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Thermal Management in Space

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The vehicles and habitats associated with space industrialization and the exploitation of nonterrestrial resources will inevitably require energy systems far exceeding the current requirements of scientific and exploratory missions. Because of the extended duration of these missions, it is not possible to consider systems involving expendables such as non-regeneratable fuel cells. Therefore, these missions become hostages to the capability of continuous-power energy systems. These systems will need to provide hundreds of kilowatts to tens of megawatts of electrical power to a product fabrication system, whether it uses terrestrial or nonterrestrial raw materials.

Because the power system will be located in an essentially airless environment, rejecting waste heat becomes a limiting aspect of it. In the following paragraphs, I will review space-based or asteroidal and lunar based power generating systems, as well as the capability of existing technologies to dissipate this heat into the airless environment of space.

It should be pointed out that in a vacuum environment, convection is no longer available and the only mechanism of rejecting heat is radiation. Radiation follows the Stefan-Boltzmann Law

$$E = \sigma T^4$$

where
E = the energy rejected
σ, the Stefan-Boltzmann constant, = 5.67 W m^{-2} K^{-4}
T = the temperature at which the heat is radiated

That is, the total amount of heat radiated is proportional to the surface area of the radiator. And the lower the radiation temperature, the larger the radiator area (and thus the radiator mass, for a given design) must be.

The radiator can only reject heat when the temperature is higher than that of the environment. In space, the optimum radiation efficiency is gained by aiming the radiator at free space. Radiating toward an illuminated surface is less effective, and the radiator must be shielded from direct sunlight.

The rejection of heat at low temperatures, such as would be the case in environmental control and in the thermal management of a materials processing unit, is particularly difficult. Therefore, the design and operation of the heat rejection system is crucial for an efficient space-based energy system.

Space-Based Power Generating Systems

In a previous paper, space-based power generating systems have been described in detail. Solar photovoltaic systems have a generating capability of up to several hundred kilowatts. The power output range of solar thermal systems is expected to be one hundred to perhaps several hundred kilowatts. While in principle these power systems can be expanded into the megawatt region, the prohibitive demands for collection area and lift capacity would appear to rule out such expansion. Megawatt and multimegawatt nuclear power reactors adapted for the space environment appear to offer a logical alternative. In this paper, I deal only with the burdens these three types of power system will place on the heat management system.

Solar photovoltaics themselves will not burden the power generating system with a direct heat rejection requirement, since the low energy density of the system requires such a great collection area that it allows rejection of waste radiant energy. However, if these systems are to be employed in low Earth orbit or on a nonterrestrial surface, then a large amount of energy storage equipment will be required to ensure a continuous supply of power (as the devices do not collect energy at night). And the round-trip inefficiencies of even the best energy storage system today will require that a large fraction—perhaps 25 percent—of the electrical power generated must be dissipated as waste heat and at low temperatures.

Solar thermal systems, which include a solar concentrator and a dynamic energy conversion system, are presumed to operate at relatively high temperatures (between 1000 and 2000 K). The efficiencies of the energy conversion system will lie in the range of 15 to perhaps 30 percent. Therefore we must consider rejecting between 70 and 85 percent of the energy collected. In general, the lower the thermal efficiency, the higher the rejection temperature and the smaller the radiating area required. As with solar photovoltaic systems, the inefficiencies of the energy storage system will have to be faced by the heat rejection system, unless high temperature thermal storage is elected.

The current concepts for nuclear power generating systems involve reactors working with relatively low-efficiency energy conversion systems which reject virtually all of the usable heat of the reactor but at a relatively high temperature. Despite the burdens that this low efficiency places on nuclear fuel use, the energy density of nuclear systems is so high that the fuel use factor is not expected to be significant.

In all of these systems the output power used by the production system in environmental control and manufacturing (except for a small fraction which might be stored as endothermic heat in the manufactured product) will have to be rejected at temperatures approaching 300 K.

I think it fair to state that, in many of the sketches of space industrial plants I have seen, the power system is little more than a cartoon because it lacks sufficient detail to address the problem of thermal management. We must learn to maintain an acceptable thermal environment, because it is expected to become a dominant engineering consideration in a complex factory and habitat infrastructure.

As an example of the severity of this problem, let us examine the case of a simple nuclear power plant whose energy conversion efficiency from thermal to electric is approximately 10 percent. The plant is to generate 100 kW of useful electricity. The reactor operates at approximately 800 K, and a radiator with emissivity equal to 0.85 would weigh about 10 kg/m^2. The thermal power to be dissipated from the reactor would be about 1 MW. From the Stefan-Boltzmann Law, the area of the radiator would be about 50 m^2 and the mass approximately 500 kg. This seems quite reasonable.

However, we must assume that the electricity generated by the power plant, which goes into life support systems and small-scale manufacturing, would eventually have to be dissipated also, but at a much lower temperature (around 300 K). Assuming an even better, aluminum radiator of about 5 kg/m^2, with again an emissivity of 0.85, in this case we find that the area of the low temperature heat rejection component is 256 m^2, with a mass approaching 1300 kg.* Therefore, we can see that the dominant heat rejection problem is not that of the primary power plant but that of the energy that is used in life support and manufacturing, which must be rejected at low temperatures. Using the waste heat from the nuclear power plant for processing may be effective. But, ironically, doing so will in turn require more radiator surface to radiate the lower temperature waste heat.

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*Using the Stefan-Boltzmann Law,

$$
\begin{aligned}
E_1 &= 5.67 \times 10^{-8}\ \text{W m}^{-2}\ \text{K}^{-4}\ (800\ \text{K})^4 \\
&= 5.67 \times 10^{-8}\ \text{W m}^{-2}\ \text{K}^{-4} \times 4096 \times 10^{8}\ \text{K}^4 \\
&= 5.67\ \text{W m}^{-2} \times 4.10 \times 10^{3} \\
E_1 &= 23.3\ \text{kW m}^{-2}
\end{aligned}
$$

900 kW $\div$ 23.3 kW m^{-2} = 38.6 m^2
and 38.6 m^2 $\div$ 0.85 = 45.4 m^2

$$
\begin{aligned}
E_2 &= 5.67 \times 10^{-8}\ \text{W m}^{-2}\ \text{K}^{-4}\ (300\ \text{K})^4 \\
&= 5.67 \times 10^{-8}\ \text{W m}^{-2}\ \text{K}^{-4} \times 81 \times 10^{8}\ \text{K}^4 \\
&= 5.67\ \text{W m}^{-2} \times 81 \\
E_2 &= 459\ \text{W m}^{-2}
\end{aligned}
$$

100 kW $\div$ 459 W m^{-2} = 0.2179 x 10^3 m^2 = 218 m^2
and 218 m^2 $\div$ 0.85 = 256 m^2

Heat Rejection Systems

In this section I will deal with systems designed to meet the heat rejection requirements of power generation and utilization. These heat rejection systems may be broadly classified as passive or active, armored or unarmored. Each is expected to play a role in future space systems.

Heat pipes: The first of these, called the "heat pipe," is conventionally considered the base system against which all others are judged. It has the significant advantage of being completely passive, with no moving parts, which makes it exceptionally suitable for use in the space environment.

For the convenience of the reader, I will briefly describe the operational mechanism of the basic heat pipe. (See figure 36.) The heat pipe is a thin, hollow tube filled with a fluid specific to the temperature range at which it is to operate. At the hot end, the fluid is in the vapor phase and attempts to fill the tube, passing through the tube toward the cold end, where it gradually condenses into the liquid phase. The walls of the tube, or appropriate channels grooved into the tube, are filled with a wick-like material which returns the fluid by surface tension to the hot end, where it is revaporized and recirculated.

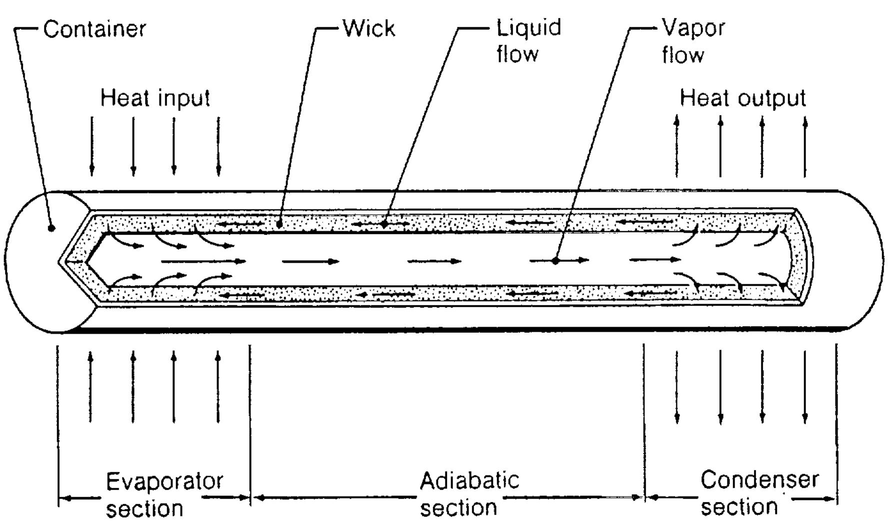


Figure 36

Components and Principle of Operation of a Conventional Heat Pipe

A conventional heat pipe consists of a sealed container with a working fluid, a passageway for vapor, and a capillary wick for liquid transport. During operation, the heat pipe is exposed to external heat at one end (the evaporator section). This heat causes the working fluid in the capillary wick to vaporize, removing heat equal to the heat of vaporization of the fluid. The vapor is forced down the center of the pipe by pressure from the newly forming vapor. When the vapor reaches the cool end of the pipe (the condenser section), it condenses to a liquid. The liquid soaks into the capillary wick, through which it travels back to the evaporator section. As the fluid condenses, it gives up the heat of vaporization, which is then conducted outside the end of the pipe.

Essentially the system is a small vapor cycle which uses the temperature difference between the hot and cold ends of the tube as a pump to transport heat, taking full advantage of the heat of vaporization of the particular fluid.

The fluid must be carefully selected to match the temperature range of operation. For example, at very high temperatures a metallic substance with a relatively high vaporization temperature, such as sodium or potassium, may be used. However, this choice puts a constraint on the low temperature end since, if the fluid freezes into a solid at the low temperature end, operation would cease until the relatively inefficient conduction of heat along the walls could melt it. At low temperatures a fluid with a low vaporization temperature, such as ammonia, might well be used, with similar constraints. The temperature may not be so high as to dissociate the ammonia at the hot end or so low as to freeze the ammonia at the cold end.

With proper design, heat pipes are an appropriate and convenient tool for thermal management in space systems. For example, at modest temperatures, the heat pipe could be made of aluminum, because of its relatively low density and high strength. Fins could be added to the heat pipe to increase its heat dissipation area. The aluminum, in order to be useful, must be thin enough to reduce the mass carried into space yet thick enough to offer reasonable resistance to meteoroid strikes.

A very carefully designed solid surface radiator made out of aluminum has the following capabilities in principle: The mass is approximately 5 kg/m^2 with an emissivity of 0.85; the usable temperature range is limited by the softening point of aluminum (about 700 K). At higher temperatures, where refractory metals are needed, it would be necessary to multiply the mass of the radiator per square meter by at least a factor of 3. Nevertheless, from 700 K up to perhaps 900 K, the heat pipe radiator is still a very efficient method of rejecting heat.

A further advantage is that each heat pipe unit is a self-contained machine. Thus, the puncture of one unit does not constitute a single-point failure that would affect the performance of the whole system. Failures tend to be slow and graceful, provided sufficient redundancy.

Pump loop system: The pump loop system has many of the same advantages and is bounded by many of the same limitations associated with the heat pipe radiator. Here heat is collected through a system of fluid loops and pumped into a radiator system similar to conventional radiators used on Earth. It should be pointed out that in the Earth environment the radiator actually radiates very little heat; it is designed to convect its heat. The best known examples of the pump loop system currently used in space are the heat rejection radiators used in the Shuttle. These are the inner structure of the clamshell doors which are deployed when the doors are opened (fig. 37).

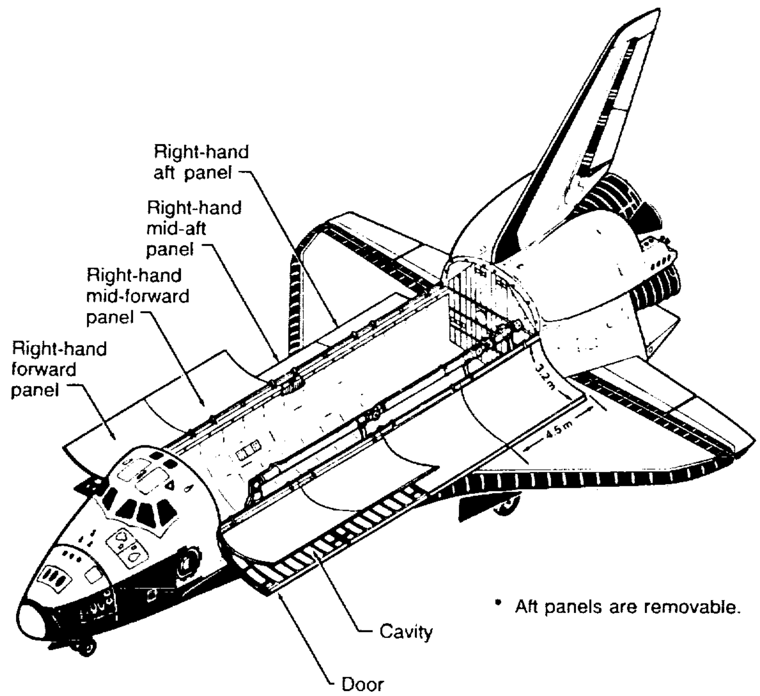
Pump loop systems have a unique advantage in that the thermal control system can easily be integrated into a spacecraft or space factory. The heat is picked up by conventional heat exchangers within the spacecraft, the carrier fluid is pumped through a complex system of pipes (extended by fins when deemed effective), and finally the carrier is returned in liquid phase through the spacecraft. In the case of the Shuttle, where the missions are short, additional thermal control is obtained by deliberately dumping fluid.

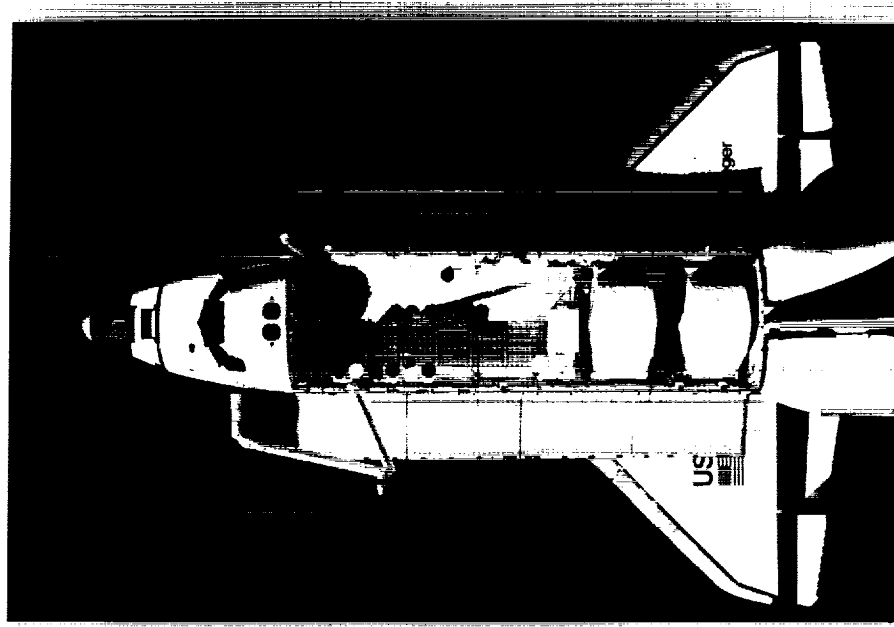
Since the system is designed to operate at low temperatures, a low density fluid, such as ammonia, may on occasion, depending on heat loading, undergo a phase change. Boiling heat transfer in a low gravity environment is a complex phenomenon, which is not well understood at the present time. Because the system is subjected to meteoroid impact, the basic primary pump loops must be strongly protected.

Figure 37

Pump Loop Radiators on the Space Shuttle Payload Bay Doors

a. The space radiators, which consist of two deployable and two fixed panels on each payload bay door, are designed to reject waste heat during ascent (doors closed) and in orbit (doors open). Each panel contains parallel tubes through which the Freon in the heat loops can pass, bringing waste heat from other parts of the orbiter. The total length of Freon tubing in these panels is 1.5 km.





b. The panels have a heat rejection capacity of 5480 kJ/hr (5400 Btu/hr) during ascent through the atmosphere with the doors closed and 23 kJ/hr (21.5 Btu/hr) during orbital operations with the doors open.

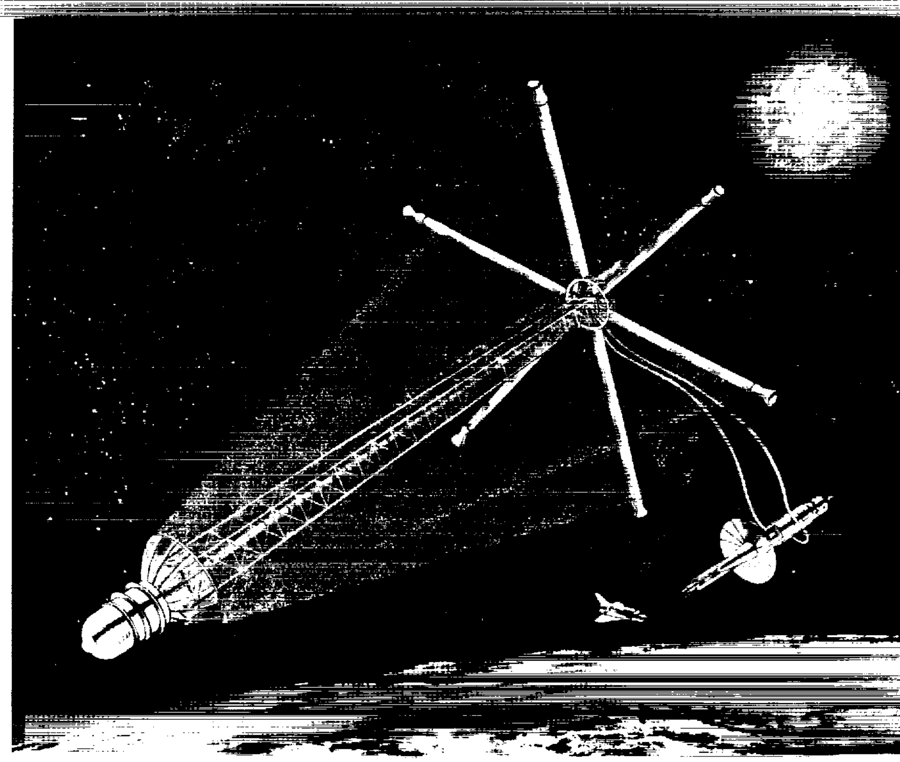
Despite these drawbacks, pump loop systems will probably be used in conjunction with heat pipe systems as thermal control engineers create a viable space environment. These armored (closed) systems are rather highly developed and amenable to engineering analysis. They have already found application on Earth and in space. A strong technology base has been built up, and there exists a rich literature for the scientist-engineer to draw on in deriving new concepts.

Advanced Radiator Concepts

The very nature of the problems just discussed has led to increased efforts on the part of the thermal management community to examine innovative approaches which offer the potential of increased performance and, in many cases, relative invulnerability to meteoroid strikes. Although I cannot discuss all of these new approaches, I will briefly describe some of the approaches under study as examples of the direction of current thinking.

Improved conventional approaches: The continuing search for ways to improve the performance of heat pipes has already shown that significant improvements in the heat pumping capacity of the heat pipe can be made by clever modifications to the return wick loop. Looking further downline at the problem of deployability, people are exploring flexible heat pipes and using innovative thinking. For example, a recent design has the heat pipes collapsing into a sheet as they are rolled up, the same way a toothpaste tube does. Thus, the whole ensemble may be rolled up into a relatively tight bundle for storing and deploying. However, because the thin-walled pipes are relatively fragile and easily punctured by meteoroids, more redundancy must be provided. The same principles, of course, can be applied to a pump loop system and may be of particular importance when storage limits must be considered. These are only examples of the various approaches taken, and we may confidently expect a steady improvement in the capability of conventional thermal management systems.

The liquid droplet radiator: The basic concept of the liquid droplet radiator is to replace a solid surface radiator by a controlled stream of droplets. The droplets are sprayed across a region in which they radiate their heat; then they are recycled to the hotter part of the system. (See figure 38.)



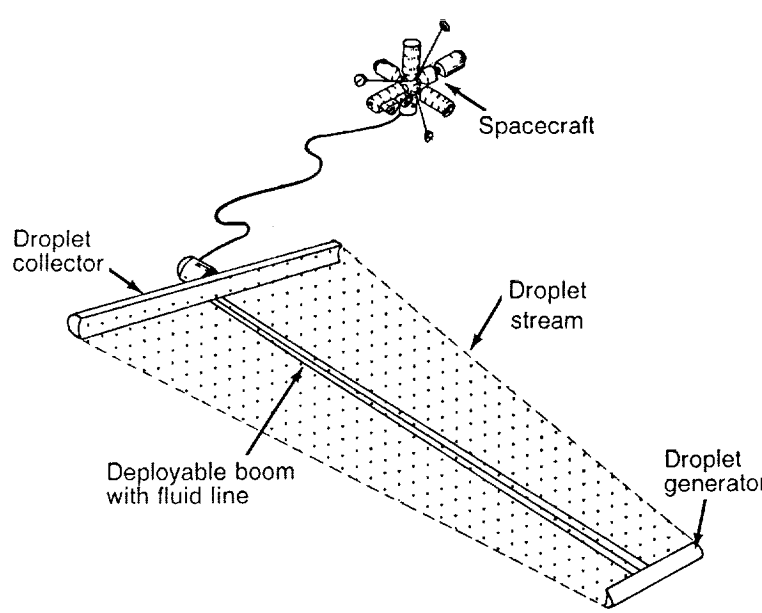


Figure 38

Two Concepts for a Liquid Droplet Radiator

In one concept (top), droplets are generated at the base of a cone which contains the source of the waste heat (a nuclear reactor, for example), and the molten droplets are sprayed to a six-armed collector array, where they are caught and then pumped back through a central pipe to the reactor. In a somewhat similar concept (bottom), a deployable boom has the droplet generator at one end and the droplet collector at the other, with a fluid feed line between. Here the droplets are sprayed in a single planar pattern.

It was demonstrated some time ago that liquid droplets with very small diameters (about 100 micrometers) are easily manufactured and offer a power-to-mass advantage over solid surface radiators of between 10 and 100. In effect, large, very thin radiator sheets can be produced by the proper dispersion of the droplets. This system offers the potential of being developed into an ultralightweight radiator that, since the liquid can be stored in bulk, is also very compact.

The potential advantages of the liquid droplet radiator can be seen if we consider again the problem that was discussed at the end of the section on heat pipe radiators. We found that a very good aluminum radiator would require 256 m^2 and have a mass of nearly 1300 kg to radiate the low temperature waste heat from lunar processing. Using the properties of a liquid droplet radiator and a low density, low vapor pressure fluid such as Dow-Corning 705, a common vacuum oil, we find that, for the same area (which implies the same emissivity), the mass of the radiating fluid is only 24 kg.

Even allowing a factor of 4 for the ancillary equipment required to operate this system, the mass of the radiator is still less than 100 kg.

To achieve efficiency, the designer is required to frame the radiator in a lightweight deployable structure and to provide a means of aiming the droplets precisely so that they can be captured and returned to the system. However, present indications are that the droplet accuracies required (milliradians) are easily met by available technology. Recently, successful droplet capture in simulated 0 *g* conditions has been adequately demonstrated. An advantage of a liquid droplet radiator is that even a relatively large sheet of such droplets is essentially invulnerable to micrometeoroids, since a striking micrometeoroid can remove at most only a few drops.

The reader may be concerned that the very large surface area of the liquid will lead to immediate evaporation. However, liquids have recently been found that in the range of 300 to 900 K have a vapor pressure so low that the evaporation loss during the normal lifetime of a space system (possibly as long as 30 years) will be only a small fraction of the total mass of the radiator.

Thus, the liquid droplet radiator appears promising, particularly as a low temperature system where a large radiator is required.

Liquid droplet radiators for applications other than 0 *g* have been suggested. For example, in the lunar environment fluids with low vapor pressures can be used effectively as large area heat dissipation systems for relatively large-scale power plants. We may well imagine that such a system will take on the appearance of a decorative fountain, in which the fluid is sprayed upward and outward to cover as large an area as possible. It would be collected by a simple pool beneath and returned to the system. Such a system would be of particular advantage in the lunar environment if low mass, low vapor pressure fluids could be obtained from indigenous materials. Droplet control and aiming would no longer be as critical as in the space environment; however, the system would need to be shaded from the Sun when it is in operation.

While this system is far less developed than the systems previously discussed, its promise is so high that it warrants serious consideration for future use, particularly in response to our growing needs for improved power management.

Belt radiator concepts: The belt radiator concept is a modification of the liquid droplet concept in which an ultrathin solid surface is coated with a very low vapor pressure liquid (see fig. 39). While the surface-to-volume ratio is not limited in the same fashion as for a cylindrical heat pipe, it does not quite match that of the liquid droplet radiator. However, this system avoids the problem of droplet capture by carrying the liquid along a continuous belt by surface tension. The liquid plays a double role in this system by acting not only as the radiator but also as the thermal contact which picks up the heat directly from a heat transfer drum. Variations on this scheme, in which the belt is replaced by a thin rotating disk, are also feasible but have yet to be fully assessed.

The systems described are only indicative of the thinking which has been stimulated by the problem of thermal management. All of these systems, if developed, offer significant promise of improvement over the conventional armored systems.

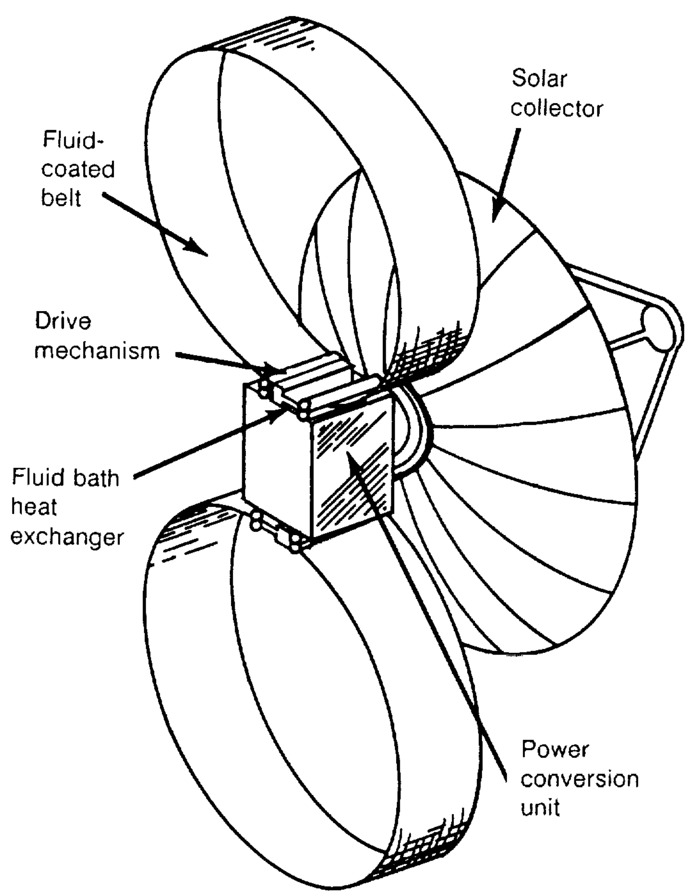


Figure 39

Belt Radiator

A related heat rejection technology is the belt radiator concept. Here the liquid is present as a thin coating on two rotating belts. As the belts rotate through the drive mechanism, they pick up hot fluid from the heat exchanger. Then, as the belts rotate through space, the fluid loses its heat. This system does not have the advantage of the high surface-area-to-mass ratio possible with a liquid droplet radiator, but it still may offer superior properties of heat transfer and damage resistance compared to solid radiators.