Thermal control in micro satellites

Lars Løge

Department of electronics and telecommunication, Norwegian University of Science and Technology, Trondheim

Introduction

There is a growing interest in development of small satellites, both from commercial and academic interests. The main reason for this is the opportunity to get a satellite into orbit at a reasonably low price. Because of the miniaturization of electronics it is possible for the satellite to handle missions with commercial and scientific gain. Development of the smallest satellites has been dominated by universities and research institutions, but the industry is becoming more and more involved.

Small satellites are classified according to the mass, and placed in the following groups [1]: Nano and pico satellites weight less than 10 kg, micro satellites weight between 10 and 100 kg and mini satellites weight between 100 and 500 kg. The focus here will be on satellites with mass less than 100 kg, and for simplicity they will all be denoted as micro satellites.

When the satellites become so small active thermal control and management is in most cases difficult to implement. It is simply not enough power and volume available. Thus, thermal control in small satellites is mainly dependent on passive techniques to do the job.

Thermodynamic Principles

On the earth thermal energy can be transported in three different ways, trough convection, conduction and radiation. In the absence of an atmosphere convection is not present in space. Thus, to control the satellite thermally in space the only tools we have at our disposal are conduction and radiation. This is a truth with some modifications as there is possible to introduce convection artificially [2].

In space it is close to vacuum so for external exchange of thermal energy radiation is the only way. There are three external energy sources where direct solar radiation is the most dominant with an average energy of about 1350 W/m^2, primarily in the visible spectrum. The second largest source is the sunlight reflected from the earth, also called Albedo, with a maximum energy in a 550 km orbit of 450 W/m^2. Both these sources are only present when the satellite is illuminated by the sun. The last external energy source is thermal radiation from the earth in the infrared spectrum. For an 550 km orbit the received energy is approximately 200 W/m^2 [3]. This energy source is fairly constant for the whole orbit, but it is usually considered to be negligible [4].

Thermal Equilibrium

All bodies absorb and emit energy in form of radiation. Absorption happens in the whole spectrum, but mainly in the visible spectrum, while emission happens in the infrared spectrum. If we let S denote the total incident energy flux on the satellite, both the direct radiation and the Albedo, we get this equation for the equilibrium temperature [2]:

$$T = \left(\frac{\alpha}{\varepsilon} \cdot \frac{A_a}{A_e} \cdot \frac{S}{\sigma} \right)^{\frac{1}{4}} \mathrm{K} \qquad (1)$$

Where α is the absorbitivity coefficient, ε is the emissivity coefficient and σ is the Stefan-Boltzmann constant. A_a and A_e are the absorbing surface area and the emitting surface area. This equation is correct under the assumption that there are no internal heat sources. An important result from this equation is the ratio between α and ε. The ratio is a good characterization of the thermal behavior of the satellite surface.

Table 1: Some typical α and ε values.

Surface	α	ε	α/ε
White paint	.20	.90	0.22
Black Paint	.95	.90	1.05
Unpolished Aluminum	.25	.25	1.00
Polished Aluminum	.20	.05	4.00
Gold	.25	.05	5.00
Solar cells	.80	.90	0.90

Table 1 shows approximate values of α and ε for some typical satellite surfaces. It is interesting to note that the deciding factor for the thermal behavior is not the material itself, but how the surface is treated. The thermal behavior of the surface is not completely characterized by the α/ε ratio. Surfaces with high α and ε values have low thermal inertia and will absorb and emit without delay. If the α and ε values are low absorption and emission will be slower, and thus have higher thermal inertia.

Thus, it is possible to design the surface of the satellite in such a way that it will hold a specific temperature as long as it is illuminated by the sun. With a given size and shape for a satellite there is only need to adjust the surface by polishing or coating with paint of correct color.

In Figure 1 the equilibrium temperature of a cubic satellite in an orbit with an approximately height of 550 km is plotted as a function of the α/ε ratio. It is assumed that 25% of the satellite surface is directly illuminated by the sun and the Albedo. Equation 1 is used in order to get this result. Figure 1 clearly shows that it is should not be difficult to design a satellite with an equilibrium temperature inside a given

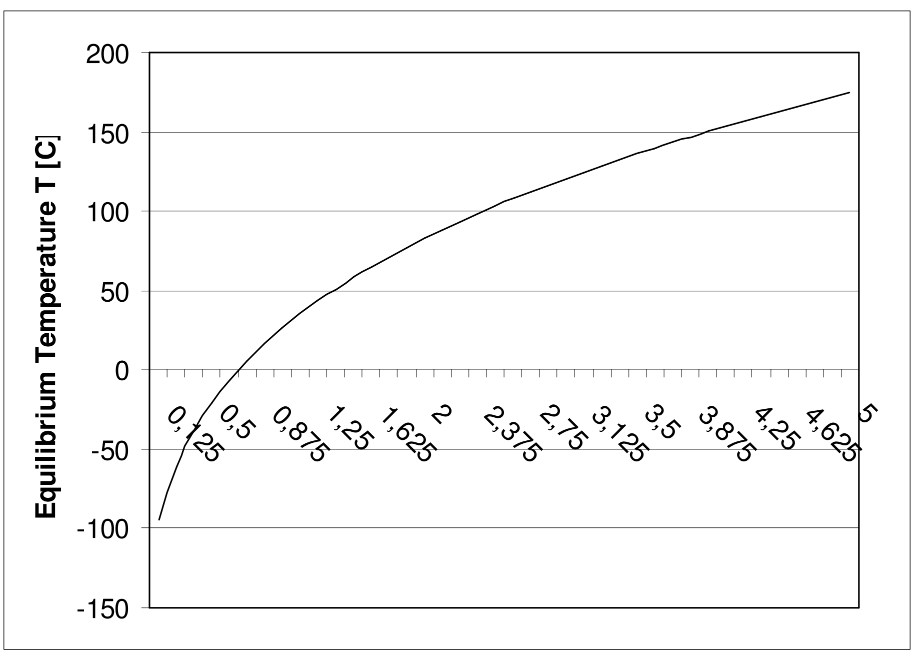

Figure 1: Equilibrium temperature as a function the α/ε ratio.

specification just by adjusting the satellite surface.

The result above is valid as long as the satellite is illuminated by the sun. When the satellite enters the eclipse the energy flux incident on the satellite from the sun and the reflection from the earth will disappear. However the radiation from the satellite will continue since it has a temperature that is higher than the surroundings. The temperature will fall in accordance to the following differential equation [2]:

$$\frac{dT}{dt} = \frac{-\varepsilon A_e \sigma T^4}{mc} \qquad (2)$$

Here m is the satellite mass and c is the satellite's specific heat. The special case of no internal heat source is still assumed.

It is at this point micro satellites get problems with thermal control. As equation 2 shows the change in temperature is dependent on the satellite's mass. Large mass will give slow temperature change, while small mass gives quick temperature change. A micro satellite operates normally in low earth orbit with an orbital time between 90 and 100 minutes. The worst case scenario is an orbit with as much as 50% of the orbit in the eclipse. With up to 50 minutes out of direct sunlight the satellite temperature can drop all the way down to -100° C [4].

It is of course possible to limit this temperature loss to some extent by adjustment of the surface so ε is lowered, but the effect on micro satellites will be negligible since the satellite mass is so small. In addition the lowering of ε may cause problems for the satellite when it is not in the eclipse, as a high α/ε ratio will give the satellite a higher equilibrium temperature.

Internal heat sources

The above discussion has assumed that there are no internal heat sources in the satellite. This can of course never be the case if the satellite is to be used purposefully at all. Everything onboard a satellite that uses power is a heat source.

This internally generated thermal energy is very useful when the satellite is in the eclipse, but it may cause overheating when it is illuminated by the sun. It is therefore crucial that the different components are placed with care in order to have well functioning satellite. The thermal energy generated by a component must be handled in some way, either by radiation into space or internal redistribution. How the components are placed in relation to each other is also important. One example is radio receivers and radio transmitters. A radio receiver needs to be

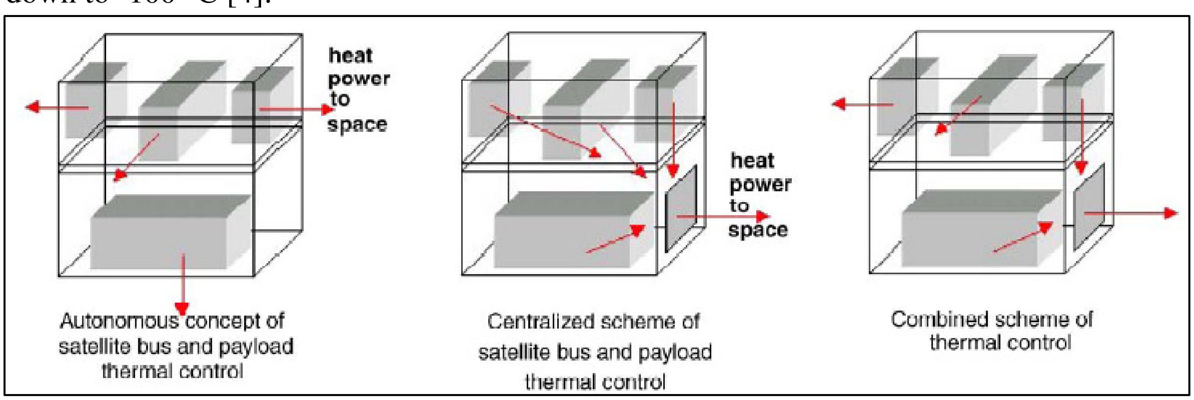

Figure 2: Thermal concepts in micro satellites.

kept cool in order to minimize self generated noise. The radio transmitter employs a power amplifier that generates a substantial amount of thermal energy [2]. So even though it may seem logical at first glance to position the radios together, it can have fatal results for the satellite.

There are three design approaches to this problem as shown in Figure 2. These are the autonomous concept, the centralized concept and the combined concept [3]. In the autonomous concept every component has its own individual thermal control system, and they are thermally disconnected from each other. In the centralized concept on the other hand every component is thermally connected to each other and there is one central radiator for external thermal energy exchange. The combined solution is as the name suggests at combination of the two where some of the components are connected to a central radiator while some of the components have individual thermal solutions. This is the most common used concept. As it is indicated above would the radio transmitter and the radio receiver benefit if they were thermally disconnected.

These concepts are of course simplifications. Even if the components are thermally disconnected to the extent that they are not connected with thermal conductors there will be some heat exchange due to radiation between the components.

There are several ways to thermally connect components together. The simplest and most used solution is by thermally conducting wire. By connecting several or maybe all heat producing components together the number of heat sinks on the external walls can be reduced. The network of thermal conductors that results is analogous to an electrical resistor network, and thus it is simple to calculate the thermal flow within the satellite. Any exterior surface with a α/ε ratio bellow one will function as a heat sink. Solar cells can therefore be used as heat sinks. It is estimated that a power of 40W can be radiated through a radiator with area of between .15 and .20 square meters [3].

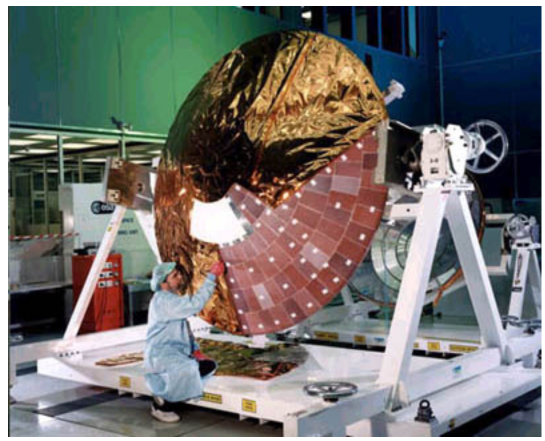

Figure 3: MLI blankets on Huygens' front shield.

Insulation

Exterior walls that are not supposed to act as heat sinks should be covered with multilayered insulation (MLI) blankets. It is the MLI blankets that have the golden appearance that some parts of a satellite often have on pictures. One example can be viewed in Figure 3 where the front of the Huygens spacecraft is being coated with MLI blankets.

Even though the spacecraft on this picture is quite large it is possible to use MLI blankets in smaller scale too. It can be used on big micro satellites, but it will probably be hard to implement on smaller satellites such as CubeSat and similar designs. On most of this kind of satellites all available area will be covered with solar cells in order to

Figure 4: A CubeSat where the exterior walls are covered with solar cells.

extract as much energy as possible from the sun. Micro satellites have in general poor, if any, attitude control. In most cases the do not even have deployable solar cell panels. Redundancy in the positioning of the solar cells is therefore necessary in order to insure that enough power is delivered to the payload, the radio and other power consuming components.

In Figure 4 a CubeSat can be seen, and there is not much surface that is not covered by solar cells. The matchbox is added in order to show how small a CubeSat actually is. The nadir side is usually the only side without solar cells, so if the designer wishes to avoid using solar cells as heat sinks the radiator for external thermal exchange must be placed there. The four side rails could have been used, but the CubeSat standard stipulates that those must be made of aluminum. From Table 1 it is clear that aluminum is not a good heat sink since it has a α/ε ratio equal or larger than one, depending on type of aluminum and how the surface is treated.

Heat pipes

As mentioned earlier is the convection phenomena not present in space due to the lack of any atmosphere, but it is possible to introduce convection artificially. This can be done through the use of heat pipes. In some satellites the power amplifiers of the radio transmitters generate so much heat that normal conduction and radiation solutions are not effective enough. Heat pipes may solve that problem.

The heat pipe principle is used in most modern day refrigerators, at least those that are based on convection. A medium is pressurized inside a sealed tube or pipe if you like, close to the saturation pressure. With adjustment of

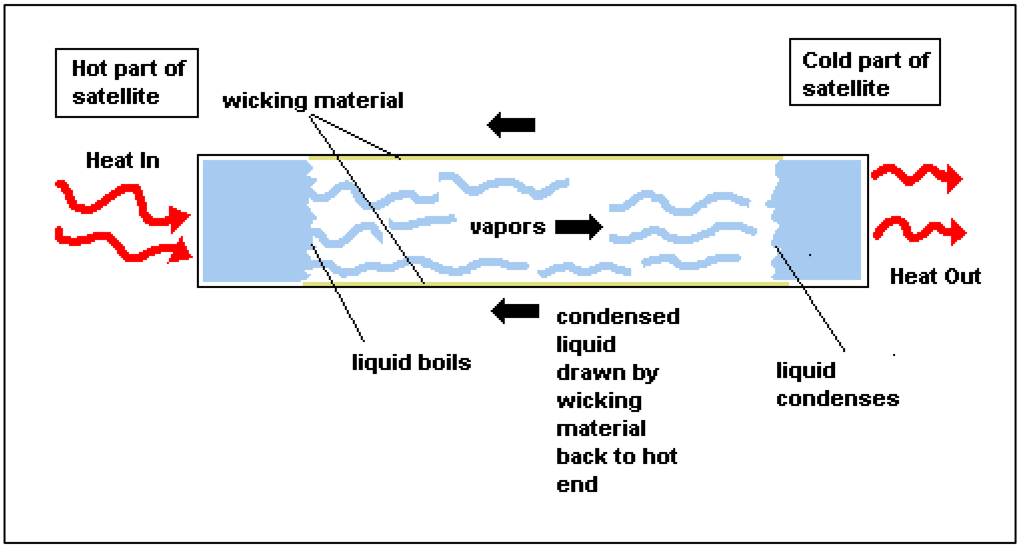

Figure 5: Conceptual drawing of how a heat pipe works

the pressure the medium can be controlled to condense and evaporate inside some specified temperature range. The pipe is placed with parts of it outside the satellite. That end function as a heat sink for the pipe [2]. The other end will be placed in contact with a heat producing part of the satellite.

Figure 5 show a drawing of how the heat pipe concept works. On the inside of the pipe there will be grooves or some sort of wicking material. As long as there is liquid in the hot end it will evaporate, and remove thermal energy from the heat producing component. This results in a constant drift of vapor toward the cold end. In the cold end the vapor will condense back to liquid. The constant drift of vapor will of course give a constant condensation. As a result liquid will be pressed back down the pipe along the grooves or wicks helped by capillary action. When it reaches the hot end of the pipe it will replenish the liquid reservoir, and be evaporated again. In this way the cycle continues and cools the satellite.

Use of heat pipes is not restricted to external thermal energy exchange only. They can also be used as thermal connections between different components inside the satellite.

The heat pipe is an excellent way to remove thermal energy from components and systems that need cooling. It can function in all relevant temperature ranges simply by using a medium that has the right characteristics. In heat pipe systems made for satellites water and ammonia are two media that normally are used.

Heat pipes have been used in satellites since the 1970s. The potential beneficial use in spacecrafts was actually one of the driving forces in heat pipe development. A heat pipe may sound like a heavy and bulky component to put into a satellite, but it does not necessarily have to be that. Because of its effectiveness in absorbing and emitting thermal energy they can be made fascinatingly small and still be able to keep high power electronics cool. Simulations show that an ammonia filled heat pipe with a total mass of only 25 gram can transport 25 W of energy. The mass of the pipe made of stainless steel is part of the total mass [5]. In order to get this result it was assumed that the temperature of the condenser was 0° C.

This result shows that it is possible to implement heat pipes in micro satellites, and not only in large satellites. Heat pipes can actually be made so small that they can be used as thermal control components in even the smallest of satellites. That includes single CubeSats that needs to meet a requirement of maximum mass of 1 kg in order to comply with the CubeSat standard.

Thermal hardware

With the technology that is available today it is not necessary for CubeSats and similar satellite designs to install heat pipes onboard the satellite. In some cases there is not need for any thermal control at all. With a certain design it has been calculated that the satellite would operate in a temperature range between -35° C and 60° C without any type of thermal control at all [3].

For some components this is a temperature range that is acceptable, but for many others such as batteries and microprocessors this is not good enough for optimal performance. Simply by the use of thermal insulation between the structure and the electronics combined with conductive wiring to improve thermal uniformity may be enough to create an environment with a stable room temperature. The thermal insulators can be combined with shock absorbing mounts for the circuit boards.

The satellite performs best if the temperature is kept constant and inside of what people would call normal comfort temperatures. This is of course difficult to accomplish when the satellite enters the eclipse. However, it is possible to slow the temperature drop slightly. As mentioned earlier the change in temperature is inverse proportional with the specific heat, as stated by equation 2. Thus, if the specific heat of the satellite is maximized, the temperature gradient is minimized. When designing the satellite, materials that have high specific heat should therefore be chosen.

Table 2: Some typical specific heat values.

Substance	Phase	c [J kg^{-1} K^{-1}]
Aluminum	solid	897.0
Ammonia	liquid	4700.0
Copper	solid	385.0
Gold	solid	129.1
Graphite	solid	710.0
Iron	solid	450.0
Water	liquid	4181.3

In Table 2 there are listed some common substances and their specific heat. Aluminum is the solid with the highest value, thus it would be profitable to use as much aluminum as possible. Beware though that aluminum is a light alloy so the payoff in regards to the temperature gradient is moderate. Never the less aluminum is one of the most popular used materials in satellites, and that is mainly because it offers good

Figure 6: A CubeSat skeleton in aluminum.

strength at a low weight. This property of aluminum is utilized in the CubeSat standard. A prefabricated CubeSat skeleton in aluminum can be studied in Figure 6.

Active thermal control

All the methods for thermal control described above have been passive methods. In many cases they will be able to keep the temperature inside of an acceptable range, but not always. The passive methods are based on the assumption that there is enough thermal energy available, either from the sun or from internal sources, and that all excessive heat can be radiated out into space. This is not always the case.

When a satellite enters the eclipse the satellite temperature drops fast, especially in a micro satellite. If the satellite do not produce enough thermal energy the temperature can come down as low as -100° C by the end of the eclipse. At this temperature components such as batteries will not function and the satellite may “die”. The easiest way to prevent that from happening is to place small electric heaters on the temperature sensitive units [2]. When the satellite enters the eclipse the heaters are turned on. That way the temperature is kept inside an acceptable range through the whole eclipse.

Heaters of this kind can be made as small as you like. Thus, implementation in micro satellites is not a problem in connection with mass and volume restrictions. They will necessarily use power and on micro satellites power may be a limited resource. Never the less it may be worth it as an insurance against satellite failure due to too low temperatures.

As mentioned earlier overheating may occur if the thermal energy can not be disposed of quickly enough. Active cooling devices can then be the solution. This is devices such as pumped-loop systems, cryogenic coolers and thermoelectric coolers. Systems of this kind are large and bulky, and are more common on large manned spacecrafts such as The International Space Station and The Space Shuttle. They are seldom used on satellites, especially not on micro satellites.

There is one active control

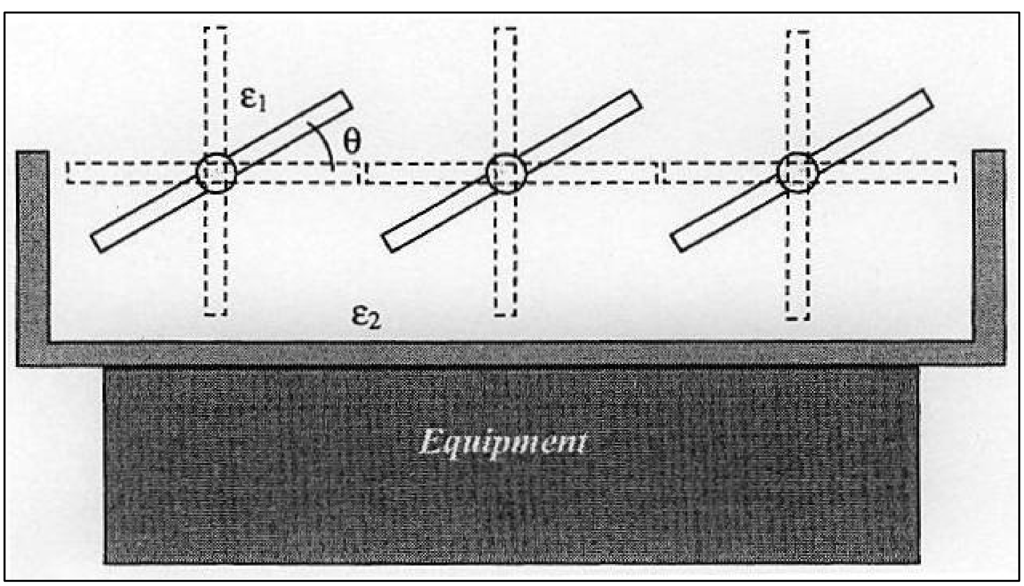

Figure 7: Louvers for thermal control on a satellite.

method that can be used as both heating and cooling device. That is the utilization of louvers. Figure 7 shows a cross section of a louver design for a satellite. The concept is quite simple. Louvers are placed over a cavity on the exterior of the satellite. The cavity should be as close as possible to the components that need cooling or heating. In the figure this is denoted as equipment. The surface of the louvers must have a different ε than the bottom of the cavity. When the angle θ increases more of the cavity floor is uncovered. If the emissivity of the cavity floor is larger than on the louvers the radiation will then increase, and the temperature of the equipment will decrease. Should the emissivity of the louvers be largest the equipment temperature will raise when the angle θ is increased.

Louvers systems can be made quite small so it is possible to implement them in micro satellites, but it is not used very often [3]. One of the main reasons for that is that it is a mechanical system. Moving parts should be avoided as much as possible in all satellites. This is especially important on micro satellites as they are smaller and have less room for system redundancy than larger satellites.

Adaptive thermal control

One of the main difficulties with thermal control of satellites is the extreme temperature variations a satellite experiences between the eclipse and when it is illuminated by the sun. In order to deal with this problem and keep the temperature stable adaptive thermal control is needed.

The passive control methods are as the name states passive. Thus, they can not be changed after launch. It is simply not possible to change paint or surface coating when the satellite is in space. To stop the convection process in a heat pipe is not possible either.

With active control methods the story is different. Electric heaters can be turned on and off, and louvers can open and close. The effect of them can even be adjusted continuously, not just on and off. Adjustment can be done manually or automatic.

Temperature sensors must be placed on temperature sensitive components and equipment. If the temperature data is downloaded to a control station down on the earth, the temperature can be adjusted manually by a human operator. Should some parts of the satellite be to cold the operator can increase the effect of an appropriate electric heater and the temperature will rise. The control station can also do this adjustment automatically for example with the utilization of look up tables.

It is also possible make the satellite do temperature adjustment all by itself. If a thermostat is incorporated into a feedback loop the satellite can continuously adjust the effect of heating systems, and keep the temperature inside the desired range at all times.

Conclusions

There exists a wide variety of ways to accomplish thermal control of a satellite. Not all of them can be implemented on a micro satellite, but surprisingly many of them can.

All passive control mechanisms can be employed by a micro satellite. Careful treatment of surfaces with paint and other coatings are most usual. If it is possible to only use surface treatment in combination with insulation that is the ideal. Heat pipes are possible to implement even in the smallest of satellites if conduction and radiation is not working well enough.

Of the active thermal control measures that can be taken only the use of small electric heaters in order to increase the temperature is normally used. Louvers are the only other alternative that can be implemented, but because of the small size it will probably not be very effective.

The biggest advantage that comes with the implementation of active thermal control is the possibility to make an adaptive system that keeps the temperature within acceptable limits at all times, even during the eclipse. This is an opportunity that will become more and more exploited in micro satellites in the future.

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