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MOVING BELT RADIATOR DEVELOPMENT STATUS

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SUMMARY

Development of the Moving Belt Radiator (MBR) as an advanced space radiator concept is discussed. The relative merits of Solid Belt (SBR), Liquid Belt (LBR), and Hybrid Belt (HBR) Radiators are described. Analytical and experimental efforts related to the dynamics of a rotating belt in microgravity are reviewed. The development of methods for transferring heat to the moving belt is discussed, and the results from several experimental investigations are summarized. Limited efforts related to belt deployment and stowage, and to fabrication of a hybrid belt, are also discussed. Life-limiting factors such as seal wear and micrometeoroid resistance are identified. The results from various MBR point design studies for several power levels are compared with advanced (5 to 8 kg/m^2) Heat Pipe Radiator technology. MBR designs are shown to compare favorably at both 300 and 1000 K temperature levels. However, additional effort will be required to resolve critical technology issues and to demonstrate the advantages of MBR systems.

INTRODUCTION

Future space missions currently being considered by NASA, the Air Force, and the Strategic Defense Initiative Organization (SDIO) will require power levels far in excess of Space Station usage. Analyses of power systems capable of supplying megawatts or even gigawatts of power have revealed a need for advanced space radiators which can reject the attendant waste heat. Heat pipe radiators (HPR), which represent the best of current technology, typically have a specific mass of 5 to 8 kg/m^2 (ref. 1). The use of advanced technology may eventually reduce this figure to 3 kg/m^2. The development of long-life advanced radiators will be an enabling technology for realization of multimegawatt space missions. Such radiators will be significantly less massive than heat pipe or pumped loop technology currently planned for the Space Station (ref. 1).

Moving Belt Radiators (MBR) represent one advanced concept currently under investigation. The basics of the MBR concept are illustrated in figure 1. A cylindrical belt revolves about its axis by means of some type of driving mechanism attached to the spacecraft. Heat is transferred from a primary heat transport loop to the belt. As the belt rotates, it radiates thermal energy to space. The belt material can be a homogeneous solid, a screen mesh holding a liquid by capillary forces, or a combination of two solid belts sandwiching some type of phase-change material. Details of the various components of an MBR system are discussed later.

The MBR shows excellent potential as an advanced radiator concept for future space missions, and compares favorably with other radiator concepts also under consideration. Although the Liquid Droplet Radiator (refs. 2 and 3) is

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considered technically feasible, the spacecraft user community is averse to the exposed working fluid of the LDR. Concerns about exposed fluids can be eliminated with an Enclosed Droplet Radiator, but such a concept has not yet been demonstrated feasible (ref. 2). Another option, the Curie Point Radiator, (ref. 4) is limited to certain rejection temperatures; furthermore, the Curie Point concept is widely regarded as possessing greater development risks than either the Liquid Droplet system or the MBR system. The Bubble Membrane Radiator (ref. 5) has not been extensively investigated, but it also appears to be associated with high development risks.

By contrast, the MBR can operate without exposing a working fluid to the space environment. The major technological challenge for the MBR appears to be maintaining the stability of a rotating belt in the presence of spacecraft attitude maneuvers. Although other issues must be resolved, an existing technology base related to these issues lessens the development risk. Another advantage of the MBR is that it may prove to be only 10 to 30 percent as massive as advanced (5 kg/m^2) HPR technology; the MBR also compares favorably with other proposed advanced radiator concepts. In addition, the MBR can be more readily stowed than a comparable HPR; this minimizes launch volume and may allow more maneuverability for SDI missions. A comprehensive review in reference 6 of these and other proposed advanced radiators describes their operation and discusses the merits of each radiator concept.

This paper reviews and summarizes the MBR technology base. This technology has been developed primarily under NASA Lewis Research Center contracts with Arthur D. Little, Inc., and under Air Force Astronautics Laboratory (formerly Rocket Propulsion Laboratory) contracts with Boeing Aerospace and Astro Research. The initial work in the early 1960's was carried out at NASA Lewis, at Cornell (under a Lewis grant), and at Rocketdyne.

First, various design alternatives for the Moving Belt Radiator are discussed. These alternatives include at least three methods of belt construction, two viable options for transferring heat to the moving belt, and several different geometric constructions for an MBR system. Then, the most critical MBR development issues are identified, and progress toward their resolution is presented. The issues addressed are the following: the dynamics of a rotating belt, heat transfer to the belt, proper sealing of the heat exchanger to ensure long life operation with negligible leakage and low belt drag, deployment and stowage of the belt, fabrication of the belt, and the effects of micrometeoroids on MBR operation and life. After discussing these technology issues, the design, performance, and specific mass of various MBR systems are summarized. Finally, recommendations for continued MBR development are presented.

Development efforts to date have been for an MBR system operating in a microgravity environment. However, because of its low specific mass, the MBR may be advantageous for other future NASA missions in reduced gravity. These include various mission scenarios on the lunar or Martian surface; such missions are currently under investigation as part of the NASA Pathfinder initiative. The results discussed below are applicable for zero-g operation. Certain issues, notably deployment and stability of a rotating belt, are clearly affected by a gravity vector; however, these issues have only been investigated for microgravity applications. Research into the feasibility of an MBR for Pathfinder missions is certainly required.

MBR DESIGN ALTERNATIVES

A number of design options have been identified while developing the basic MBR system shown in figure 1. Three different options exist for constructing a low-mass belt. In addition, at least three fundamentally different methods exist for transferring heat to the belt. Also, several different belt geometrical configurations have been identified.

The MBR concept was first proposed in 1959. All of the work done in the early 1960's (refs. 7 to 10) was for high-temperature (1000 K) applications, and envisioned the radiating belt being constructed from a flexible solid material. A graphite-steel composite (ref. 7) was first suggested to take advantage of the higher heat capacity of graphite. Consideration of tensile strength, heat capacity, and density revealed Be as an excellent candidate; similarly, a belt composed of a thin outer layer of Mo and an inner layer of Be is even lower in mass (ref. 10). For lower rejection temperatures (300 to 400 K), materials such as Kapton or Teflon appear to be suitable. Achieving and maintaining high emissivity surfaces is desirable regardless of the belt material chosen. This MBR option, using either a homogeneous or a composite solid belt, will be termed a solid belt radiator (SBR).

In order to improve the heat capacity of the belt and thereby reduce belt mass, the Liquid Belt Radiator (LBR) has been investigated (refs. 11 and 12). The belt of an LBR system is a wire mesh filled with a liquid held in the belt by surface forces. The liquid forms menisci in each cell of the wire mesh, and most of the radiation emitted from the belt emanates from these liquid menisci. The LBR has two compelling advantages over an SBR system. One, heat transfer to the belt is readily accomplished, since the wire mesh belt is drawn through an interface heat exchanger (IHX) bath containing the hot liquid. Since the belt contains the liquid in the form of menisci, the belt temperature close to the bath exit is always very near the IHX bath temperature. Another advantage of the LBR option is that the system can readily be designed to exploit the latent heat of fusion of a solidifying working fluid. Because the latent heat of fusion for a given material is much higher than its sensible heat, the mass of the belt and of the entire LBR system can be reduced substantially.

The technical feasibility issues peculiar to the LBR option have been investigated by Arthur D. Little (refs. 11 and 12). The capillary forces which contain the fluid as menisci in the wire mesh predominate over the centrifugal forces accompanying belt rotation. Thus, the fluid does not become dislodged from the belt for belt velocities of practical interest (ref. 11). However, if a solidifying working fluid is employed, the fluid menisci will freeze; the effects of a flexing belt on the frozen working fluid have not been addressed. A detailed point design of an LBR system using an oil at 300 to 330 K revealed that the radiator specific mass (in kg/kW) was 30 percent that of advanced (5 kg/m^2, $\varepsilon = 0.85$) heat pipe technology (ref. 12). However, parametric studies indicated that liquid metal LBR systems using Li, Ga, or Sn probably would not offer significant mass savings over 5 kg/m^2 HPR technology; this is primarily due to the low emissivities and high densities of liquid metals. Only an LBR system employing solidifying Li as the working fluid appeared attractive from a specific mass (kg/kW) standpoint (refs. 11 and 12).

Since the LBR was found to be advantageous only around 300 to 350 K, this MBR option is not being pursued further at this time. As with the Liquid

Droplet Radiator, user concerns about exposed working fluid in space must be considered. This is true for both low vapor pressure oils and Li systems sensitive to atomic oxygen.

A novel MBR concept which incorporates the best features of the SBR and the LBR has recently been conceived (ref. 13). In the Hybrid Belt Radiator (HBR) concept, a phase-change material is encapsulated by two solid belt surfaces; thus, there is no working fluid exposed to space. Similar to a phase-change LBR, the HBR capitalizes on the latent heat of fusion of the phase-change material. The phase-change material sandwiched between the solid layers is in a liquid phase upon leaving the heat exchanger; after the belt has made one revolution, the material is in a frozen, lower energy phase. Heat capacities of hybrid belts are much higher than those of solid belts or non-phase-change liquid belts. As a result, the belt velocity can be reduced, which simplifies the design of long-life fluid seals. Hybrid belts can also be made substantially less massive than comparable solid belts.

The method of transferring heat from the spacecraft to the rotating belt has a profound impact on the feasibility of the MBR. Both preliminary and more detailed MBR point designs indicate that the heat exchanger can comprise 10 to 50 percent of the mass of the entire MBR system. Three different heat transfer techniques have been identified (ref. 10). First, the belt can be heated by direct radiation from the spacecraft heat transport loop. Although this alternative eliminates the need for rotary or linear seals, radiative transfer to the belt results in a more massive MBR system (ref. 10), and therefore has not been investigated further. Second, heat can be transferred conductively between a heated drum and the belt. Third, the belt can be passed through a liquid bath to transfer heat to the belt by convection. These latter two options have been investigated analytically and experimentally; the results of this research are discussed later.

Several different belt geometries have been identified (ref. 10). The design shown in figure 1 uses two cylindrical belts; this arrangement minimizes heat-exchanger mass and maximizes radiative transfer from the belt surfaces. The belt aspect ratio (circumference/width) is kept large to ensure view factors from the inner surface to space of 0.80 or larger. Another belt geometry which has been proposed is elongation of the belt (see ref. 10). With this arrangement, the view factor between the inner surface and space is near zero, and the belt mass is nearly twice that required for a circular belt. Thus, if the configuration of figure 1 can be proven dynamically stable, it would be less massive than any other belt geometry.

STATUS OF CRITICAL TECHNICAL ISSUES

Belt Dynamics

A critical issue in MBR development is the determination of the stability of the belt configuration shown in figure 1. The belt is assumed to have a cylindrical shape initially, and the method of deployment is not at issue here; determining how the belt will be deployed to the state shown in figure 1 is discussed later. Belt stability is affected by spacecraft attitude control maneuvers, docking with another spacecraft or space structure, and potentially, by low-frequency vibrations of the spacecraft structure. To date, work on belt

stability has included computer code development and lab-scale testing in normal gravity.

Initial attempts to understand the dynamics of a rotating belt were carried out at Arthur D. Little (A.B. Boghani and M.W. Wentworth under NASA contract NAS3-24650, eliminate). A literature review suggested that a closed-form solution to the problem probably does not exist, primarily because belt motion is restricted at the heat exchanger. Therefore, as shown in figure 2, a lumped-parameter computer model of the belt was employed. The belt is modeled as a variable number of nodes, or lumped masses. Any specific lumped mass is modeled as being connected to adjacent nodes by linear springs and dashpots which simulate tension, compression, and damping in the belt. Similarly, rotational springs and dashpots simulate bending and damping in the belt, respectively. The Cartesian coordinate system is as shown in figure 2, where the origin is at the center of the heat exchanger.

The belt is subject to both in-plane and three-dimensional (out-of-plane) perturbations. Referring to the coordinate system of figure 2, any spacecraft acceleration in the x-y plane will produce belt responses solely in the x-y plane. Similarly, rotation of the spacecraft about the z-axis will produce comparable in-plane motions, as illustrated in figure 3. Conversely, spacecraft accelerations having a z-component, or rotations about the x- or y-axes, will lead to much more complex, out-of-plane responses in the belt, as shown in figure 4. Because of the added complexity introduced by out-of-plane belt deformation, and given the resource limitations of the program, the Arthur D. Little computer code could not account for the responses of figure 4. However, a simplified analysis suggested that the belt is more sensitive to x- or y-axis accelerations than to those along the z-axis. Thus, the results of the computer modeling are believed to represent a realistic simulation of belt stability in zero gravity.

The rotating belt was modeled for x- and y-axis accelerations of various magnitudes and durations. Failure of the belt was assumed to occur when the belt touched itself (doubled up) or the spacecraft, or when the allowable belt shear stress was exceeded. Doubling up of the belt was determined by examining the positions of adjacent nodes in computer-generated plots. For accelerations entirely in the y-direction, figure 5 summarizes the results of the computer simulations. The baseline design employs a belt 13 m in diameter with a linear velocity of 1 m/s; this baseline belt has a bending stiffness of 5.95×10^{-3} N m. Such a bending stiffness is typical for a belt constructed of a square mesh screen of twisted glass fibers. Figure 5 indicates that the baseline design is stable in the presence of 10^{-2} g accelerations lasting 10 s or less. In order to withstand higher acceleration levels, either the belt velocity or the bending stiffness must be increased.

The computer program was also used to examine the effects of one-g accelerations of very short duration, such as 0.2 s. The belt was stable in such cases, although it would fail after 10 s of sustained one-g load.

Computer simulations were also run for accelerations solely in the x-direction. The belt is more susceptible to failure from x-axis accelerations, since it is more likely to crease shortly after exiting the heat exchanger. However, unlike accelerations along the y-axis, bending stiffness has little influence on x-axis behavior.

The initial work at Arthur D. Little was extended at Boeing (ref. 14). The Boeing analysis was quite similar in that a lumped-parameter computer code was developed. The Boeing code incorporated a more detailed and accurate model of the heat exchanger-belt interface. This work showed that if the belt drive mechanism was designed improperly, the belt would tend to be unstable even in the absence of spacecraft maneuvers. The principal additional finding of the Boeing model was that belt stability is strongly influenced by heat exchanger design. The angle at which the belt enters and exits the heat exchanger was shown to be critical in determining the stability of the belt. Ideally, the heat exchanger should be designed such that the belt shape is as close to a perfect circle as possible. Therefore, future, more refined dynamic analyses must incorporate a detailed model of the heat exchanger-belt interface in order to properly model belt dynamics.

Development of the computer codes to investigate belt dynamics revealed the need for fundamental physical property data for candidate belt materials. Although material property data are available for nylon, Mylar, and fiberglass, the desired values are unknown for screen mesh belts made from these materials. Since the damping and stiffness properties of a material change after it has been crimped, woven, and bonded into a screen mesh, the required properties of nylon, Mylar, and fiberglass meshes were determined experimentally by using a tensile test machine (W.P. Teagan and T.A. Longo under NASA contract NAS3-24650, Task 4). Stiffness and damping values in both bending and stretching were measured directly, or calculated from these measured values. Because test segments of a hybrid belt were not available, only candidate LBR materials could be tested.

A detailed understanding of the dynamics of the rotating belt is essential to a proper assessment of MBR feasibility. Therefore, efforts have been made to verify existing computer codes experimentally. In normal gravity, it is impossible to accurately simulate a rotating flexible belt intended for zero-g operation. Nevertheless, some simple experiments were conducted by W.P. Teagan and T.A. Longo under NASA contract NAS3-24650, eliminate in order to further understanding and to aid in the design of zero-g experiments. Test belts were rotated about their axes; in one series of tests, the axis was parallel to the gravity vector, and in the other, perpendicular. The tests involving rotation perpendicular to gravity were inconclusive, since gravity elongated the belt. A circular belt could not be formed even at 740 rpm (8 m/s). This suggests that belts will not be stable when subjected to one-g acceleration, which is in agreement with the findings of the computer model.

A second series of tests employed a rubber belt 175 cm in circumference and 15 cm wide. The belt axis of rotation was parallel to gravity, such that gravity exerted an equal force on every element along the belt circumference. The findings are summarized in figure 6. The first six frames simulated the deployment of the belt by centrifugal force. At 150 rpm (4.4 m/s), the belt is completely round. The next six frames simulate the response of the belt to a low-level acceleration. In frames 7, 9, and 11, the spinning belt is struck briefly with a thin rod, as shown, to simulate an attitude control maneuver. The condition of the belt 2 s after impact is shown in frames 8, 10, and 12, which indicate that the belt can rapidly recover from the imparted disturbance. In all three tests, the belt returned to its initial, unperturbed state within 6 s after impact.

The belt stability experiments performed in normal gravity are insufficient and somewhat inconclusive, since it is impossible to eliminate the effects of gravity on the belt merely by increasing centrifugal force. In order to demonstrate belt stability in a mission environment, related experiments in microgravity must be carried out. Early in 1989, Arthur D. Little, under NASA contract, will conduct a series of 40 experiments aboard a KC-135 aircraft. One apparatus will be designed to demonstrate deployment of the belt, while a second experiment will investigate belt stability in the presence of various acceleration waveforms. Concurrent with the KC-135 testing, a related experiment for a Shuttle flight will be defined as part of the NASA Office of Aeronautics and Space Technology (OAST) In-Space Experiments Program. The results from the KC-135 testing will be utilized to develop a conceptual design to demonstrate MBR operation, including proper sealing of the heat exchanger, on a Shuttle flight.

The KC-135 testing is intended to determine how the belt can be deployed and stowed. It may be necessary to rely on a telescoping, extendible boom to deploy the belt. If this deployment method is found to be necessary, the rotating belt dynamics would be altered, since the belt would be fixed at two diametrically opposed points. Similarly, the telescoping boom may be required principally to stabilize the rotating belt, in which case its use to simplify deployment would be a secondary benefit. If a telescoping boom is required for either reason, the experimental apparatus being defined for the Shuttle would incorporate the required changes.

Heat Transfer to Belt

The size and mass of the entire MBR system are determined by the rate of heat transfer to the belt. (The thermal energy radiated from the belt has been determined, given the rejection temperature, belt emissivity, and velocity. The relations among these parameters are given in references 10, 11, and 14.) The heat exchanger required to transfer heat from the spacecraft to the belt must be as lightweight as possible. System studies (refs. 11, 12, 14, and 15) have indicated that an inefficient heat exchanger will result in an MBR system more massive than HPR technology. Furthermore the heat exchanger must be designed with long-life seals to permit operation for mission lifetimes of 7 yr or more. It is also necessary to minimize mass losses of any heat exchanger fluids. Three criteria, mass, seal life, and fluid loss, must be considered when evaluating various design options. Considering these criteria, direct radiant heating of the belt (ref. 10) was determined to be too massive an option, since the belt reradiates almost as much thermal energy back to the spacecraft.

A rotating heated drum was the first concept proposed, in 1959 (ref. 7). The internally heated drum transfers heat to the belt through contact conduction between the belt and the drum. A recent improvement on the original concept is shown in figure 7. A pressure belt is used to increase the contact conductance between the radiating belt and the heated drum. The two radiating belts will thus revolve in opposite directions, which may help to reduce any effects of belt rotation on the spacecraft. (The magnitude of any such interactions is presently unknown, but the effects are presumed to be negligible.) Proper sizing of the drum requires a knowledge of the heat transfer coefficient between the belt and the drum.

The first analysis (ref. 9) of the required heat transfer coefficient considered heat transferred both to and from the belt. The results of the analysis were used in conjunction with a preliminary mass estimate of a SBR system. By assuming that the specific mass of competing technology is 0.55 kg/kW (ref. 9), to be competitive, heat transfer coefficients of 2500 W/m^2 K, or better, are required for a rejection temperature of 1000 K. (With 5-kg/m^2 HPR technology, current values are 0.06 kg/kW at 1000 K and 2.0 kg/kW at 500 K (ref. 2).) For lower temperature requirements (300 K), the heat transfer coefficient must be 200 W/m^2 K or better (ref. 15) to maintain the substantial mass savings of the MBR concept.

Contact conductance between two surfaces is a strong function of surface finish, vacuum level, and contact pressure. Because of this, it is difficult to find measured values which can be directly applied to the design of an MBR system. Data for contact conductance between an Al and a UO_2 surface indicate values as high as 9000 W/m^2 K are possible with a 100-psi contact pressure (ref. 10). Other data indicate that 1000 W/m^2 K is readily achievable at 10 psi, and that 7000 to 8000 W/m^2 K may be achievable between two Cu surfaces with 50-psi contact pressure (ref. 16). As part of the MBR program, conductance values of 20 W/m^2 K were measured for an aluminized Kapton belt rolling over an Al cylinder, with 0.1-psi contact pressure (ref. 15). Such a value is clearly inadequate and indicates that a heated drum system should maintain at least a 10-psi contact pressure. Since the above experimental results were obtained at 10- to 100-psi contact pressures, the required contact pressure would be easily achievable. However, the structural requirements attendant with the desired contact pressure must also be considered.

A number of approaches exist for achieving the required contact conductance without having to rely on a high contact pressure. Conductance to the Al-coated Kapton belt was increased from 20 to 160 W/m^2 K when silicone grease was applied between the belt and the Al drum. The pressure belt shown in figure 7 is intended to increase the actual contact area (geometric area reduced by some factor depending on the surface profile) between the rotating drum and the radiating belt. Thus, higher effective contact conductances can be achieved at the same contact pressure. Use of a high thermal conductivity fluid between the belt and the rotating drum has more of the desired effect than the silicone grease mentioned above. For lower temperatures, a grease or wax can be loaded with colloidal or powdered metal, whereas for higher temperatures, a molten metal such as Ga or Sn could be used in a thin layer between the belt and drum. However, these approaches introduce the added complexity of maintaining the molten metal or grease on the drum, without appreciable carryover on the belt. It is also necessary to determine the change in belt emissivity associated with any carryover.

Although heat transfer from the drum to the belt has the largest influence on the overall heat transfer coefficient, heat transfer to the inner drum surface must also be considered. Figure 8 shows a recent heated drum concept which utilizes condensation in Gregorig grooves to heat the inner surface of the rotating drum. The design is described in more detail in references 14 and 17. Note that the design requires one rotary seal at the vapor inlet. As discussed in the section Heat Exchanger Seals, demonstrating successful long-life operation of such a seal represents the most challenging development issue for the heated drum concept.

Direct convective heating of the belt by a fluid is being actively investigated at Arthur D. Little. The Interface Heat Exchanger (IHX) concept, shown in figure 9, appears to be a more promising alternative than the heated drum concept. The cooled belt enters the IHX, where it is drawn through a bath of molten Ga. After passing through linear labyrinth and scraper seals, the belt again makes its traverse through space. The Ga is, in turn, heated by a fluid-fluid heat exchanger from the spacecraft primary waste heat transport loop. Because of the high thermal conductivity and negligible vapor pressure of Ga, design of this heat exchanger should be straightforward, and therefore, is not considered to be a critical technical issue.

Gallium is the IHX fluid of choice. In addition to high thermal conductivity, it has a viscosity near 1.7 cP (0.0017 N s/m^2), which will keep viscous drag losses low (ref. 18). Gallium melts at 303 K and has a vapor pressure below 10^{-6} torr up to ≈950 K; thus it is a candidate IHX fluid over at least a 650 K range. Gallium has a surface tension of 720 dynes/cm, which is a tremendous advantage in developing leak-free seals for the IHX. Furthermore, observations have shown that Ga does not wet a variety of candidate belt materials. Measured contact angles (ref. 11) for molten Ga on nylon, polyethylene, Vespel, Teflon, Ta, steel, Al, and glass were greater than 108°. Thus, it is quite possible for IHX linear seals to operate with little drag, and at the same time eliminate entrainment of a thin Ga film on the belt.

Gallium is much more benign than other liquid metals. It does not readily form Ga_2O_3 or other oxides under MBR operating conditions of interest. Samples of Ga were exposed to a simulated atomic oxygen environment (0.23 eV and 80-μm Hg vacuum) in a plasma asher at NASA Lewis. There was no evidence of oxide formation after 360 hr of exposure; no change in either mass or surface appearance of the samples was noted. Containment of Ga is easily accomplished with certain types of stainless steels, as long as the alloy does not contain a free-machining additive such as S. Researchers at Lawrence Livermore National Laboratories (personal communication with C.D. Hendricks, Livermore, CA) have forced molten Ga through 10-μm-diam orifices. When the Ga is contained by #303 stainless steel (SS), the orifices do not plug. With S-containing alloys, Ga forms amalgams, which eventually flake off and prevent flow through the orifices. Although Ga dissolves Al almost instantaneously, it does not pose a serious materials problem, since it can be contained by many stainless steels. Above 800 K, however, only tungsten can be used to contain Ga (ref. 18). Potential interactions between candidate MBR materials, including Ga, are currently being investigated at NASA Lewis.

Heat transfer in an IHX has recently been demonstrated at Arthur D. Little (W.P. Teagan under NASA contract NAS3-24650, Task 6). The experimental apparatus is shown in figure 10. A Teflon belt, 125 μm thick by 15 cm wide by 168 cm in circumference, was passed through a Ga bath; the bath was maintained at a constant temperature near 325 K, about 25 K above the temperature of the entering belt. Belt velocity was varied, and the belt temperatures on exiting from the bath were observed to be within 3 K of the bath temperature. Since data analysis is not yet complete, overall heat transfer coefficients have not yet been determined.

Heat Exchanger Seals

The potential lifetime and performance of the MBR heat exchanger seals will perhaps determine whether the heated drum concept or the convective IHX design is chosen for further development. As can be seen in figure 8, the heated drum requires at least one rotary seal to contain the fluid from the spacecraft thermal loop. Depending on the precise heated drum design, the fluid to be contained may be either a liquid or a vapor. Boeing has recently evaluated the rotary seal requirements (ref. 14) for a heated drum designed for a 10-yr life. At 45 rpm, the drum would undergo 240 million revolutions. Under a Boeing IR&D program, a ferrofluidic rotary seal was successfully operated for 3 million revolutions (6000 hr of testing). In actual practice, mechanical seals or a combination of mechanical and ferrofluidic seals might be required. Seals made of low wear resistance materials (such as Riton for the 300 to 400 K range) must be demonstrated for at least 10 million revolutions.

Lifetime considerations also indicate that rotary seals must have low leakage rates to minimize both spacecraft contamination and makeup fluid mass. Leakage rates for an MBR rejecting 20 kW were estimated for the rotary seal of a heated drum using ammonia as a condensing fluid (ref. 14). The estimate was based on leakage rates observed for 60 000 test revolutions of a molybdenum disulfide rotary seal at ambient temperature. If a seal employing low-wear Riton instead of molybdenum disulfide were used, total leakage through the seal over 10 yr would be 2.5 kg, or ≈1 percent of the total MBR mass. Boeing considers this to be an upper limit for the leakage rate. Based on the 60 000 test revolutions, seal drag was estimated to be insignificant, although the influence of bearing friction on parasitic power may be significant (ref. 14).

Acceptable performance of linear seals for the convectively heated MBR has recently been demonstrated at Arthur D. Little (D.H. McFadden and W.P. Teagan under NASA contract NAS3-24650, Task 2). A 125-μm-thick Teflon belt was passed through a Ga IHX, as shown in figure 10. The Ga IHX requires end seals at the entrance and exit of the Ga bath. Although Teflon scraper and clearance seals appeared to be unacceptable, successful sealing was demonstrated with closed-cell foam strips ("squeegee" seals). Belt velocity was varied up to 0.6 m/s with the belt always in contact with the foam strips. No liquid Ga was observed on the moving belt for the velocity range tested. However, further research at velocities of 5 m/s or more is required, since an optimized MBR system will likely operate above 0.6 m/s.

In order to determine seal drag, the entire Ga bath and heat exchanger was mounted on the low-friction linear bearing subassembly shown in figure 10. After accounting for the friction inherent in the linear bearing, a load cell was used to determine the total drag force which includes drag between the seal and belt, and between the belt and liquid Ga. The measured drag was 1 to 3 lb. This is an insignificant fraction of the radiated thermal energy, being less than 1 percent for a scaled-up system.

These preliminary tests merely indicate the feasibility of relying on linear seals. A comprehensive testing program must be undertaken to demonstrate long-life performance of space-qualified seals at temperatures up to 1000 K. Because of program constraints, labyrinth seals or other more advanced designs could not be tested. However, the use of Ga is expected to aid in achieving long seal life. Because of its high surface tension, the Ga will tend to

remain agglomerated in the bath. The fact that Ga does not wet any candidate belt materials will eliminate concern about entrainment of Ga on the moving belt. In addition, the low viscosity of Ga will minimize total drag and probably increase seal life.

Deployment and Stowage

Mechanisms by which a belt would be deployed, retracted, and stowed in microgravity have received comparatively little attention. Although several techniques for deploying a rotating belt in microgravity have been proposed (refs. 11, 14, and 15), none of these concepts have been investigated. Ideally, the belt will assume its cylindrical shape without the aid of extravehicular activity, an existing manipulator arm, or a dedicated mechanical deployment system. Such automatic self-deployment would eliminate a substantial fraction of the nonbelt mass of an MBR system. Experiments to demonstrate belt deployment in a KC-135 aircraft are currently underway. A number of deployment options (which have not yet been identified) will be investigated experimentally in a microgravity environment. Results from the KC-135 testing will be used to help define a Shuttle experiment. This In-Space Experiment is intended to demonstrate deployment of a moving belt in microgravity.

If planned KC-135 testing indicates that neither automatic self-deployment nor any other mechanical deployment concepts are feasible, another alternative would be a telescoping boom. As shown in figure 11, the boom would extend away from the spacecraft. Rollers on the end of the boom would stabilize the belt at two positions. With such a system, deployment is straightforward even in the case of a sudden, unexpected spacecraft acceleration during deployment. A telescoping boom would fix the circular belt at two points 180° apart and increase the dynamic stability of the belt. However, there may be a significant mass penalty attendant with a telescoping deployment concept. A preliminary estimate (ref. 11) for a 300 K LBR design indicates that the additional structural mass would be between 0.5 and 10 times the mass of the belt alone. Estimates of the total MBR system mass further indicate that structural mass must be comparable to belt mass in order to maintain the mass advantages of the MBR. Therefore, concurrent with the development of a telescoping boom, estimates of MBR system mass would need to be made to ensure that the mass advantages of the MBR are maintained.

Hybrid Belt Fabrication

The HBR concept incorporates the best features of SBR and LBR systems. The first priority in HBR development is to identify how a hybrid belt would be fabricated. Three methods for encapsulating a phase-change material are shown in figure 12. The simplest option, shown in figure 12(a), is to inject the molten phase-change material into every compartment of a solid belt structure. This technique will be discussed below. A second option (shown in fig. 12(b)) is a solid belt containing randomly distributed microspheres which encapsulate the heat of fusion material. Fabrication of both hollow and liquid-filled microspheres is a well established technology for laser fusion research. Lawrence Livermore National Laboratories and KMS Fusion, for example, routinely encapsulate liquid deuterium in glass spheres smaller than 25 μm in diameter. A third option, shown in figure 12(c), is to employ a material which undergoes

a transition from a solid phase (e.g., α-phase) to a second (β) solid phase at the desired HBR operating temperature. The heat capacity of the hybrid belt would be greatly enhanced by the phase-change enthalpy.

The hybrid belt concept of figure 12(a) appears to be much more straightforward to develop and demonstrate than those of figure 12(b) and (c). Therefore, efforts to date have focused on the concept of figure 12(a). The phase-change material of this belt must be contained in separate compartments for two reasons. First, the belt must remain uniform in thickness around its circumference to ensure proper operation of the heat exchanger seals and the desired radiative transfer. Second, only the material in a given compartment could be lost if that belt segment were penetrated by a micrometeoroid. However, if the phase-change material from a ruptured compartment were lost, the belt thickness at that point could change. It is necessary to determine what effect, if any, a ruptured compartment would have on sealing of the IHX.

A test segment of a hybrid belt has recently been fabricated at Arthur D. Little (W.P. Teagan under NASA contract NAS3-24650, Task 6). The two outer layers of the test segment were 125-μm-thick Teflon belts. After injecting liquefied paraffin into each of the five compartments shown in figure 13 and eliminating air bubbles, the compartments were sealed with adhesive plugs. The assembled test segment was 15 cm by 28 cm (6 in. by 11 in.), and consisted of the five paraffin-filled segments. The integrity of the assembled test segment was demonstrated by exposing the stationary segment to a 250-W heat source. The belt temperature remained nearly constant while the paraffin was melting.

Further research is needed to demonstrate the potential of hybrid belts. Bending and stiffness properties of hybrid belts with both molten and solidified inner cores will need to be measured. The effects of thermal contraction or expansion for a phase-change material must be considered. The encapsulated material of the hybrid belt in figure 13 must have sufficient mechanical strength. The voids created by volume changes may affect heat transfer within the belt. Life testing of hybrid belts will be required in order to ensure that the belt will remain within the required thickness range. Life testing is also required to determine if overall heat transfer is affected by repeated mechanical stressing of the belt. It is anticipated that joining two ends of a hybrid belt to form a continuous loop may be easier than for a solid belt. The junction must be uniform in thickness, and the transition between the belt continuum and the junction must be smooth. Otherwise, there will be a small increase in drag as the belt junction passes through the IHX seals, which may increase the rate at which the seals wear. Such an increase in drag was observed during testing of a solid Teflon belt (W.P. Teagan under NASA contract NAS3-24650, Task 6).

Protection From Micrometeoroids

Moving Belt Radiator systems are much less susceptible to micrometeoroids than HPR systems. Only the heat exchanger (either heated drum or convective IHX) must be armored, and the compactness of this component will keep armor mass to a minimum.

The rotating belt cannot effectively be bumpered against micrometeoroid impacts. However, no significant reduction in active radiator area would

result from micrometeoroid penetrations (ref. 14). Puncture of the outer layer of a hybrid belt may result in loss of the phase-change material, depending on the hole size; however it could be lost only from the damaged belt compartment. Although the potential for spacecraft contamination by the phase-change material exists, the scenario is similar to the puncture of an individual heat pipe of a HPR system.

A punctured belt may affect the desired operation of the heat exchangers, particularly for a Ga-filled convective IHX. If penetration roughens the surface of the belt, the potential exists for the belt or IHX seals to become damaged as the belt enters or leaves the Ga bath. A small hole in the belt may entrain Ga in the belt by capillary force as the belt exits the bath. For this reason, it may be necessary to position small rollers at the entrance to the bath or heated drum to smooth out the belt. (See fig. 9.) Further examination of these issues must be undertaken concurrently with life testing of the heat exchanger.

ANALYSIS OF THE MOVING BELT RADIATOR SYSTEM

A number of parametric studies of MBR systems have been conducted for various power levels (refs. 10, 12, 14, 15, and W.P. Teagan, K.F. Fitzgerald, and K.B. Goodall under NASA contract NAS3-24650, Task 3). A detailed, comprehensive review of the findings of these studies is outside the scope of this paper. However, to aid in comprehending the size of various MBR systems, the results from six point design studies are presented in table I. For comparative purposes, specific masses for advanced heat pipe technology are assumed. At 300 K, heat pipe radiator mass is 7.3 kg/kW for 5 kg/m^2 technology, and at 1000 K, about 0.09 kg/kW for the 8 kg/m^2 technology assumed. These HPR specific masses are based on a NASA Lewis evaluation (unpublished) of existing heat pipe radiator designs for temperatures between 370 and 1000 K.

Table I shows that the MBR systems generally compare quite favorably to HPR systems. Note that the results of table I are based on preliminary designs, whereas state-of-the-art (5 kg/m^2) heat pipe technology has been developed over a 25-yr period. It is possible that MBR mass will decrease as HPR mass has, as system design is improved. For the low-temperature MBR systems of table I, the 4.4-kg/kW figure is considered most accurate, since the 75-kW system design is more detailed than those of the 12.5-kW or 20-kW systems. The 4.4-kg/kW result was arrived at after designing every component of an LBR system. A significant portion of the LBR mass for the 75-kW design is for additional oil to replace the Santovac-6 which would evaporate over a 5-yr mission life. In this LBR system, the Santovac-6 remains in the liquid state, and the latent heat of fusion cannot be exploited. For an HBR system operating at the same temperature, a specific mass estimate of 2 to 3 kg/kW seems reasonable, since a hybrid belt has been estimated to be 10 to 30 percent as massive as the Santovac belt.

The high-temperature point design studies are inconclusive on several issues. As discussed earlier, contact conductances at 1000 K must be at least 3000 W/m^2 K to remain competitive with the HPR. Although the 30-MW design assumes a contact conductance of 8000 W/m^2 K, the Be belt system is not competitive because structural mass predominates and the specific heat of Be is not large enough. When a composite belt of higher heat capacity is assumed, as in

the 68-MW design, the specific mass of the SBR system is seen to be less than that of the 8-kg/m^2 HPR technology. When the heated drum of the 68-MW design is replaced by a convective heat exchanger (1-MW design), the MBR specific mass is reduced even more, from 0.057 to 0.017 kg/kW. This reduction occurs despite the fact that the Be belt of the 1-MW system is more massive than a comparable graphite-steel composite belt. However, the 0.017-kg/kW specific mass estimate for the 1-MW system must be put into perspective. The opinion of this author is that the Astro Research point designs (12.5-kW and 1-MW systems) may underestimate MBR mass, and that specific mass estimates of 4.1 kg/kW and 0.034 kg/kW (respectively) are more reasonable. Nevertheless, table I indicates that SBR system mass is still substantially less than HPR mass, and that HBR mass will be even lower.

Because the Hybrid Belt concept has only recently been identified, detailed point designs have not yet been conducted. However, preliminary indications are that HBR systems will be significantly lower in specific mass than the one LBR and five SBR designs of table I. This is principally due to the high heat capacity of hybrid belts, as well as because of the high surface emissivity possible with a solid belt. The point design studies to date have indicated that belt mass for a well-designed system is 30 to 50 percent of total radiator mass. Hybrid belts show promise of being 10 to 20 percent as massive as comparable solid belts (W.P. Teagan under NASA contract NAS3-24650, Task 6). Therefore, preliminary indications (W.P. Teagan and W.P. Teagan, K.F. Fitzgerald, and K.B. Goodall under NASA contract NAS3-24650, Tasks 6 and 3, respectively) are that low-temperature HBR systems will be 30 to 50 percent of the mass of heat pipe radiators. Design of, and therefore system mass estimates for, high-temperature belt and heat pipe radiators are more preliminary. However, calculations indicate that MBR systems designed for 1000 K operation may be only 20 to 30 percent as massive as 8-kg/m^2 HPR's.

Studies of various MBR systems have also examined the merits of heated drum and convective heat exchangers. Although parametric studies for both options were carried out at Astro Research (ref. 15), the heated drum studies were at 300 K, whereas the convectively heated belt studies were for 800 to 1200 K rejection temperatures. The only direct comparison of both heat exchanger options is a recent Boeing study (ref. 14). The MBR systems were each designed to reject 20 kW at 305 K. For the heated drum concept, the mass was 5.85 kg/kW, assuming a reasonable value of 1135 W/m^2 K for heat transfer from drum to belt. The specific mass of the convective IHX design was almost identical, about 5.4 kg/kW. However, these two estimates were based only on the masses of the belts and heat exchangers.

A more realistic evaluation of the two heat exchanger concepts would consider both parasitic power requirements and structural mass. Unfortunately, these were not properly accounted for in the Boeing study. In evaluating the IHX design, viscous DC-705 was selected as the heat exchanger fluid instead of Ga. (The viscosity of DC-705 is 170 cP at 305 K, but only 1.8 cP for Ga.) Similarly, the vapor pressure of Ga at 305 K is at least three orders of magnitude below that of DC-705; at the melting point, the vapor pressure of Ga cannot be measured. If structural mass, viscous drag, seal drag, seal leakage, and evaporative mass losses were properly accounted for by using Ga instead of DC-705 in the fluid bath, the convective heat exchanger would be slightly more attractive than the heated drum at 305 K; however, exact figures have not been calculated. At 800 to 1000 K rejection temperatures, the convective heat

exchanger is even more attractive because the required contact conductance for a heated drum is 13 to 15 times the conductance required at 300 K. Such values are difficult to achieve and may be possible only by using a thin layer of molten Sn between belt and drum (ref. 10).

When the modified findings of the Boeing study (ref. 14) are considered in conjunction with the parametric studies performed by Astro Research (ref. 15), the advantages of a convective heat exchanger are apparent. The convective concept is at least marginally better than the heated drum at any temperature and may offer substantial advantages near 1000 K. In addition, the fluid contained in the IHX may possibly help to dampen vibrations in the rotating belt better than a heated drum would. Therefore, NASA Lewis is continuing development of the convective heat exchanger first proposed by Astro Research (ref. 15). The ongoing investigation will initially consider belt dynamics and long-life seal performance for an MBR system utilizing a convective heat exchanger.

Mass models of MBR systems have also been utilized to predict the maximum power levels that a single MBR system employing two belts could accommodate (ref. 13 and W.P. Teagan, K.F. Fitzgerald, and K.B. Goodall under NASA contract NAS3-24650, Task 3). Factors considered included Shuttle bay dimensions, limitations of seal technology, and the parasitic power required by a specific design. Although higher belt velocities can decrease radiator specific mass, the belt velocity was constrained to 5 m/s to keep estimated seal wear at a reasonable level. The 5-m/s constraint is based on experience in both aerospace and other industries. Viscous drag, seal drag, and pump power were evaluated to assure that total parasitic power was less than 1.5 percent of the heat rejection load. On the basis of these criteria, Arthur D. Little estimated that a single 200-MW HBR system could fit in the Shuttle bay. This 200-MW system employs two belts rejecting heat at 750 K. However, no other design details (mass, stowage volume, or dimensions) were given. By contrast, SBR and LBR systems were limited to thermal loads below 20 MW (ref. 13). These findings clearly suggest the great promise of the HBR concept, as compared with SBR and LBR systems.

CONCLUSIONS AND RECOMMENDATIONS

Development efforts to date all indicate that the MBR concept is feasible. Although Solid and Liquid Belt systems compare favorably with Heat Pipe Radiator specific masses, the biggest advantage of the MBR concept is evident with Hybrid Belt systems. An HBR exploits the phase-change potential of an LBR, yet can also offer high surface emissivities, even at liquid metal temperatures. Hybrid Belt systems rejecting 200 MW may be compact enough to be launched by a single Shuttle flight and will not expose a working fluid directly to space. Because of the merits of HBR systems, their development will continue to be pursued at NASA Lewis.

A number of critical issues have been partially resolved, but more effort is required in almost every technology area. The preferred heat exchanger design has been identified, and heat transfer to a moving belt has been demonstrated. Laboratory testing of this convective heat exchanger confirmed that linear seals can contain Ga in the fluid bath. Although no Ga was observed on

the belt over a short test period (two months of intermittent operation), long-life operation of linear seals must be demonstrated. A lumped-parameter computer model indicated that the belt is stable for low-level accelerations of moderate duration. However, the model indicates that one-g accelerations cannot be tolerated for more than 1 or 2 s. Experimental verification of the computer model in normal gravity was somewhat inconclusive and revealed that microgravity testing aboard a KC-135 or the Shuttle will be required. Plans for tests aboard both are underway. Deployment of a belt system must be demonstrated in microgravity, since normal gravity testing would be inconclusive. Deployment will also be demonstrated on a KC-135 in FY 1989.

Technology demonstration experiments planned by NASA for the next several years will yield much more insight about the feasibility of the HBR concept. If the concept looks as promising after these experiments as it does now, the next logical step would be the demonstration of a prototype HBR system aboard the Space Station. Further mission studies and technology development under NASA Pathfinder programs may indicate the need for developing a HBR system for lunar or planetary surface missions.

REFERENCES

1. Fleming, M.; and Hoehn, F.: Radiator Selection for Space Station Solar Dynamic Power Systems. Energy - New Frontiers (22nd IECEC), Vol. 1, AIAA, 1987, pp. 208-213.

2. White, K.A., III: Liquid Droplet Radiator Development Status. AIAA Paper 87-1537, June 1987. (NASA TM-89852).

3. Taussig, R.T.; and Mattick, A.T.: Droplet Radiator Systems for Spacecraft Thermal Control. J. Spacecr. Rockets, vol. 23, no. 1, Jan.-Feb. 1986, pp. 10-17.

4. Carelli, M.D., et al.: A Novel Heat Rejection System for Space Applications: The Curie Point Radiator. Advancing Toward Technology Breakout in Energy Conversion (21st IECEC), Vol. 3, American Chemical Society, Washington, D.C., 1986, pp. 1875-1880.

5. Webb, B.J.; and Antoniak, Z.I.: Rotating Bubble Membrane Radiator for Space Applications. Advancing Toward Technology Breakout in Energy Conversion (21st IECEC), Vol. 3, American Chemical Society, Washington, D.C., 1986, pp. 1881-1885.

6. Mattick, A.T.; and Hertzberg, A.: Advanced Radiator Systems for Space Power. IAF Paper 87-230, Oct. 1987.

7. Weatherston, R.C.; and Smith, W.E.: A Method of Heat Rejection from Space Powerplants. ARS J., vol. 30, no. 3, Mar. 1960, pp. 268-269.

8. Weatherston, R.C.; and Smith, W.E.: A New Type of Thermal Radiator for Space Vehicles. Aerospace Eng., vol. 20, no. 1, Jan. 1961, pp. 16-17, 48-58.

9. Burge, H.L.: Revolving Belt Space Radiator. ARS J., vol. 32, no. 8, Aug. 1962, pp. 1243-1248.

10. Flaherty, R.J.: Heat-Transfer and Weight Analysis of a Moving-Belt Radiator System for Waste Heat Rejection in Space. NASA TN D-1990, 1964.

11. Teagan, W.P.; and Fitzgerald, K.F.: Preliminary Evaluation of a Liquid Belt Radiator for Space Applications. NASA CR-174807, 1984.

12. Teagan, W.P.; and Fitzgerald, K.F.: Liquid Belt Radiator Design Study. NASA CR-174901, 1986.

13. McFadden, D.; and Teagan, W.P.: Performance Characteristics of Moving Belt Radiators. Energy - New Frontiers (22nd IECEC), Vol. 4, AIAA, 1987, pp. 2029-2033.

14. Lawrence, M.A.; Johnson, D.W.; and Thornton, M.M.: Moving Belt Radiators for Space. AFAL-TR-87-076, 1988.

15. Knapp, K.: Study of Moving Belt Radiators for Heat Rejection in Space. AFRPL TR-84-001, Jan. 1984.

16. Rohsenow, W.M.; and Hartnett, J.P.; eds.: Handbook of Heat Transfer. McGraw Hill, New York, 1973.

17. Webb, R.L.: A Generalized Procedure for the Design and Optimization of Fluted Gregorig Condensing Surfaces. J. Heat Trans., vol. 101, no. 2, May 1979, pp. 335-339.

18. de la Breteque, P.: Gallium and Gallium Compounds. Kirk-Othmer Encyclopedia of Chemical Technology, Wiley, New York, Vol. 11, 1980, pp. 604-620.

TABLE I. MBR POINT DESIGN PARAMETERS

Heat rejected	Rejection temperature, K	Belt velocity, m/s	Belt diameter, m	Belt width, m	Specific mass,[a] kg/kW	Specific mass,[b] kg/m^2	Assumed Emissivity	Ref.	Type of belt	Heat exchange medium
12.5 kW	300	1.0	4.2	6.6	2.05	0.30	0.8	15	Kapton SBR	Al drum, 120 W/m^2 K
20 kW	305	1.8	8.1	1.3	5.85	1.62	.8	14	Al SBR with oxide coating	Cu-plated Al drum, 1135 W/m^2 K
75 kW	330	.53	14	3.3	4.4	1.28	.8	12	Santovac LBR	Santovac oil bath
———	300	----	----	----	2.3	----	.85	--	Estimate for HBR	Liquid Ga bath
1 MW	1000	3.0	2.3	4.9	.017	.47	.8	15	Be SBR	Liquid Na bath
30 MW	1000	16.6	84	6.1	.35	3.26	.9	10	Two Be belts (SBR)	Mo drum, 8000 W/m^2 K
68 MW	990	30.5	42	12	.057	1.22	.9	7	Graphite-steel composite belt (SBR)	Steel drum, h unknown
———	1000	----	----	----	.015-.03	-	.85	--	Estimate for HBR	Liquid Ga bath

[a]At 300 K, 5 kg/m^2 HPR mass is 7.3 kg/kW.
[b]At 1000 K, 8 kg/m^2 HPR mass is 0.09 kg/kW.

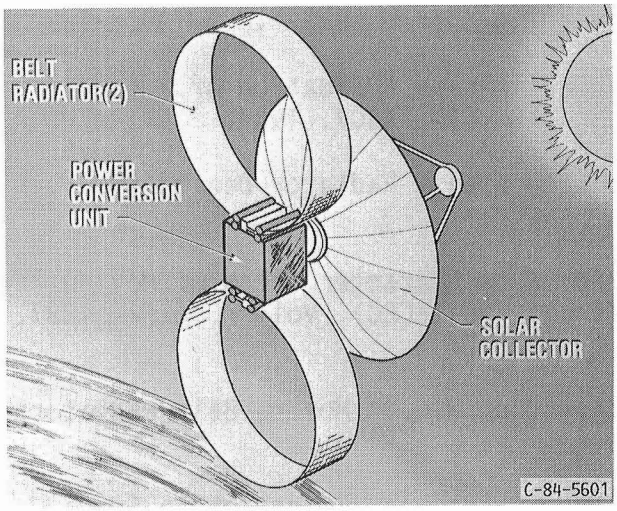


FIGURE 1. - MOVING BELT RADIATOR CONCEPT.

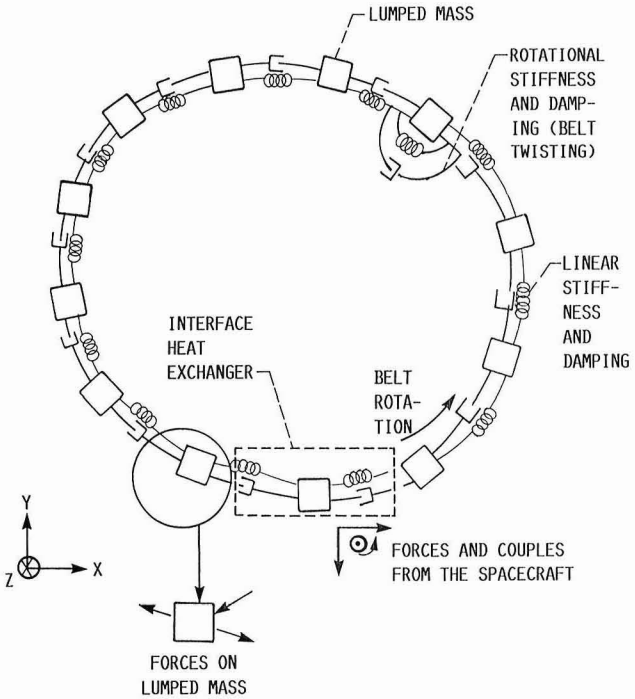
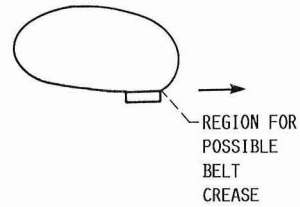
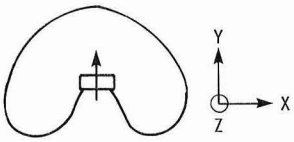


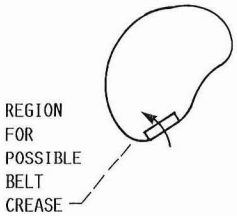
FIGURE 2. - LUMPED PARAMETER BELT MODEL (FROM W.P. TEAGAN UNDER NASA CONTRACT NAS3-24650).



(a) TRANSLATION ALONG X-AXIS.

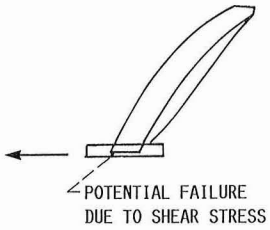


(b) ACCELERATION ALONG Y-AXIS.

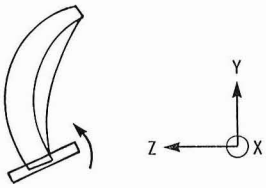


(c) ROTATION ABOUT Z-AXIS.

FIGURE 3. - BELT DEFORMATIONS IN X-Y PLANE (FROM W.P. TEAGAN UNDER NASA CONTRACT NAS3-24650).



(a) ACCELERATION ALONG Z-AXIS.



(b) ROTATION ABOUT X-AXIS.

FIGURE 4. - BELT DEFORMATIONS OUTSIDE OF X-Y PLANE (FROM W.P.TEAGAN UNDER NASA CONTRACT NAS3-24650).

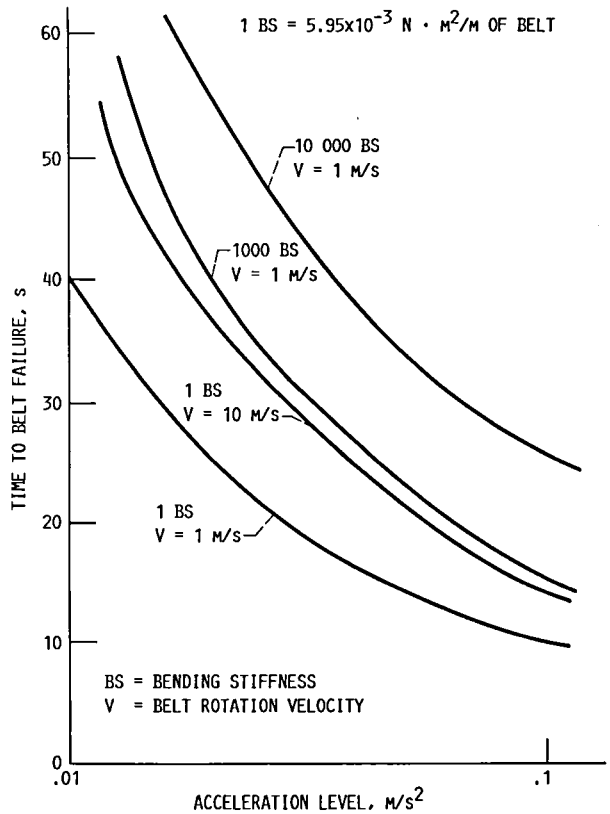


FIGURE 5. - BELT STABILITY ENVELOPE FOR STEADY-STATE Y-AXIS ACCELERATION (FROM W.P.TEAGAN UNDER NASA CONTRACT NAS3-24650).

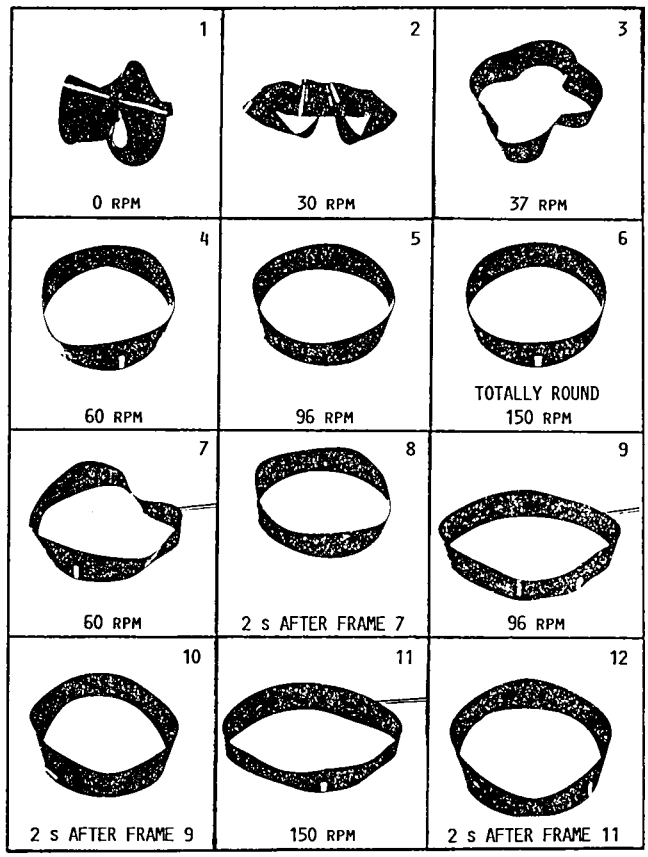


FIGURE 6. - BELT DEPLOYMENT AND STABILITY IN EARTH GRAVITY. (RUBBER BELT REVOLVING ABOUT GRAVITY VECTOR, FROM W.P.TEAGAN UNDER NASA CONTRACT NAS3-24650).

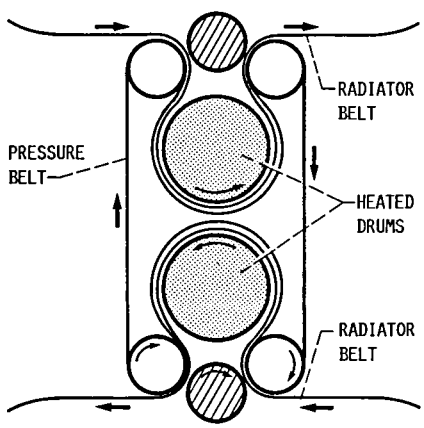


FIGURE 7. - SCHEMATIC OF HEATED DRUM DRIVE SYSTEM (FROM REF. 14).

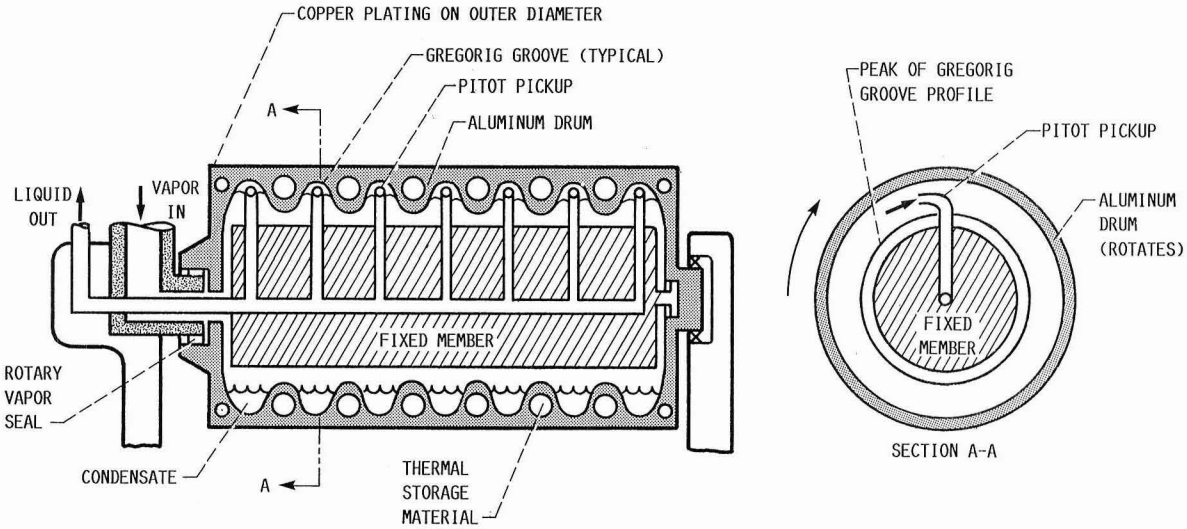


FIGURE 8. - SCHEMATIC OF MBR HEATED DRUM CONDENSER (FROM REF. 14).

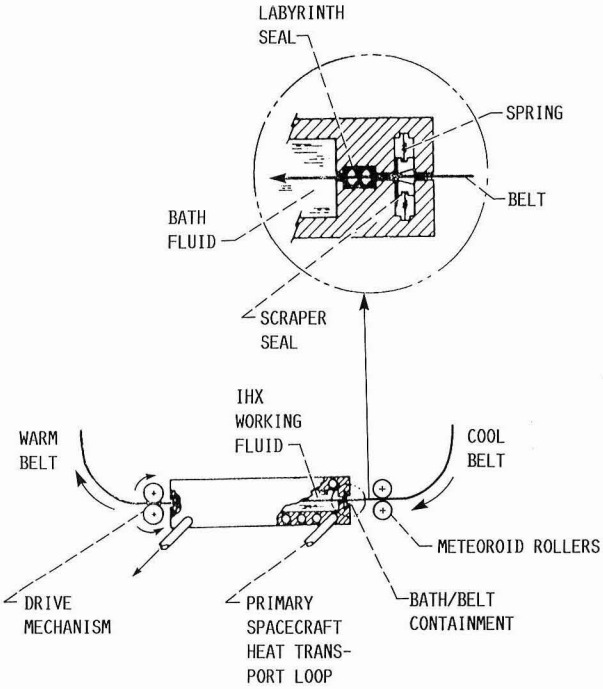


FIGURE 9. - INTERFACE HEAT EXCHANGER AND SEAL CONCEPT (FROM W.P.TEAGAN UNDER NASA CONTRACT NAS3-24650).

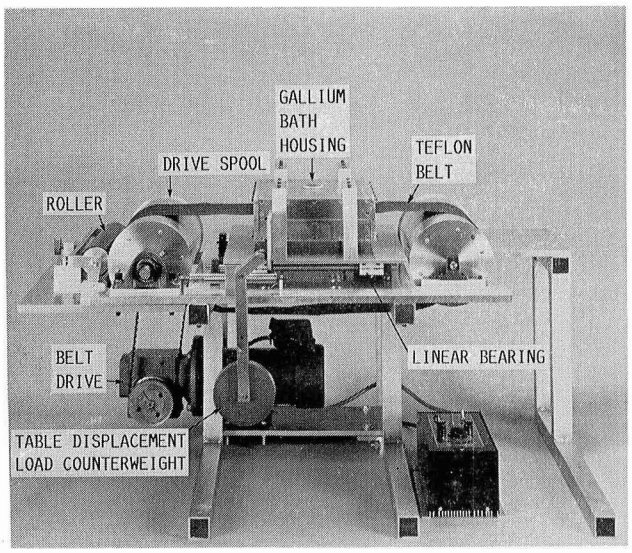


FIGURE 10. - INTERFACE HEAT EXCHANGER TEST APPARATUS (FROM W.P. TEAGAN UNDER NASA CONTRACT NAS3-24650).

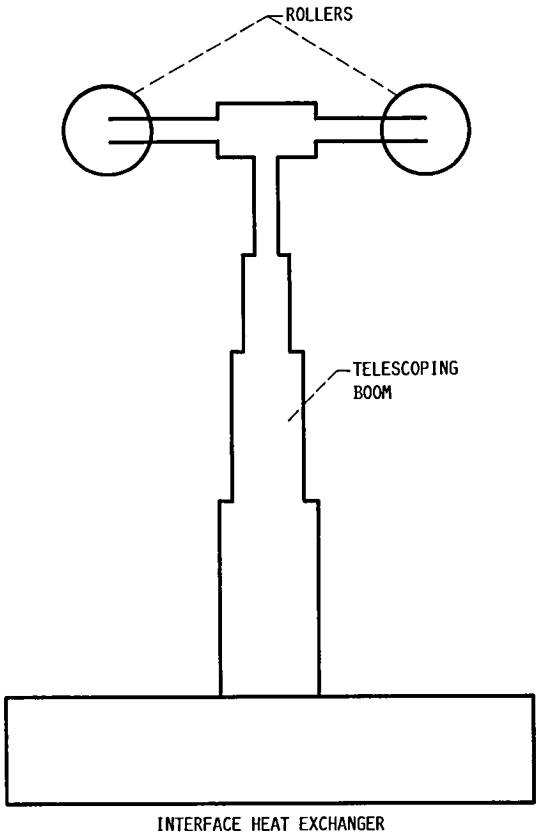


FIGURE 11. - TELESCOPING BOOM DEPLOYMENT.

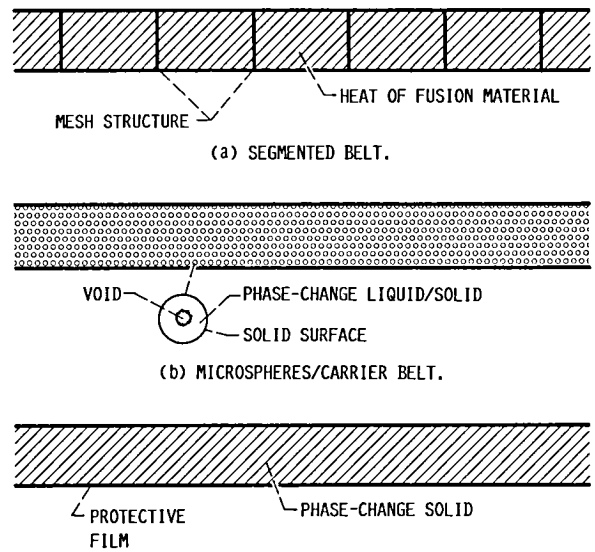


FIGURE 12. - CANDIDATE HYBRID BELT STRUCTURES.

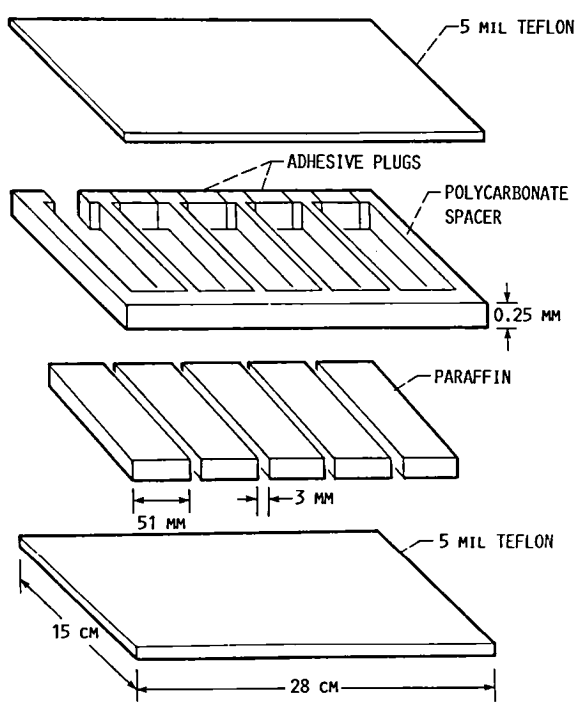


FIGURE 13. - CONSTRUCTION OF HYBRID BELT TEST SECTION (FROM W.P.TEAGAN UNDER NASA CONTRACT NAS3-24650).

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15. Supplementary Notes

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16. Abstract

Development of the Moving Belt Radiator (MBR) as an advanced space radiator concept is discussed. The relative merits of Solid Belt (SBR), Liquid Belt (LBR), and Hybrid Belt (HBR) Radiators are described. Analytical and experimental efforts related to the dynamics of a rotating belt in microgravity are reviewed. The development of methods for transferring heat to the moving belt is discussed, and the results from several experimental investigations are summarized. Limited efforts related to belt deployment and stowage, and to fabrication of a hybrid belt, are also discussed. Life-limiting factors such as seal wear and micrometeoroid resistance are identified. The results from various MBR point design studies for several power levels are compared with advanced (5 to 8 kg/m^2) Heat Pipe Radiator technology. MBR designs are shown to compare favorably at both 300 and 1000 K temperature levels. However, additional effort will be required to resolve critical technology issues and to demonstrate the advantages of MBR systems.

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