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Priscilla S. Diem-Kirsop
Lewis Research Center
Cleveland, Ohio

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ADVANCED RADIATOR CONCEPTS

Priscilla S. Diem-Kirsop
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

This paper discusses two spacecraft radiators currently under study by the NASA Lewis Research Center: the Liquid Droplet Radiator and the Liquid Belt Radiator. These advanced concepts offer benefits in reduced mass, compact stowage, and ease of deployment. Operation and components of the radiators are described, heat transfer characteristics are discussed, and critical technologies are identified. Finally, the impact of the radiators on large power systems is assessed.

INTRODUCTION

With the advent of the Space Station, there is increased interest in large power systems for space. When current technology is scaled to Space Station initial operating condition power levels, the radiator comprises 30 to 50 percent of the total power system mass. Therefore, the radiator is an obvious target for reducing system mass, and thus launch cost.

Several low mass radiator concepts have been identified and two are being evaluated at NASA Lewis Research Center. These are the Liquid Droplet Radiator (LDR) and the Liquid Belt Radiator (LBR). Conventional radiators use pumped fluid loops or the capillary action of heat pipes to transport waste heat to fins for radiative cooling. The pipes carrying the fluid must be heavily armored against micrometeoroid penetration. Thus, these structures are heavy and bulky. Moreover, high surface emissivity is provided by coatings which degrade with exposure to the environment in low earth orbit.

Both concepts under investigation propose to do away with metallic radiating surfaces and expose the fluid directly to space, thus eliminating the need for micrometeoroid protection. The radiating surface is replaced with a surface which is of lower density and little or no rigidity so that it can be compactly stowed. Also, surface coatings are avoided.

Another advantage to these radiators is that they may be used over a wide temperature range, from room temperature applications such as astronaut housekeeping or electronics cooling, to moderate and high temperature applications such as heat sinking a Brayton or Stirling cycle.

LIQUID DROPLET RADIATOR

NASA Lewis and the Air Force Rocket Propulsion Laboratory (AFRPL) have a joint program for the technical assessment of the LDR. This concept takes advantage of a sphere's high surface area to volume ratio to create a radiator with a very low specific mass (radiator mass/area). In the LDR millions of submillimeter droplets are shot along a fixed trajectory to form a thin cloud-like sheet which radiates to space. The effective emissivity of the sheet can be much higher than for a droplet alone because of interdroplet reflections. The concept is illustrated in figure 1.

Fluid is pumped through a heat exchanger where it picks up the waste heat of the spacecraft. From the heat exchanger the fluid flows into a pressurized plenum chamber (droplet generator) where the fluid is forced into space through hundred-micron sized orifices. An oscillating pressure causes the streams to break-up uniformly into droplets, with equal size and spacing. After cooling, the droplets are captured, consolidated, and pumped back to the heat exchanger.

Technology for the generation of submillimeter streams with micro-radian accuracy is available from ink-jet printers. Extension to the LDR requires development of fabrication of methods for large scale arrays of orifices. Commercially manufactured orifices using laser drilling and chemical milling were compared to mechanically drilled orifices manufactured in-house. In all cases the mechanically drilled orifices exhibited a smoother profile which is believed necessary for parallel stream formation. Burrs formed near the exit during the drilling process cause the stream to attach itself at that point yielding misdirected streams. At NASA Lewis mechanical fabrication of orifice arrays has progressed so that multi-hole orifice plates are routinely fabricated by a computer controlled mechanical drilling rig.

Initial experimentation at NASA Lewis has determined that countersunk cylindrical orifices provide the straightest trajectory with the least pressure drop. Other geometries were investigated: cylindrical, ASME rounded entrance, double chamfered (countersunk inlet and exit); but they were not satisfactory.

In-house droplet formation studies show that there is an envelope of pulse frequencies which yield uniform droplets for a range of stream velocities. Frequencies outside this envelope cause the formation of tiny satellite droplets. Figure 2 shows droplet formation in five parallel streams. Satellite droplets can be seen in the center stream. (Scale divisions in the figure are 0.5 mm.)

During droplet formation testing a fluid film on the downstream side of the orifice plate interfered with parallel stream flow. In zero-gravity, surface tension forces are significant and may cause films to develop on the plates. Verification of droplet formation and fluid film interaction will be investigated in a series of zero-gravity experiments at NASA Lewis.

The design of the collector has required the most extensive development work. The LDR concept depends critically on complete capture of the droplets. Billions of droplets must be collected without benefit of pressure or gravity. Many concepts using magnetic, centrifugal, or electrostatic forces for active droplet collection were proposed; however, the collector concept chosen for additional study was a passive linear collector illustrated in figure 3.

The droplets impinge at some angle to the curved collector surface with or without a fluid film on the surface. Droplet momentum is changed and the droplets flow together to the pump inlet. A positive displacement gear or lobe pump then pressurizes the fluid to feed a recirculating pump.

LIQUID BELT RADIATOR

A second radiator concept proposed for spacecraft power systems is the Liquid Belt Radiator. The LBR has been investigated by A.D. Little under contract to NASA Lewis. It offers a distinct advantage over the LDR in that the fluid is controlled throughout its entire exposure to space. In this concept, illustrated in figure 4, the fluid forms menisci on a mesh belt which guides its transit through space.

By means of a motor drive, the belt is drawn through a fluid bath heat exchanger which serves as the thermal sink of the spacecraft and is then passed into space. The belt assumes a cylindrical shape due to centripetal acceleration. In the latent heat mode of operation, the fluid begins to solidify almost immediately and returns to the fluid bath completely solid. In the sensible heat mode, the fluid cools to a temperature dictated by the power level.

One system configuration uses the motor drives to deploy the belt. Engaging the forward drive pulls the belt from the stowage module and imparts an initial velocity to the belt. In time, the belt assumes the cylindrical shape. Rearward motors provide redundancy and allow for retracting the belt in the event of rapid spacecraft maneuver or reduction in heat load. An alternative deployment mechanism has the belt coiled on a spring loaded roller. Once in orbit, explosive bolts release the roller and the belt unfolds.

The design of the heat exchanger is influenced by the power cycle. In the initial configuration, the LBR was interfaced directly with the power system. For a Brayton power system, however, the requirements of a low gas side pressure drop coupled with the relatively poor heat transfer coefficient of the gas make a direct gas/LBR working fluid heat exchanger difficult to design.

WORKING FLUID

One of the primary requirements for the working fluid is low vapor pressure. Evaporative losses are minimized to keep fluid inventory low and to avoid contamination of other surfaces of the spacecraft. A second requirement for the fluid is that it is a good radiator in the infrared (high emissivity) and a poor absorber of solar radiation.

Diffusion pump oils are likely candidates to meet both of these requirements for low temperature radiators. Vapor pressures are low, typically 10^{-8} torr at room temperature, and transmission measurements indicate that there may be a step change in absorption at about 1600 cm^{-1}. Normal emissivity of a film of DC 704 diffusion pump oil was measured by Teagan and Fitzgerald (ref. 1) using a Fourier Transform Infrared Spectrometer (FTIR). At a thickness of 0.06 cm, the average film emissivity of DC 704 was 0.95 between 1400 and 400 cm^{-1}. At a thickness of 0.03 cm, the average film emissivity was 0.70. (See figs. 5 and 6.)

Liquid metals are proposed working fluids for high temperature radiators. Vapor pressures are extremely low, in some cases immeasurable, especially near the melting point of the material. In addition, liquid metals have low viscosities, keeping parasitic power losses to a minimum.

Unfortunately, because liquid metals are such good reflectors, they make very poor emitters.

HEAT TRANSFER ANALYSES

Because the area of a radiator is inversely proportional to its emissivity, the mass advantage of the LDR or the LBR over conventional radiators is lost if the emissivity is low.

At first glance, the emissivity of the belt radiator is the emissivity of the fluid film. The surface is textured, however, due to the concave menisci forming between the mesh. Preliminary analysis to determine the effect of this texturing on emissivity suggested that emissivity could be at best improved by a factor of 2 when the emissivity was initially low. This suggests that liquid metal emissivities, typically 0.1 to 0.2, may be enhanced by the nature of the belt radiator. Further enhancement of liquid metal emissivities by other means requires additional investigation.

In order to predict the emissivity of the droplet sheet, Hertzberg and Mattick (ref. 2) assume that the droplets behave as opaque gray bodies with isotropic scatter, and that the sheet is isothermal through its thickness. The hemispherical emissivity is determined by using the equations of radiative transfer in an absorbing and scattering plane layer. The solution is expressed by a nonlinear integral equation that was solved numerically. Results are shown in figure 7. The sheet emissivity is a function of droplet emissivity and optical depth of the sheet. Optical depth is defined normal to the sheet as $\tau_S = n \sigma S$, where n is the droplet number density per unit volume, σ is the cross-sectional area of a droplet, and S is the thickness of the sheet.

Sheet emissivity depends not only on the configuration of the droplet sheet, but also on the emissivity of the droplets. Although droplet emissivity has not been measured, the data reported by Teagan and Fitzgerald suggests that droplet emissivity will decrease with droplet diameter for diameters less than 0.06 cm. This is because transmission through the droplet increases as the droplet becomes smaller. It has been suggested that the power to mass ratio of a droplet may be made arbitrarily large by decreasing the radius. In the optically thin limit, however, droplet emissivity is linearly proportional to radius so that this is no longer the case.

A refined analysis of either droplet or belt emissivity would consider the variation of absorption and scattering coefficients with frequency, ν. An iterative procedure allows determination of these coefficients from absorption measurements of thin films in the infrared. Graf, Koenig, and Ishida (ref. 3) have reported the method. The apparent absorptive index, $k(\nu)$, is calculated from the experimental absorption spectrum. The KramersKronig integral relates the refractive index and the absorptive index so that an apparent refractive index, $n(\nu)$, is obtained. The absoption spectrum is then calculated using these trial values for $k(\nu)$ and $n(\nu)$. It is compared to the experimental spectrum and a refined estimate of $k(\nu)$ is made. The process is iterated until agreement between the experimental spectrum and the calculated spectrum is good.

Currently software from Graf et al. is being installed on a VAX 11/750 computer to perform this analysis. A communications link between the computer-run FTIR and the VAX is being selected. Data from FTIR analyses of the absorption spectra of diffusion pump oils will be analyzed at NASA Lewis in this way.

Predictions of sheet emissivity will be evaluated in-house by measuring a sensible heat loss from the droplet sheet and equating it to the net radiation loss from the sheet to its surroundings. A heat transfer rig is being fabricated (schematic shown in fig. 8) to make these measurements. The rig has a maximum flow rate of 5 gal/min allowing testing of optical depths up to 0.4. The test fluid can be preheated in the supply tank up to 150 °C; however, the likely upper temperature is 70 °C to keep the vapor pressure of the test fluid low. The droplets fall through a liquid nitrogen jacketed vacuum chamber to simulate the space environment. Although maximum vacuum capability is 10^{-6} torr, expected operation is 10^{-4} torr to minimize evaporative heat loss.

The sensible heat loss will be determined from differential temperature measurements of the streams. Moving at velocities of 5 to 50 ft/sec, the droplets will cool in the chamber for 2 sec or less. Temperature probes will translate across the width and depth of the streams to obtain a temperature profile in addition to the average temperature drop. Expected temperature drops are on the order of 2 to 8 °C. Estimated error for the calculated values of sheet emissivity is less than 10 percent.

CRITICAL ISSUES

The environment in low earth orbit (LEO) is characterized by ultraviolet radiation, atomic oxygen, and a variety of charged particles. The development of a working fluid which has the approriate material properties and which will stand up to LEO environment is critical to the success of these radiators. Degradation of the working fluid due to environmental exposure could preclude the use of these radiators for LEO applications; however, they could still find application in geosynchronous orbit, or in deep space or lunar base missions.

The measurement and enhancement of liquid metal emissivities will determine the suitability of the LDR and the LBR for high temperature applications. It is well known that surface contaminants reduce the reflectivity of pure metals and thereby improve their emissivity. A case in point is lithium. Nitrogen and oxygen in the atmosphere react so readily with lithium that the surface is visually a dull gray instead of the silvery surface that exists for a pure sample. In the atmosphere, it is the lithium compounds, rather than pure lithium, which are stable. In space it is not known what types of impurities or compounds exhibit the long term chemical stability necessary for the operation of the radiators in LEO.

For the LDR the critical technology is the capture of droplet streams. Two mechanisms exist to reduce collector efficiency: misdirected streams and splashing at the collector. Preliminary studies at NASA Lewis show that if only one in one million streams is misdirected, fluid inventory will be rapidly depleted. Work at Grumman Aerospace under contract to AFRPL has shown that there is a wide envelope of angles of attack for which splashing losses are less that one in 100 million for velocities of 5 m/s or less (ref. 4).

A second issue is the repressurization of the droplet streams. Studies at Grumman showed that the velocity after impact was only a few percent of the incoming velocity. Additional work is needed to define the pressure recovery and to determine the necessity for single versus multistage pumping.

A critical issue for the LBR is the dynamic stability of the mesh belt. The shape of the LBR is determined by a delicate force balance. The effects of any perturbation in that balance is unknown. For example, torsional and longitudinal modes of oscillation may cause the belt to collapse, misfeed, or twist possibly resulting in tearing of the belt or jamming of the drive mechanism.

Preliminary analysis has determined that the belt will assume a catenary-like shape (elongated hoop) under the prolonged application of a uniform acceleration field (ref. 5). The analysis assumed no internal belt stiffness, a conservative assumption particularly in the phase change mode of operation. The analysis also showed that the belt will return to its cylindrical shape after removal of the field. Additional analysis needs to be done to estimate belt stiffness and to determine the magnitude and duration of acceptable acceleration fields.

A second technology issue relative to the LBR is the containment of the fluid bath within the heat exchanger. This amounts to a sealing problem, but it is significant since the seals must work against a pressure gradient and against surface forces without benefit of body forces. In the microgravity environment the surface forces causing creep are significant.

IMPACT ON POWER SYSTEMS

These radiators can impact the power system of the spacecraft in two ways. First, the low specific mass of the radiator reduces overall power system mass. Secondly, the low mass radiator may cause the system to mass optimize at a different operating point.

When the LBR was designed for use with a Brayton power cycle delivering 37.5 kW of electric power, it was 40 percent as massive as the fin and tube radiator it replaced. This point design used a diffusion pump oil in the sensible heat mode. Additional system studies (ref. 5) for both sensible and latent modes of operation over a range of temperature levels (300 to 650 K) show that LBR system mass is 0.6 to 1.3 kg/m^2, about 20 to 50 percent that of heat pipe radiators.

Conventional radiators typically drive the heat rejection temperature upward reducing radiator area as the fourth power of temperature. The low mass of these radiators removes that driver. In particular, these radiators may cause the power system to optimize at a lower heat rejection temperature, thereby increasing power system efficiency. Alternatively, a lower heat rejection temperature may ease the requirements for high temperature power system components such as the turbine.

It is apparent that spacecraft radiators can no longer be an add-on to the power system. They must be designed as an integral part of the power system, particularly as power levels increase over several orders of magnitude. The LDR and the LBR show promise for reducing the overall system mass of these new power systems.

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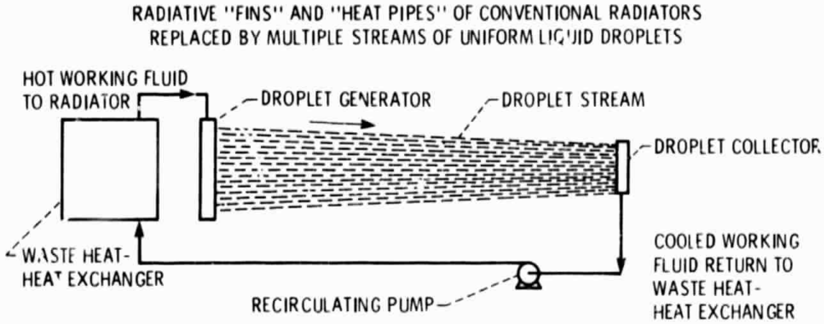

Figure 1. - Liquid droplet radiator concept.

Figure 2. - Droplet formation. Satellite drops visible in central stream.

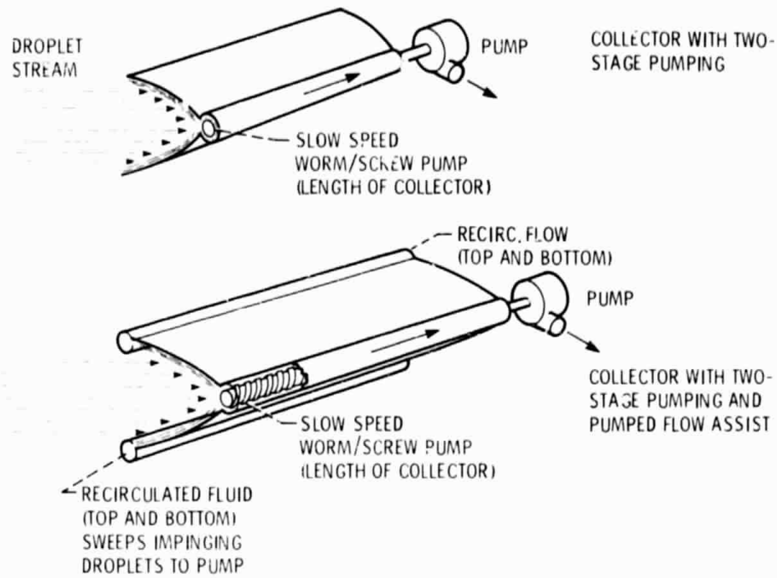

Figure 3. - Passive linear collector concept (concept proposed by Grumman Aerospace Corporation).

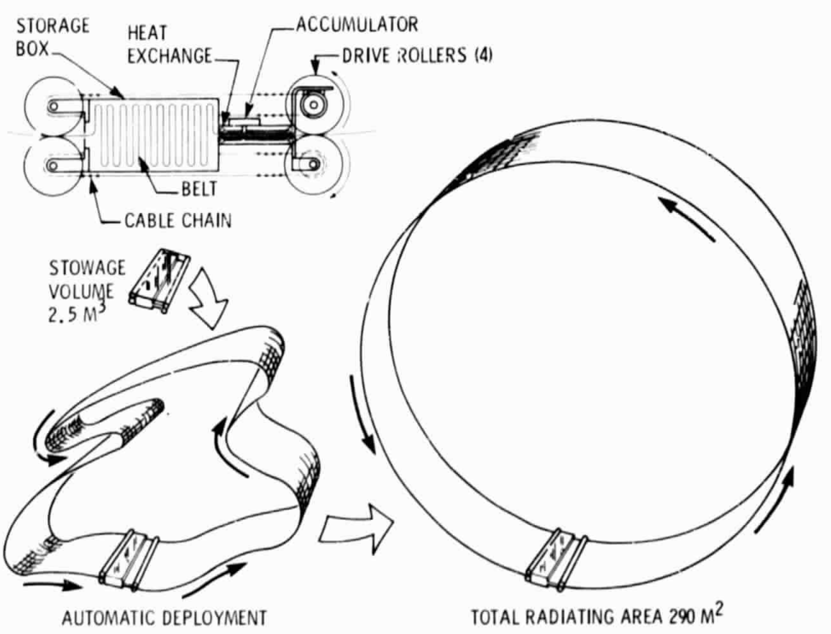

Figure 4. - Liquid belt radiator concept. Stowage and deployment for 75 kW thermal radiator shown (concept proposed by A. D. Little, Inc.).

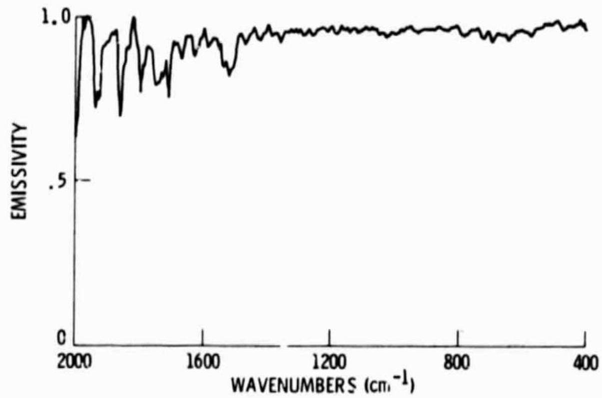

Figure 5. - Normal emissivity of a thick (0.06 cm) film of DC 70' [1].

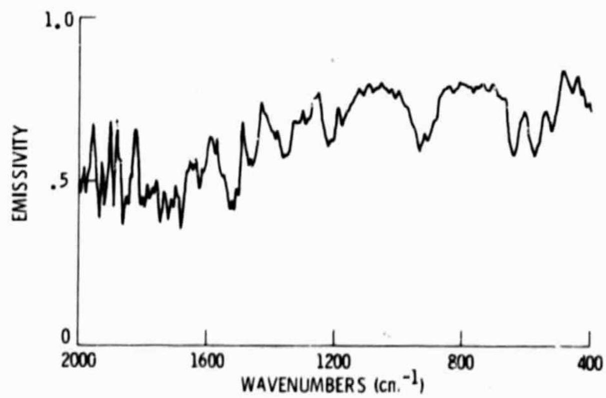

Figure 6. - Normal emissivity of a thin (0.03cm) film of DC 704[ ].

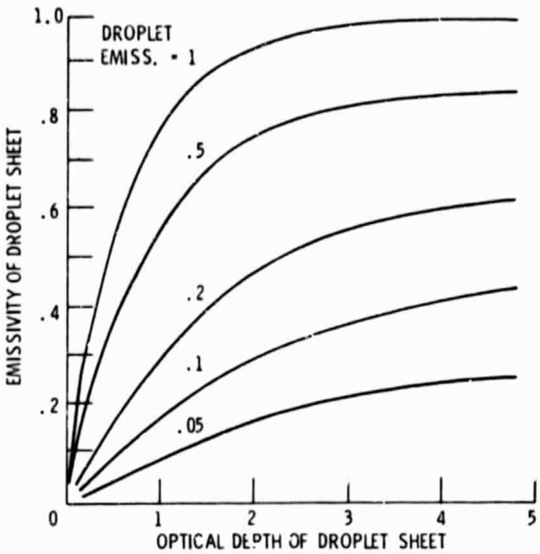

Figure 7. - Hemispherical emissivity of liquid droplet radiator[2].

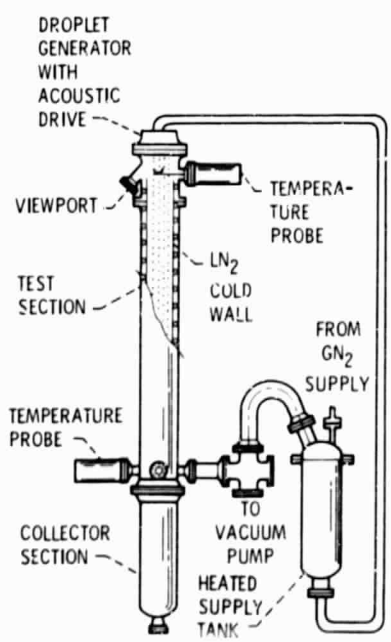

Figure 8. - Cartoon of rig for LDR heat transfer studies.