Super Low Temperature Endurance Test and Thermal Analysis for Night Survival on Moon

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Abstract
The moon surface temperature varies violently, such as 120°C at noon and -180°C at night. In order to carry out the mission, night survival is the one of the most important issues. Since, super low temperature endurance test was performed to some devises. In addition, using the ANSYS, thermal analysis software of finite element method, temperature response of the lunar regolith and the rover were obtained.

月面夜間保温に向けた極低温環境試験と熱解析

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月の表面温度は昼夜で激しく異なり、赤道付近では、正午には120℃まで上昇し、夜間には-180℃まで下がる。そこで、現有機器の低温耐性はどの程度か、試験した。

又、有限要素法の熱解析ソフトであるANSYSを用いて、月面の熱数学モデルを作成し、レゴリスの温度応答を求めると共に、レゴリス上のローバの温度応答を求めた。

1. Introduction

Now, a new moon lander plan is starting to be studied. This is a progressive plan instead of the existing moon soft landing plan (SELENE-B). The different item from the SELENE-B is mission length, the lander stops activity at night on moon and starts mission again when the day breaks. The lander intends to carry out mission for approximately 1 year at cycles of working at daytime after night survival.

The environmental outline of the moon surface is shown below.

- High Vacuum
- Daytime: about 15 earth days, Nighttime: about 15 earth days
- Sunlight irradiation intensity 1421 W/m² (Max.)
- Moon surface temperature day: rises to 120°C, night: descends to -180°C

Although lander studies at daytime have been done well until now, night survival study for lander has been seldom performed. For this reason, on the beginning night survival study at moon, supper low temperature endurance test of equipment was started.

2. Supper low temperature endurance test

2-1 Outline of Test

After preparing test equipment and confirming that its function is normal, the test equipment is placed in the space chamber. The space chamber is exhausted to a vacuum, hereafter cooled down by liquid nitrogen and held environment of -180°C over 24 hours in order to keep the test equipment to supper low temperature. Then, the space chamber is returned to room temperature and opened the door and taken out the test equipment. After confirming that the functions of the test equipment are normal, supper low temperature endurance is evaluated.

The outline of space chamber is shown in Fig. 1. Profile of endurance test is shown in Fig. 2.
2-2 Test Equipment

Test equipment for super low temperature endurance test is desirable to fulfill next conditions. It fulfills space equipment specification and is normal in function and permits to be broken at the test. Although engineering model of satellite is considered as such equipment, the flight model of the SFU (Space Flyer Unit) could be used in this endurance test.

The SFU was developed as a free-flying space platform, launched by the H-II on March 1995 and retrieved by Japanese astronaut Koichi Wakata boarded the Space Shuttle using the manipulator on January 1996.

The equipment used the satellite is normal in function and was used at this test under comprehension that it has no problem even if it breaks in the test, since the original mission was finished. As test equipment, four SFU flight models and two commercial motors for vacuums were selected. The details of them are shown in Table 1.

Table 1 Test Equipment

<table>
<thead>
<tr>
<th>Equipment Name</th>
<th>Size (cm)</th>
<th>Main Parts</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-band Hybrid</td>
<td>7x5x1</td>
<td>Board, Connector</td>
</tr>
<tr>
<td>S-band Diplexer</td>
<td>20x7x7</td>
<td>Filter, Diode</td>
</tr>
<tr>
<td>S-band Switch</td>
<td>5x4x1</td>
<td>Coil, Diode</td>
</tr>
<tr>
<td>S-band Transponder</td>
<td>25x20x10</td>
<td>Transistor, IC</td>
</tr>
<tr>
<td>Small Motor for Vacuums</td>
<td>φ 1.7x7</td>
<td>Motor, Magnetic Encoder</td>
</tr>
</tbody>
</table>

2-3 Test Result

Super low temperature endurance test performed for 4 days in a row. The temperature profile from start to end is shown in Fig 3.

The problems of this test are summarized below.

- Both cool down and warm up speed were too
rapid to keep 6°C/h as planned.

- The temperature rise had happened in the trouble at the time of unmanned automatic operation at night. Therefore, duration to keep the test equipment under supper low temperature turned into 48 hours. (our plan was 24 hours)
- Because of not enough thermal contact to cooling board, some pieces of test equipment could not reach at -180°C.

Evaluation of cooling condition at the test is shown in Table 2.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Equipment Name</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Under -180°C</td>
<td>S-band Hybrid</td>
<td>Keeping over 24hours continuously</td>
</tr>
<tr>
<td></td>
<td>S-band Diplexer</td>
<td></td>
</tr>
<tr>
<td>Under -160°C</td>
<td>S-band Switch</td>
<td>Keeping over 24hours continuously</td>
</tr>
<tr>
<td></td>
<td>S-band Transponder</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Small Motor</td>
<td></td>
</tr>
</tbody>
</table>

2.4 Evaluation of Performance

After the space chamber was returned to room temperature, performance confirmations of them were performed using a network analyzer.

As a result, the S-band transponder contained IC board did not work correctly. The others contained passive devices, such as connectors, filters and switches, were normal. The motors rotated normally and the encoder output signals were also normal.

The detailed investigation about the cause of failure of S-band transponder is underway.

3. Thermal Analysis

In order to estimate night survival ability of lander and rover on the moon, temperature response caused by the sunlight irradiation, the moon surface radiation at daytime, thermal radiation at night was obtained by using thermal analysis. In this analysis, the ANSYS, a thermal analysis software based on the finite element method, was used.

3.1 Condition of Thermal Analysis

Physical properties of the regolith that covers moon surface widely and the aluminum alloy, which is the main material of the lander and rover, are shown in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>Regolith</th>
<th>Aluminum Alloy</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>density ( \rho )</td>
<td>1680</td>
<td>2690</td>
<td>Kg/m³</td>
</tr>
<tr>
<td>specific heat ( c )</td>
<td>700</td>
<td>847</td>
<td>J/Kg·K</td>
</tr>
<tr>
<td>thermal conductivity ( \lambda )</td>
<td>0.1～1.0</td>
<td>130</td>
<td>W/m·K</td>
</tr>
</tbody>
</table>

In order to shorten calculation time, the values of the density and specific heat were made 1/150 and 1/10 respectively in the calculation. This means one second in the calculation corresponds to 1500 second in the actual time. Therefore, a half-day on the moon, 15 earth days, becomes 864 seconds.

The solar irradiation intensity was given as heat flux \( F \) to the surface which is exposed to the sun light. \( F \) from \( t=0 \) is given by the following formula during two days and nights.

\[
F = 1400 \sin(nt/864) \quad t=0 \sim 864, \quad 1728 \sim 2592
\]

\[
F = 0 \quad t=864 \sim 1728, \quad 2592 \sim 3456
\]
3-2 Rover Model on the Moon

The rover model on the moon surface is shown in Fig. 4. The size of the moon surface is 10x10 m, the size of the rover main part is 80x80x60 cm and the emissivity of the moon surface equals to 1. The upper surface of rover is covered with OSR and other surfaces are covered with MLI. The emissivity of the upper surface and other surfaces are 0.8 and 0.6, respectively. The sunlight absorptivity of the rover upper surface is 0.2. Moreover, the contact heat conduction coefficient TCC is set up between regolith and the wheels of the rover. It is assumed that TCC is 10. Since they are exposed to the space environment, surrounding temperature of -270 degree C is used.

3-3 Rover Temperature Response

Above-mentioned thermal flux $F$ was given to the moon surface and thermal flux of $0.2 \times F$ was given to the upper surface of the rover, and the temperature responses were calculated. The result is shown in Fig. 5.

![Fig 4 Rover Model on Moon](image1)

![Fig 5 Temperature Responses](image2)

It was found that the temperatures decreased at the beginning. The reason why was that the initial temperatures of both the rover and the moon surface were set 0°C. The surface temperature of the moon became 120°C at noon, and -180°C before dawn, respectively. These results were in agreement with above-mentioned environment of the moon. The rover temperature at noon was 60°C. This means that the temperature rise was suppressed well by the OSR. However the temperature of the rover continued falling at night and reached under -160°C before dawn. This result shows that the thermal conditions on the moon surface are very severe.

As a reference, the temperature distribution at noon is shown in Fig 6. The reason of high temperature under the rover is caused by not considering the shadow of the rover itself.

3-4 An example of heat insulation at night

For night survival, two active methods have been proposed. One is method that the rover is warmed by electrical heaters with batteries. Another is method that the rover is warmed by the heat energy stored in the TES(thermal energy storage) during daytime. It is disadvantageous that these methods require additional weight and space on the rover.

On the other hand, passive method does not require any additional weight and space. A survival method that uses regolith as a heat insulator at night was proposed. The effect of heat insulation of regolith tunnel was examined here. The tunnel model is shown in Fig 7.
The regolith size is 2.2x2.2 m and the tunnel diameter is 2 m, so the thickness of the thinnest regolith in the upper part of the tunnel is 10 cm. An aluminum cube of 1x1x1 m simulates a lander or rover. And it is assumed that it is floating at the center of the tunnel. The models having tunnel length of 5 m and 10 m were used.

An extreme case was assumed here. The emissivity ε=1 was given to the upper surface of regolith, the inner wall of the tunnel, and outer surface of the rover. The closed space temperature is -270°C. The temperature response of both 5 m and 10 m tunnels at the regolith thermal conductivity λ=0.5 and λ=0.1 are shown in Fig 8 and Fig 9, respectively.

Also, examples of temperature distribution at noon and before dawn are shown in Fig. 10 and Fig 11 respectively. The temperature change of the rover in the second day is shown in Table 4.

From this table, it is understood that the rover temperature changes are smaller than that without tunnel, and heat insulation by the tunnel is quite effective. Moreover, it is found that the longer tunnel has the higher effect of heat insulation. The lowest temperatures in the case of 5 m and 10 m tunnel were suppressed up to -100°C and -80°C, respectively.

Similarly, the result of changing the thickness of regolith is shown in Table 5 at 10 m tunnel.

From Table 5, it can be said that 50 cm or more thickness of regolith has no effect in the case of λ=0.1. In addition, if the rover has appropriate thermal insulation device, such as MLI, the lowest temperature in the Table 5 can be improved further because the rover is not covered with the MLI in this simulation.

4. Conclusions

For night survival on the moon, supper low temperature endurance test was performed. As a result, it was confirmed that passive equipment could withstand low temperature condition, however active equipment lost function.

In addition, the effect of heat insulation using regolith tunnel as passive survival method was evaluated by thermal analysis. Although the effect depended on the conditions, the lowest temperature of rover was suppressed up to -80°C even if the rover was covered with the regolith of 10 cm in the tunnel of 10 m. And the lowest temperature was able to be suppressed up to -55°C if the rover was covered with the regolith of 1 m. If the rover has appropriate thermal insulation device, such as MLI, the lowest temperature in the Table 5 can be improved further because the rover is not covered with the MLI in this simulation.
Fig 8  Temperature Response at $\lambda = 0.5$  

Fig 9  Temperature Response at $\lambda = 0.1$  

Fig 10  Temperature Distribution at noon  
($\lambda = 0.5, \text{ Length}=10\ m$)  

Fig 11  Temperature Distribution at dawn  
($\lambda = 0.5, \text{ Length}=10\ m$)