Engineering Notes

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Feasibility Study of a Low-Temperature Expandable Megawatt Pulse Power Radiator

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Introduction

FUTURE space missions require development of lightweight, large-surface-area radiators. For some missions and orbital duty cycles envisioned,[1] peak electric power in the multimegawatt range may be required. These conceptual systems are envisioned as generating waste heat in the form of pulses with peak-to-average power ratios of 10^4 - 10^5. Conventional radiators are sized to reject peak powers and "turned down" to reject off-peak loads. Such conventional radiators would be massive for the multimegawatt pulse power heat rejection, especially in the "electronic" temperature regime (300-400 K). Use of an expendable fluid may be precluded by virtue of contamination or propagation considerations.

The present Note focuses on the definition of a "collectible" expendable concept. During the pulse, heat is removed directly from a high-power density component through flash or spray evaporation. The vapor generated is collected in an expandable, variable-volume, variable-surface-area radiator. The vapor is condensed within the radiator during an interpulse period and recirculated to the coolant reservoir to be recycled.

The concept of a flexible, variable-volume, variable-surface-area radiator is not new. Leach and Cox,[2] and later Oren,[3] have developed a flexible tube and fin radiator. This "roll-out" radiator has plastic or elastomeric transport tubings that distribute a single-phase heat-exchange fluid. The radiator unrolls like a party whistle or window shade, using a gas pressurant to inflate two tubes on either side of the flexible panel. This radiator concept was intended to meet heat rejection needs up to 12 kW with modest peak-to-average heat loads (100/1 or less).

For higher peak-to-average heat loads, a more promising conceptual approach is an inflatable bag or bellows structure by virtue of its large energy storage per unit mass characteristic. Such an expandable volume can store a large amount of vapor during the pulse period and reject waste heat through condensation and radiation during the interpulse period. The radiator can be fabricated from a high-strength, low-density, thin flexible material that can be collapsed and stored in a compact form and deployed and readily expanded when high-peak heat loads are imposed. This concept results in a lightweight retractable radiator that can be easily protected from micrometeoroid damages when not in use. The intrinsic contamination problems with this bellows radiator are greatly reduced as compared with other "free-surface" (e.g., droplet) radiator concepts.

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Heat-Transfer Duty Cycle

A representative power demand profile can include short periods of high power draw interspersed with longer interpulse periods when greatly reduced power is needed. The following illustrative case is considered. An orbital altitude of 1000 km is assumed. This corresponds to an orbital period of 6300 s. It is assumed that high power is needed during 1/6 of the orbital period or about 1000 s. During these 1000 s, termed the "ground station" flyover period, a high-peak power draw is needed for 5 s, followed by a low power period of 95 s, followed by another 5-s draw of high peak power, and so on. Thus, during the flyover period, there will be a total of 10 pulses. The waste heat generation profile is assumed to be similar to the power profile. For the rest of the orbital period, the power demand is low. The expandable radiator makes use of this period, known as the rest period, to reject most of the orbital period waste heat stored in the radiator.

Dynamic Response of the Expandable Radiator

A lumped thermal model of the cylindrical expandable radiator is assumed to illustrate the concept further. The model is based on the following assumptions:

1) The radiator has a fixed diameter but a varying length to maintain isothermal and isobaric operation (i.e., saturation conditions) with the storage volume.

2) The inlet fluid to the radiator is saturated vapor.

3) The heat removal from the vapor is controlled by radiation from the bellows surface; i.e., the thermal resistance between the vapor to the condensing surface and that of the thin radiator wall are negligible.[4]

4) Spacecraft heat generation rates other than during the flyover period are negligible.

An energy balance for the control volume (see Fig. 1) results in a first-order differential equation for the radiator volume V as a function of time (see Appendix),

$$\rho_v h_{fg}\dot{V}+4\epsilon\sigma(T^4-T_s^4)V/D=\dot{Q}_L-\epsilon\sigma(T^4-T_s^4)\pi D^2/4 \quad (1)$$

where ρ_v and h_{fg} are the density of the vapor and latent heat of vaporization, respectively; T is the temperature of the radiator, $\dot{Q}_L$ the instantaneous waste heat generation rate, D the diameter of the cylindrical bellow, ϵ the effective emissivity of the bellow wall, and σ the Stefan-Boltzmann constant. The background temperature T_s of the near-Earth environment varies during an orbit. However, it was shown that it is reasonable to assume an average temperature of 250 K for the background temperature.[5]

Table 1 Input to dynamic response calculations

Temperature of radiator, T	373 K
Heat sink temperature, T_s	250 K
Diameter of cylindrical radiator, D	3 m
Emissivity of radiator surface	0.7
Peak load, maximum of $\dot{Q}_L$	5 MW
Pulse duration	5 s
Period between pulses	95 s
Number of pulses	10
Orbital altitude	1000 km
Orbital period	6300 s
Flyover period	1000 s
Rest period	5300 s

Table 1 lists the set of parameter values assumed to illustrate the time-dependent heat-transfer rates and volume characteristic of the concept described by Eq. (1). The length of a 3-m diam radiator vs time is shown in Fig. 2. At the beginning of the flyover period, which starts at time zero, it is assumed that the radiator has an initial length of zero. The maximum deployed length of the radiator is 19.9 m, occurring at the end of the last pulse during the flyover period. It can be seen that, while the radiator partially retracts during the flyover period, most of the heat rejection occurs during the rest period. This long rest period is essential to the operation of the expandable radiator in order to limit the deployed volume, as well as provide time to recirculate the condensed working fluid.

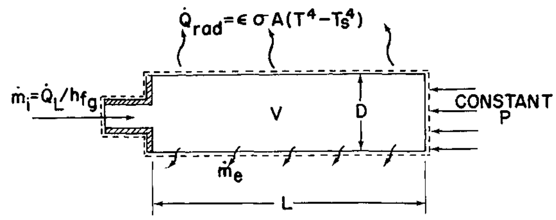

Fig. 1 Control volume of a cylindrical bellows radiator.

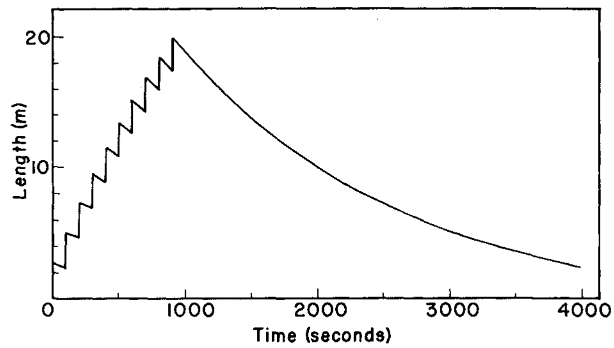

Fig. 2 Length of radiator vs time.

Discussion

There are two promising methods of deploying and retracting the bellows radiator (see Fig. 3). The first method, similar to the one employed by flexible roll-up solar arrays, utilizes a roll drum driven by an electric motor. Two roller rods can be used to squeeze out any vapor and liquid during roll-in to ensure that the bellows is completely collapsed. The electric motor is conceptually controlled by pressure sensors located inside as well as at the inlet of the radiator. The drum is held in a stable position by an extendable, retractable boom or bistem structure.

The second type of radiator resembles a paper lantern. There is a large helical spring attached to the cylindrical surface of the bellows. In the stowed position, the bellows can be very short. During deployment, the internal pressure due to the incoming vapor extends the spring and pushes the bellows out. As the vapor condenses, the spring will pull the end of the bellows back toward the spacecraft. Using an aspiration pump, the condensate can be pumped back through the liquid return channels, which run lengthwise along the bellows wall.

The merits of a space radiator design depend significantly on the overall size, mass, and durability. For the duty cycle studied in this Note, the bellows is extended to about 20 m, corresponding to a surface area of about 200 m^2. If a thin lightweight polymer material (1 kg/m^2) is used, the bellows will have a mass of 200 kg. The mass of the coolant inventory should be about 100 kg. Thus, the total mass of the radiator is about 300 kg. For a conventional radiator sized to reject the peak power of 5 MW, the surface area required is 8000 m^2. With a characteristic mass per unit area of 5 kg/m^2, the mass of the radiator would exceed 40,000 kg.

The use of a vapor phase thermal storage space radiator (such as the present concept) is absolutely necessary for high-power heat rejection at low temperature when the peak-to-average power ratio is very high. It is also clear that the present expandable radiator concept is a sound one and should be further developed. Studies on micrometeoroid penetration, structure materials selection, and liquid recirculation techniques are continuing.

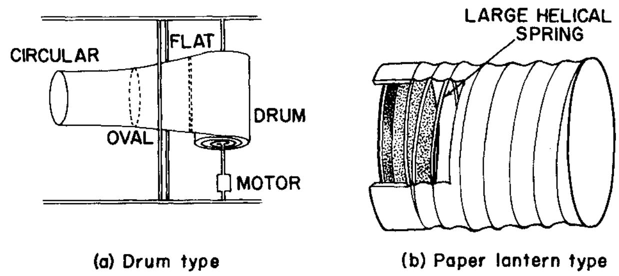

Fig. 3 Two possible radiator configurations.

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Appendix

An energy balance for the control volume as shown in Fig. 1 yields

$$\dot{m}_i h_g = \dot{Q}_{\rm rad} + \dot{m}_e h_f + \dot{W} + \dot{E} \tag{A1}$$

where $\dot{m}_i = \dot{Q}_L / h_{fg}$ is the vapor mass flow rate into the radiator and h_f and h_g are the specific internal enthalpy of the saturated liquid and vapor, respectively; $\dot{m}_e$ is the rate of condensate mass being removed from the radiator, $\dot{Q}_{\rm rad} = \epsilon\sigma A(T^4 - T_s^4)$ the heat rejection rate to space from the radiator surface of area A, and $\dot{W} = P\dot{V}$ the work done by the control volume; P is the restoring force per unit cross-sectional area of the radiator and is the same as the vapor pressure, and $\dot{E}$ is the rate of energy stored in the radiator.

The surface area of the radiator A is given by

$$A = \pi DL + \pi D^2/4 = 4V/D + \pi D^2/4 \tag{A2}$$

Assuming that there is no significant accumulation of condensate, the condensate removal rate is

$$\dot{m}_e = \dot{m}_i - \dot{m}_v \tag{A3}$$

where $\dot{m}_v$ is the rate of vapor mass accumulated inside the radiator. If the volume occupied by the condensate inside the radiator is negligible, then

$$\dot{E} = \dot{m}_v u_g = \rho_v \dot{V} u_g \tag{A4}$$

where u_g is the specific internal energy of the vapor. The energy balance, Eq. (A1), can be rewritten as

$$\rho_v u_g \dot{V} = \dot{Q}_L h_g / h_{fg} - \epsilon\sigma A (T^4 - T_s^4) - (\dot{Q}_L / h_{fg} - \rho_v \dot{V}) h_f - P\dot{V} \tag{A5}$$

It can be shown that Eq. (A5) is identical to Eq. (1).

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Companion: An Economical Adjunct to the Space Shuttle

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Introduction

THE Space Shuttle provides routine transportation from Earth to low-Earth orbit. The purpose of this note is to introduce the concept of a "Companion" system which would operate with the shuttle to provide lower cost transportation.

The Companion system would operate as shown in Fig. 1. The Shuttle would be launched and would deliver a payload in the usual manner. The Companion system would be subsequently launched and would also deliver a payload. The Companion booster would fly back to the launch site for reuse. The Companion orbital stage would rendezvous with the Shuttle Orbiter and would be returned to Earth in the payload bay of the Orbiter. Two constraints that apply to the concept are that the Shuttle Orbiter could not return a payload other than the Companion orbital stage and that the Companion system would have to be launched into the same orbital plane as the Shuttle. Because many Shuttle missions involve delivery of satellites bound for geosynchronous orbit and orbit-transfer stages, the first constraint would still allow frequent operation of the Companion system. The second constraint may mean that the Shuttle Orbiter would need to stay in orbit an extra day or two before the Companion system could be launched and recovered.

The primary benefit of the Companion system would be its low operating cost. Because all components except the payload shroud would be reusable, the cost of a Companion mission could be significantly lower than the cost of a Shuttle mission or an expendable launch vehicle with an equal payload. Although actual costs are difficult to estimate because no experience exists for similar systems, the cost per flight would certain be less than $10 million and possible less than $1 million. The development cost of the Companion system would be less than the development cost of reusable systems that do not operate in conjunction with the Shuttle because such systems would require entry and recovery system that would increase costs directly and through size increases. Application of typical cost estimating relations to the Companion system indicates that the development cost could be considerably less than a billion dollars if most of the subsystems are adapted from existing vehicles.

System Description

Figure 2 shows the general characteristics of the Companion system, and Table 1 lists the system masses. The orbital stage is cylindrical and is sized to fit in the payload bay of the Shuttle Orbiter. Two boosters are placed on opposite sides of the orbital stage. The rocket engines on the orbital stage and both boosters operate from liftoff to staging. The boosters stage at

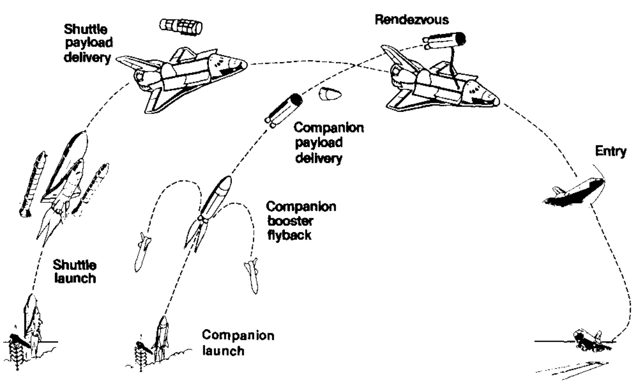

Fig. 1 Companion system operations.

Table 1 Masses of companion system, kg

Orbital stage	8,200
Payload and shroud	10,100
Burnout	18,300
Propellant	152,900
After staging	171,200
Boosters (two)	15,00
Before staging	186,200
Propellant	71,800
Gross	258,000
Orbital Stage	8,200
Oxygen	130,800
Kerosene	44,200
Hydrogen	1,900
Gross	185,100
Booster (one)	7,500
Oxygen	17.700
Kerosene	5,900
Hydrogen	300
Gross	31,400

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