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IMPLEMENTATION OF HEATERS ON THERMALLY ACTUATED SPACECRAFT MECHANISMS

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ABSTRACT

This paper presents general insight into the design and implementation of heaters as used in actuating mechanisms for spacecraft. Problems and considerations that were encountered during development of the Deep Space Probe and Science Experiment (DSPSE) solar array release mechanism are discussed. Obstacles included large expected fluctuations in ambient temperature, variations in voltage supply levels, outgassing concerns, heater circuit design, materials selection, and power control options. Successful resolution of these issues helped to establish a methodology which can be applied to many of the heater design challenges found in thermally actuated mechanisms.

INTRODUCTION

The aerospace industry's trend away from pyrotechnic devices is resulting in the development of new non-explosive actuator technologies. Many of these new devices are thermally actuated mechanisms which convert heat into kinetic work. Paraffin actuators and shape memory alloys represent two examples of flight qualified, thermally actuated technologies. Although such actuators are typically simple in construction, re-usable, and safe to handle, implementation of the heating elements which govern actuation is not trivial. The vacuum of space, variations in spacecraft temperatures and supply voltages, and minimum outgassing requirements all work against the design of a simple heater. Design and implementation are further complicated by the frequent necessity of maintaining intimate contact between the heater and an element in motion. This paper uses the development of Frangibolt[R] heaters for the DSPSE solar array release to chronicle the design and development issues that were addressed in successfully implementing spacecraft mechanism heaters.

The Frangibolt is a non-explosive release device which uses shape memory alloy (SMA) to forcefully break a bolt in tension [1]. Figure 1 illustrates the device, showing a notched bolt element passing through a

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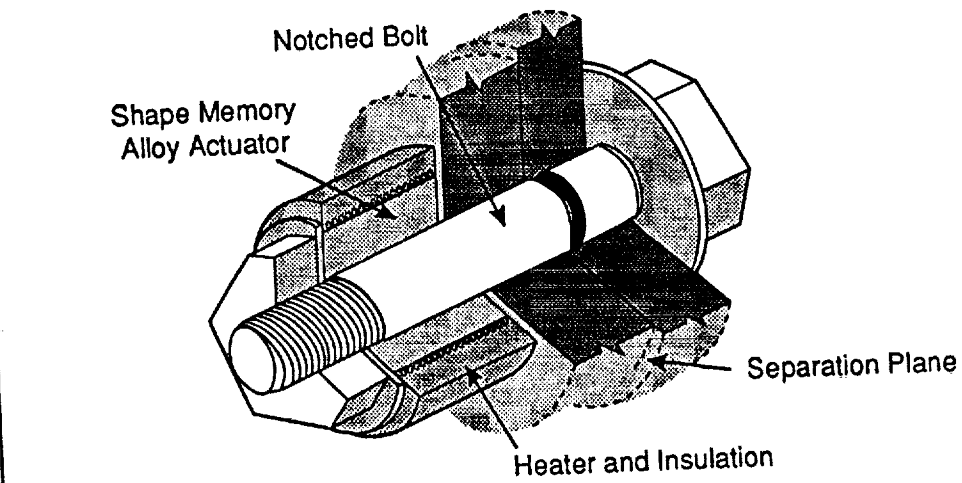

Figure 1: Schematic Illustration of Frangibolt Device and Heater Location

compressed SMA cylinder. When the SMA is heated above its transformation temperature, it recovers to its original length thereby stretching the bolt to failure. It is the heater which mounts to the outer surface of the SMA cylinder that inspired this paper. Using the Frangibolt heater design as a case study, issues common in designing, developing, and qualifying such devices are highlighted and discussed.

SPACECRAFT MECHANISMS AND HEATERS

The number of commercially available mechanisms which are thermally actuated is growing. In addition to the conventional applications of heaters on board spacecraft, such as for thermal control and temperature management, the push for non-pyrotechnic actuators is leading toward more challenging applications for heaters in the control of mechanical devices. Thermal energy is the basic trigger on such technologies as shape memory alloys, paraffin, low melting temperature alloys, and fusible links. Table I summarizes the operation and uses of these technologies.

Thermal actuators which can be operated by joule heating, such as burn-wires and small SMA wires, have an obvious advantage with respect to heater implementation: the element itself is the heater. However, for larger SMA elements, paraffin actuators, and low melting temperature alloy devices, a separate heater must be provided.

TABLE I: Thermally Actuated Spacecraft Mechanisms

Technology	Typical Method of Heating Joule	External	Real Applications
SMAs	Yes	Yes	Frangibolt, pin pullers, latch releases
Paraffin	No	Yes	Pin pullers/actuators
Low Melting Temp. Alloys	No	Yes	Active dampers
Fusible Links	Yes	No	Pin pullers, separation nuts

TYPICAL SPACECRAFT SPECIFICATIONS

Two of the most important criteria in accepting a heater for spaceflight are that it provide ample heat energy under all expected conditions and that it not exceed the specified outgassing limits. This is a significant challenge in view of the potentially wide variations in supply voltages and ambient temperatures. Table II presents some of the basic requirements as they applied to the use of Frangibolt heaters on DSPSE, the Advanced Release Technologies (ARTS) project, and the Total Ozone Mass Spectrometer (TOMS) satellite. Much of the difficulty in designing these heaters stemmed from the requirement by all three spacecraft that power be provided from an unregulated voltage supply. Combining the effects of variations in ambient temperature with an unpredictable power level presented a significant challenge in developing heater integrity.

TABLE II: Heater Specifications

Temperature to Reach:	150°C
Expected Voltage	
Minimum:	24 volts
Maximum:	36 volts
Max. Current Allowed:	5 amps
Expected Temperature	
Minimum:	-50°C
Maximum:	+50°C
NASA Outgassing (SP-R-0022A)	
Total Mass Loss:	< 1.0%
CVCM:	< 0.1%
Redundancy:	Yes

For a heating element with a 10 Ω resistance, the specified 22 to 34 volt range translates directly into 56 to 130 watts of power delivered. This is a variation of ± 40% from the mean. Variations in temperature from -50 to +50°C imply that the total increase in temperature required to effect actuation can vary by 100°C. Depending on the heat capacity of the component(s) to be heated, this can represent a significant amount of energy. Therefore, design of the heater must allow for the possible variations in both the power delivered as well as the component's temperature. This must be achieved without exceeding the NASA outgassing standards.

ESTABLISHING HEATING REQUIREMENTS

Calculating the heat energy required to increase the temperature of a component or substance to a specific level is relatively straight forward. Ascertaining the rate of heat loss from the system is more difficult and depends on temperature gradients and paths of escape. Thermal actuators which can be heated very quickly, such as SMA wires and burn-wire devices, are not as prone to heat loss since the duration of the heating event is relatively short. For actuators requiring longer heating times, the rate of heat loss becomes much more important.

Three basic factors make up the heat input requirements: heat capacity, latent heat of transformation, and expected heat loss. That is

$$Q_{IN} = Q_{STORED} + Q_{TRANSFORMATION} + Q_{LOST} \tag{1}$$

Paraffin and SMA actuators undergo phase transformations which absorb appreciable quantities of heat energy. Burn-wire devices, however, typically fail in tension before the material changes phase into the molten state and thus the latent heat of transformation is negligible.

The stored energy term is described simply by the expression:

$$Q_1 \text{ (joules)} = m \bullet c_p \bullet (T_{FINISH} - T_{START}) \tag{2}$$

The second term, if a phase transformation is expected, can be calculated by:

$$Q_2 \text{ (joules)} = m \bullet \lambda \tag{3}$$

where m is the mass of the heated element, c_p is its specific heat capacity, and λ is its latent heat of transformation. The minimum power requirement is then determined by dividing the total heat energy ($Q_1 + Q_2$) by the desired response time. To this must then be added the expected rate of heat loss.

Using the DSPSE Frangibolt hardware as a specific example, the SMA actuator requires 1475 joules of heat energy to increase its temperature to 150°C from the coldest expected temperature (-50°C), and 575 joules to undergo the phase transformation. Thus, not including heat losses, a total of 2050 joules is needed. To actuate the SMA cylinder in 1 minute under these conditions, the power consumption would be 2050/60 J/sec = 34 watts.

Simple estimates of heat loss out of the SMA cylinder were made by examining two paths of escape: conduction out of each exposed end and radiation away from the outer surface. In the case of the DSPSE application, one end of the SMA actuator had only the bolt head in its conduction path, while the other end had an aluminum flange which was integrally attached to the spacecraft frame. Titanium washers were used on each end in part as thermal insulators. Only the end which was in contact with the attachment flange was considered in the analysis of heat loss.

Using Equation (4), the conduction losses out of the SMA cylinder and across the titanium washer and aluminum flange were estimated.

$$q_C \text{ (watts)} = \frac{k \bullet A \bullet (T_{SMA} - T_{FLANGE})}{t} \tag{4}$$

where k is thermal conductivity, A is the surface area, and t is the thickness of the insulating material(s). The conducted loss out of the system, assuming in worst case a 200°C gradient, was predicted to be 32 watts. Equation (5) was then used to estimate maximum possible heat loss due to radiation,

$$q_R \text{ (watts)} = \sigma \bullet A \bullet (T_1^4 - T_2^4) \tag{5}$$

where σ is the Stefan-Boltzmann constant = 5.67×10^{-12} W/cm^2-K^4, A is now the outside surface area, and T_1 and T_2 represent the two facing temperatures in degrees kelvin. For the DSPSE Frangibolt device, this was calculated to be 2.5 watts, indicating that losses by radiation were small.

After making the estimates described above, the conclusion was drawn that 2100 joules of heat energy was required to sufficiently heat up the actuator from its coldest possible starting temperature, approximately 35 watts of additional heat would be lost to the environment, and power delivered must be adequate over the entire range of 24 to 36 volts. To determine power consumption, the maximum allowable actuation time under worst case conditions (24 volts) was assumed to be 80 seconds. Using Equation (6),

$$\begin{aligned} \text{Power} &= Q/T + q_{LOSS} \\ &= 2100/80 + 35 \\ &= 61 \text{ watts} \end{aligned} \tag{6}$$

This implies that at 24 volts, 35 watts is lost to the environment via conduction and radiation while 26 watts is available for heating the SMA actuator. At 36 volts, the same 35 watts is lost but now 104 watts is available for heating. This factor of 4 difference in available heat energy exemplifies the challenge in heater design.

Continuing with this example, the SMA surface watt density which results from this power variation ranges from 4 to 9 watts/cm^2. Watt density is typically a very important factor in the design of a heater as it will often limit the choices available in selecting the materials for construction and insulation. This is discussed in more detail later in the paper.

HEATER TECHNOLOGIES CONSIDERED

Since radiation and conduction are the only two modes of heat transfer that can be considered for spacecraft heater applications, it was simple to narrow the choice to conduction transfer. Using only radiation transfer would have required, under ideal conditions, bringing a surface concentric about the SMA cylinder to a temperature of 1000°C or above. This was not considered a desirable feature within a reusable spacecraft mechanism.

Focusing on conductive approaches to heat transfer, there were again two alternatives: chemical and resistive. Commonly used chemical heaters comprise a cold-rolled steel tube packed with a slow burning pyrotechnic composition. Such heaters can provide 5500 to 26,000 joules of heat energy in 1 to 3 seconds. The fact that these chemical heaters are one shot devices, with no provision for pre-flight testing, significantly reduces their attractiveness to spacecraft applications. However, where significant heat is required to be delivered in a short duration and with minimal electrical energy consumption, they are certainly a viable alternative.

Four basic types of resistive heating elements were investigated for the Frangibolt mechanism:

a) wrapped wire
b) band heaters
c) etched foil
d) cable heaters

The first approach explored consisted of wrapping the SMA cylinder with Nichrome wire, sandwiched between two layers of Kapton tape. The desired watt density could be achieved by varying wire diameter and number of wraps. The performance, however, was less than desirable. The temperature of the Nichrome element was sufficiently high so as to "burn" a cavity within the insulation that resulted in the wire shifting and occasionally shorting between wraps. After two or three cycles, these heaters became unreliable.

The second type of heater examined was the band heater. These are commercially available units with stainless steel or mica jackets containing the heating wire element(s) and packed with a high temperature insulation (typically an MgO filler). A variation on this design was also tested that comprised a stainless steel tube in which the walls were packed with the filler and heating elements. In both cases, the inside diameter of the heater, no matter how intimately pressed against the SMA cylinder, would expand away from the SMA surface, thus breaking its conductive path. This effect was doubled when the actuator began to recover: the SMA grows in length to break the bolt, but must decrease in diameter to conserve volume. Therefore, shortly after the heater was turned on, it lost intimate contact with most of the SMA cylinder and thereby thermal conduction was drastically reduced. This effect was observed only during tests in vacuum, because convection heat transfer during atmospheric tests produced false positives.

Etched foil heating elements appear the most sophisticated, but are in fact simple to manufacture and easy to install on flat or curved surfaces. They are also more flexible than other heater configurations, which can be important for applications requiring physical movement of the heated element. Figure 2 shows a photograph of the etched foil element used on the Frangibolt actuator. Power output is determined by the thickness of the foil, its width and total length. The serpentine patterns are designed on a CAD system, a mask is made, and then the foil is etched using standard lithography techniques. A major benefit of this approach is that the heating element has a large surface area in contact with the heated component, whereas wire elements can have at best a line contact with the heated surface. The disadvantage of the etched foil, as will be discussed later, is that it is prone to buckling when adhered to a surface that contracts and expands through a large percentage.

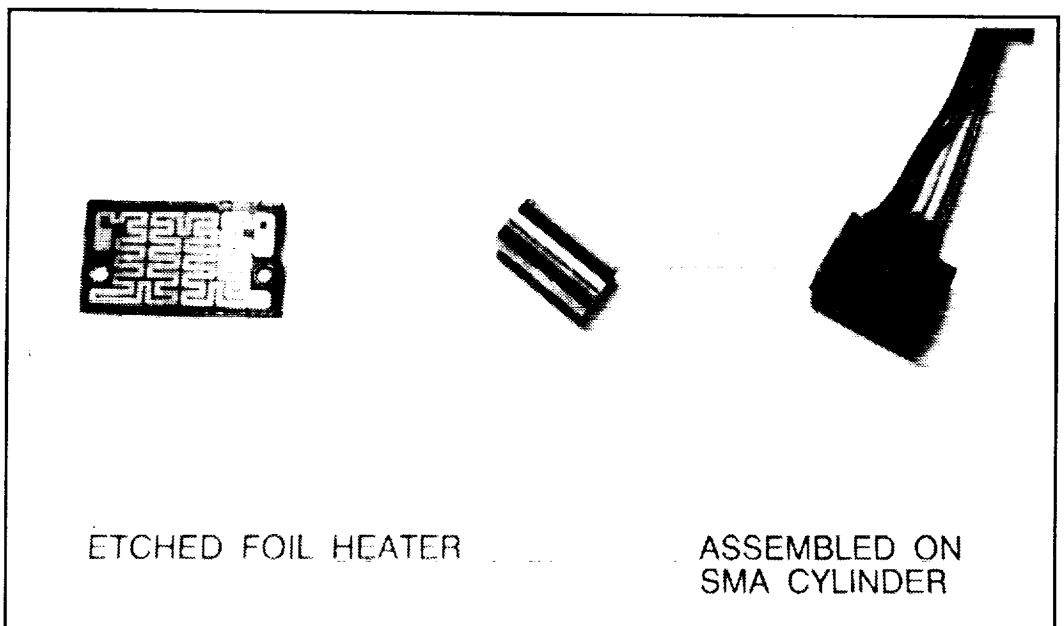

Figure 2: Photograph of an Etched Foil Heater

Cable heaters are thin walled stainless steel tubes which comprise the heating wire and insulative filler. These tubes can be drawn down to diameters as small as 1.5 mm. During the Frangibolt investigation, two different types of cable heaters were tested: a 3 mm diameter tube with a flattened edge (to provide a "D" shaped cross-section) and a small 1.5 mm diameter tube. Both were wrapped in helical fashion around the SMA cylinder. The larger of the two behaved similarly to the band clamps described above; despite the flattened surface to maximize contact, it still tended to grow away from the SMA surface. The smaller cable heater was wound into a helix to a diameter just smaller than the SMA cylinder (see Figure 3). Even as the heater increased in temperature, its elastic propensity to decrease in diameter kept it in good conductive contact with the cylinder.

Other types of heaters that are available, but which were not investigated for the Frangibolt, include cartridge, ceramic fiber, strip and radiant heaters. The cartridge heater incorporates a Nichrome wire element and MgO filler inside an Incoloy sheath. Commercially available diameters range from 3 to 25 mm, and lengths can range from 3 to 180 cm. These cartridges can be

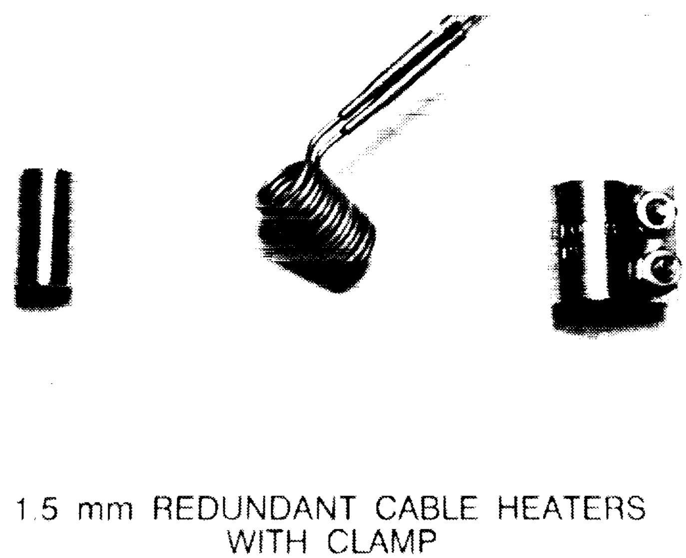

Figure 3: Photograph Showing Cable Heater

heated to 870°C with a maximum watt density of 62 watts/cm^2. Ceramic fiber heaters provide for very high temperature operation, incorporating iron-chromium-aluminum heating elements within a matrix of ceramic fiber insulation. Operating temperatures can be as high as 1200°C and watt densities as high as 4.6 watts/cm^2. Strip heaters are flat plate stainless steel sheaths containing heater wire or etched foil elements within mineral or mica insulation. The watt densities can be as high as 15 watts/cm^2 and temperatures can go to 760°C. The commercially available radiant heaters are larger in size and use either radiating panels or quartz tubes with reflectors. Radiant heater temperatures typically range from 540°C to 1100°C, and watt densities can range from 1.5 to 6.2 watts/cm^2. [2]

EMBEDDING THE HEATING ELEMENTS

Integrating the heater with the component or substance to be heated also requires careful consideration. Clamping a helical heater to the surface of an SMA cylinder as shown in Figure 3 poses little difficulty and minimal concern for outgassing. Embedding an etched foil heater in Kapton or silicone rubber, however, requires close examination of watt densities and material limitations. Table III presents the watt densities of several standard insulation materials [3].

TABLE III: Comparison of Heater Insulation Materials

	Max. Watt Densities @		
	-50°C	+50°C	+150°C
Mica	17.0 W/cm^2	17.0	15.5
Silicone Rubber	9.3	7.8	3.1
Kapton	7.8	6.2	0.8
Nomex	5.1	1.6	0

Kapton insulation was tried with minimal success. An etched foil heating element was sandwiched between two layers of kapton film and bonded with an FEP filler. The total thickness of the assembly was approximately 0.2 mm. Contact between the Kapton and SMA surface was achieved with a high temperature adhesive. Initial tests using a watt density of 4 watts/cm^2 resulted in burning of the Kapton film and failure of the heating element. Adhesion to the SMA surface was maintained, but local hot spots created some gaseous discharge.

A single stage silicone rubber was then analyzed. This heater was constructed by vulcanizing the etched foil heater (shown in Figure 2) directly to the SMA surface with a sandwich structure of thin silicone rubber sheets. This assembly was then placed in a mold and an outer jacket of silicone rubber was vulcanized in place. The resulting heater exhibited excellent adhesion qualities to the SMA cylinder even after numerous mechanical and thermal cycles. The benefit of silicone in this application is that it easily tolerates the 3% strain compression and elongation of the SMA actuator without delamination. The disadvantage is that it is more prone to outgassing if the heater(s) were to remain on indefinitely.

To identify the limitations of the selected silicone rubber, a thermal gravimetric analysis was performed on a sample piece. Figure 4 shows that the material is stable to approximately 370°C, after which the total mass loss exceeds 1% [4]. Based on this data, the upper temperature limit of the silicone rubber during use was defined to be 300°C. This provided a 150°C margin above the temperature required to actuate the SMA cylinder under all possible conditions. To meet the NASA outgassing standards, the assembled actuators needed only to be heated in vacuum at 125°C for 24 hours.

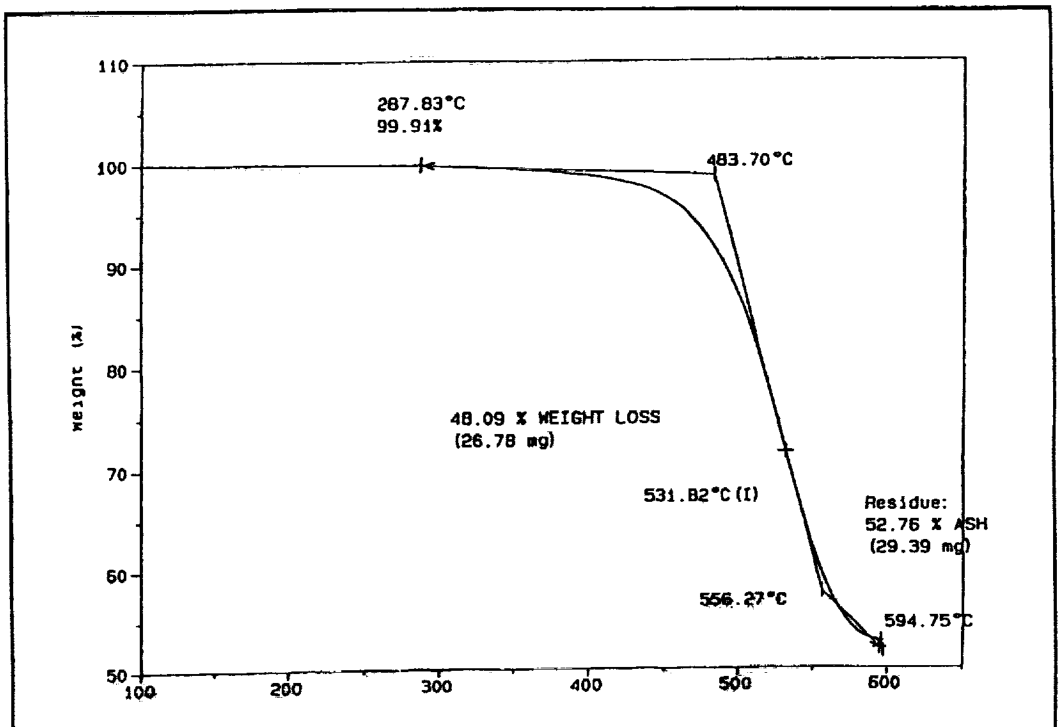

Figure 4: Thermal Gravimetric Analysis of Selected Silicone Rubber

The silicone rubber heater provided the best heat transfer and easily tolerated the compression and elongation of the SMA cylinder. Even so, it was decided that a second heater design would be provided for applications hypersensitive to outgassing. The second design uses the small helical cable heaters described above. This unit provided the same watt density against the SMA surface, yet could reach temperatures of up to 900°C with effectively no outgassing.

CONTROLLING THE HEATING ELEMENTS

Another important consideration in applying heaters on spacecraft mechanisms is the method of control and shut-off. Since these heaters will be operated remotely under computer command, the simplest of control schemes should be used to ensure high reliability. Five different approaches were investigated for the Frangibolt system:

1) Timer
2) Deployment switch
3) Self-regulating resistance element
4) Thermal cut-out
5) Thermocouple feedback

Timing circuits are used in most spacecraft heater applications as a safety measure to ensure that the duration of the event is limited. This has been the case in most uses of the Frangibolt and High Output Paraffin actuators. If the heaters are left on too long, they will likely outgas and deteriorate. Thus, additional control elements may be added in series with the timing circuit to ensure that overheating does not occur, especially during ground tests of flight hardware.

For the TOMS satellite, TRW elected to use only a timing circuit to control the Frangibolt heaters. It was their determination after performing thermal vacuum tests that actuation from worst case conditions would occur within 60 seconds. Further, even if the hot extreme case was encountered (+50°C and 34 volts), the 60 seconds on time would not result in undesirable outgassing. Therefore, the TOMS satellite will supply power to the primary heaters for 60 seconds each, and then, after a specified waiting period, to the secondary circuits for 60 seconds each.

For the DSPSE satellite, NRL chose to add a deployment switch through which the heater power passed. The heaters automatically turned off upon release of the solar panels, thereby eliminating the chance of overheating the heating elements.

Self-regulating resistive elements have been applied to heaters for many years, but with only limited success. The material is usually made from nickel-iron alloys which increase in resistance proportionally with their temperature. The temperature coefficient of resistance for these materials is typically 0.25% per °C. The disadvantage of this technology in practice is that there is a high in-rush current, followed by a quick decrease in current flow, and then little additional ability to control temperature. Applications which do benefit from self-regulating heaters are those with constant heat loads, a wide range of acceptable temperatures, and low watt density requirements.

Another type of heater control considered was the thermal cut-off (TCO) switch. At a predetermined temperature, these switches interrupt current flow. The solid state devices can interrupt currents up to 40 amperes and will range in size from 0.8 to 6.2 cm^3 [5]. The TCO was not incorporated in the Frangibolt heater design because of the physical size. To incorporate such a switch within the silicone rubber molding around the SMA cylinder would have doubled the size of the actuator.

A control scheme that was short-lived during the initial investigation was that of using a thermocouple embedded in the heater to complete a control loop. For critical temperature maintenance this may be a necessary requirement, but for thermally actuated devices this was considered too complex. Demanding complicated electronics to drive single event mechanical systems is contrary to the philosophy of simplifying spacecraft mechanisms. Therefore, it was necessary to find simpler and even more reliable means for controlling the Frangibolt heaters, such as the timer and deployment switch combination.

SELECTED HEATER DESIGN FOR DSPSE

The final configuration of the Frangibolt heaters for use on DSPSE was defined in conjunction with NRL. The etched foil heating element design using the low outgassing silicone rubber insulation was selected. Electrical redundancy was provided by using two heater circuits on each SMA cylinder in an over/under manner. This increased the surface area for each heating element which, in turn, reduced the watt density demanded of the heaters. As mentioned above, DSPSE incorporated deployment switches on each solar panel to turn power off immediately after actuation. Power was supplied from an unregulated bus and temperatures of the release mechanisms were expected to range from -10°C to +50°C. Actuation times of the flight units during pre-flight tests confirmed that each heater worked as expected.

FAILURE MODES OBSERVED AND PROBLEMS RESOLVED

During the two years of developing the Frangibolt heaters, only three failure modes were observed. These failures resulted from localized buckling of the etched foil elements, an inferior electrical connection to one heater circuit, and overheating of the silicone rubber jacket. None of these problems was inherent to the mechanism design, but rather to the design, fabrication, and use of the heating elements.

One of the benefits discussed regarding non-pyrotechnic spacecraft mechanisms is their ability to be re-used in most instances. For thermally actuated devices, this means that the heaters must be re-usable and yet remain reliable. Numerous compression and elongation cycles performed on Frangibolt prototypes revealed localized hot spots within the heaters and, on two occasions, failure of the etched foil element due to excessive buckling. This was caused by having segments in the etched foil serpentine pattern which were too long in the direction of the compression and elongation strain.

Although the silicone rubber conforms easily to the 3% strain deformation, the etched foil material does not. Initial prototypes, which had longitudinal runs as long as 70% of the cylinder's length, exhibited buckling directly in the middle of each longitudinal segment. This buckling occurred within the first four cycles and created localized areas where the heating foil delaminated from the silicone rubber. The points of delamination caused the hot spots that were observed.

This problem was solved by redesigning the etched foil pattern so as to minimize the length of any longitudinal segments. Figure 2 shows the second of three revisions of this serpentine pattern. The longer segments are all oriented in a circumferential manner, leaving only short segments in the longitudinal direction. This pattern eliminates the buckling problem by providing the necessary compliance against repeated compression and elongation.

The second failure encountered was that of a poor electrical connection between a lead wire and an etched foil element. Close examination revealed that bonding the wire to the thin pad is a difficult manual operation, and that better screening procedures were required during its manufacture. Since the addition of an in-process inspection of this joint, no further failures have been experienced.

Overheating of the silicone rubber jacket was the third failure mode observed. This resulted from continuing to apply power at high voltages to the secondary circuit after the point of actuation. The heater was optimized as much as possible to operate effectively over the entire specified voltage range and from any anticipated temperature. However, even though the units operated effectively from -50°C at 24 volts (61 watts) and from +50°C at 36 volts (136 watts), the latter condition, when applied to the secondary heaters, created the potential for an excessive rise in temperature. If this high power level was driven through the secondary heater after actuation had occurred, the temperature would rise to 300°C within an additional 15 to 20 seconds. Beyond this point, outgassing would exceed the levels accepted by NASA.

The overheating problem was solved three different ways. For the TOMS application, the maximum sustained voltage level under load does not exceed 34 volts, and thus the problem does not manifest itself. For DSPSE, the specified voltage range did extend to 36 volts. Therefore, incorporation of the deployment switches ensured that the heaters would shut off immediately upon actuation. For future satellites, where high voltages are anticipated and no deployment switch is desired, use of the stainless steel heater configuration shown in Figure 3 would provide the heat requirement without the concern for outgassing.

CONCLUSIONS

Two different approaches were developed to heat an SMA cylinder in a vacuum for spacecraft applications. The course of designing and refining these heaters identified important considerations which are applicable to most applications of heaters on spacecraft (see Figure 5). These include designing heaters to accommodate large fluctuations in voltage supply and temperature, providing direct intimate contact to either stationary or moving components, and minimizing outgassing potential during use. It was concluded that silicone rubber heaters offer relatively high watt densities and are extremely flexible. Stainless steel cable heaters provide very high temperatures with no outgassing, but are not as efficient in thermal transfer. Implementation of heaters on spacecraft mechanisms will often require that the driving circuit be limited to a timer and simple shut-off scheme. Use of sophisticated controls for single event heater operation is generally discouraged.

ACKNOWLEDGEMENTS

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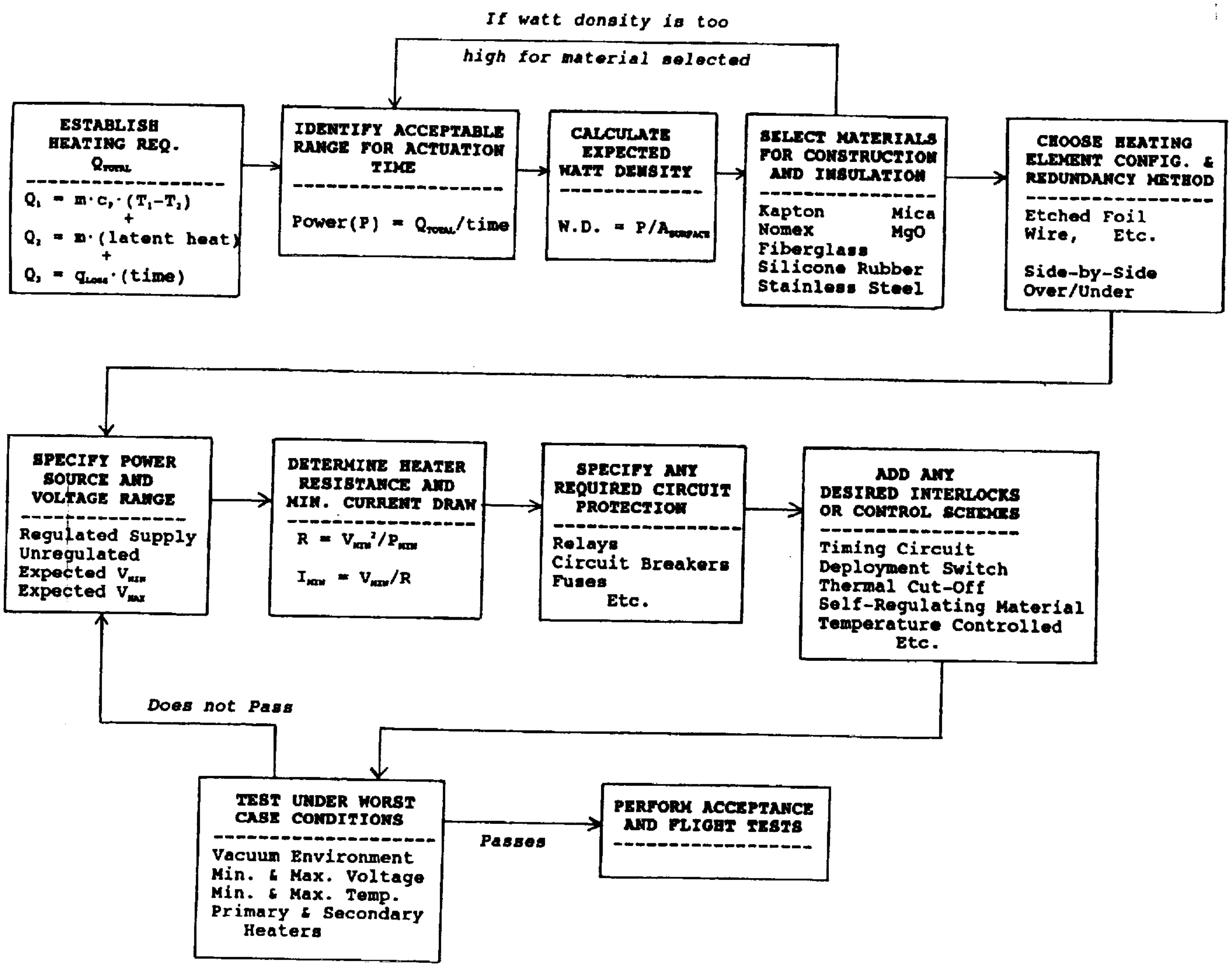

Figure 5: Suggested Heater Design Methodology for Spacecraft Mechanisms