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Salvatore M. Oriti and Jeffrey G. Schreiber
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A Stirling Radioisotope Generator (SRG110) is being developed for potential use on future NASA space science missions. The development effort is being conducted by Lockheed Martin under contract to the Department of Energy (DOE). The Stirling Technology Company supplies the free-piston Stirling power convertors, and NASA Glenn Research Center (GRC) provides support to the effort in a range of technologies. This generator features higher efficiency and specific power compared to the currently used alternatives. One potential application for the generator would entail significant cruise time in the vacuum of deep space. A test has been conceived at GRC to demonstrate functionality of the Stirling convertors in a thermal vacuum environment. The test article resembles the configuration of the SRG, however the requirement for low mass was not considered. This test will demonstrate the operation of the Stirling convertors in the thermal vacuum environment, simulating deep space, over an extended period of operation. The analysis, design, and fabrication of the test article will be described in this paper.

Nomenclature

SRG110	Stirling Radioisotope Generator 110 W
GRC	Glenn Research Center
GPHS	General Purpose Heat Source
RTG	Radioisotope Thermoelectric Generator
DOE	Department of Energy
STC	Stirling Technology Company
TDC	Technology Demonstration Convertor
LMA	Lockheed Martin Astronautics
W_e	Watt electric
TRL	Technology Readiness Level

I. Introduction

Lockheed Martin Astronautics (LMA) has been contracted by the Department of Energy (DOE) to develop a radioisotope powered generator for potential use in future space science missions[1]. The generator would ultimately produce 110We from two Plutonium-238 General Purpose Heat Source (GPHS) modules. The generator would use Stirling convertors to convert the thermal power from the GPHS modules to electrical power, and has thus been named Stirling Radioisotope Generator (SRG110). The SRG110 has potential multi-mission applications for Mars surface (i.e., in atmospheres) as well as deep space missions. The SRG110 offers the potential for higher efficiency and specific power than Radioisotope Thermoelectric Generators (RTGs). LMA's preliminary design for the SRG110 is shown in Figure 1. The design consists of two Stirling convertors each being supplied heat by one GPHS module. Each TDC produces nominally $55W_e$.

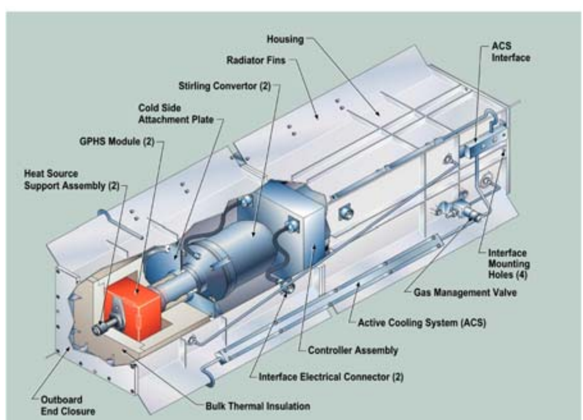

Figure 1.—Preliminary design of the SRG110 by LMA.

The power convertors used in the SRG110 were designed and manufactured by Stirling Technology Company (STC) of Kennewick WA. The convertor was named the Technology Demonstration Convertor (TDC) while being developed by STC under previous contract to the DOE[2]. A schematic of the STC 55W_e TDC is shown in Figure 2. STC is presently a subcontractor to LMA as the development of the SRG110 continues.

NASA Glenn Research Center (GRC) has been conducting research in support of LMA's development of the SRG110[3]. Space science missions that may utilize the SRG110 would involve continuous operation of the generator for upwards of 14 years. In addition to ongoing experiments, the TDCs are planned to undergo testing in a thermal vacuum environment. This is an effort to simulate a mock-up of the SRG110 operating in a relevant environment.

The experiment will use a vacuum chamber (fig. 3) to simulate the vacuum of space, and liquid nitrogen (LN2) supplied cold shroud to simulate space-like temperatures. Operation in a relevant environment will transition the TDC to Technology Readiness Level (TRL) 5. Per request of NASA Headquarters, the TDCs will be operated continuously in the thermal vacuum configuration for the duration of three years.

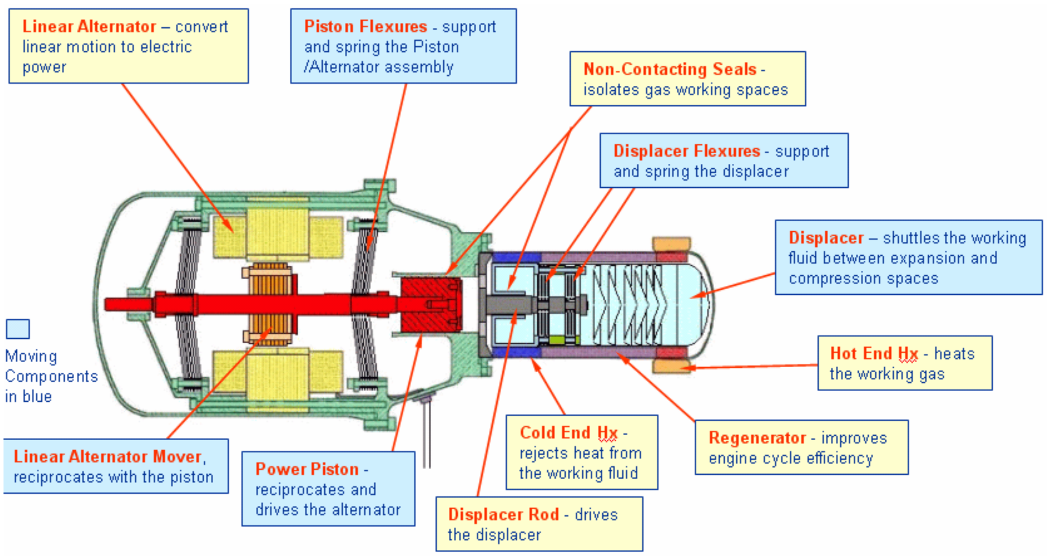

Figure 2.—STC 55 W_e Technology Demonstration Convertor (TDC).

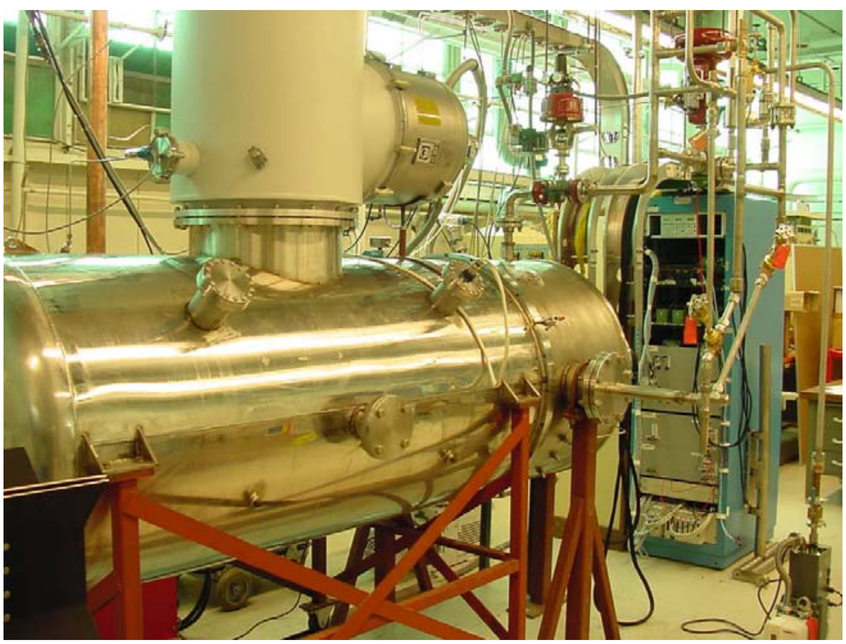

Figure 3.—Vacuum facility 67 at NASA Glenn Research Center.

The TDC makes use of the Stirling thermodynamic cycle. This cycle requires both heat input and rejection. Most testing at GRC employs an electric heater to supply the heat input, and heat is rejected by circulating ethylene glycol through a cooling jacket surrounding the heat rejection zone. When integrated into the SRG110, heat will be supplied by a GPHS module. Heat will be rejected through a radiator that views deep space. For the thermal vacuum test, both the heat input and rejection hardware had to be altered to better approximate the SRG110 setup.

II. Heat Input Hardware Design

Stirling experiments at GRC have employed an electric cable or a set of cartridge heaters to supply heat. In the case of the former, the cable is wrapped around the circumferential section of the heater head corresponding to the hot heat exchanger, and brazed in place. In the case of the latter, a nickel ring is brazed to the same section of the heater head and the cylindrical cartridge heaters inserted into this ring. Both of these mechanisms do not accurately reproduce the method in which a GPHS module would deliver heat to a TDC. The GPHS module is rectangular in cross-section, and must be adapted to the cylindrical heat input zone on the TDC. To simulate how this would be accomplished on the SRG110, a heat collector was conceived that interfaces the two surfaces. Nickel 201 was chosen for the heat collector material because of its ability to withstand the heat input temperature of 650 °C and its material compatibility with the Inconel 718 heater head. For the thermal-vacuum test, a *Boralectric*® electric heater will simulate the GPHS module. This heater is constructed of a graphite element encapsulated by Pyrolytic Boronitride (fig. 5). The heater is held against the surface of the heat collector by an attachment plate, also made of Nickel 201. The plate fastens to the heat collector with four #4-40 screws. See Figure 4 for an illustration of the heat input hardware.

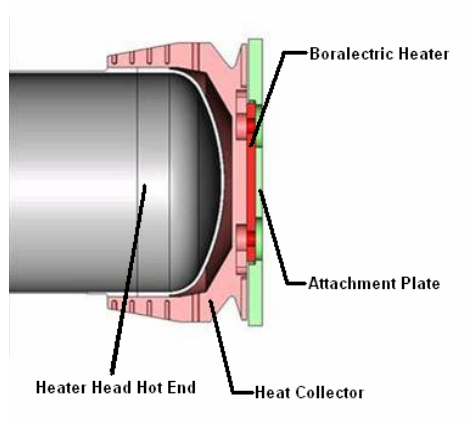

Figure 4.—Heat input hardware.

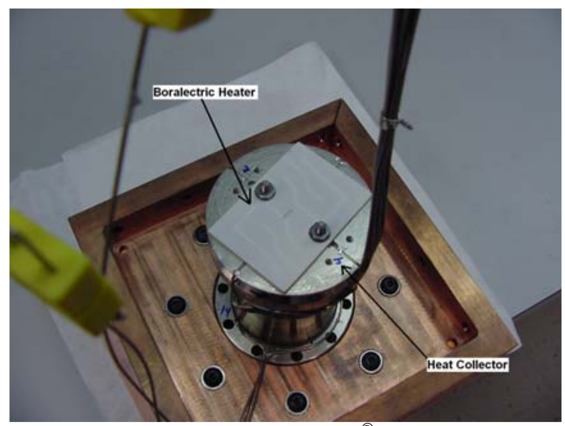

Figure 5 —*Boralectric*® heater.

The TDC is designed to accept heat at 650 °C. It has been estimated that the *Boralectric*® heater temperature will reach 800 °C. Materials were chosen for the fastening hardware to withstand the high temperatures. The fasteners and washers were made of molybdenum. This is the material suggested by Advanced Ceramics, the manufacturer of the *Boralectric*® heater.

The heat collector was designed using the optimizer of the ANSYS finite element (FE) analysis package. The optimizer allows a user to enter design variables, state variables, and an objective function. Design variables may include geometrical coordinates or boundary conditions. State variables may include specific results, such as temperature of a surface, or stress at a certain point. The objective function is a statement indicating what must be satisfied in order for the design to be considered optimized, such as minimize mass, or maximize factor of safety. The user specifies the desired range of the design and state variables. The optimizer algorithm then solves multiple configurations within the design space, defined by the design variables. The algorithm monitors how changes to the design variables affect convergence to the objective function. Configurations in which any of the state variables are outside of their specified constraints are discarded. There are several algorithm options. One method is brute

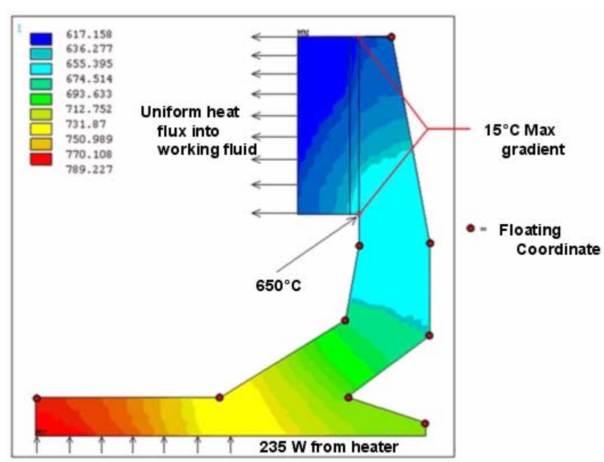

Figure 6.—Heat collector design optimization.

force, in which the optimizer solves every possible configuration of the design space. The configuration that best attains the objective function is the optimal solution. Another method is the gradient algorithm. This method calculates the derivative of the objective variable with respect to each design variable. With this information, the algorithm is able to determine which of the design variables have most effect on the objective, and which are insignificant.

The initial geometry of the heat collector was first conceived by knowing it must adapt the rectangular *Boralectric*® heater to the heater head of the TDC. The FE model used two-dimensional axisymmetric elements. The convertor requires 235 W heat input when operated at full power, so a heat load of -235 W was applied to the inner area of the hot heat exchanger. A heat load of +235 W was applied to the face of the collector. The heat loads were applied in the form of heat fluxes. The heat flux value was calculated by dividing 235 by the appropriate area. The rectangular heater footprint was approximated by a circle of area equal to that of the heater. In the 2–D axisymmetric model, the heat flux in was applied along the radius of this circle. The maximum hot end operating temperature of 650 °C was applied at the hottest point of the heater head. The convertor operates most efficiently with a uniform temperature along the heat input zone. Since the heat source is remote (as opposed to the cable or cartridge heaters), an axial temperature gradient along the heated zone results. The temperature gradient along the axial direction of the heat input zone was defined as a state variable and limited to a maximum of 15 °C. See Figure 6 for illustration. The maximum temperature of the heat collector was defined as a state variable and limited to 800 °C. The objective function was set to minimize mass. Figure 6 depicts the final geometry attained by the optimizing algorithm.

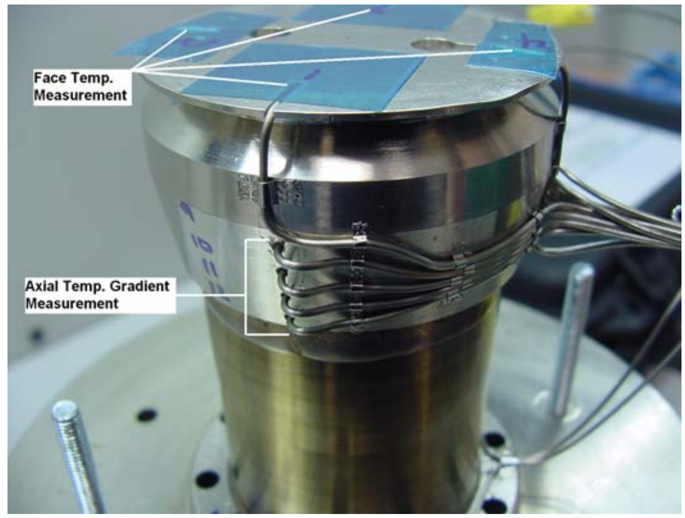

Figure 7.—Heat collector thermocouple instrumentation.

The heat collector was instrumented with type-K thermocouples to validate the results of its design. The axial temperature gradient along the heat collector will be measured at four points, and in two quadrants opposite each other on the heat collector. The face temperature will be monitored at four locations as shown in Figure 7.

The heat input hardware and regenerator section of the TDC heater head are insulated by *Min-K*® *1302* insulation (fig. 11). *Min-K*® *1302* is a machinable, ceramic, micro-porous insulation manufactured by Thermal Ceramics. The insulation design consists of a stack of overlapping layers. The overlapping seams help reduce the line of sight from the heater to the cold shroud.

III. Heat Rejection Hardware Design

Testing at GRC employs a cooling jacket to extract the waste heat from the Stirling cycle. The jacket forms an annular gap around the cold end of the TDC. Ethylene glycol, or a mixture of water and glycol is circulated through the gap. A remotely situated chiller is used to control the temperature of the circulating fluid. The chiller is connected to the jacket with tubing. When integrated into the SRG110, the heat will be rejected by a radiator that views space. For the thermal vacuum test, the heat rejection mechanism was designed to better simulate operation in the relevant environment.

The LMA preliminary design of the SRG110 uses a flange to couple the rejection side of the convertor to the radiator housing. To approximate this setup in the thermal vacuum test, each convertor will have a set of four radiation panels coupled by a flange to their cold sides. Required radiation panel area was estimated using the Stefan-Boltzman equation. A hybrid flange was designed consisting of an inner nickel 201 layer sandwiched between two copper layers as

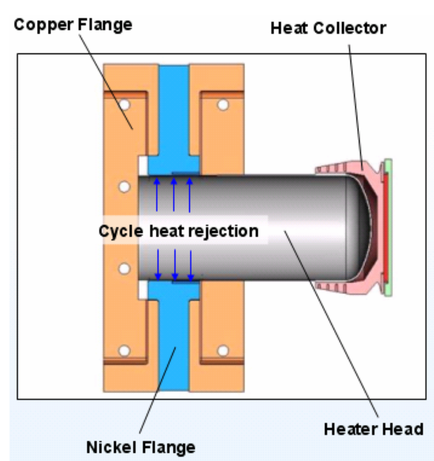

Figure 8.—Hybrid heat rejection flange.

shown in Figure 8. The nickel 201 section is brazed to the heat rejection zone of the TDC. The copper layers increase the effective thermal conductivity of the flange. The layers are held together with a bolt pattern. Layers of *Thermagon*® thermal interface material are placed between mating surfaces to improve thermal contact resistances (fig. 10). The aluminum radiation panels are bolted to the outer faces of the copper flanges, as shown in Figure 11. The panels are coated with IITRI MH2200 optical absorber coating. This increases the emissivity of the aluminum from ~0.2 to at least 0.8.

The geometries of the nickel and copper sections were determined by design iterations in ANSYS. The symmetry of the rejection flange allowed simplification of the model geometry. The model was defined about two perpendicular adiabatic planes simplifying the model to a 1/8 section. When operated at full power, the convertor is designed to reject 170W at a cold-end temperature of 80 °C. Therefore, the flange design was required to conduct 190W (for ~10% over-design) with a temperature drop of no more than 15 °C as shown in Figure 9. The thicknesses of each layer were varied within the allowable physical limits until the mass was minimized while still meeting the thermal requirements. This analysis did not make use of the automatic ANSYS optimizer as was used for the heat collector design. Instead, the model was setup parametrically with a command file. The use of the command file enabled rapid solving of different design iterations. Provisions for fine tuning the cold-end temperature have been integrated into the heat rejection system. An auxiliary cooling loop is attached to one side of the flange. This will allow a remotely situated chiller to add or extract a small amount of heat to trim the cold-end temperature. Figure 10 shows the exploded view of the heater head assembly.

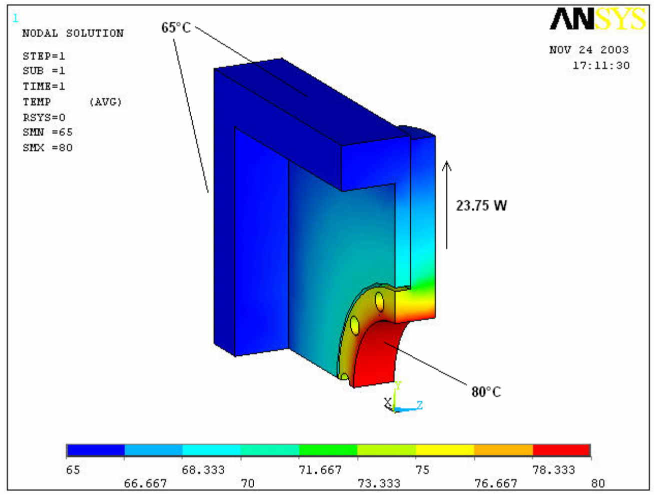

Figure 9.—Heat rejection flange thermal simulation.

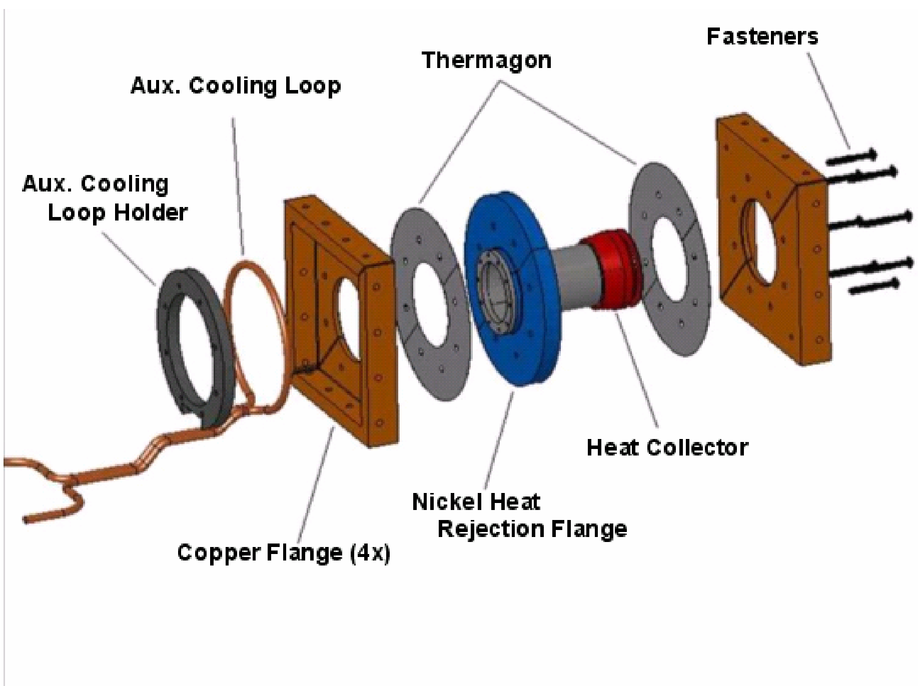

Figure 10.—Heater head assembly with heat input and rejection hardware.

IV. System Level Thermal Analysis

The thermal vacuum test article consists of two TDCs arranged in the "dual-opposed" configuration. This means that the convertors will be rigidly mounted to each other, and situated with their alternator ends facing each other. The two convertors are then attached to the mounting structure in the vacuum tank. Figure 11 illustrates the configuration of the test article.

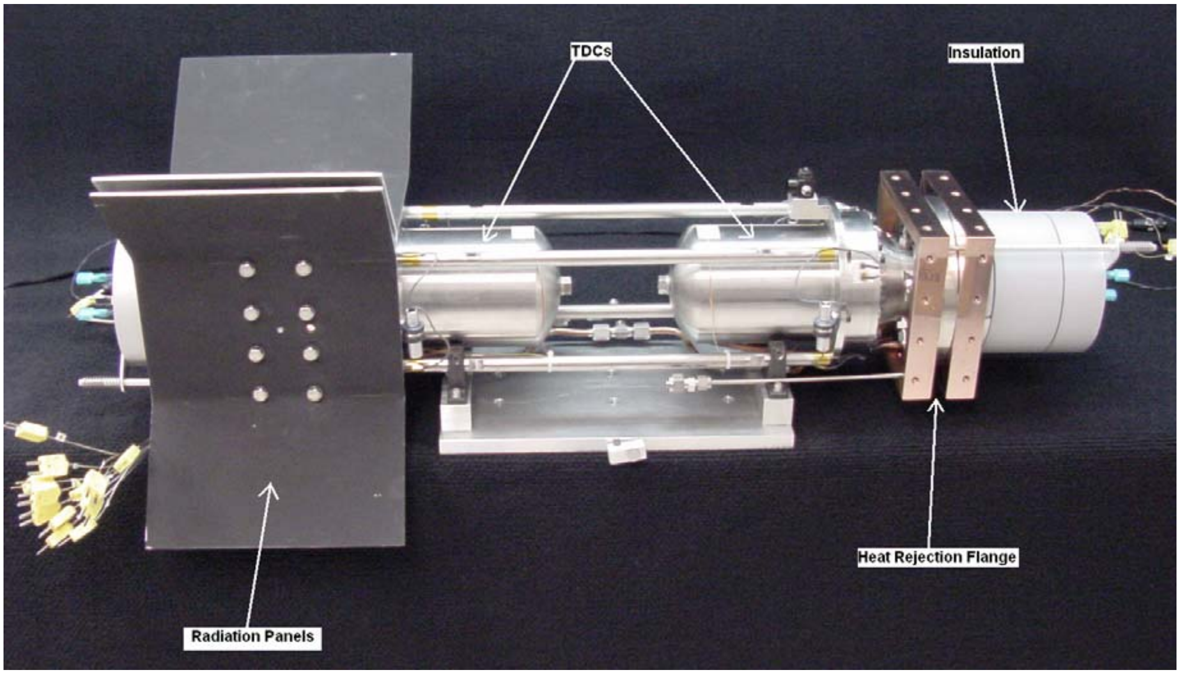

Figure 11.—Thermal vacuum test article with one set of radiation panels removed.

A system level thermal analysis was performed to obtain temperature estimates of various components during steady-state operation. A three dimensional model was constructed in ANSYS. The geometry consisted of one of the convertors and its supporting hardware (radiation panels, heat rejection flange, heat collector, insulation, etc.). The same boundary conditions were applied as those used in the analysis of the heat input and rejection hardware. Figure 12 illustrates the boundary condition setup. A heat load of +235 W was applied to the face of the heat collector, evenly distributed over the area occupied by the heating element. A heat load of -220 W was applied to the inner diameter of the heater head, along the region occupied by the hot heat exchanger. A heat load of +170 W was applied to the inner diameter of the heater head along the region occupied by the cold heat exchanger. The alternator heat generation was approximated by applying a heat load of 10 W to the inner diameter of the alternator housing (alternator not shown). Each heat load boundary condition was applied in the form of heat flux. The heat flux values were calculated by dividing each heat load by the appropriate area. A space node temperature of -109 °C was used to which all components radiated. This simulated the LN2 cold wall which will surround the test article.

One goal of the system level thermal analysis was to estimate the heat rejection temperature of the TDC. The TDC has been tuned to operate at an 80 °C rejection temperature. The analysis was performed twice, with two different length radiation panels. The results indicated that the heat rejection flange coupled to the smaller set of panels will provide sufficient cooling to maintain a cold-end temperature below 80 °C. In addition to the rejection temperature, the alternator housing temperature is important. During testing the alternator housing must be kept below 80 °C to maintain the magnets at a temperature well below their demagnetization temperature. The results of the analysis indicated that alternator housing will be at a temperature below 80 °C.

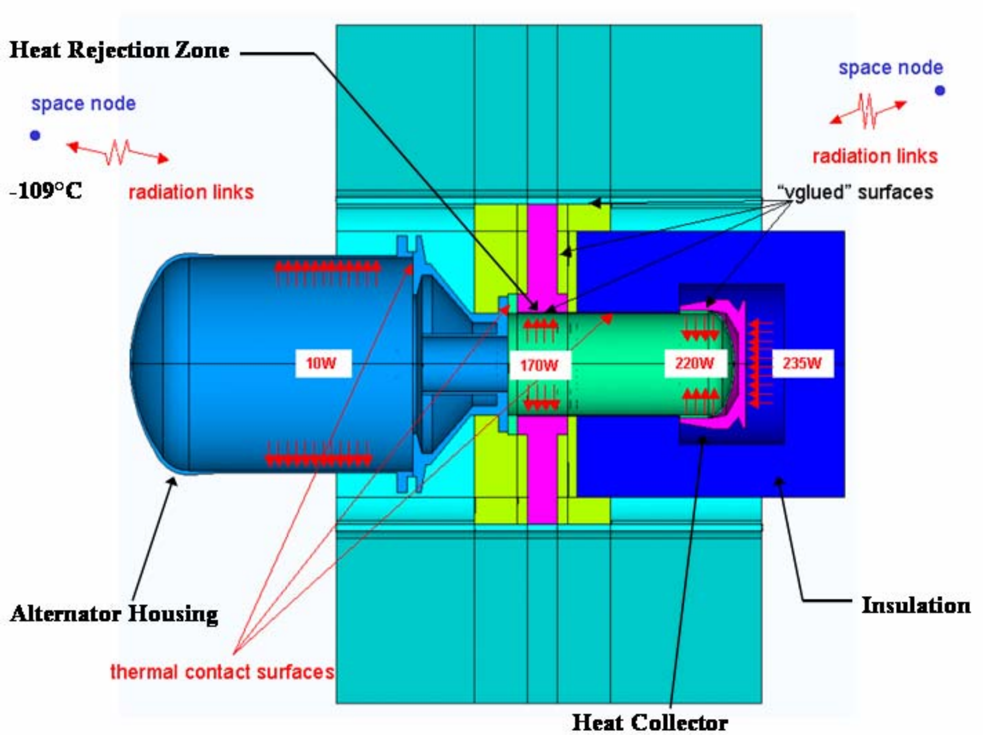

Figure 12.—Thermal simulation boundary conditions.

V. Conclusions

In order to demonstrate use of Stirling power conversion in a relevant environment, a thermal-vacuum test was conceptualized. The necessary hardware was designed to adapt the convertors for operation in this configuration. Thermal FEA was performed using the ANSYS software package. Finite element analysis proved to be a useful tool during the design phase of the components. Once the designs were solidified, a system level thermal analysis was performed. The results of this analysis suggest the convertor will be able to perform at full operating capability in the thermal-vacuum environment.

The current plan for testing includes an initial check-out to show operation with the new heating and cooling mechanisms in the new environment. After the initial check-out, the TDCs will under go a 500hr.'bake-out' procedure in which they will be evacuated while being heated to approximately 75 °C. The goal of the bake-out is to drive out impurities that may have dissolved into the internal components of the convertor. After the impurities have been removed, the convertors will be charged with high-purity (99.999%) helium to the necessary pressure. After successful completion of these items, continuous, unattended operation will commence. The plan calls for three years of cumulative continuous operation.

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