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Abstract

An improved heat sink for space vehicles was proposed in ORNL-CF-59-1-21. Subsequent work on the problem has indicated that there is a substantial probability of a puncture of such a radiator by meteors. To meet this problem a modified geometry has been evolved for which the probability of a meteor puncture should be reduced by a factor of at least 100 relative to the radiator of the original proposal at the expense of an increase in radiator weight of possibly 30%. This memorandum outlines the approach to the problem and a series of similar promising solutions.]

This proposal constitutes what is believed to be a new concept in the design of radiators for space vehicles in that fins are provided on the radiator tubes in such a manner that, when used in conjunction with an involute heat reflector, they protect the vulnerable portion of the tube wall from direct impingement by meteors, and in this way greatly reduce the probability of a meteor puncture of the vulnerable tube wall.

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Radiators for Space Power Plants

A vital consideration in the design of power plants for space vehicles arises from the high incidence of small meteoric particles; about 2×10^8 meteors sufficiently large to be visible to the naked eye strike the earth each day. Many more of smaller size also strike the atmosphere to give an aggregate mass of meteoric material of 1000 tons/day incident on the earth. The bulk of the meteors are much like cinders in that they are stony and very porous, having an average density of only about 0.06 g/cm^3 . The smallest meteors visible to the naked eye have a mass of about 0.1 g and a mean diameter of about 1.5 cm. As might be expected, the incidence of meteors is inversely proportional to particle size. Meteors weighing 0.06 mg (about 1.5 mm in diameter) are about 1000 times more numerous than the smallest visible to the naked eye, and are capable of penetrating sheet aluminum about 1 mm thick. Much smaller meteors down to less than 1 micron in diameter present an erosion problem such that optical surfaces will be seriously damaged in about a year, but they should not pose difficulties in the design of radiators.

The kinetic energy of an incident particle piercing a thin sheet of metal is sufficient to vaporize both the incident particle and the slug that it punches out of that sheet if the mass of the two is roughly the same. If the sheet thickness is large compared to the diameter of the particle, however, the bulk of the kinetic energy of the incident particle goes into a shock wave. The shock wave is propagated radially outward from the area of impact and forms a crater, a part of the material from the crater going into the crater rim while the balance is blown out of the crater and dispersed. This is apparently what has happened when large meteors have struck either the moon or the earth. Of course, in some instances, meteors which have come in along paths nearly tangent to the earth's surface have passed through so much of the atmosphere that most of their kinetic energy has been dissipated before they have struck the earth's surface, in which case the portion of the meteor not vaporized during

its passage through the atmosphere has survived more or less intact. Such meteors appear to have been more the exception than the rule. The relatively high concentration of cobalt and nickel in the deep-sea ooze in the ocean bottoms indicates that meteors striking the ocean surface have penetrated the water sufficiently far that the material of the meteor was fragmented and chilled so that it sank to the bottom as very fine dust.

On the basis of the best data available it appears that a nuclear power plant designed to produce 20 kw of electricity and employing a radiator of the type covered in the reference memorandum would be subject, on the average, to one puncture per year. This low reliability would be quite unacceptable for most missions. Further, the probability of such a failure would increase rapidly as the size of the power plant -- and hence the radiator -- is increased.

The probability of a radiator puncture can be reduced by reducing the mean projected area of the radiator or by thickening the radiator tube walls. Another helpful measure would be the use of a more refractory tube material because it appears that perforation is accomplished through conversion of the kinetic energy of the incident meteor into heat on impact so that this heat causes melting and/or vaporization of the material in the tube wall. A refractory metal such as columbium or molybdenum will absorb a greater amount of heat per unit weight before melting or vaporizing than will the stainless steels. F. L. Whipple has proposed that a bumper or relatively light metal shield be placed a short distance away from the wall which it is to protect. A meteor striking this shield will be vaporized and the resulting vapor, while carried forward by the momentum of the meteor, will be much more readily deflected by the solid radiator tube surface than would a solid particle. It should be noted that the kinetic energy in a meteor is sufficient to vaporize a mass of roughly 100 times the mass of the meteor.

A first step in reducing the projected area of the vulnerable portion of the radiator would be to employ fins on the tubes since the heat transfer coefficient is much higher inside the tube than outside. This will also serve to reduce the liquid holdup in the radiator. The

thermal conductivity of the iron-chrome-nickel alloys is so low that such fins must be made of a material such as copper if a reasonable fin efficiency is to be obtained with reasonable fin thicknesses and weights. A careful examination of the circumferential temperature distribution around a tube with two axial fins discloses that, with a stainless steel tube, conduction of heat circumferentially through the tube wall to the fin is so poor that the bulk of the wall will be ineffective as heat transfer area on the working fluid side within the tube. Thus, if the tubes are to be of iron-chrome-nickel alloys, they should be jacketed over most of the perimeter with a layer of high thermal conductivity material such as copper. If this is done the projected area of the vulnerable portion of the radiator can be reduced to perhaps one-fifth that of a bare unfinned tube.

Unfortunately, the small difference between the tube wall operating temperature and the melting point of copper would make it relatively ineffective as a buffer material to protect the base metal of the tube from meteors. This in turn suggests that a refractory metal such as columbium or molybdenum be employed. Both of these metals have the further advantage that their thermal conductivities are roughly five times that of stainless steel. With a columbium tube the circumferential temperature drop in the tube wall will be acceptable and will permit operation with as few as two fins if relatively small tube diameters, i.e., 0.5 in., are employed with tube wall thicknesses of about 0.060 in. The probability of a puncture of a columbium or molybdenum tube provided with copper fins should be reduced by a factor of 10 relative to simple circular tubes of iron-chrome-nickel alloy.

The use of a bumper as a means of disintegrating an incident meteor before it could impinge on a radiator tube surface has not appeared attractive because a simple cylindrical bumper would serve as reflective insulation and would reduce the effective radiator operating temperature by something like 400°F, thus greatly reducing its thermal efficiency and greatly increasing the surface area and weight required. A different approach is suggested by the fact that the involute reflector proposed in CF-59-1-21 will serve to shield roughly half of the projected area

of the round tubes of that memorandum. A radial extension of the reflector for perhaps one tube diameter outward from the horns as indicated in Fig. 1 would provide even greater protection and would reduce the probability of a meteor striking the tube surface directly. If the tube is made substantially smaller in diameter and provided with fins, the involute reflector should be made the same as for an unfinned circular tube which would be the envelope for the tips of the fins for the finned tube. This can be deduced by examining some typical paths of thermal radiation from the hot surfaces as indicated in Fig. 2. It is true, of course, that the dual fins of Fig. 2a make less effective use of a given area of involute reflector surface than the simple round tube of Fig. 1, but the vulnerability of the tube has been greatly reduced.

Additional fins can be provided in unusual configurations as indicated in Fig. 3 so that a portion of the fins will act as bumpers or shields to prevent direct impingement of meteoric particles on the base tube, and hence greatly reduce its vulnerability. As long as these unusual fin configurations are designed so that they stay within a circumscribed circle which corresponds to the tube of Fig. 1, they should be quite effective in dissipating the heat energy from the tube to space.

A careful evaluation of the temperature distribution in the tube wall and fins of configurations of the sort proposed must be carried out to disclose the relative merits of each type. This investigation should include not only the effects of fin configuration, but also the effects of the use of different materials including stainless steel, columbium, and molybdenum in the tubes, and stainless steel, columbium, molybdenum, copper, and silver in the fins. In all instances the fin configuration should be such as to provide complete enclosure of the vulnerable tube so that no meteor can impinge directly on it without having passed through either the reflector or a fin.

The figures of merit for the various configurations include the fin efficiency, the fin-and-tube form factor (i.e., the degree to which the fin material is effective in irradiating heat to the reflector or space rather than to other fins or the base tube wall), and the extent to which the tube-and-fin configuration utilizes the available heat-

radiating capacity. The best over-all measure of these parameters is the over-all weight of radiator required to dissipate a given amount of energy with a given probability of penetration by a meteor. Table I has been prepared to indicate the sort of analysis envisioned. Six different fin configurations are shown together with rough preliminary estimates for many of the figures of merit mentioned above. The effects of fin material, thickness, and height together with tube material, wall thickness, and diameter on the various figures of merit should be determined. This is important as it may be worthwhile for some applications to accept a higher weight of unit in order to reduce the over-all volume of the radiator and hence the space required in the launching vehicle.

TABLE I

Preliminary Estimates of the Effectiveness of Involute-Reflected
Finned-Tube Radiator Configurations

Fin Configuration
1. Form factor	1.00	0.75	0.625	0.5	0.75
2. Utilization of involute	0.67	0.84	0.86	0.92	0.84
3. (1) + (2) ÷ 2	0.84	0.80	0.74	0.71	
4. Fin efficiency	90	93	95	96	90
5. Relative weight					

Tube OD = 0.5 in.

Tube wall thickness = 0.060 in.

Tube material = columbium

Fin height = 0.75 in.

Fin root thickness = 0.025 in.

Fin tip thickness = 0.010

Fin material = copper

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