# Thermal Behavior of Spacecraft Liquid-Monopropellant Hydrazine($N_2H_4$) Propulsion System

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# 인공위성 단기액체 하이드라진($N_2H_4$) 추진시스템의 열적 거동

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## 초록

단기액체 하이드라진 ($N_2H_4$) 추진제를 사용하는 인공위성 추진시스템의 열적 거동을 기술한다. 운용궤도에서 액체추진제의 동결을 방지하기 위한 열제어 성능이 모사궤도환경하에서 시험, 검증되었다. 궤도열환경은, 우주환경 모사챔버내에서 흡수열유속법에 의해 구현되었다. 흡수열유속법은 추진시스템을 감싸고 있는 위성체 버스패널에 인위적인 가열을 하여 열환경을 모사하는 방법이다. 시간대별로 얻어진 추진계 구성품의 온도분포가 제시되고 이 열적 거동은 각 구성품들의 열제어를 위하여 장착된 비행용 히터의 작동 사이클 수로 변환된다. 작동 사이클 수는 전력으로 환산되어 추진시스템의 열제어를 위하여 운용궤도에서 요구되는 총전력량을 예측가능하게 한다. 부가적으로, 인공위성의 열평형상태에서 얻어진 추진계 구성품들의 주기적 온도가 설계허용온도와 비교되고 시스템검증의 시각에서 평가된다.

## ABSTRACT

Thermal behavior of spacecraft propulsion system utilizing monopropellant hydrazine ($N_2H_4$) is addressed in this paper. Thermal control performance to prevent propellant freezing in spacecraft-operational orbit was test-verified under simulated on-orbit environment. The on-orbit environment was thermally achieved in space-simulation chamber and by the absorbed-heat flux method that implements an artificial heating through to the spacecraft bus panels enclosing the propulsion system. Test results obtained in terms of temperature history of propulsion components are presented and reduced into duty cycles of the avionics heaters which are dedicated to thermal control of those components. The duty cycles are subsequently converted into the electrical power required in the operational orbit. Additionally, cyclic temperature of each component, which was made under thermal-balanced condition of spacecraft, is compared to the acceptable design range and justified from the viewpoint of system verification.

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## 1. Introduction

Korea Aerospace Research Institute (KARI) and TRW (Redondo Beach, California, USA) have jointly developed a sun-synchronous low-earth-orbit satellite called KOMPSAT (Korea Multi-purpose Satellite). Its Flight Model has been integrated at KARI and the functional and environmental test were completed in mid 1999. Aboard a Taurus solid rocket built by OSC(Orbital Science Corporation, USA), it is supposed to launch from Vandenberg Air Force Base in California, USA in late 1999, and will be placed into its circular operational orbit of 685 km altitude and 98 deg. inclination to facilitate cartography which is its primary mission, ocean color imaging, and ionosphere measurement.

Liquid propulsion system using monopropellant hydrazine($N_2H_4$) as its fuel was equipped on KOMPSAT. The propulsion system provides velocity change and three-axis vehicle attitude control impulse for orbit transfer, drag makeup, and backup attitude control of the spacecraft.

On orbit, satellites are exposed necessarily to high vacuum and extremely low temperature of deep space that is 4 K ideally, as well as spatial-environmental heating. The principal forms of environmental heating are sunlight, both direct and reflected off(albedo) of the earth, and IR(infrared) energy emitted from the earth itself. Thermal control of a satellite on orbit is achieved by balancing the energy emitted by the spacecraft as IR radiation against the energy dissipated by internal electrical components plus the energy absorbed from the environment.

Spacecraft propulsion system is composed mostly of mechanical components, that means there are rarely electrical heat dissipation in itself. Components of the propulsion system which contains hydrazine shall include heater circuits to prevent propellant freezing on orbit. Besides all the components are to be completely enclosed by MLI(Multi-layer Insulation) blanket except for thrusters only. Differently from the other bus components whose temperature is controlled by the heaters located nearby, each propulsion component has its own heaters to ensure the prevention of freezing. This necessitates abundant flight heaters dedicated only to propulsion system for its thermal control on orbit: Totally 25 heater circuits were installed to propulsion system, while the rest of KOMPSAT bus system has 26 circuits.

Although the propulsion system is independent from the rest of bus system in thermal control, it is radiatively coupled to the bus enclosure panels, bus equipments, and a platform where the bus electronics are laid. The thermal performance of propulsion system is, therefore, verified with assembled to spacecraft bus system. Three tests described in MIL-STD-1540B[1)] associated with space vehicle level are thermal cycling, thermal vacuum, and thermal balance. The thermal cycling tests are primarily environmental screens to expose design, workmanship, material, and processing defects. This test is optional at the spacecraft level and usually replaced by thermal vacuum test. The objective of thermal vacuum test is to expose spacecraft to environments which are nondestructive in nature, but yet able to provide assurance of detecting any deficiencies. This test is constituted primarily of system-level functional performance tests between, and at temperature extremes. Emphasis is put on component and subsystem interaction and interfaces, and on end-to-end electrical system performance.

Thermal balance test is comprised of dedicated thermal tests conducted during thermal vacuum test to verify the thermal analytic models and the thermal design by way of the functional demonstration of thermal control hardware and software. A successful test and subsequent model correlation establishes the ability of the thermal control subsystem to maintain the satellite within specified temperature limits for all mission phases. Several mission phases such as launch, solar array deployment, sun pointing, science, and safe haven mode, etc. are commonly involved in satellite operation with their specific thermal environments and electrical power configurations. As operation use time of thermal facilities is expensive, a judicious choice of test cases should be made. KOMPSAT thermal balance test was performed with two extreme cases of environments and configurations of cold BOL (Beginning-of-Life) Safe Haven Mode and hot EOL(End-of-Life) Science Mode. Hot case falls under high solar energy absorption at EOL of high absorptivity and such high, yet realistic, levels of equipment usage as an active operation of payloads. Minimal equipment usage, bus voltage, and solar heating such as safe haven mode at BOL are the conditions for cold case.

High vacuum and extremely low temperature of spatial environments are achieved by space-simulation chamber equipped with liquid-nitrogen-cooled internal shrouds and cryo-pumps of high capability$^{2)}$. Specific power configuration of spacecraft equipments is made by EGSE (Electrical Ground Support Equipment) through powering and controlling the operational state of all the bus equipments. However, realization of the on-orbit environmental heating is the very matter of delicacy. Simulation methods of environmental heat loads are divided into two categories : absorbed-heat flux and incident-heat flux. Their detailed methodology, comparison of merits and demerits can be found in Ref. 3 and Ref. 4. With the former method chosen in KOMPSAT thermal test, test-only heaters are directly affixed to the bus panels and the environmental flux to be imposed is managed by a heat-loads control system. Under those high vacuum, extremely cold deep-space, and with the spatial environmental heating simulated, the spacecraft including propulsion system is thermal-tested.

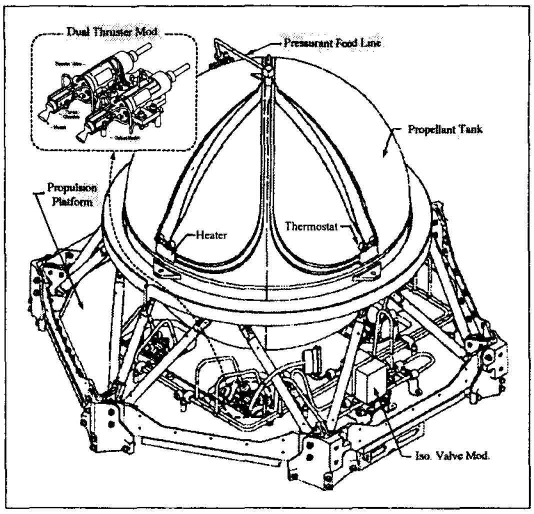

Fig. 1 Spacecraft Propulsion System Configuration

Results analysis is confined to the thermal behavior and performance of propulsion system only, because the rest of bus system and payloads are of another complexity and have their own specific thermal control logic and design which are nearly decoupled from propulsion system. Through the thermal vacuum and balance test, thermal hardware functions dedicated to propulsion system were verified. Test results obtained in terms of temperature history for the period of cold/hot thermal balance are presented and reduced into flight-heater duty cycles, and subsequently converted into the electrical power required for thermal control of propulsion system on orbit. Additionally, cyclic temperature of each component, which was made under thermal-balanced condition of spacecraft, is compared to the acceptable design range and justified from the viewpoint of system verification.

## Ⅱ. Propulsion System Configuration and Test Setup for Thermal Performance Verification

### 2.1 Propulsion System Configuration

KOMPSAT bus structure consists of a payload module, an electronic equipments module, a propulsion module, and a launch vehicle adapter with two solar array wings. The propulsion module contains propulsion system with seated on propulsion platform and tank support structure. Figure 1 shows the propulsion system comprising a fuel tank, a fill/drain module, a filter/pressure transducer module, an isolation valve module, propellant lines, and four(4) dual thruster modules (DTM) : the fill/drain and filter/pressure transducer modules are not currently shown but will appear in later figure. It is an all-welded, monopropellant hydrazine system. Impulse is provided by the catalytic decomposition of monopropellant grade hydrazine which is stored in a propellant tank and supplied to the thrusters in a blowdown pressurization mode. Eight(8) 4.45 N (1 $lb_f$) thrusters with dual-seat thruster valves are used for orbit transfer and on-orbit functions such as drag makeup, momentum unloading, and attitude control. The thrusters are packaged into DTM's with one primary and the other redundant thruster. Three(3) catalyst bed heaters are incorporated on each thruster to keep the catalyst bed above 177 ℃ prior to and during the thruster firing for normal operations. All the hydrazine-wetted components shall be maintained at all times above 5℃ and below 49℃. Exceptions are for the thruster valves for which the maximum

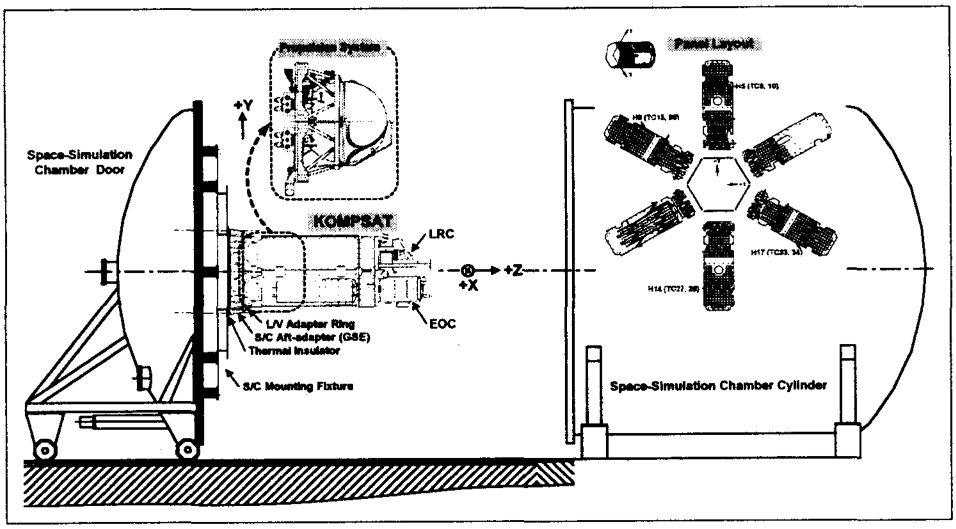

Fig. 2 Spacecraft Setup for Thermal Performance Test

allowable temperature resulting from the heat soakback of thruster firing is 116℃ and the propellant tank for which the maximum shall not exceed 38℃ to keep away from over-vaporization of fuel. Avionics heaters are sized and installed to maintain the required minimum temperature of components. Propellant feeding lines are completely wrapped around by strip heaters, and other components are incorporated by patch-type heaters. All the heaters have redundant circuits and are thermostatically controlled excluding the catalyst heaters which are controlled directly by PCU(Power Control Unit) relays. Resultantly the total number of heater circuits dedicated to the propulsion system amounted to 25.

### 2.2 Test Setup and Instrumentation

The spacecraft is placed in a space-simulation chamber with a cryogenic shroud. The shroud is chilled upto the temperature less than -170℃ with liquid nitrogen to simulate the cold sink of outer space. The condition of high vacuum of $10^{-5}$ Torr or less is achieved by cryo-pumps. Figure 2 shows the spacecraft installed on the mounting fixture of space-simulation chamber whose available diameter/length is 3.6×3.0 m. The propulsion module is enclosed by six bus enclosure panels. Second Surface Mirrors (SSM) as a representative radiator are adhered to the enclosure panels. The panels are completely covered with MLI only except for the SSM. The MLI insulates the bus from heat flows either into or out of the bus structure, while the SSM allows radiation to space. The SSM's reflect most of the incident solar radiation when they are exposed to the sun and albedo heat loads. SSM of 6 mil thickness has the radiative property that is IR emissivity, $\varepsilon = 0.78$, and solar absorptivity, $\alpha = 0.07$(BOL) to 0.15(EOL). Such environmental heat loads are, by the employment of absorbed-flux method, simulated with test-only heaters affixed directly to the radiator zones of enclosure panels. The enclosure-panel layout can be found around right-upper corner in Fig. 2. It reveals that 17 test heaters were applied to the radiator zones, among which 4 circuits(H5, H8, H14, and H17) are directly faced with the propulsion module. Lower part of the +X+Y panel on which electronics are exteriorly positioned, does not have SSM's, and the central and lower SSM region of -X-Y panel-side represents a onboard battery radiator so that the enclosure panel itself does not have any radiator.

Satellite is subjected to three times of thermal vacuum cycling followed by one temperature cycle during which CPT (Comprehensive Performance Test) and thermal balance tests are performed at the cold and hot extremes: i.e., at the end of three cyclings, cold CPT, cold thermal balance, hot CPT, and hot balance test follow, and the test ends with a leak check of propulsion system.

Table 1 lists the environmental heat loads practiced through cold and hot balance phase by the simulation heaters affixed to panel radiators. Two control thermocouples at least, are associated to each heater for providing against single thermocouple fault. The simulation powers to be assigned to radiators are obtained from thermal analysis of spacecraft in its operational orbit. The orbit-averaged values are real outcome of TRASYS[5] run. The detailed simulation method, simulation equipment system, and simulation data are comprehensively described in Ref. 3, 4, 6 and 7.

Figure 3 shows typical positioning of

Table 1. Environmental Heat Loads through Spacecraft Enclosure Panels

| | | Environmental Heat Loads per Test Phase(Watts) | | |
|---|---|---|---|---|
| Heater Ckt. # | Location | Control TC's | Cold Balance | Hot Balance |
| H5 | +Y Lower Equip. Rad. Panel | 9,10 | 5.2 | 9.6 |
| H8 | -X+Y Lower Equip. Rad. Panel | 15,98 | 7.5 | 12.3 |
| H14 | -Y Lower Equip. Rad. Panel | 27,28 | 4.4 | 6.8 |
| H17 | +X-Y Lower Equip. Rad. Panel | 33,34 | 6.5 | 10.0 |

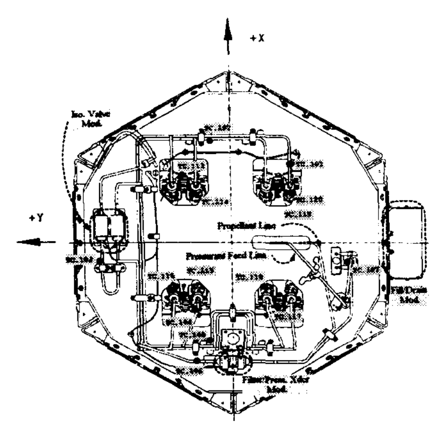

Fig. 3 Thermocouple Instrumentation on Propulsion Components

thermocouples on DTM's and propellant lines with indicating the location of fill/drain module and filter/pressure transducer module. Twenty(20) thermocouples of the type, 'T' (copper/constantan) were instrumented on all the propulsion components and over avionics heaters to monitor their thermal behavior and proper functioning.

## Ⅲ. Results and Discussion

### 3.1 Thermal Behavior of Propulsion Components

The test has been performed from April 9 to April 20, 1999. Cold balance test started at 10:00 AM, April 15, and ended at 05:00 AM, April 16. The hot balance started at 05:00 AM, April 19, and was over at 02:00 AM, April 20.

Functioning of in-flight thermal control heaters could be seen at all thermal test phases. As mentioned before, on-orbit temperature of the propulsion system can be maintained above the lower allowable limit only by avionics heaters because it rarely has the electronics which are potential heat sources. This necessarily results in a vivid on/off of the heaters. Table 2 is the check list of flight heater. functioning. All the primary and redundant heaters were observed to turn on/off except for the primary catalyst-bed heater and one of the redundant catbed heater (Cadbed R3) which were not commanded to enable during the test. It is known that a chemical species may be outgassed resulting in a breakage of vacuum environment and a possibility of contamination if the catalyst(alumina pellets impregnated with iridium) were heated up. This is why catbed heaters were not enabled. However, the trial to have enabled catbed heaters(Cadbed R12) at cold phases revealed it was an imaginary fear, at least at cold condition. Checkout of the catbed heaters under ambient condition was taken prior to

Table 2. List of Avionics Heaters and Their Functional Verification Results

| Component Module | Heater Desig. | Pri / Red | T/S Id. | Unit/Area | T/C # | Turn ON Temp.(C) Required | Turn OFF Temp.(C) Required | Heater On/Off Checkout during T/V |
|---|---|---|---|---|---|---|---|---|
| Propellant Line | C.1 | Pri. | T/S1-P1 & T/S1-P2 | Cir. #1 | 102,101,103 | 10 | 17 | O |
| | | Red. | T/S1-R1 & T/S1-R2 | | | 7 | 17 | O |
| | C.2 | Pri. | T/S2-P1 & T/S2-P2 | Cir. #2 | 105,104,106 | 10 | 17 | O |
| | | Red. | T/S2-R1 & T/S2-R2 | | | 7 | 17 | O |
| | C.3 | Pri. | T/S3-P1 & T/S3-P2 | Cir. #3 | 107 | 10 | 17 | O |
| | | Red. | T/S3-R1 & T/S3-R2 | | | 7 | 17 | O |
| Prop. Tank Htr | P1, P2, P3, P4 | Pri. | T/S-P1 & T/S-P2 | Tank +Z | 108,109 | 10 | 17 | O |
| | R1, R2, R3, R4 | Red. | T/S-R1 & T/S-R2 | Tank -Z | | 7 | 17 | O |
| Fill/Drain Mod. | P1 | Pri. | T/S-P1 & T/S-P2 | FDM Htr Plate | 110 | 10 | 17 | O |
| | R1 | Red. | T/S-R1 & T/S-R2 | | | 7 | 17 | O |
| Iso. Valve Mod. | P1 | Pri. | T/S-P1 & T/S-P2 | IVM Htr Plate | 112 | 10 | 17 | O |
| | R1 | Red. | T/S-R1 & T/S-R2 | | | 7 | 17 | O |
| Filter/P-Xducer | P1 | Pri. | T/S-P1 & T/S-P2 | FPXM Htr Plate | 111 | 10 | 17 | O |
| | R1 | Red. | T/S-R1 & T/S-R2 | | | 7 | 17 | O |
| DTM #1 | Valve H2, H4 | Pri. | TSP1 & TSP2 | Thr. #1 Pri. | 113,114 | 10 | 17 | O |
| | Valve H1, H3 | Red. | TSR1 & TSR2 | Thr. #1 Red. | | 7 | 17 | O |
| DTM #2 | Valve H2, H4 | Pri. | TSP1 & TSP2 | Thr. #2 Pri. | 115,116 | 10 | 17 | O |
| | Valve H1, H3 | Red. | TSR1 & TSR2 | Thr. #2 Red. | | 7 | 17 | O |
| DTM #3 | Valve H2, H4 | Pri. | TSP1 & TSP2 | Thr. #3 Pri. | 117,118 | 10 | 17 | O |
| | Valve H1, H3 | Red. | TSR1 & TSR2 | Thr. #3 Red. | | 7 | 17 | O |
| DTM #4 | Valve H2, H4 | Pri. | TSP1 & TSP2 | Thr. #4 Pri. | 119,120 | 10 | 17 | O |
| | Valve H1, H3 | Red. | TSR1 & TSR2 | Thr. #4 Red. | | 7 | 17 | O |
| DTM #1/2/3/4 | Catbed Primary | Pri. | N/A | Pri. Thrusters | N/A | N/A | N/A | * |
| | Catbed R12 | Red. | N/A | Red. Thrusters | N/A | N/A | N/A | O |
| | Catbed R3 | Red. | N/A | Red. Thrusters | N/A | N/A | N/A | * |

* Did not enable during the test.

the thermal test.

Figure 4 represents the thermal behavior of selected components through the entire thermal test. Test timeline of the three thermal vacuum cyclings, cold CPT, cold balance, hot CPT, and hot balance test followed by returning to ambient condition can be macroscopically found. There can be also uncovered that the heaters associated to each component did not turn on around hot extremes, as expected. Cycling range of tank temperature is notably narrower than other components and the tank thermally behaves relatively lagged, too. This is because it has tens times larger mass (15.5 $lb_f$) resulting in still more thermal inertia than others. One thing of remark is all the components show a cyclic behavior even at hot balanced condition. This is coincident with the fact that the propulsion system has little heat dissipation source of electronics and thus necessarily causes the vivid activation of heaters though the system was posed already to hot condition: The hot balanced condition should be distinguished from the hot extremes which is made artificially to expose the spacecraft to deficiency-detecting environments.

An equilibrium or constantly cycling temperature of the components which could be obtained through the thermal balancing of spacecraft, is compiled in Table 3. All the components could be found to thermally cycle very frequently: In case its thermal control strongly depends only on heaters the cycling frequency is supposed to be inevitably high. The table says all the components could be safely kept within its operating temperature range. The only exception is the slight

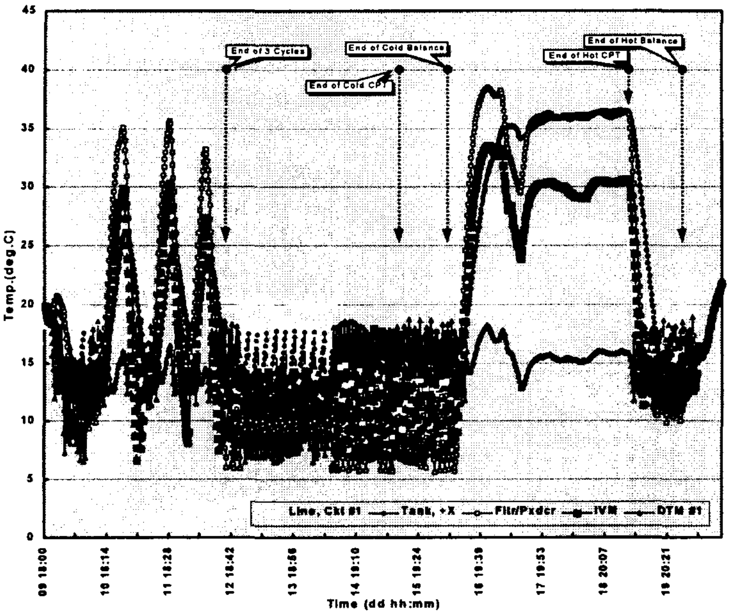

Fig. 4
Thermal Behavior of Selected Components with Spacecraft Thermal Test Timeline

deviation of propellant line(4℃) from its lower limit(5℃). It is also discovered in the table that there exists a difference of turn-on temperature between at cold and hot balance: Lower points of the cyclic temperatures (turn-on of heaters) under cold balance scatter around 7℃ but those under hot balance scatter around 10℃. Upper points (turn-off of heaters) scatter around 20℃ both at cold and hot balance. These are explained by that only redundant heater bus was so enabled at cold balance that the thermostats associated to redundant heater circuit have ever controlled each redundant heater, while both primary and redundant buses were enabled at hot balance so that the thermostats associated to primary heater controlled each primary heater. Revisiting the Table 2, on/off set points of redundant thermostats are 7/17℃ and those of primary are 10/17℃. The scattering or deviation of the acquired on/off temperature from the required can be ascribed again to the thermal inertia of components and partially to an uncertainty relevant with temperature detection.

Table 3. Cyclic Temperature of Components under Thermal Balanced Condition

| | Temp. Limit (deg.C) | | | | | Cyclic Temp. Balanced (deg.C) | |
|---|---|---|---|---|---|---|---|
| Module | Low. Red | Low. Yel. | Up. Yel. | Up. Red | TC# | At Cold | At Hot |
| Propellant Tank | 5 | 10 | 33 | 38 | 109 | +6 to +15 | +10 to +28 |
| Propellant Lines | 5 | 10 | 44 | 49 | 101,107 | +4 to +36 | +7 to +35 |
| Fill/Drain Mod. | 5 | 10 | 44 | 49 | 110 | +7 to +16 | +12 to +21 |
| Filter/P-Xducer Mod. | 5 | 10 | 44 | 49 | 111 | +5 to +12 | +9 to +12 |
| Iso. Valve Mod. | 5 | 10 | 44 | 49 | 112 | +6 to +17 | +11 to +14 |
| DTM#1 | 5 | 10 | 111 | 116 | 114 | +9 to +22 | +10 to +22 |
| DTM#2 | 5 | 10 | 111 | 116 | 116 | +5 to +20 | +6 to +18 |
| DTM#3 | 5 | 10 | 111 | 116 | 118 | +8 to +17 | +9 to +18 |
| DTM#4 | 5 | 10 | 111 | 116 | 120 | +7 to +24 | +10 to +22 |

### 3.2 Data Reduction to Duty Cycles and Power Consumption of Avionics Heater

Duty cycle of the flight heaters could be calculated with an exhaustive analysis of the temperature outcome obtained under the thermal-balanced condition. How much

Table 4. Duty Cycles and Electrical Power Consumption of Avionics Heaters

| HTR Desig. | Htr Spec., Watts (@28V) | Htr Spec., Watts (@32V) | Htr Duty (%) @ Balance | | Average Pwr, Watts (w/ 28V) | | Average Pwr, Watts (w/ 32V) | |
|---|---|---|---|---|---|---|---|---|
| | | | Cold | Hot | Cold | Hot | Cold | Hot |
| Line Htr Ckt #1 | 6.44 | 8.41 | 20.1 | 21.7 | 1.3 | 1.4 | 1.7 | 1.8 |
| Line Htr Ckt #2 | 6.44 | 8.41 | 24.8 | 25.8 | 1.6 | 1.7 | 2.1 | 2.2 |
| Line Htr Ckt #3 | 3.56 | 4.65 | 23.9 | 19.1 | 0.9 | 0.7 | 1.1 | 0.9 |
| Tank Htr | 7.74 | 10.11 | 37.0 | 36.8 | 2.9 | 2.8 | 3.7 | 3.7 |
| FDM Htr | 2.72 | 3.56 | 36.5 | 38.6 | 1.0 | 1.1 | 1.3 | 1.4 |
| IVM Htr | 2.72 | 3.56 | 40.4 | 34.6 | 1.1 | 0.9 | 1.4 | 1.2 |
| FPXM Htr | 2.72 | 3.56 | 18.4 | 11.8 | 0.5 | 0.3 | 0.7 | 0.4 |
| | | | | Sub-total | 9.2 | 8.9 | 12.0 | 11.6 |
| DTM #1 Valve Htr | 3.40 | 4.44 | 45.3 | 61.2 | 1.5 | 2.1 | 2.0 | 2.7 |
| DTM #2 Valve Htr | 3.40 | 4.44 | 33.2 | 60.5 | 1.1 | 2.1 | 1.5 | 2.7 |
| DTM #3 Valve Htr | 3.40 | 4.44 | 43.1 | 61.3 | 1.5 | 2.1 | 1.9 | 2.7 |
| DTM #4 Valve Htr | 3.40 | 4.44 | 35.8 | 61.3 | 1.2 | 2.1 | 1.6 | 2.7 |
| | | | | Sub-total | 5.4 | 8.3 | 7.0 | 10.9 |
| Catbed Htr, Pri. * | 9.15 | 11.95 | *100.0* | *100.0* | *9.2* | *9.2* | *12.0* | *12.0* |
| Catbed Htr R12 ** | 6.10 | 7.97 | 100.0 | 0.0 | 6.1 | 0.0 | 8.0 | 0.0 |
| Catbed Htr R3 *** | 3.05 | 3.98 | ***100.0*** | ***100.0*** | ***3.1*** | ***3.1*** | *4.0* | *4.0* |
| Total Average Power with Catbed R12 ON | | | | | 20.7 | | 27.0 | |
| Total with (Catbed Primary + Catbed R3) ON | | | | | < 26.8 | < 29.4 | < 34.9 | < 38.4 |
| Total Average Power with (Catbed R12 + Cadbed R3) ON | | | | | < 23.7 | | < 31.0 | |
| Total Average Power with Catbed R3 ON | | | | | > 17.6 | > 20.3 | > 23.0 | > 26.5 |

* Enabled only on Initial Orbit Adjust, Sun-pointing, and del-V Burn.

** Enabled on Contingency (Redundant Side) Mode. *** At all times enabled.

percentage the heater will be turning on in an operational orbit is definitively represented by the duty cycle. With the power specification of flight heaters, Table 4 lists up the data reduced to the duty cycle and converted into the orbit-averaged power. During thermal balance tests 32 Volts(31.8 Volts exactly) was streamed out to flight heaters from PCU : The bus output voltage necessarily depends upon the solar array and battery charging status on orbit and may vary from 24 to 32 Volts. 28 Volts is typical of normal operation orbit. The total power calculated with 32 Volts was nearly consistent with the consumed power measured by PMTS(Power Monitoring Test Set): This means the data reduction process was very exact.

Thermal design for propulsion system requires a maximum duty cycle shall be less than 70 %. Table 4 shows the requirement are satisfied. It is natural the heaters should have turned on less under the hot than the cold if the environmental heat loads of hot case through enclosure panels were higher than cold case as listed in Table 1. Examining the duty cycles and averaged power of thruster-relevant heaters in Table 4, however, the values of hot balance(8.3 Watts with 28 Volts) is one and half times higher than those of cold balance(5.4 Watts). This can be explained again by taking the operated condition of catalyst bed heaters on both cases into account. As mentioned before, during cold balance the catbed heater(Catbed R12) was enabled by PCU command while any catbed heaters were not enabled during hot balance. Three(3) Catbed heaters per thruster were incorporated into catbed chamber. Thruster valve locates just upward of the catalyst chamber. Once the catbed heater is turned on, heat is promptly conducted to thruster valve. This fact made the situation that the duty cycle of valve heaters under cold case was less than under the hot case. Except for the valve heater, the duties of the rest components are comparable and similar on both hot and cold cases. Practically there is little difference of system configuration between cold and hot case. The only exception is that the redundant power bus was enabled at cold and both of primary and redundant bus were enabled at hot case. Therefore the difference of duties could come only from that of environmental heat loads. Although there considerably exist a difference of environmental heating between cold and hot case(see the Table 1), radiative heat exchange between components and panels is attenuated by MLI covering all the components, and subsequently the difference of thermal influence to the heater activation between cold and hot case are mitigated. This is why the duties of cold case is slightly higher than the hot case.

On orbit a catbed heater(Catbed R3) will be at the enabled state at all times to help a sudden usage of redundant thrusters in any contingency mode. For normal science-operation mode(a hot case) the thrusters are not required. All the spacecraft buses get into redundant side in a safe haven mode, and if there occurs any need to use the thrusters the redundant catbed heater(Catbed R12) will be enabled. The usage of primary catbed heaters are met at an orbit transfer or del-V burn to adjust the orbit. Table 4 shows the resultant powers expected under all the circumstances possible. Inequalities were introduced by considering the heat dissipation through a heat flow path from catalyst chamber to thruster valve and the inter-relationship of raising-reducing the duties in between the catbed and valve heater. Analytical prediction for propulsion system says 20 Watts of heater power[8] is to be drained when using one set of catbed heaters (primary or catbed R12 & R3). The power was calculated based on 25.5 bus Volts. While it can be simply converted to 24 Watts in case 28 Volts are impressed. Table 4 clearly indicates that 24 Watts lies between the cold and the hot extreme case. Normally spacecrafts are so thermally designed that flight heaters are minimally cycling on orbit. Minimizing of the heater duty is imperative in the light of electrical power budget and the lifetime of heaters. Table 4 verifies the total power of propulsion system which are required for thermal control on orbit, is smaller than the power budget allotted to the propulsion system.

## Ⅳ. Summary and Conclusion

Spacecraft liquid propulsion system using monopropellant hydrazine was introduced with its thermal control configuration to protect propellant freezing in its operational orbit. Spacecraft thermal test setup was also presented with a brief description on the orbital environment simulation. Reviewed and discussed are contents as follows:

1) Functional verification result for flight heaters dedicated to propulsion system was shown.
2) Thermal behavior of components which was got through the entire thermal test was depicted.
3) Thermal-balanced cyclic temperatures of the components were listed and commented referring to design requirements : The thermal performance of propulsion system to keep its temperature above design limit was verified
4) Result of temperature-data reduction to the heater duty cycle and of conversion to the electrical power was discussed : Electrical power budget allotted to propulsion system was satisfactorily met.

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