7 Heaters

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Introduction

Under ideal circumstances, thermal control of a satellite or component would be achieved only through passive techniques, such as the use of surface finishes. Unfortunately, though, variations in environment and component heat-generation rates, along with the degradation of surface finishes over time, can drive temperature variations in a passive design to ranges larger than some components can withstand. Heaters therefore are sometimes required in a thermal design—to protect components under cold-case environmental conditions or to make up for heat that is not dissipated when an electronics box is turned off. Heaters may also be used with thermostats or solid-state controllers to provide precise temperature control of a particular component. Another common use for heaters is to warm up components to their minimum operating temperatures before the components are turned on. Each of these three applications is described in this chapter.

Heater Types

The most common type of heater used on spacecraft is the patch heater, several of which appear in Fig. 7.1. It consists of an electrical-resistance element sandwiched between two sheets of flexible electrically insulating material, such as Kapton. The patch heater may contain either a single circuit or multiple circuits, depending on whether or not redundancy is required within it. Redundancy is generally required on spacecraft systems, because heater circuits can fail. Sometimes

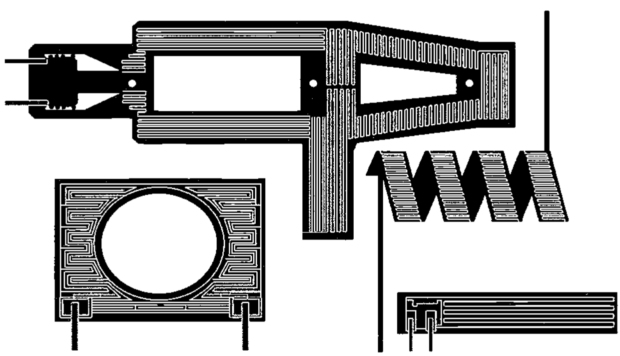

Fig. 7.1. Patch heaters made in custom shapes.

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the redundancy is provided within the patch heater, and sometimes it is provided externally, through the use of two separate patches. The patch heaters in Fig. 7.1 illustrate custom shapes in which these heaters may be made. In most instances, however, the patch is a simple rectangle of standard dimensions.

Another type of heater, the cartridge heater, is often used to heat blocks of material or high-temperature components such as hydrazine-thruster catalyst beds. Such a heater, shown in Fig. 7.2, consists of a wound resistor enclosed in a cylindrical metallic case. Typically a hole is drilled in the component to be heated and the cartridge is potted into the hole. Another attachment technique involves the use of a clamp or small bracket to hold the heater. Cartridge heaters are usually a quarter-inch or less in diameter and up to a few inches long.

Control

Almost all heaters allow some sort of control over their operation. This capability typically involves a relay that is commandable from the ground to enable or disable power being supplied to the heater, a fuse to protect the spacecraft from a short circuit, and, usually, a thermostat or solid-state controller to turn the heater on and off at predetermined temperatures. In more sophisticated satellites, onboard computers sometimes monitor temperatures and turn heaters on and off at appropriate times using relays.

The simplest control arrangement involves only the heater itself, a fuse, and a ground-commandable relay to turn the heater on and off. This arrangement is generally used for heaters activated only for special events, or for heaters that can be left on all the time. A common application is heating up the catalyst beds on hydrazine thrusters to around 100°C before thrusters are fired. (Firing with a low initial catalyst-bed temperature decreases the catalyst life.) The heater is commanded on, the catalyst-bed is heated, the thruster is fired, and the heater is turned off until the next maneuver, all under ground control. A heater used with a hydrazine thruster is illustrated in Fig. 7.3.

Most applications of heaters on spacecraft require some automatic heater control to keep a component at a desired temperature and to minimize the amount of time the heater is on so as to reduce power consumption. Historically, the most common control device has been a mechanical thermostat, such as the Elmwood thermostat shown in Fig. 7.4. These usually consist of a small, hermetically sealed can containing a switch driven by a snap-action bimetal actuator. The temperature at which the thermostat clicks on, known as its set point, is fixed for any given thermostat. The engineer can either order a custom device or select one from an array of standard thermostats available from the manufacturer to get a set point close to what is desired.

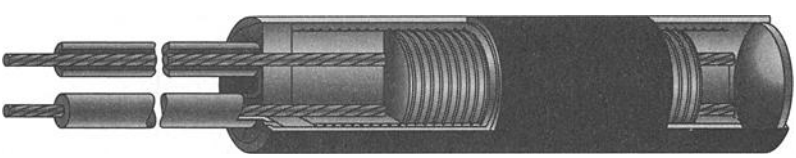


Fig. 7.2. Cartridge heater.

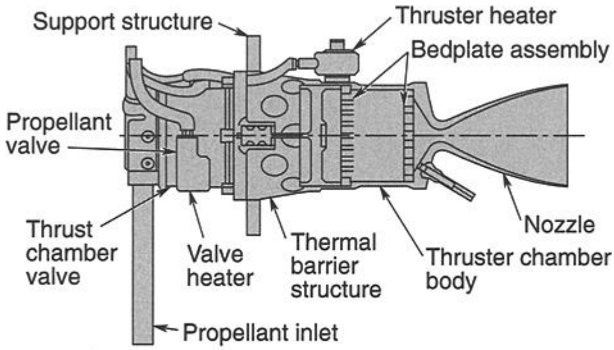


Fig. 7.3. Hydrazine thruster with heater.

In addition to the set point, the dead band, the difference between the temperatures at which the thermostat turns on and turns off, is important. A small dead band reduces the temperature swing of the device being heated and reduces power consumption a little (since the average temperature is lower). On the other hand, a small dead band also increases the number of cycles on the thermostat itself and decreases its reliability. Dead bands less than 4°C are not recommended, because of past problems. Small dead bands have been known to increase the chance of "dithering," a state in which the thermostat rapidly cycles on and off. This is a failure condition that can cause the set point to drift lower, resulting in an excessively low temperature of the component being controlled.

Even though thermostats are fairly reliable, a large number may be present on a typical satellite (up to several hundred), so occasional on-orbit failures may occur. Because of this risk, and the increasing life requirements of satellites, solid-state controllers are becoming more common. Such a controller (Fig. 7.5, Table 7.1) replaces the mechanical switch with an electronic device that has a higher reliability and life expectancy. Solid-state controllers are used extensively on the Defense

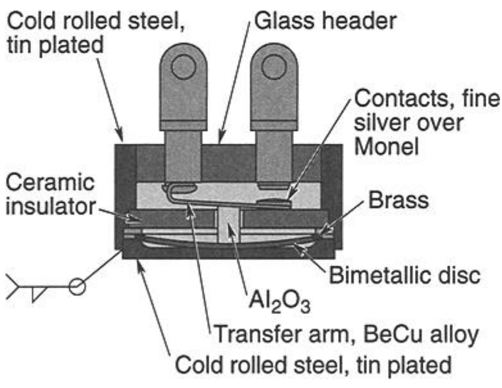


Fig. 7.4. Elmwood thermostat.

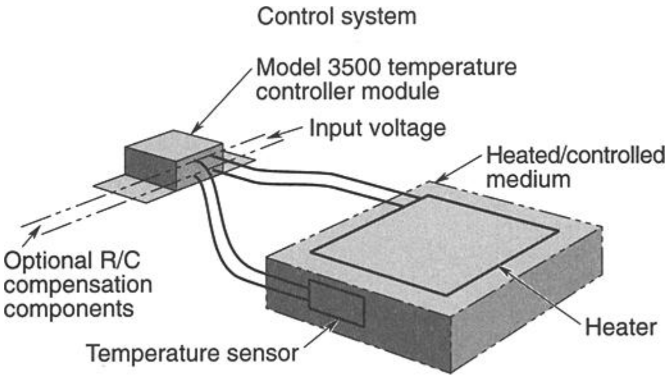


Fig. 7.5. Tayco solid-state controller.

Table 7.1. Tayco Solid-State Controller Specifications

Characteristic	Value
Package	Hermetically sealed can, 16.5 × 21.6 × 24.1 mm
Control power (heater)	0 to 100 W, higher power available
Quiescent power (standby)	30 mW
Input power	28 Vdc nominal, 15 Vdc to 45 Vdc range
Efficiency	98% minimum
Set-point accuracy	.25°C, closer tolerances available
Weight	Less than 30 g
Loop gain	Provisions for external adjustment of control-loop gain
Compensation	Provisions for addition of loop compensation
MTBF	4.7 million hours minimum @ 25°C controller ambient
Electronic components	Meet requirements of JAN TXV, MIL-8838, MIL-R-55182, and MIL-C39014 (commercial model also available)
Module ambient (heat-sink temp)	–55 to +75°C

Meteorological Satellite Program, the Hubble Space Telescope, and the International Space Station. They employ a temperature sensor that can be located either internally or at remote locations. Another advantage of solid-state controllers is that extremely tight dead bands (< 0.1°C) are possible for very precise temperature control, such as is required by the Hubble Space Telescope. Optical systems, some sensors, and electronic-frequency standards often require precise temperature control, which cannot be achieved with a thermostat.

Recently, a number of military and scientific satellites have started to use onboard computers to control heaters. Such systems read the temperatures from telemetry sensors placed throughout the vehicle and send signals to turn relay-controlled heaters on and off as required. This process allows enormous flexibility, because it enables the control set points and dead bands to be adjusted on orbit by uplinking new tables and/or logic to the spacecraft computer. In one instance, the loss of an entire satellite was averted because of the flexibility of its computer-controlled heaters.

Failure Modes of Mechanical Thermostats

While mechanical thermostats have generally proven very reliable, they may occasionally fail closed (i.e., with the heater on), fail open (with the heater off), or dither (resulting in reduced heater output). The primary causes of failure are internal contamination, manufacturing defects, excessive narrowness of the dead band, inadequate screening, improper installation, excessive current, and pitted contacts. Thermostats may fail closed as a result of welding of the contacts under high current. Failures in the open position may result from the intrusion of a contaminant between the contacts that prevents them from closing. Dithering may occur if the dead band is less than 4°C or if a contaminant-induced increase in electrical resistance between the contacts results in internal thermostat heating and early trip-off. The Hubble Space Telescope and several other programs had a number of thermostats fail open during ground testing. Analysis of the failed units showed that they contained water and ambient air. When the temperature dropped below freezing, ice formed on the contacts, preventing electrical contact when the thermostats reached their set points, which were all below 0°C.

An analysis performed at The Aerospace Corporation showed how increases in the internal electrical resistance of a thermostat can cause internal self-heating and thermostat dithering. The analysis was performed after examination of a number of dithering thermostats from a military satellite program showed that internal contamination by carbon, silicon, and silver had caused the thermostats' resistance to increase from 25 to 300 mOhm. A 40-node analytical model of the thermostats in question, attached to an electronics box, showed that only 100 mW of internal heating were needed to cause dithering. As shown in the analysis results summarized in Fig. 7.6, even small increases in resistance in larger heaters (greater than 2 amps) can cause enough internal heating to induce dithering, and smaller heaters (0.7 amp) could be problematic with large resistance increases. The predicted temperatures, shown in Fig. 7.7, illustrate how the dithering thermostat kept itself warm while allowing the electronics-box temperature to fall.

While process improvements have been instituted by thermostat manufacturers to address these issues, problems still occasionally occur. Therefore, for design robustness, the power of individual heater circuits should be kept below 20 W to minimize sensitivity to contact electrical-resistance increases. In applications below 0°C, solid-state controllers or computer-controlled heaters are recommended to eliminate the possibility that the heater will be disabled as a result of ice forming on the contacts. In all cases, because failures like those discussed above may only show up after hundreds of cycles, an adequate test program should be implemented to ensure that failures occur on the ground, where they can be corrected.

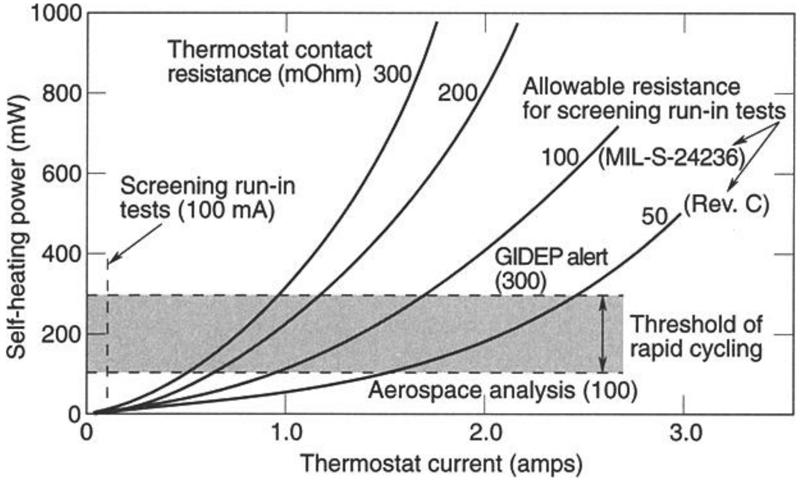


Fig. 7.6. Thermostat self-heating resulting from contact electrical resistance.

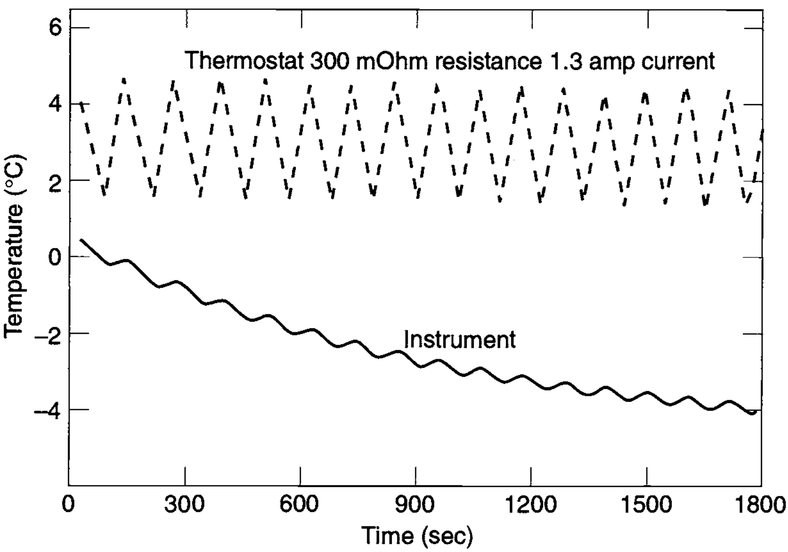


Fig. 7.7. Effect of thermostat dithering on component temperature control.

Circuits

A typical satellite has dozens of heaters and may use different thermostats, relays, solid-state controllers, and computers to control them. Many different types of redundancy schemes may be employed, even on the same satellite, depending on the criticality of a given heater.

The representative heater in Fig. 7.8 consists of redundant resistance elements in a single-patch heater. Each element is powered by a separate spacecraft power bus

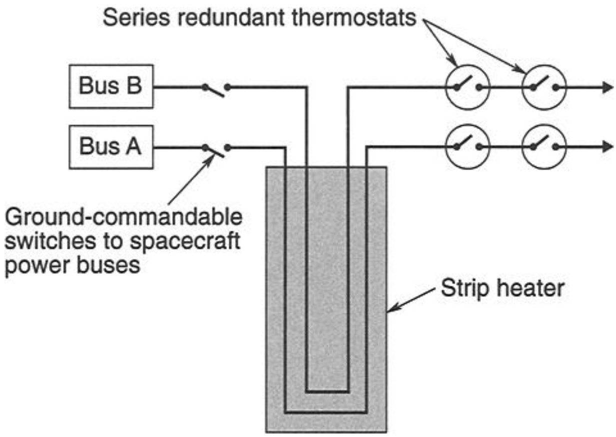


Fig. 7.8. Heater circuit example.

(satellite power systems are normally redundant), and each element has its own enable/disable relay, which is commandable from the ground. Series-redundant thermostats provide single-fault tolerance on each element for a thermostat that fails closed. If one of these thermostats fails open, however, the circuit is dead. A number of these heaters are used on the satellite. A typical panel of equipment with heater and thermostat locations is shown in Fig. 7.9. The heaters are the dark rectangular patches, and the thermostats are the black dots. The branch of the bus that supplies power to these heaters is fused, although this is not shown in Fig. 7.8.

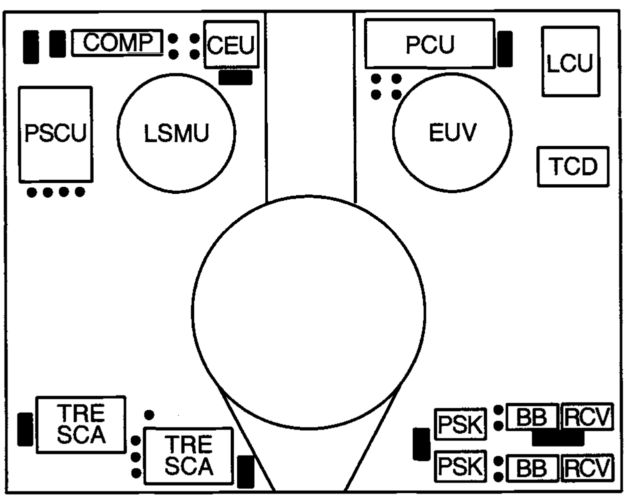


Fig. 7.9. Heater and thermostat layout.

There are many ways to lay out heaters and thermostats, depending on the level of reliability required. Figure 7.10 shows four different schemes used on one satellite. The most reliable (Type I in the figure) consists of redundant resistance elements working off of different power buses, each element employing "quad-redundant" thermostats. A quad-redundant arrangement requires at least two failures to disable thermostatic control. The other arrangements represent designs that have lower reliability but require fewer thermostats.

A schematic for the heater system used on one equipment panel on the Defense Satellite Communication System (DSCS) spacecraft, shown in Fig. 7.11, illustrates a typical application. Two sets of heaters are used: a set of survival heaters, with a set point of −18°C, which are used during launch before the spacecraft is fully powered up in its operational orbit, and a set of control heaters, with a set point of 13°C, which are used during normal on-orbit operations. The survival heaters have a lower set point to reduce their power draw (less heat is radiated away from the spacecraft at the lower temperature). The operational heaters, however, need a higher set point, since the satellite's electronics boxes will not function properly at the survival temperature. Two sets of heaters would not be required if the satellite used a computer-controlled heater system in which software could access different groups of set points during survival-mode and normal on-orbit operations.

The survival heaters are not redundant because they are not normally used and because the failure of a single heater would not result in a loss of the mission. They are, however, always connected to the power bus, without relays, to protect the spacecraft at all times. The control heaters, on the other hand, are completely redundant in circuitry, with one control thermostat on each circuit. Each circuit also has an overtemperature thermostat that switches off the heater at 20°C if the primary thermostat fails closed. Some of the "A-side" heaters are grouped together

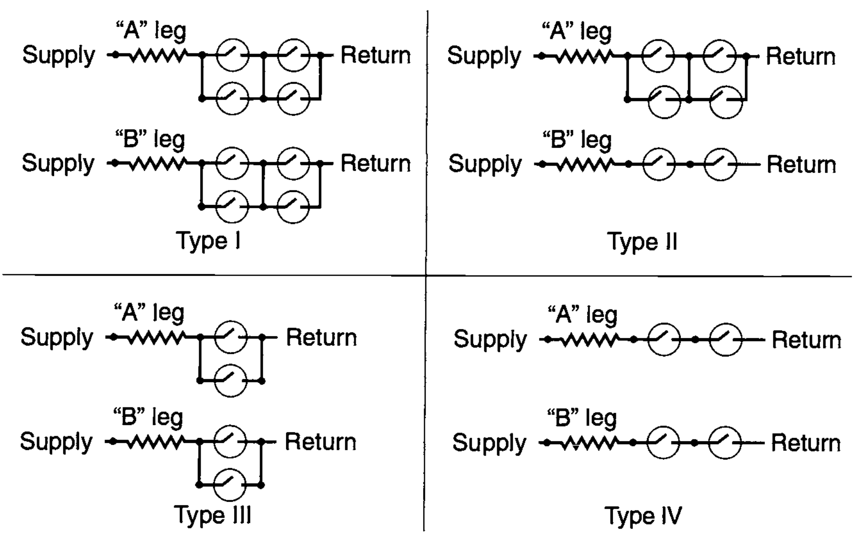
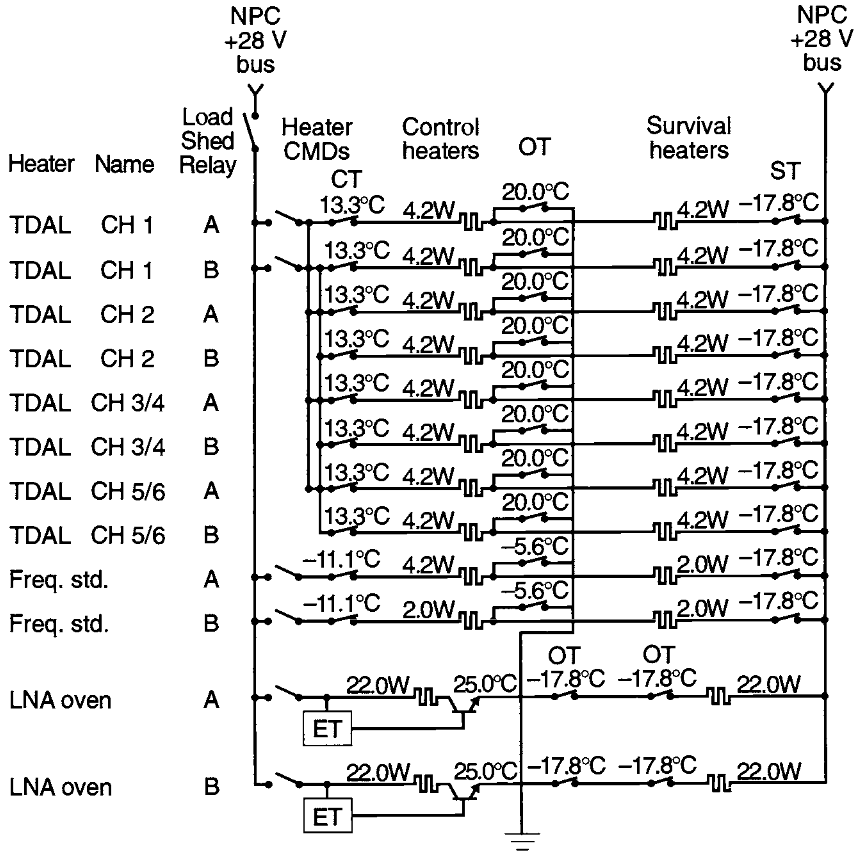


Fig. 7.10. Some heater wiring schemes.



CT: Control thermostat
OT: Overtemperature thermostat
ST: Survival thermostat
ET: Electronic thermostat
Temperature shown is thermostat set point

Fig. 7.11. DSCS satellite north panel heater schematic.

on a single commandable enable/disable relay, as are some of the "B-side" heaters. Two of the heaters are controlled by electronic thermostats used on the low-noise amplifier oven to precisely control the temperature of an oscillator crystal. This DSCS heater schematic is offered only as an example; wide variations in heater-circuit layouts are found on different satellites.

Computer-Controlled Heater System Example

Milstar (Fig. 7.12) is a large geosynchronous military communication satellite that uses a computer-controlled heater system. In addition to keeping components

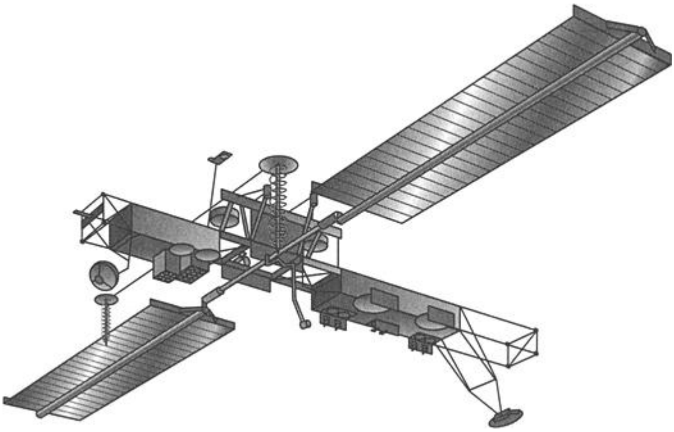


Fig. 7.12. Milstar satellite.

warm, computer control allows temperature set points to be changed during the mission, allows multiple propellant tanks to be kept at precisely the same temperature, and allows attitude-control gyros to be kept at a very constant temperature, all while enhancing spacecraft peak-power management capability.

Heater System Architecture

The overall architecture of the heater system (Fig. 7.13) consists of several layers of increasingly distributed control electronics, starting with the central spacecraft computer (the Milstar satellite processor) and ending with the actual heater elements used to warm 143 separate thermal zones scattered throughout the spacecraft. While management of the heater system occurs through the spacecraft computer, most of the actual heater-control logic resides in several lower-level distributed processor units located in different parts of this rather large vehicle. As shown in Fig. 7.13, each distributed processor contains three data files that store the current status of all heaters and telemetry temperature-sensor readings, the specified temperature set points for each heater, and addressing information that allows the processor to control multiple heaters over a single digital-signal bus. Processor software compares the temperature of each component being heated to the stored set points and turns the appropriate heaters on or off, as needed, to keep all temperatures within the desired control range.

Each distributed processor unit drives a number of controller units that convert the digital commands from the processor into the analog signals needed to drive the heater switch units (HSUs) that actually turn the individual heaters on and off. Each controller drives several heater-circuit zones. The distributed processor units also convert analog telemetry-sensor signals (temperature, heater on/off status, etc.) to digital form for heater control-loop feedback and periodic downlinking to the ground station for monitoring the vehicle's state of health.

As is the case with most spacecraft components, the heater system incorporates redundancy for high reliability. The central Milstar satellite processor, the distributed

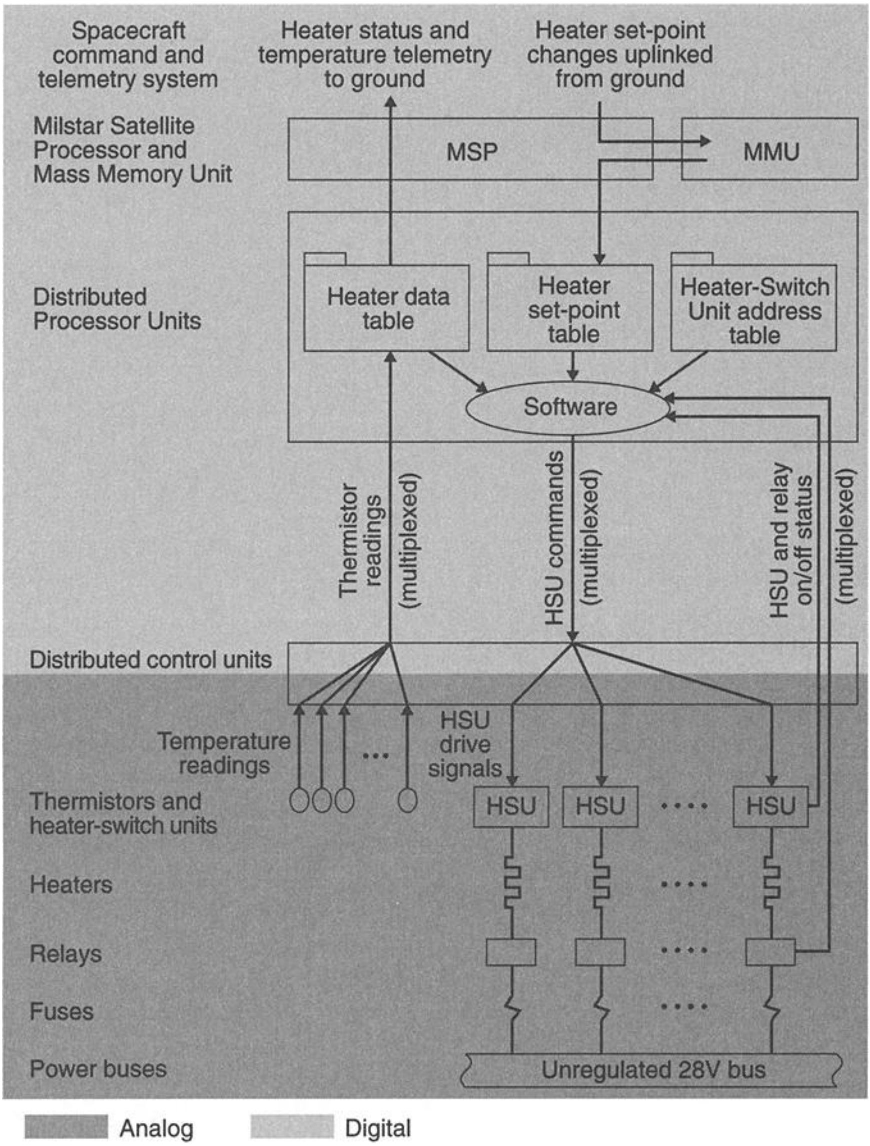


Fig. 7.13. Heater system architecture.

processor units, the controller units, the heaters and thermistors all have redundant A and B sides that are fully cross-strapped, as shown in Fig. 7.14. In such an arrangement, no single failure can disable a heater, and some multiple-failure scenarios can be accommodated. While most of the figures and discussion that follow describe a single side of the heater-control system, the reader should bear in mind that an essentially identical backup side also exists.

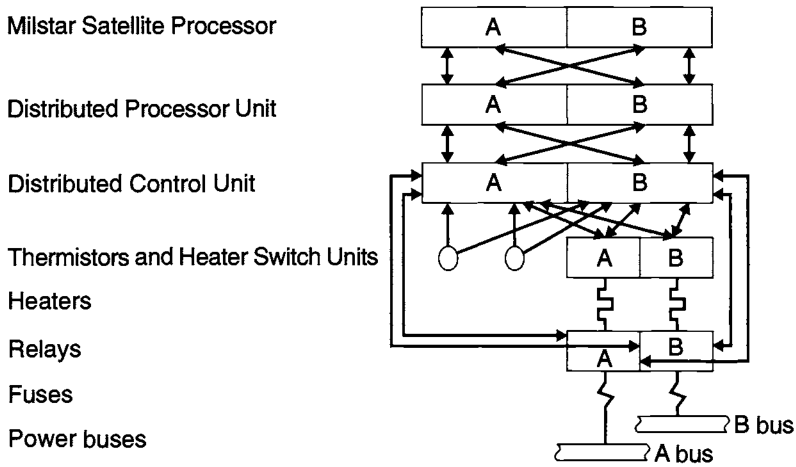


Fig. 7.14. Heater-system redundancy.

Hardware

Heater Switch Units

There are 156 heater switch units (HSUs) located throughout the spacecraft, each capable of switching on and off a heater of up to 225 W while dissipating no more than 9.6 W of internal waste heat. A typical HSU (Fig. 7.15) consists of a copper-cased microcircuit hybrid unit mounted on a circuit board and enclosed in a rectangular case measuring 3.5 by 3.3 by 1.0 cm. The hybrid microcircuit consists of a transistor switch and associated SGEMP (system-generated electromagnetic pulse) suppression components required to survive in hostile military environments. A + or – 15 Vdc drive signal from the controller unit maintains the HSU in either an on or off state, respectively. If the drive signal is interrupted, a bank of capacitors in the controller unit power supply provides a sustained –15 Vdc drive to place all HSUs in an off state. This is done to prevent all of the HSUs driven by that controller from turning on if the supply of power to the controller is momentarily interrupted.

Thermistors

Four different types of thermistor are used to sense temperatures on the spacecraft. In most thermal zones, a Yellow Springs thermistor with a calibration range of –40 to 85°C is used. For components or structural elements that experience a wider range of temperatures, Rosemount thermistors with a range of –157 to +121°C are used. (Sketches of these two sensors appear in Fig. 7.16.) The attitude-control thruster manufacturer also supplies two kinds of Tayco wire-type resistor temperature sensors with their hardware; the sensors on the valves, which have a useful range of –18 to +260°C, and the sensors on the injectors, which have a useful range of –18 to +677°C.

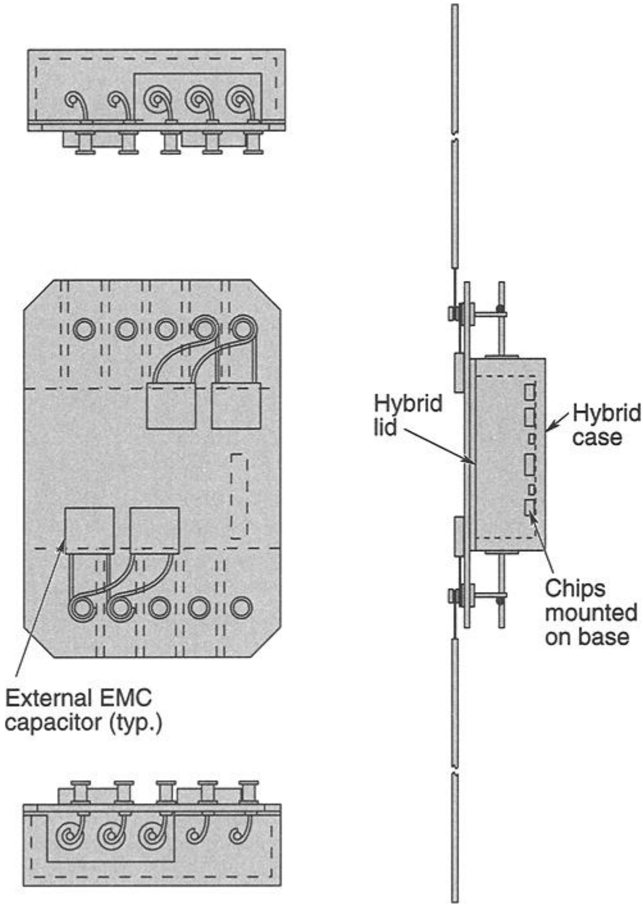


Fig. 7.15. Heater Switch Unit (HSU).

For sensors installed inside the spacecraft, where they are protected from extraneous signal noise, the thermistor assembly consists basically of a temperature-sensitive resistor, as shown in Fig. 7.17(a). For externally mounted sensors, SGEMP protection is provided by diodes installed in the thermistor-diode assembly module, as shown in Fig. 7.17(b). Each assembly can have either one or two thermistors; the one-thermistor version is used for health and status monitoring, while the two-thermistor unit is used for heater control.

Heaters

Milstar uses several different Tayco heaters. Except for those used by the propellant lines and thrusters, all spacecraft surface heaters are flat single- or dual-element patch heaters, as shown in Fig. 7.18. The propellant lines use dual-element spiral or circular patch heaters shaped to fit around the propellant lines, as shown

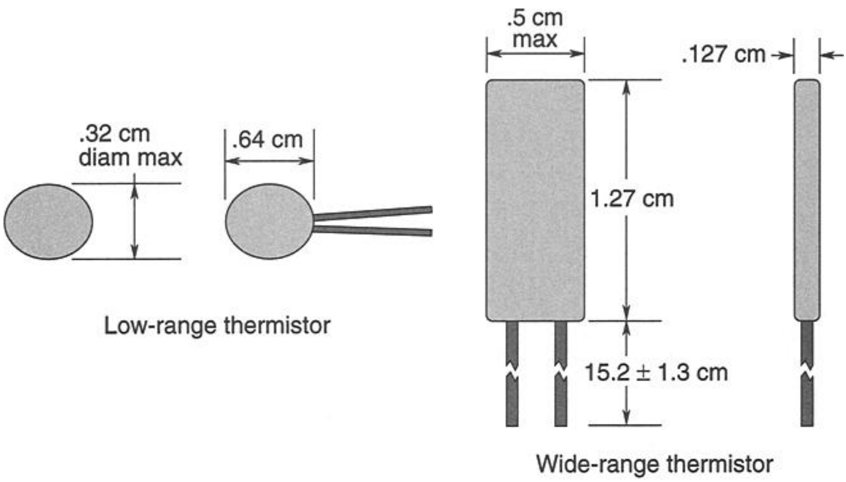


Fig. 7.16. Temperature sensors.

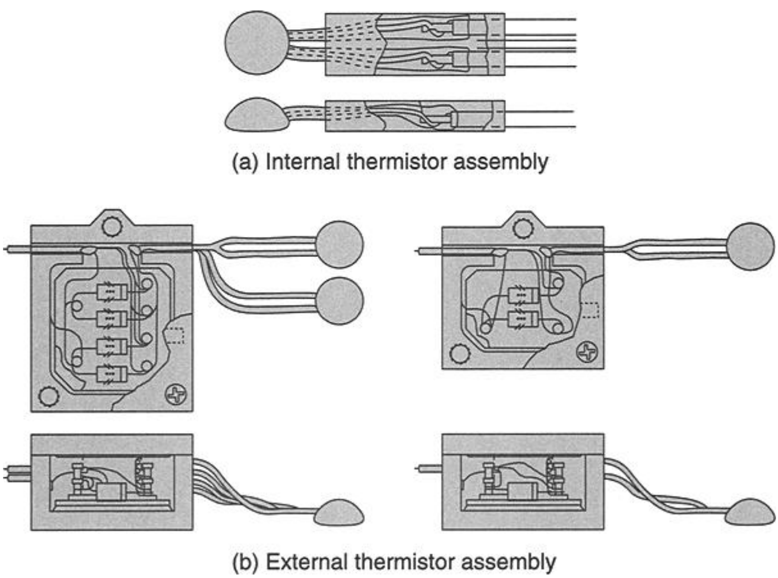


Fig. 7.17. (a) & (b) Temperature-sensor assemblies.

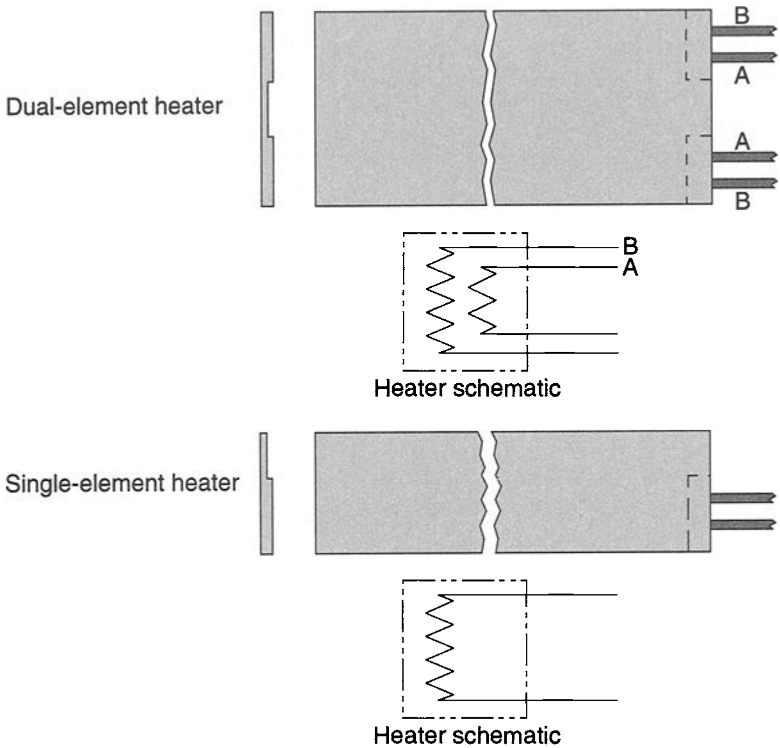


Fig. 7.18. Flat patch heaters.

in Fig. 7.19. All of the patch heaters consist of a wire heating element embedded in a Kapton laminate. Thruster heaters consist of a wire heating element embedded in magnesium oxide and encased in stainless steel.

Relays

As is the case on most spacecraft, relays are provided to enable or disable the power supplied to the heaters. Commands from the ground can be sent through the Milstar satellite processor and the appropriate processor unit and control unit to disable any heater that has failed on or developed a soft short.

Fuses

Each heater circuit has a fuse, as shown in Fig. 7.13, to ensure that a hard short in the circuit does not immediately drag down the entire power bus before a command can be sent from the ground to disable the shorted heater.

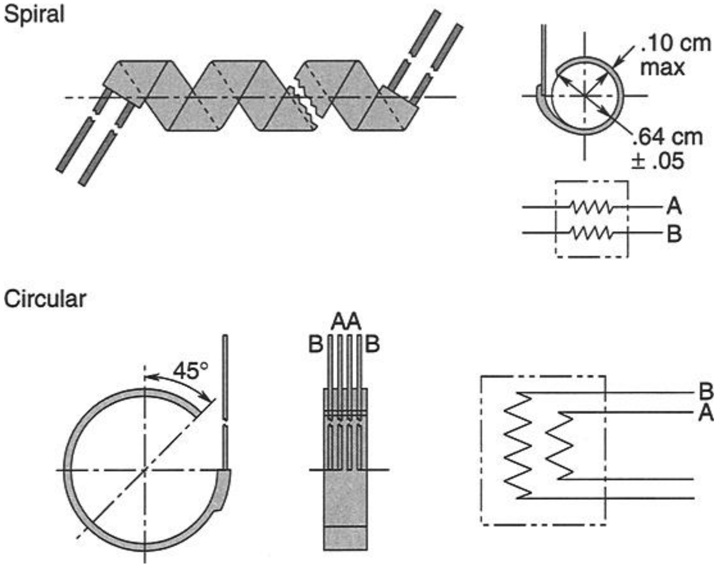


Fig. 7.19. Propellant-line heaters.

Software Control Algorithm

As was mentioned earlier, heater system operation is controlled in the distributed processor units, which contain software that monitors component temperatures and turns heaters on and off, as appropriate, to maintain the desired temperature.

Reading and Calibrating Temperatures

The first step in the control process is for the processor units to read and calibrate the temperature-sensor data sent to them by the controller units. Temperature is actually measured indirectly by measuring the resistance of the sensing thermistor. Table 7.2 shows the relationship between resistance and temperature for one particular thermistor. After reading the thermistor, however, the control unit does not output the resistance, R_t, as a decimal number, but quantizes it in "counts" according to the following equation:

$$\text{Counts} = \frac{(9.9875)(R_t) - 5.6355}{0.1079 + (0.009766)(R_t)} \tag{7.1}$$

Figure 7.20 shows the resulting relation between telemetry counts and temperature for the thermistor described in Table 7.2.

Because component tolerance, temperature, aging, and radiation affect the measurement process, each controller unit has several high- and low-resistance precision-reference resistors that the distributed processor unit uses to calibrate the measurements reported by that controller. The processor reads the resistances of all of the thermistors and reference resistors, compares the measured values for the reference resistors to their known values to derive a correction term, adjusts all

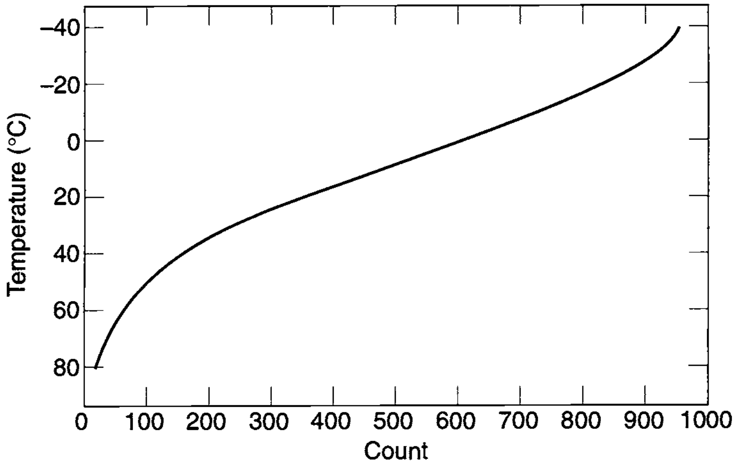


Fig. 7.20. Calibration curve for thermistor described in Table 7.2.

Table 7.2. Sample Thermistor Characteristics

Temperature (°C)	Resistance (Ω)	Nominal Telemetry Count
–40	168,300 ± 1.33	956
–30	88,530 ± 0.80	903
–20	48,560 ± 0.70	823
–10	27,670 ± 0.65	716
0	16,330 ± 0.52	589
10	9951 ± 0.48	457
20	6247 ± 0.45	336
30	4029 ± 0.43	235
40	2663 ± 0.40	157
50	1801 ± 0.38	98
60	1244 ± 0.36	57
70	875.7 ± 0.34	27
80	628.1 ± 0.39	6
90	458.2 ± 0.50	Saturates
100	339.6 ± 0.60	at 0 counts
–54	1580[a]	82
–31	90,900[a]	906

[a]Precision reference resistor

of the thermistor resistance (temperature) readings, and stores the corrected values as counts in the heater and thermistor data table.

Heater Switching

Once calibrated temperature measurements have been made, the distributed processor units compare the measured temperatures to the set points for each of the heaters that is stored in the heater set-point table. When the measured temperature drops to the set point, the processor uses the address found in the heater-switch-unit address table to send a digital signal to the appropriate controller to turn on the heater. The controller unit then sends an analog +15 Vdc drive signal to the HSU, which activates the heater. (The power is supplied to the heater from the 28 Vdc heater power bus, not the 15 Vdc drive signal.) When the temperature rises 2.8°C above the set point, the processor sends a digital signal to the controller to turn the heater off. The controller then changes the HSU analog drive from +15 to −15 Vdc, disconnecting the heater from the power bus. The 2.8°C dead band is achieved by storing the temperatures in the processor unit's set-point table with a granularity of 2.8°C. Figure 7.21 shows the resulting heater temperature cycling.

To ensure that a failed thermistor does not cause a heater to stick on or off, the distributed processor unit actually reads both the primary and redundant temperature sensors associated with each heater. If both thermistors' counts are all zeros or all ones (off scale high or low), the processor switches to the redundant heater-control circuit. If one thermistor's count is all zeros or ones, it is rejected as being too hot or cold to be a valid reading and the other thermistor is used for heater control. If both thermistors' values are within the valid range, the lesser (warmer) value is used to control the heater.

Spacecraft Modes

Different spacecraft operating modes often require different temperatures for the same thermal zone. To support this requirement, the distributed processor units change the set points that are used during the different mission phases. The processors accomplish this change using different look-up tables for different operating modes. Table 7.3 lists the various heater modes used during different phases of the mission. Set-point tables for all of these modes are stored in the spacecraft's mass memory unit and can be downloaded to the distributed processor units via the Milstar satellite processor.

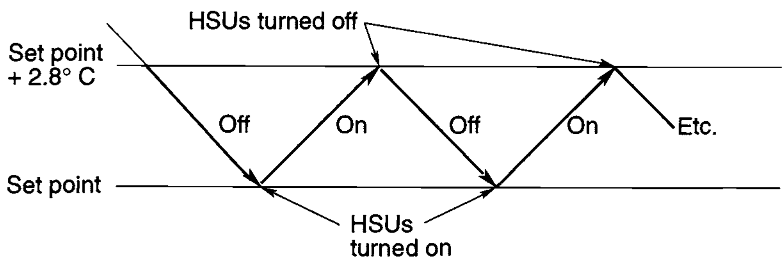


Fig. 7.21. Heater cycling.

Table 7.3. Correspondences between Heater Control Modes and Spacecraft Operational Modes

Heater Mode	Description
Initialization/ascent	Most zones control at survival temperature. Some zones preheat to survival +6°C.
Centaur discrete 5	Most zones control at survival temperature. Some zones control at survival +8°C.
Centaur discrete 7	All zones control at survival temperature.
First eclipse	Most zones control at survival temperature. Some zones preheat to 17°C via MSP command.
Equipment heat-up	Some zones control at minimum operating temperature. Some zones at minimum operating temperature +17°C.
Functional temperatures	All zones control at minimum operating temperature.
Orbit eclipse	Most zones control at minimum operating temperature. Some zones preheat to 17°C via MSP command.
Safe mode	Some zones control at minimum operating temperature. Some zones control at survival temperature.
Load shed	Some zones control at minimum operating temperature. Some zones control at survival temperature.

Radioisotope Heater Units

Spacecraft traveling to the outer planets (Jupiter and beyond) face a fundamental power/thermal challenge because the very low levels of solar radiances at such great distances from the sun create a cold environment and make solar power generation unattractive. Traditionally, the solution to the power challenge has been the use of radioisotope thermoelectric generators (RTGs). Their low efficiency and high cost, however, still make power a precious commodity. A particularly clever response to this challenge has been JPL's development of radioisotope heater units (RHUs), devices that place the heat of radioactive decay directly where it is needed, thereby bypassing the inefficiency of converting the heat in the RTG to electricity and then back into heat in an electrical-resistance heater.

At the center of each RHU, shown in Fig. 7.22, is a plutonium-dioxide ceramic fuel pellet. A single RHU weighs 42 g and fits snugly in a cylindrical enclosure 26 mm in diameter and 32 mm long. Each unit delivers 1.04 ± 0.3 W of heat at the time of encapsulation by means of radioactive decay of its plutonium fuel. From that point on, however, the heat-generation rate decreases with time. Figure 7.23 shows the decay curves for the Cassini/Huygens mission, for both primary and backup launch dates. Cassini/Huygens used a total of 117 RHUs.

While the application of a nearly constant heat source to a spacecraft component can be accomplished by attaching one or more RHUs, the ability to control the application of heat at a particular temperature, as a thermostatically controlled heater does, would provide much more flexibility. The variable radioisotope heater unit (VRHU) was developed to provide just such a capability. It consists of a cylindrical RHU holder that contains up to five RHUs and rotates on bearings

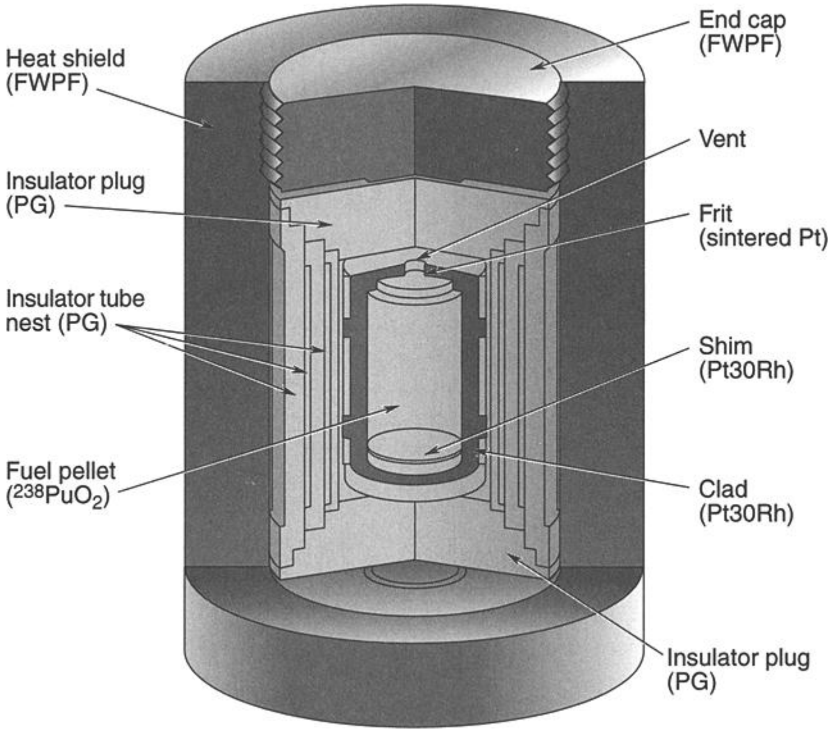


Fig. 7.22. Radioisotope Heater Unit (RHU). (Provided courtesy of the Jet Propulsion Laboratory.)

when driven by two temperature-sensitive bimetal springs. As illustrated in Figure 7.24, one side of the cylindrical RHU holder is painted white while the other side is covered with a 22-layer, all-Kapton (high-temperature) multilayer insulation (MLI) blanket. The RHU holder is thermally isolated from the bimetal actuator, which is thermally coupled to the hardware that is being temperature-controlled. When the hardware temperature goes below the set-point temperature of the bimetal springs, the holder is rotated so that the high-emittance surface (the side painted white) faces the hardware and the blanketed side faces space. When the hardware temperature goes above the set point, the holder rotates to expose the high-emittance side to space and the blanketed side to the hardware. The bimetal springs can be calibrated for any desired open-point temperature between –20 and +50°C with the fully open condition occurring 28°C above the open-point temperature. Figure 7.25 shows a VRHU. Without RHUs, the unit weighs 390 g.

RHU heat dissipation decreases with time, and that condition affects VRHU performance. Figure 7.26 shows the VRHU performance for the Cassini/Huygens mission for both the primary and backup launch dates. The upper curve represents the maximum VRHU performance that occurs at the beginning of the mission for

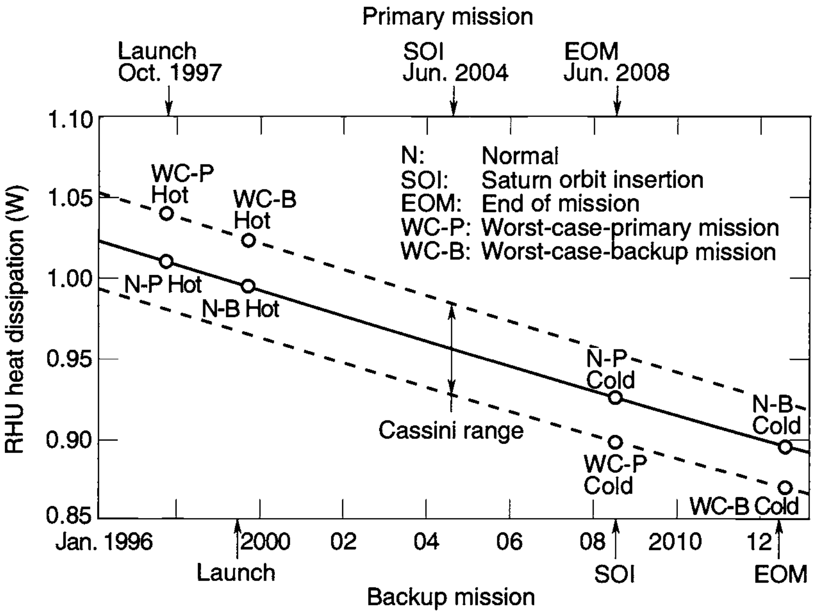


Fig. 7.23. RHU heat dissipation for the Cassini/Huygens mission. (Reprinted with permission from SAE Paper No. 941268 ©1994 Society of Automotive Engineers, Inc.)

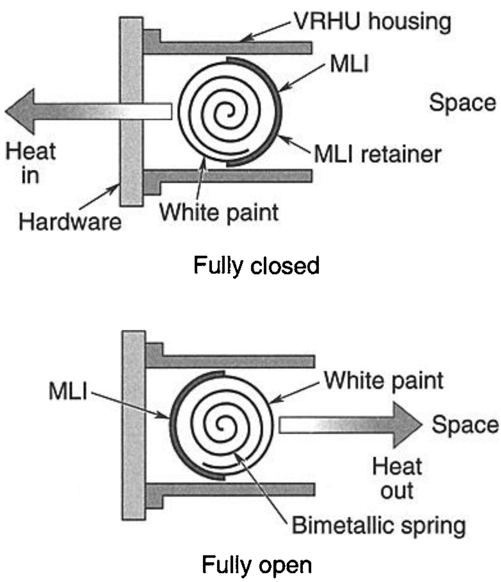


Fig. 7.24. The Variable Radioisotope Heater Unit (VRHU) concept. (Reprinted with permission from SAE Paper No. 941268 ©1994 Society of Automotive Engineers, Inc.)

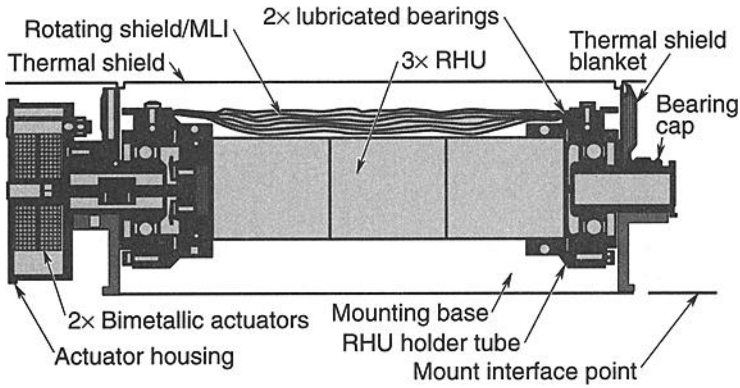


Fig. 7.25. Variable Radioisotope Heater Unit (Reprinted with permission from SAE Paper No. 941268 ©1994 Society of Automotive Engineers, Inc.)

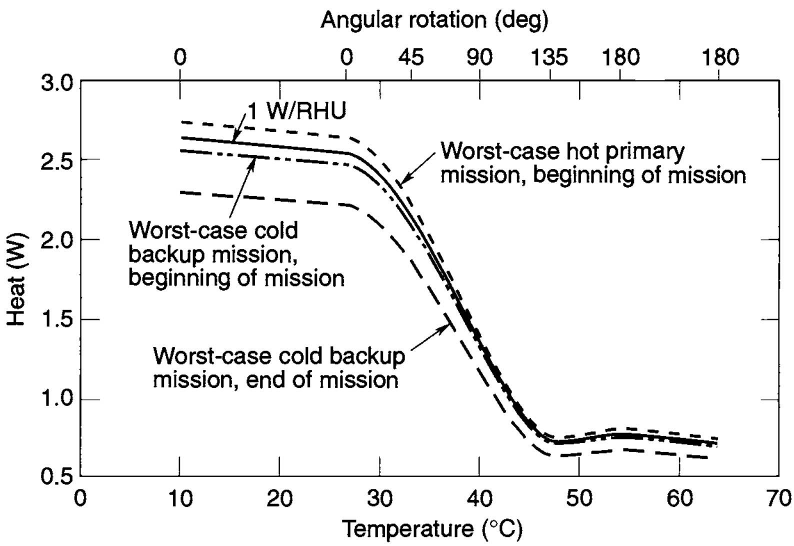


Fig. 7.26. VRHU Cassini/Huygens mission characterization. (Reprinted with permission from SAE Paper No. 941268 ©1994 Society of Automotive Engineers, Inc.)

the primary (earliest) launch, when the individual RHUs have their highest heat output. The bottom curve corresponds to the end of the mission and is based on data that assumes the backup (latest) launch date has a longer total flight time. This lower curve represents minimum VRHU performance resulting from the reduction in heat output that occurs almost 13 years after the RHU was loaded with plutonium. The performance for a given VRHU decreases 8% and 10% over the course of the 11- and 13-year primary and backup missions, respectively.

Since VRHUs may also be exposed to sunlight, testing was performed to characterize the effect of solar illumination on their performance. Steady-state results for the worst-case condition of sun normal to the opening, at varying irradiances, are shown in Table 7.4, which also shows performance characteristics without sun for comparison. As can be seen in the data, the absorbed solar backload increases with mounting-plate temperature. This occurs because more of the paint (as opposed to MLI) is directly exposed to the sun when mounting-plate temperatures are higher. This change in exposed surface, coupled with cavity effects, causes more sunlight to be absorbed and conducted to the mounting plate. The solar load is large and may be significant in steady-state applications. It may be reduced by design changes that lessen the cavity effect and modify the thermal-shield height, although such changes lower efficiency somewhat.

While RHUs and VRHUs are very useful for government-sponsored deep space missions, the presence of plutonium precludes their use on most other projects. Even if control of the nuclear material were not an issue, the cost of RHUs makes them less attractive than electrical-resistance heaters for most missions where solar electric power is practical.

Table 7.4. VRHU Performance with and without Solar Illumination[a]

	Solar Irradiance (suns)					
	1.0	1.0	0	2.7	2.7	0
Performance (W)						
Solar load	1.60	2.14	0	4.64	6.28	0
RHU heat	2.54	1.95	1.95	2.54	1.35	1.35
Total	4.14	4.09	1.95	7.18	7.63	1.35
Temperature (°C)						
Mounting plate	26	36	36	26	43	43
RHU holder	91	101	78	110	146	74
Actuator housing	27	37	36	29	45	43
Mounting base	29	38	37	30	47	44
Thermal shield	52	52	31	89	114	37

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