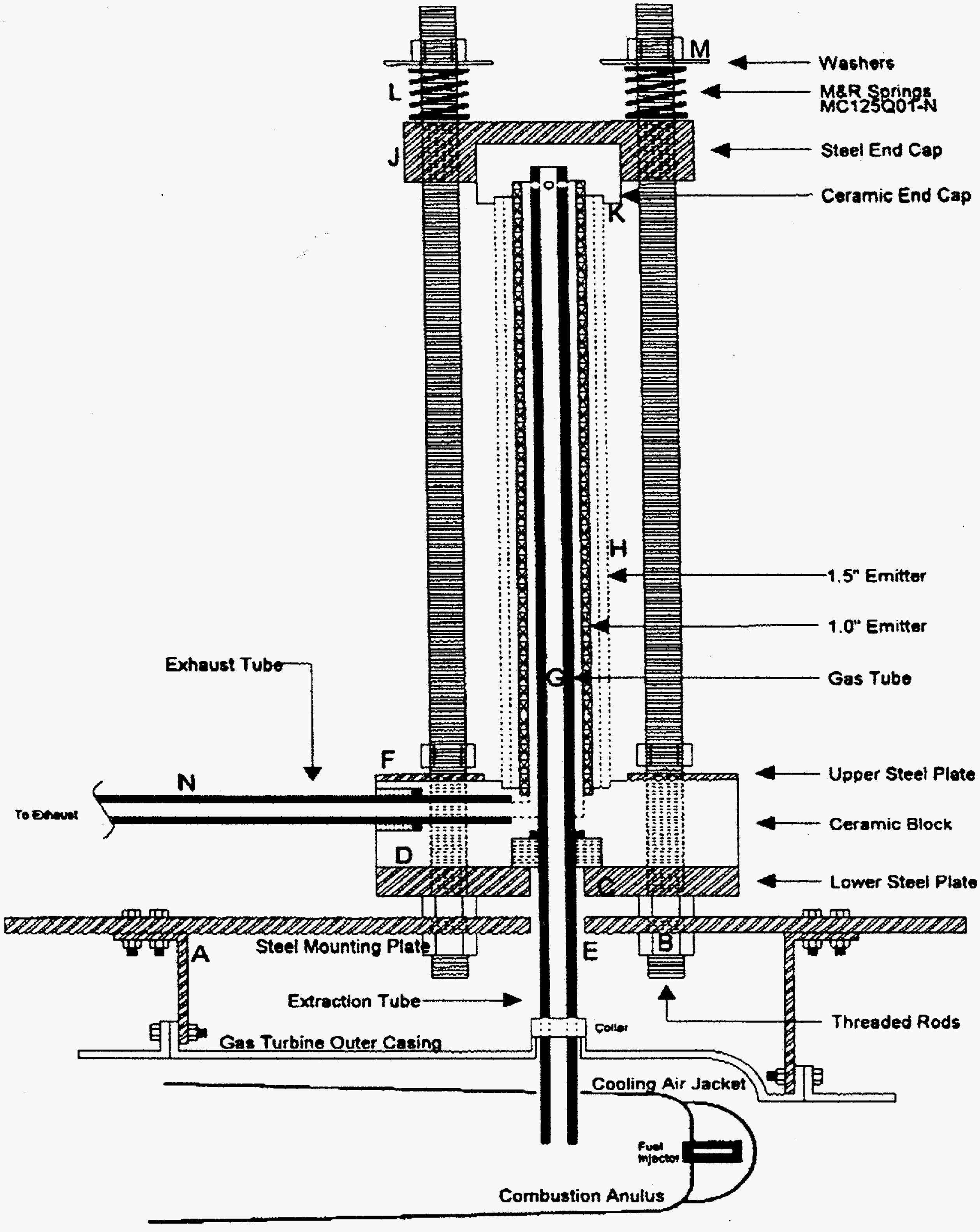

Figure 2. TPV Generator Design

The aluminum silicate material simplifies the attachment of the extraction tube and the gas tube (parts E and G, Figure 2). Since the alumina silicate is easily machined, it was possible to cut a collar from the block and then thread both pieces. This collar compresses an alumina

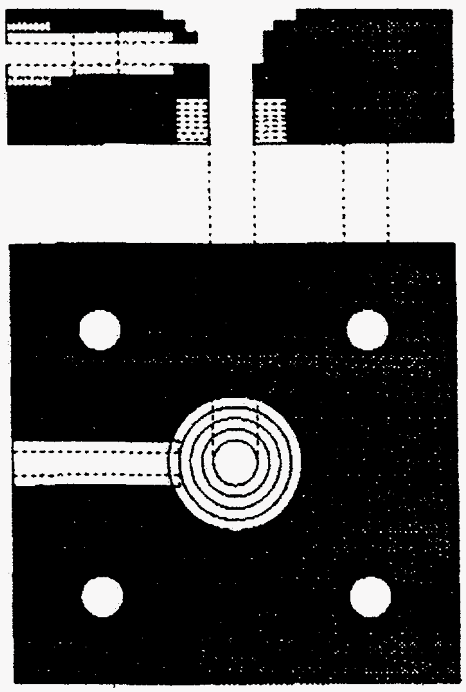

Figure 3. Ceramic Block

fiber seal when screwed in tightly. As the seal is compressed, its inner diameter decreases, forming a tight seal around the extraction/gas tube.

EXTRACTION TUBE

The extraction tube is the small tube that connects the thermophotovoltaic generator to the combustion gases inside the T-58 gas turbine. Failure of this component could destroy the turbine portion of the engine by foreign object damage (pieces of the extraction tube). The extraction tube must be strong enough to withstand the drag force due to the velocity of gas past its outer diameter, while being subjected to combustion temperatures as high as 1900C in an oxidizing environment. It must withstand high thermal shock, since turbine start up will increase its temperature from room temperature to 925C in less than 30 seconds. The extraction tube will also experience a large thermal gradient resulting from the change in temperature between the combustor and the cooling air that flows around the combustor.

Due to the physical and thermal stresses that the component would undergo inside the turbine, a monolithic composite would not work for this application. However, a ceramic composite would work, particularly if a single tube was used for the extraction tube and the gas tube. The single tube would be easier to construct and seal inside the ceramic block. A carbon fiber matrix, densified with an inert ceramic, would be protected from oxidation and yet still be strong.

A collar (part E, Figure 2) was made of aluminum silicate to hold the extraction tube to the top of the outer casing of the T-58 gas turbine. This piece has many of the dimensions of the ignitor it replaced, except that the component is thicker, making it easier to machine. The extraction tube fits in the center of this collar, and is packed with carbon fibers to ensure a gas tight seal. The collar and tube bolt to the pad that originally held the ignitor. The collar holds the extraction tube steady, and prevents combustion gas or cooling air from escaping through the ignitor port.

UPPER STEEL PLATE

The upper steel plate (part F, Figure 2) mounts to the generator above the ceramic block. It provides some structure to the ceramic block and separates the ceramic block from the copper cooling module. Type 304 stainless steel was used for this component because of its resistance to oxidation, especially when heated.

Depending on whether or not the cooling module is installed, the nuts which secure the lower assembly in compression bolt directly on the upper steel plate or just above the lower foot of the cooling module. The upper steel plate distributes the force of these nuts over the 25 in^2 of the ceramic block's top surface.

GAS TUBE

The gas tube takes the combustion gas to the top of the generator where it is turned 180 degrees. The gas then travels in the space between the gas tube and the inside surface of the emitter itself. This is done to get an even temperature distribution across the emitter.

In this configuration, the gas tube must withstand high temperatures in an oxidizing environment. To meet this requirement, the gas tube was combined with the extraction tube, woven as a single piece from carbon fiber and densified with silicon carbide (Ceramic Composites Inc.). The ceramic composite offers the advantage of having high strength and temperatures, while being able to be rolled to any specified diameter. The densification process allows the composite to be designed using materials that will not be affected by the oxidizing environment.

EMITTER

The emitter (Part H, Figure 2) is the heart of the thermophotovoltaic generator. The emitter converts the heat energy from the combustion process into thermal radiation for conversion to electricity by the thermophotovoltaic cells.

The emitter is a hollow tube heated internally by a hot gas through convection. Once hot, the emitter transfers heat to its surroundings, primarily by radiation. This radiation is absorbed by TPV cells and converted into electricity. The size of the tube is dependent on the desired temperature and the mass flow rate of the combustion gas.

Based on an estimated mass flow rate of 200 lb/hr, the emitter can not be larger than approximately 1 inch in diameter. The exact dimension of 1 inch has been chosen for simplicity, since 1 inch is a standard tube size, thus not requiring custom manufacturing or tooling. Provisions for a 1.5 inch diameter emitter have also been incorporated into the design. The generator has been designed with the intention of easily removing the emitter tube and replacing it; thus allowing for different materials to be tested.

The emitter material was optimized for its ability to withstand a high temperature corrosive environment, while maintaining a very high emissivity. The high emissivity requirement further reduces the number of possible materials for the emitter. For the prototype generator, a silicon carbide matrix composite design was formulated (Ceramic Composites Inc.). The prototype was a hand woven, single weave silicon carbide composite, similar to the extraction/gas tube except larger in diameter. The second generation was a triple weave variant of the same dimensions.

COOLING MODULE

The cooling module fits around the emitter and is designed to carry the thermophotovoltaic cells and insure their cooling. Mostly assembled from copper, the cooling module will incorporate gold reflectors in those areas, facing the emitter, which do not carry thermophotovoltaic cells.

The central design of the cooling module is based on ½ inch square copper tubing. The tubing was soldered into four bundles, each consisting of two, 9 7/8 inch tube lengths. These four bundles were soldered to the bottom plate (1/8 inch copper) to form four sides of an octagon centered on the emitter (see Figure 4). Additional ½ inch square tubing connects the four cooling bundles to allow for a single inlet and exit for the cooling water. Filling the four remaining faces of the octagon are copper sheets which have a thin layer of gold on the side that faces the emitter. Fittings for a rubber hose were soldered to two of the bundles for connection to cooling water. The top of the cooling module is similar to the bottom plate, and will be soldered onto the module after installation of the thermophotovoltaic cells.

The cells were mounted to copper plates that were fastened to the inside of the bundles with high temperature adhesive. The copper backing conducts the heat from the cells to the bundles where the cooling water absorbs the heat energy. The flow rate of the water is adjustable and maintains the thermophotovoltaic cells below 90C for more efficient operation.

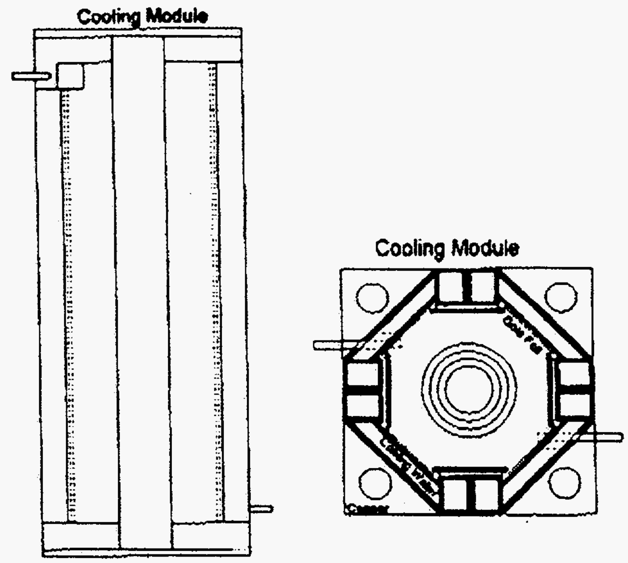

Figure 4. Cooling Module (Cross Section)

STEEL END CAP

The steel end cap (Part J, Figure 5) forms the top of the thermophotovoltaic generator, and is made from type 304 stainless steel. The steel end cap is bored out to make a pocket to hold a ceramic end cap. The steel cap also has four holes for the threaded rods to pass through. It is the only structural member above the emitter and serves as the attachment point for the four sets of springs, washers, and nuts that hold the generator together.

The ceramic end cap is designed to shield the steel from high temperatures, but some heat is conducted into this component; therefore, requiring the non-oxidizing properties of the type 304 stainless. On the top of the steel end cap, four large springs provide approximately 250 lb force to prevent the gas from escaping from around the edges of the emitter.

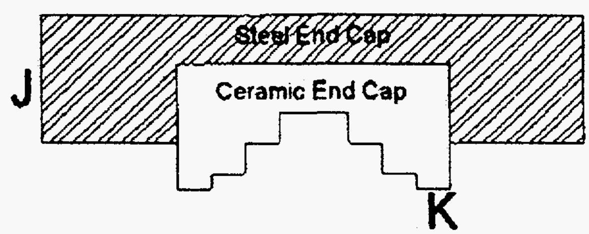

Figure 5. Ceramic and Steel End Cap

CERAMIC END CAP

The ceramic end cap (Part K, Figure 7) fits snugly into the pocket bored from the steel end cap. The ceramic end cap protects the steel from the intense heat and corrosive properties of the combustion gas. The ceramic end cap has several grooves cut in its front surface, which hold the top of the emitter and gas tube in place. It accepts both 1 inch and 1.5 inch diameter emitters.

The ceramic end cap was cut from the machinable

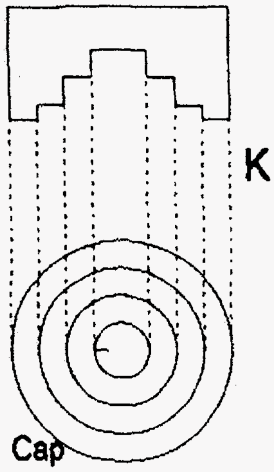

Figure 7. Ceramic End Cap

ceramic aluminum silicate. This component was subject to the same material requirements as the ceramic block. The cap was machined and fired. The dimensions had to be altered slightly for machining to counter the 2% increase in size.

SPRINGS

Concern for compressive stress on the emitter brought about the use of springs to hold the steel end cap in place above the emitter. The springs allow for the expansion of the emitter without stretching the threaded rods. The modulus of elasticity for the emitter is unknown, due to its custom made composite nature. The modulus of elasticity would allow the calculation of the equilibrium deformation of the emitter and the threaded rods, under the expansion of the emitter. The deformation determines the stress on the emitter. Springs allow the end cap to float upwards, absorbing the force of the expanding emitter. By absorbing this force, the emitter will be able to expand as if one end was left free.

As the springs compress due to the expansion of the emitter, some force will be applied in the opposite direction, trying to compress the emitter. Since force on the emitter is to be as low as achievable, the springs must be as small as possible. A worst case expansion for the emitter was calculated using the expansion rate of silicon/silicon carbide, which has an order of magnitude greater expansion rate than other monolithic ceramics. On a 10 inch emitter, the expansion was approximately 0.1 inches. The lightest springs that would fit on the threaded rods produced 6 pounds of force on the emitter when compressed 0.1 inches.

The length of expansion was not the only concern for spring selection. Just as in a turbine, the gas, changing directions 180° on a turning vane, produces a force, calculated to be 247 pounds. This force would lift the steel end cap and the gas would escape in between the top of the emitter and the ceramic end cap. Therefore, springs that could provide at least 247 pounds of force were required. This, however, then places a force of 247 pounds directly on the emitter when no gas is flowing through the generator. To prevent this force from pushing directly down on the emitter, the cooling module has been designed to stop the downward travel of the steel end cap, preventing compression of the emitter when the generator is not operating.

TEMPERATURE PROFILE TEST

In order to determine the optimal insertion depth for the extraction tube, it was necessary to measure the temperature of the turbine combustor. Entering through one of two ignitor ports, a thermocouple was used to measure the gas temperature at the center-line of the combustor and at ± 0.25 inch and ± 0.5 inches from center. The temperature at each depth was taken for a range of turbine operating powers. The temperatures were recorded from 95% of full power down to 56% power (idle speed) in 5% increments. Additionally, the temperature was measured 1 inch downstream from the ignitor port. This thermocouple was destroyed before the power could be changed, but still yielded useful data. This data was corrected for the radiation emitted by the thermocouple inside the combustor.

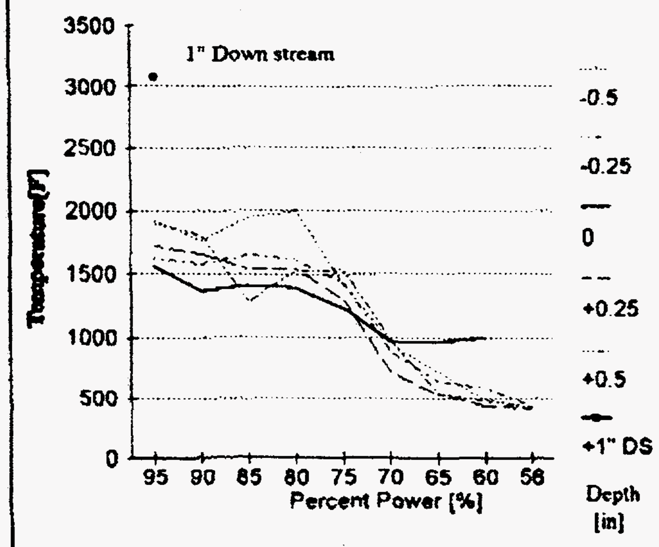

Figure 6. Temperature Profile

The data (see Figure 6) showed that the temperature of the gas at the ignitor port is too low to power the thermophotovoltaic generator. At the ignitor port, the maximum temperature of 2000°F occurred at 80% power at a depth of -0.5 inches from the centerline. However, much higher temperatures were found downstream of the ignitor port. It may be necessary to tap into the side of the combustor if continued combustion in the gas extraction tube is not sufficient to obtain the high temperatures needed for TPV power generation.

PROJECT RESULTS

The following products were the result of the U.S. Naval Academy Thermophotovoltaic Generator Trident research:

1. A comprehensive design analysis was conducted to meet the criteria for a prototype thermophotovoltaic generator. Reference (5) details this design analysis and includes the blueprints for the completed TPV generator. The blueprints contain a step by step assembly of the generator and schematics for all individual components including selected materials.

2. A temperature profile for the T-58 gas turbine combustor was successfully measured. The data collected resulted in a graph that shows the temperature as a function of depth and operating power. This information will be used to determine the optimum placement of the generator's extraction tube.

3. A prototype generator was constructed to the design specifications. Although untested at this juncture, the generator is complete and ready for testing.

CONCLUSIONS

1. There is a sufficient materials technology base to support continued development of TPV generators that utilize combustion gas. These materials are expensive but are available and are potential solutions to the material challenges encountered with the high temperatures of a TPV generator.

2. The temperature of gas at the ignitor port of a T-58 gas turbine is below 2400°F, rendering it impossible to meet desired temperatures for the generator's emitter, unless combustion continues within the extraction tube.

3. Tapping the turbine combustor downstream could yield the necessary gas temperature to heat the emitter to 2400°F.

4. Thermal shock and oxidation are the primary concerns for selecting a material for use in a hot gas powered TPV generator. High strength is also a major concern for the component that is inserted into the turbine. This piece could cause foreign object damage (FOD) if it structurally failed and was swept into the turbine blades.

5. Ceramic composites are the only solution to thermal shock problems encountered with the rapid temperature increase during turbine start-up.

6. It is possible to extract hot gas from the combustor without affecting the performance of the engine.

7. A system for the controlled expansion of the emitter and gas tubes is necessary to prevent extremely large compressive stresses. Springs can be used to provide this controlled expansion.

REFERENCES

(1) Iles, Peter A., "Photovoltaic Principles Used in Thermophotovoltaic Generators," AIP Conference Proceedings 321: The First NREL Conference on Thermophotovoltaic Generation of Electricity, New York: American Institute of Physics Press, 1994.

(2) Krist, K., "GRI Research on Thermophotovoltaics," AIP Conference Proceedings 321: The First NREL Conference on Thermophotovoltaic Generation of Electricity, New York: American Institute of Physics Press, 1994.

(3) Noreen, Darryl, and John P. Brenner. "Heat Sources and the Emitting Surfaces," AIP Conference Proceedings 321: The First NREL Conference on Thermophotovoltaic Generation of Electricity, New York: American Institute of Physics Press, 1994.

(4) Lindler, Keith, USNA TPV. Vers. 1.0. Computer Software, U.S. Naval Academy, 1995. Quattro Pro® for Windows 5.0 or higher 901K, disk.

(5) Erickson, Timothy A., "Design and Construction of a Thermophotovoltaic Energy Conversion System Utilizing Combustion gas from a T-58 Gas Turbine." Trident Scholar Report. U.S. Naval Academy. May, 1997.