Thermal Design of the Satellite Energization and Radiation in Geospace

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The thermal control design of the Energization and Radiation in Geospace satellite (ERG) is presented. ERG is a spin-stabilized science research satellite with an orbit altitude that varies within 300–30000 km so as to pass the orbit of the Van Allen Belts. Because of this orbit, ERG will be exposed to a severe space environment. ERG will be lanched in 2015 by an Epsilon-2 rocket from the Uchinoura Space Center. ERG is divided into two elements: a bus system and a payload system. The payload system has plasma and particle sensors, electric field and plasma wave sensors, and magnetic field sensors. The mission is to study Solar Cycle 24 by direct measurement of space storms. ERG is controlled mainly by passive thermal devices. Due to the mission requirement, the thermal material must be radiation resistant and the surface must be electrically conductive. We carried out thermal balance tests at ISAS in September 2013 by using IR panels.

Nomenclature

Ag teflon	=	Silverized Teflon
BAT	=	Batteries
ERG	=	Energization and Radiation in Geospace Satellite
IR	=	Infrared
ISAS	=	Institute of Space and Astronautical Science
ITO	=	Indium Tin Oxide
JAXA	=	Japan Aerospace Exploration Agency
MLI	=	Multi-layer Insulation
OSR	=	Optical Solar Reflector
RCS	=	Reaction Control Subsystem
RTV	=	Room-temperature Vulcanization Silicone Gum
SAP	=	Solar Array Panel
TMM	=	Thermal Mathematical Model

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TTM	=	Thermal Test Model
α	=	Solar Absorptance
ε	=	Hemispherical Emissivity

I. Introduction

The Energization and Radiation in Geospace (ERG) satellite is developed by the Institute of Space and Astronautical Science (ISAS)/Japan Aerospace Exploration Agency (JAXA). This project is aimed at exploring the behavior of relativistic electrons in Earth's radiation belts behave.[1] In this mission, we will observe plasma and particles across a wide energy range and electric and magnetic fields across a wide frequency range to understand particle acceleration and loss mechanisms and the dynamical evolution of space storms. The ERG will be launched during the declining phase of Solar Cycle 24 by an Epsilon-2 rocket from the Uchinoura Space Center.

II. ERG System

Figure 1 shows an image of the configuration of ERG. The orbit is elliptical with an orbit altitude between about 300 and 30000 km. ERG is a sun-oriented satellite and spin-stabilized with a spin rate of 7.5 revolutions per minute. It is divided into two parts: the payload system (top part) and the bus system (base part). The main part of the base has already been developed except for some portions for satellite control, which are likely to be used other satellite. Therefore, we need to newly develop the payload system. The development goals for this are low cost, rapid development, and increasing the capacity for development of equipment typical of space science missions.

The bus system of ERG uses a developed bus of the same type as used in HISAKI (launched in September 2013), which is the world's first space telescope for remote observation of the planets, particularly Venus, Mars, and Jupiter, from an orbit around the earth. The size of the bus is about 1 m^3, which makes ERG a small satellite. This is located on the bottom of the satellite and is mounted on the main system of the satellite—the battery (BAT), solar array panel (SAP), reaction control system (RCS), etc. All side panels (±X, ±Y) have radiative surfaces. The payload system has scientific sensors to observe plasma and particles. The mission system does not have power and BAT, so this is supplied from the bus. In the payload system, the size of the base is a bit larger than typical and about 60 cm high. The scientific instruments are all mounted on side panels. The total mass is estimated at 350 kg, which is typical for a small satellite.

ERG has 8 sensors: four electron sensors (LEP-e, MEP-e, HEP-e, and XEP-e) measure electrons from 12 eV to 20 MeV; two ion sensors (LEP-i and MEP-i) measure ions from 10 eVq^{-1} to 180 $keVq^{-1}$; an electric field sensor and plasma wave sensor (PWE) observes from DC to 10 MHz and from a few hertz to 100 kHz, respectively; and a magnetic field sensor (MGF) observes the ambient magnetic field. This mission has three research teams: the observation team, a ground-based network observation team, and the integrated data analysis and simulation team.

ERG will be exposed to high-intensity radiation as it repeatedly passes through the Van Allen belts. A radiation-resitant surface and a electrically conductive surface are needed to ensure mission survival and to acquire data without noise.

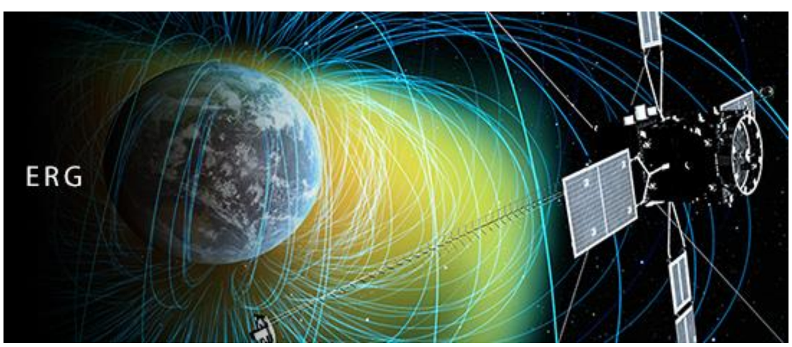


Figure 1. ERG configuration image

III. Thermal Design Requirements

There are three requirements on the thermal design. First, all equipment should be maintained their temperature limits until the end of mission. Second, the thermal control materials used in ERG need to be radiation resistant because ERG passes through the Van Allen belts to make direct observations. Third, all of the satellite's surface materials must be electrically connected to the panels to prevent charging and remove the noise.

The ERG development time of three years is challenging. The ERG uses the same bus system as HISAKI. This system was developed as a small standard scientific satellite bus, and has the benefits of being low in cost and quick to build, so that it can be ready for launch. On the other hand, a new thermal design must be created for each mission because of changes in the surrounding thermal conditions.

IV. Thermal Control

ERG's thermal control is independent between the bus and the payload system, which is a standard concept in bus design. Insulating spacers and multi-layer insulation (MLI) are located in-between the bus and the payload system. The amount of heat exchange and the boundary temperature are defined at the interface point. However, power for the heater is supplied from the bus's BAT. ERG has another interface points between the payload system and each sensors. These interface points define the boundary temperature, the contact conductance, and the heat generation density.

ERG is controlled by passive thermal techniques: an optical solar reflector (OSR), Ag Teflon (i.e., silverized Teflon), paints, and MLI. The main surfaces with the highest emitted radiation are installed along the ±X and ±Y planes so that they are not directly exposed to sunlight. All equipment must be able to withstand low temperatures because the sun is eclipsed for about 2 hours during some parts of the orbit. When the surface temperature drops to below the ordinary range, the components draw a significant amount of heat to maintain permissible temperatures. Therefore, we would like to minimize radiation from surfaces to conserve power.

Electrically conductive thermal control material will be used on the outer surface of the satellite because this is necessitated by the mission goal of observing low-energy particles. Therefore, Black Kapton film (160XC), OSRs and Ag Teflon with an indium tin oxide (ITO) top coat, and conductive white paint were selected. In addition to selecting appropriate surface materials, it is necessary to ensure that no non-conductive materials appear on the surface.

V. Thermal Development Test

We had two challenges in the course of development. One is the MLI tended to be released; the other is that the Ag Teflon, used as a radiative material, degraded under irradiation. We tested all other systems, which resulted in some changes in design from the preliminary design review.

A. MLI perforation

ERG is launched nominally by an Epsilon-2 rocket. During the launch of the rocket, peeling and withdrawal from the structure of MLI is a concern because rapid decompression of the fairing occurs. The Epsilon-2 rocket undergoes more rapid decompression than the HⅡ-A rocket does. It is therefore necessary to design the MLI in a way that eliminates the possibility of peeling during launch. One method is to perforate the MLI, which eliminates peeling at the cost of insulation performance and may allow direct sunlight to pass through the perforations. We therefore seek a design that minimizes the ratio of holes to total area and still eliminates peeling. To this end, we performed pressure reduction tests by using MLI in a thermal test model (TTM) on the ground and recreating the pressure reduction profile of the Epsilon-2 rocket. The left panel of Fig. 2 shows the test setup and the right panel of the figure shows the pressure profiles of an Epsilon-2 rocket and an HⅡ-A rocket.

Unfortunately, the MLI was peeled off by swelling during testing in the case of only anti-aligned holes (left panel of Fig. 3). We observed expansion of the MLI by up to about 3 cm. To remedy the expansion, we changed to through holes without changing other conditions. As a result, the MLI no longer expanded (right panel of Fig. 3). This shows that through holes are effective for releasing the air between films.

It is important to test for interference with the field of view because the mission requires a clear view along the panels, the fixed deployment parts, and the extension mechanism.

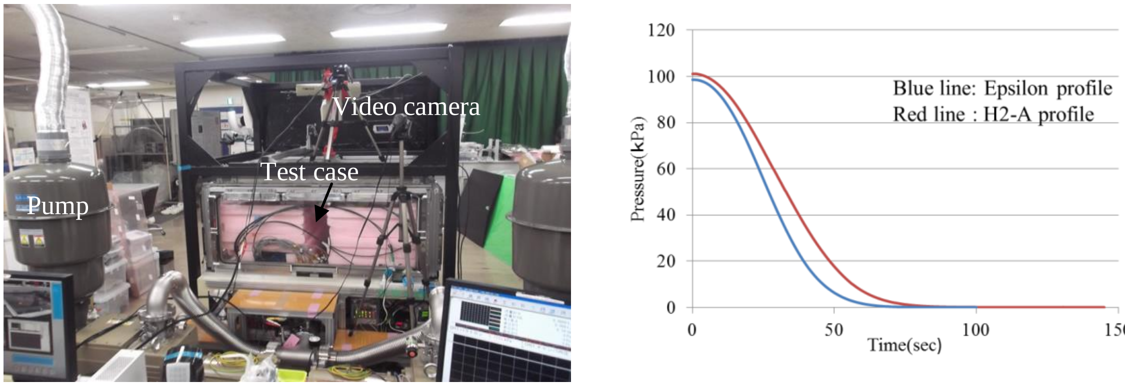


Figure 2. Test configuration (left) and pressure profile (right)

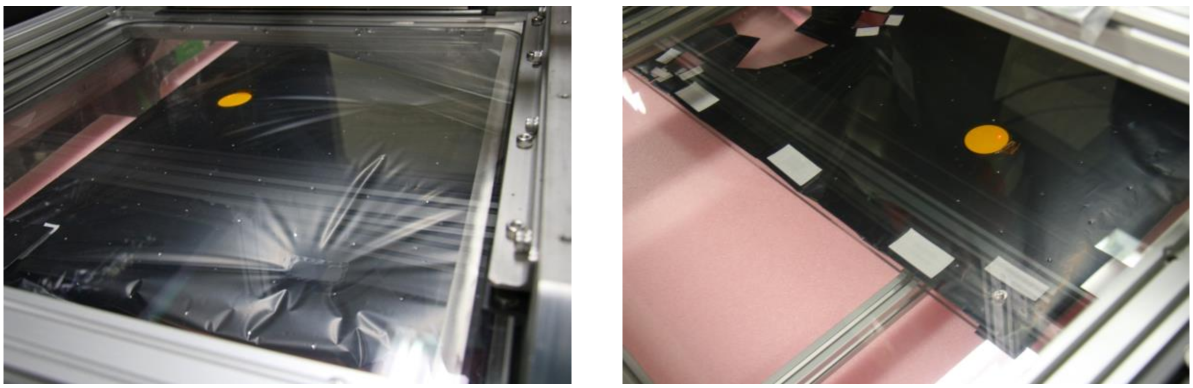
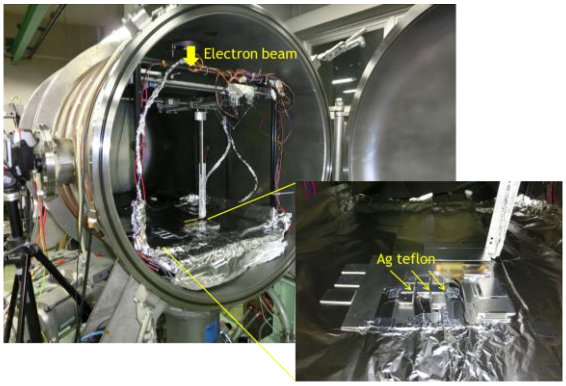


Figure 3. Test of anti-aligned holes (left) and through holes (right)

B. Electron irradiation test

ERG will pass through the Van Allen belts, and therefore it is necessary to use thermal control materials radiation-resistant. We had planned on using Ag Teflon as a thermally radiative surface because it is quick and easy to mount. This reduces both costs and effort by reducing the amount of working hours needed for insulation, in addition to which the material cost is lower than other OSR candidates. The overall performance of Ag Teflon as a thermally radiative surface is good when the material costs, handling costs, and shedule for installation are considered. However, it is well-known from experiences with the Hubble Space Telescope, [2] LDEF, [4] and some ground tests [3] that Ag Teflon film is deteriorated to failure by exposure to the space environment, and particularly to radiation, including ultraviolet radiation, and atomic oxygen. For ERG, we plan to use Ag Teflon monted on the side panels with adhesive. Even when Ag Teflon deteriorates from space radiation, its thermal control properties are maintained so long as it does not come loose from the panel. Before deciding to use the Ag Teflon, we tested it under electron irradiation to be certain that it offered the necessary radiation resistance and thermal control properties.

We estimated the total electron dose that ERG would receive in one year from SPENVIS data. We used two levels of beam energy: low energy (10 keV) and high energy (1 MeV). Ag Teflon was installed on Al plates with either double-sided adhesive tape or RTV and vertically irradiated by electrons. ERG requirements also stipulate surface electrical conductivity, so an ITO coat was applied to the Ag Teflon. The range of 10-keV electrons is too short to penetrate the Teflon, and so low-energy irradiation damaged the only Teflon surface; the 1-MeV beam, in contrast, passed through both the teflon layers and the adhesive. Figure 4 shows setup of each test. During the vertical irradiation of electrons, the surrounding environment was kept in a vacum or N_2 flow condition except for the presence of atomic oxygen.



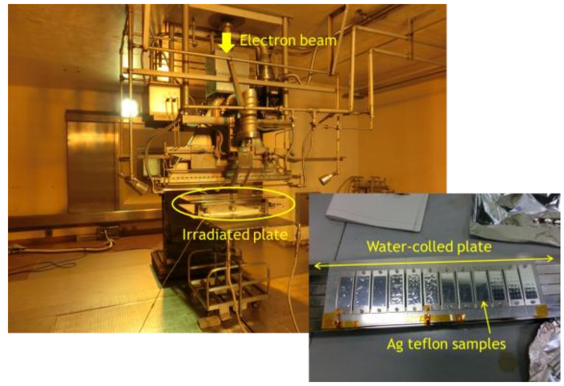


Figure 4. Test setup for low-energy electrons (left) and high-energy electrons (right)

During the low-energy electron irradiation test, the Teflon surface turned slightly yellow and developed a few white spots. Small scratches appeared and the entire surface became rough (Fig.5). All degradation from the electron beam affect only surface appearance. We were concerned that the ITO top layer would be damaged and lose conductivity, but this did not occur, and the α and ε values were little changed.

During the high-energy irradiation tests, the Teflon and adhesive were both detertiorated. Ag Teflon was bonded by double-sided type (Y9704) and irradiated by an electron dose equivalent to the estimated dose from 1.5, 3, 6, 12, or 24 months of on-orbit exposure. At the time of irradiation for 1.5 months, the samples were affected by outgassing from the adhesive surface, which indicates that the adhesive tape is not flat and has partially separated from the panels. If a gap is formed between the panel and the Ag Teflon, then this part will have decreased thermal conductance and reduced effective emissivity. In such cases, heat dissipation may become inadequate. Additional samples of Ag Teflon were examined. Local detachment points appeared around the perforations in about 20% of the area in the samples. To address this, the tape was replaced by RTV, which undergoes less outgassing than the double-sided tape. However, the RTV also lifted, though on a smaller (4%) area. After a 6–month dose, signs of degradation appeared in the Teflon, such as cracks and breaks. However, α and ε were not significantly affected. If we use Ag Teflon, then we need to estimate the degradation rate and analyze the thermal model under the assumption of decreasingly effective thermal radiation.

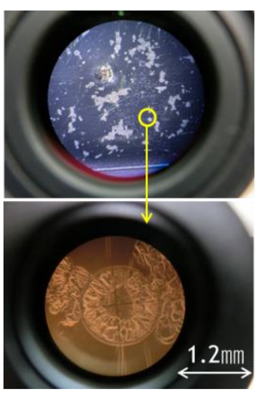


Figure 5. Result of low-energy irradiation

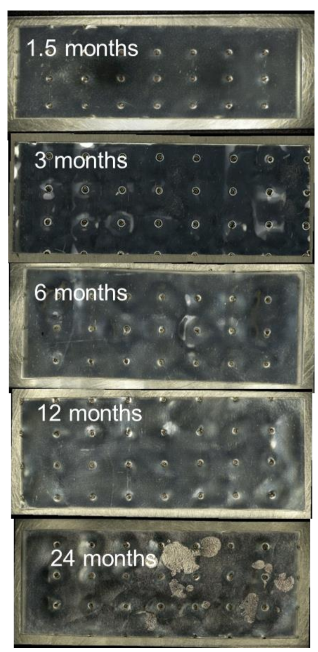


Figure 6. Result of high-energy irradiation

VI. Thermal Analysis

The thermal designs of ERG's bus and payload system were analyzed individually. For the payload system, each mission component was analyzed. A thermal mathematical model (TMM) of the payload system was built that accounts for each mission component. After the suitability of the thermal design of the mission system was verified, a whole-system model was constructed to include the mission-system model and the resulting ERG model was analyzed by using Thermal Desktop. The interface between the bus and payload system is defined by two constraints: border temperature and amount of heat exchange.

We simulated performance of the launch and on-orbit conditions. Five different cases were analyzed, one hot and four cold: (1) the hot worst cases where all sensors were turned on in the maximum sun-shine period, (2) the cold worst cases where all sensors were turned on in the maximum eclipse period, (3) the survival mode where all sensors turned off in the maximum eclipse period, (4) the minimum observation mode-1 where the limited number of sensors ware turned on and (5) mode-2 where the only CPU and PSU was turned on. The power resources are strained by the long time spent in eclipse, so it may be necessary to limit observations during cold periods.

VII. Thermal Balance Test

The TTM of ERG's payload part was tested with IR panels at ISAS in September 2013. ERG's bus has already tested as a standard bus, and the thermal conditions of ERG were assumed during testing. Therefore, we plan to test only the flight model because we consider the development of the bus to be complete. In contrast, the payload system is unique to ERG, having been newly developed and tested with IR panels.

ERG's payload system has many sensors and a TTM was prepared for each. Testing provided confirmation of the validity of the thermal design and model, the interface between the bus and payload system, and each payload sensor and its mounting. The TTM was surrounded by IR panels to simulate heat input during orbit. The test configuration is shown in Fig. 7. We carried out the examination for two hot modes and three cold modes: (1) the worst hot and cold modes where all sensors were turned on, (2) the survival cold mode where all sensors were turned off, (3) additional hot and cold modes in order to increase the accuracy of the correlation.

As the results, the stipulated temperature data were matched and the goal were achieved. After correlating the TMM to the experimental results, the temperature difference between the simulated and measured temperatures was brought to within about 5 °C, and heater power was confirmed to within 5 W. Additionally, the prescribed conductance was obtained.

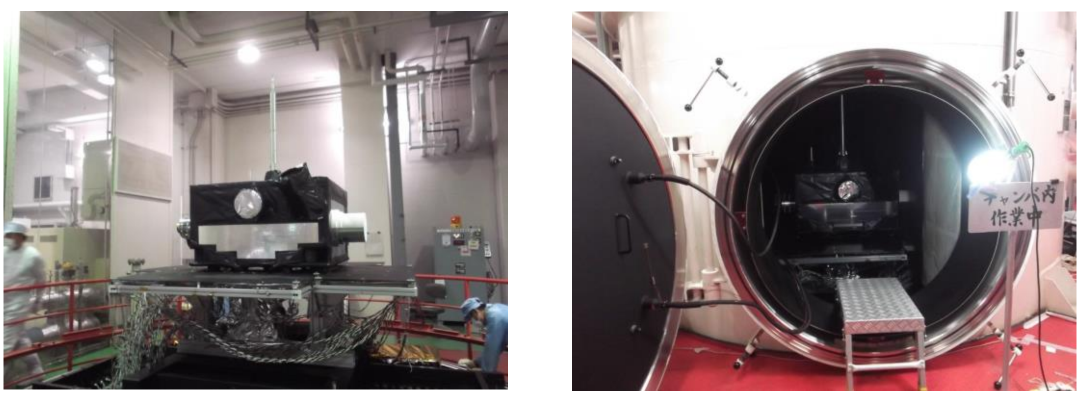


Figure 7. Thermal balance test configuration

VIII. Conclusion

The thermal design of ERG was described in this paper. The thermal and system requirements have been fulfilled. ERG's thermal model completed the thermal test, and the correlated model confirmed that ERG should achieve acceptable temperature ranges for each part during its orbit.

Acknowledgments

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