Nuclear and Emerging Technologies for Space, American Nuclear Society Topical Meeting
Richland, WA, February 25 – February 28, 2019, available online at http://anstd.ans.org/

DESIGN OF ETG FOR LOW ORBIT TEST OF THE KOREA LAUNCH VEHICLE

Jintae Hong[1], Kwang-Jae Son[1], Jong-Bum Kim[1], and Jin-Joo Kim[1]

[1] *Department of HANARO Utilization and Research, Korea Atomic Energy Research Institute, 989-111 Daedukdaero, Yuseong-gu, Daejeon 34057, Republic of Korea, +82-42-868-4420, jthong@kaeri.re.kr*

Korea Aerospace Research Institute will launch a satellite for a low-orbit test of the Korea Launch Vehicle in 2021. An electrically heated thermoelectric generator (ETG) with mass of 850 g will be one of its payloads. To assure the design heritage and the reliability of the ETG in the space environment, a small ETG will be tested at the top of the satellite for more than a year. In this study, an ETG with 10 W of heat input was designed through simulations such as heat transfer analysis, modal analysis, thermoelectric analysis, and structural analysis. In addition, a mockup was fabricated and basic performance tests were carried out.

I. INTRODUCTION

Generally, an electrically heated thermoelectric generator (ETG) that uses an electric heater as a heat source needs to be developed prior to the development of a radioisotope thermoelectric generator (RTG). When all the tests related with mechanical and electrical performances are finished using the ETG, the RTG can be made by replacing the electric heater with a radioisotope heater unit. In Korea, research on an RTG was started in 2016 in accordance with a plan for the launch of a lunar explorer (Ref.1). After the conceptual design for the RTG with 120W_{th} of heat input, an ETG was produced and basic performance tests were carried out. In addition, a satellite intended to verify the performance of the Korean launch vehicle was planned for 2021, and the ETG was selected as one of the payloads to check its reliability in the space environment. The payload of the RTG developed for lunar exploration is less than 7 kg and produces 5 W_e of electric power at 120 W_{th} of heat output. However, the payload of the ETG on the performance verification satellite is limited to 850 g. Therefore, we decided to develop an ETG with electric output of about 200 mW with 10 W_{th} of heat input. In the ETG performance test, 10 W of electric power with 28 V of unregulated voltage will be supplied to the heater in the ETG. The surface temperature of the satellite body will be kept within the range 0-15 ℃. In this study, the dimensions of the ETG were chosen with reference to the Russian Angel RTG (Ref. 2,3), and the conceptual design was carried out according to the heat flow. Several finite element (FE) simulations, including such as structural analysis, heat transfer analysis, and vibration analysis were carried out to design the thermal control mechanism, thermoelectric module, and structure. Then, a mockup was fabricated and its performance was tested in a vacuum chamber.

II. DESIGN AND ANALYSIS OF ETG

Because the Russian Angel RTG weighs 800g and the heat output is known to be 8 W_{th}, the initial design of the ETG was made similar to the shape of the Angel RTG, as shown in Figure 1. Then, the design of each module was changed using various simulations.

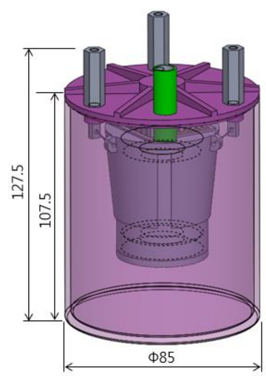
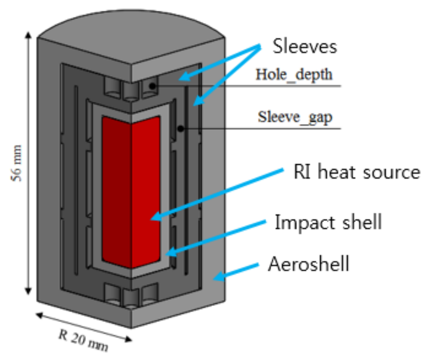


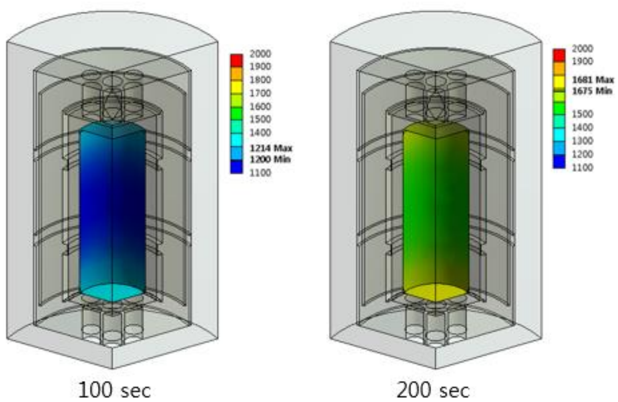
Fig. 1. Initial design of the 10 W_{th} ETG (Type 1).

II.A. Heat Source Protection Module

Although an electric heater is used for this ETG, its volume is the same as that with a plutonium heat source with thermal power of 8 W_e. Because the electric heater will be replaced with radioisotopes when it is used in a space mission, a module to protect it from reentry accidents should be developed. The heat source protection module for re-entry accidents is made of carbon composite. According to Hong (Ref. 4), a heat flux of 2 MW/m^2 is generated with a 0.4 kW_e plasma machine. This is similar to the heat flux that would occur on the surface of the radioisotope heater unit (RHU) in a reentry accident. According to Hong's experiments, when an air plasma with heat flux of 2 MW/m^2 is applied to a carbon composite, the recession rate is 0.5 mm/min. Assuming that the aerodynamic heat affects the RHU for 200 s during a reentry accident, the thickness of the aeroshell needs to be at least 5.0 mm if the safety factor is set at 3.0 for redundancy. Based on this, the sleeve and impact shell were designed through heat transfer analysis, and the results are compared in Figure 2. The analysis results show that the maximum capsule temperature will be about 1681 ℃ after 200 s of aerodynamic heating when the depth of the hole at the sleeve cover, and the gap between sleeves, is 6 and 4 mm, respectively.



(a) RHU design for 10 W_{th} ETG



(b) Temperature distribution of heat source capsule during aerodynamic heating (hole depth:6 mm, sleeve gap: 4mm)
Fig. 2. Design of RHU for 10 W_{th} ETG by heat transfer analysis.

II.B. Design Assembly Structure of ETG

It is estimated that heat loss would be about 18% through the heat transfer analysis of the initial design, Type 1 (Figure 3). The thermoelectric module was designed using a thermoelectric design simulator developed by Kim (Ref. 5). As shown in Figure 4, vibration analysis shows that the primary resonance mode occurs at 617 Hz, and this satisfies the design criteria of the Korean launch vehicle: 100 Hz. However, because the first, second, and third modal shapes show that the heat source fixture moves like a pendulum, the heat source could be disassembled during the resonance. Although an insulator is to be placed between the heat source module and the case, two types of assembly structure were designed to enhance the integrity of the heat source module, as shown in Figure 5. Heat transfer analysis and vibration analysis were carried out for the new ETG designs. Figure 6 shows the results of the heat transfer analyses for ETG Type 2 and Type 3. Type 2 loses 1.95 W_{th} of heat by radiation and conduction through chains. Type 3 loses 1.58 W_{th} of heat through radiation and by conduction through chains and insulator. Therefore, the Type 3 design showed the best heat transfer efficiency.

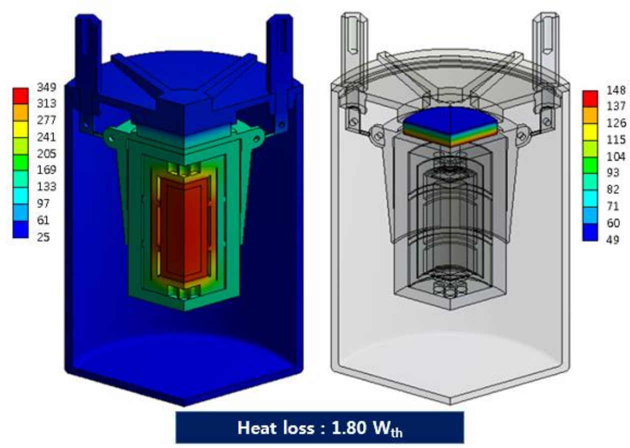
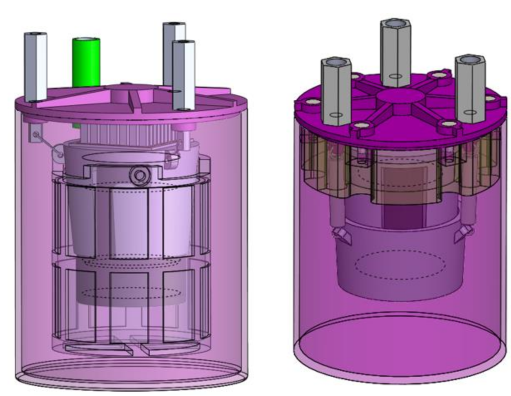


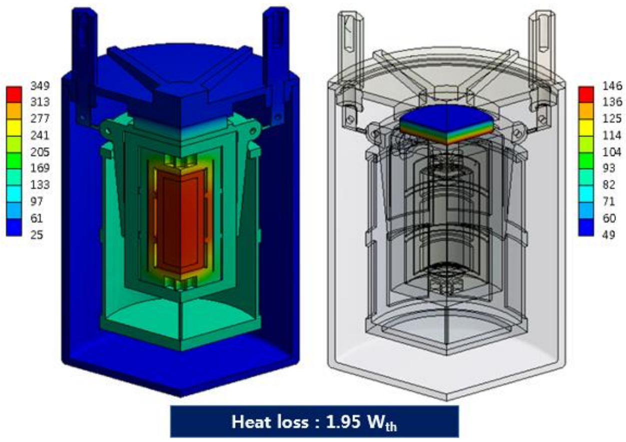
Fig. 3. Heat transfer analysis of the ETG assembly.

Fig. 4. Modal analysis of the ETG assembly.

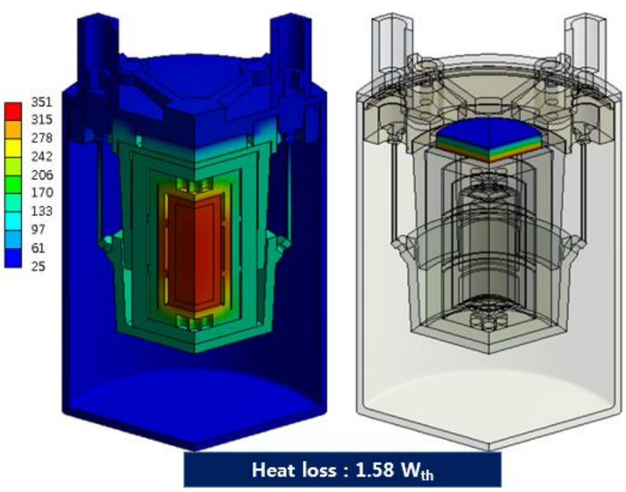


(a) Type 2 (b) Type 3
Fig. 5. Improved ETG design.

According to the results of the vibration analysis, the primary resonance frequency of Type 2 was 499 Hz. The first, second, and fourth resonance occurred in the heat source module. The primary resonance frequency of the Type 3 was 1235 Hz. In addition, the first, second, and third resonance occurred at supports, and the heat source had little effect from the resonance. Therefore, the Type 3 design showed satisfactory heat transfer efficiency and vibration resistance.



(a) Type 2



(b) Type 3

Fig. 6. Heat transfer analysis of improved ETG design.

II.C. Thermoelectric Module Design

Based on the results of the Type 3 analysis, assuming that 8.42 W_{th} heat power is transferred to the thermoelectric module, the thermoelectric module was designed as shown in Table 1 using the thermoelectric module design simulator developed by Kim (Ref. 5).

TABLE I. Design variables of a thermoelectric module for a 10 W_{th} of heat source.

Design Variables	Unit	Value
Leg length	mm	p type: 2.96 n type: 2.96
Leg section area	mm^2	p type: 1.4 n type: 1.4
Number of pairs		31
T_h (hot shoe temperature)	K	407
T_c (cold shoe temperature)	K	307
Heat loss	%	15.8
Contact resistance	$\mu\Omega/cm^2$	380
Output voltage / power	Volt/Watt	0.857/0.35
System efficiency	%	3.5

The thermoelectric material selected was BiTe, and the dimensions of the legs were 1.4 × 1.4 × 2.96 mm. Thirty-one pairs of legs had to be integrated within a 30 × × 30 mm direct bonded copper (DBC) substrate, and it was estimated that the module would generate 350 mW_e of electric power. However, in general, the empirical electric power of a thermoelectric module is 60 - 80% of the theoretical value due to manufacturing errors and low material uniformity. Therefore, the electric power will most likely be about 210 - 280 mW_e.

III. TEST OF ETG PROTOTYPE PERFORMANCE

The Type 3 ETG prototype of which the design was described in the previous section was fabricated using aluminum alloys, as shown in Figure 7. The ETG supports were attached to the satellite main body, and the heat generated by the heater of the ETG flows to the satellite main body through the supports. Therefore, the ETG prototype was fixed on a plate of which the temperature was maintained at 5 ℃ by water cooling. In addition, the ETG was put in a 10^{-3} Torr vacuum chamber to remove any convection effect owing to the air, as shown in Figure 8. Then, the performance of the ETG was tested by applying 10 W_e of electricity to the heater.

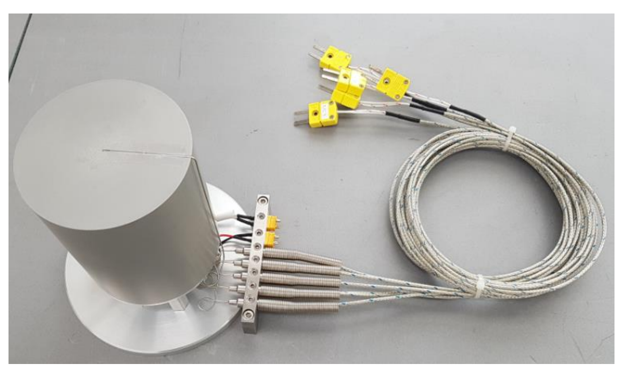


Fig. 7. Fabrication of the ETG Mockup.

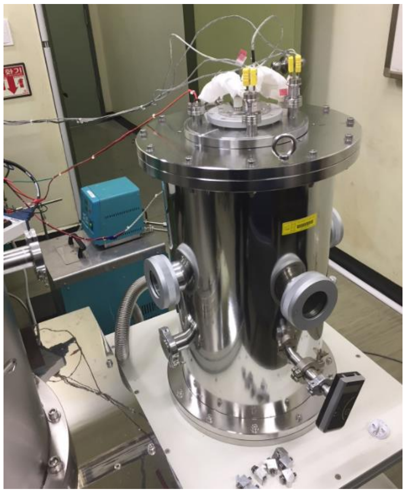


Fig. 8. Installation of the ETG in the vacuum chamber.

As shown in Figure 9, the ETG achieved steady state in 3.5 h. At that time, the temperature of the heater was 604.7 K, and the temperature at both ends of the thermoelectric module were 413.6 K (140.6 ℃) and 300 K (27 ℃). The electric output was 0.821 V and 195 mW_e, 55.7% of the theoretical figure. When the thermoelectric module array was checked by visual inspection, some legs were found tilted from the correct position in the DBC.

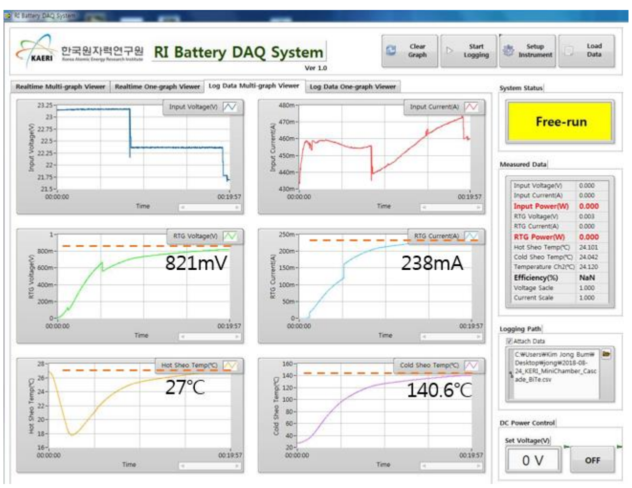


Fig. 9. System efficiency of the ETG prototype.

IV. CONCLUSIONS

A mini-ETG to be used for a reliability test in the space environment was designed with reference to the Russian Angel RTG. The original design was improved through several FE analyses such as heat transfer analysis and vibration analysis. Then, a prototype was fabricated using aluminum alloys and carbon composite. BiTe was used to fabricate the thermoelectric module.

The performance test of the ETG prototype was carried out in a vacuum chamber. When the electric heater in the ETG was turned on, the ETG achieved steady state in 3.5 h. At steady state, 195 mW_e of electric power was generated from the ETG, which is 55.7% of the theoretical estimate. The error is mainly due to defect from the brazing process used for the legs and to low uniformity of the thermoelectric material. It is not difficult to improve the brazing process by making jigs, and the thermoelectric conversion efficiency will be increased.

In the near future, the reliability test and qualification test for the space vehicle will be carried out. Once the test results satisfy certain criteria, the ETG will be installed in the satellite of the Korean launch vehicle to be launched in 2021. During the low orbit test of the satellite, 5 hours, 3 months, and 1 year performance tests will be carried out to check the ETG performance.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (2016M1A3A9005565).

REFERENCES

1. J. T. Hong, K. J. Son, J. B. Kim, J. H. Park, J. J. Kim, and T. H. Yang, "Design status of Korean nuclear battery for lunar exploration," Proc. of Korean Society for Aeronautical and Space Science, Autumn meeting, Jeju, Korea, November (2015).
2. L. Summerer, *Technical Aspects of Space Nuclear Power Sources-Radioisotope Heater Units*, ACT-RPT-2327-RHU, ESA, (2006).
3. A. Pustovalov, *Mini-RTGs on Plutonium-238: Development and Application*, 18th International Conference on Thennoelectrics, (1999).
4. B.G. Hong, *Development of the heat protection model of the RTG for lunar mission using a plasma wind tunnel*, ChonBuk National univ., (2017).
5. J. B. Kim, K. J. Son, J. T. Hong, and J. H. Park, *Development of Analysis Program for Radioisotope Thermoelectric Generator using One Dimensional Heat Transfer Model*, KAERI/TR-5923/2015, KAERI, (2015)