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Thermal Management for Large Space Platforms

J.A. Oren* and R.L. Cox†
Vought Corporation, Dallas, Tex.

This paper provides an evaluation of heat rejection techniques applicable to multihundred-kilowatt space platforms. A number of promising heat rejection concepts were parametrically weight-optimized over a wide range of conditions to provide a 99% reliability of achieving a 10-yr life for the multihundred-kilowatt space platform. Three panel designs were considered: 1) an advanced meteoroid-bumpered hybrid heat pipe concept, 2) a bumpered liquid concept, and 3) a space constructable heat pipe radiator. The following are some of the significant findings from the study: 1) A single subsystem approach can be used with the heat pipe system, whereas several smaller subsystems are required for the pumped fluid systems. 2) The space constructable radiator approach offers a 10% weight reduction and operational advantages over the conventionally deployed panels.

Introduction

THE technologies required to support large, multihundred-kilowatt space platforms forecast for the 1990s are currently being evaluated.[1,2] One of the important technologies is thermal management, including the acquisition, transport, and rejection of waste heat. This paper addresses the heat rejection aspect of the thermal management problem. It focuses on the determination of the type of space radiator system which should be used, given the requirement for long life, the large system sizes, and the space environment within which the system must operate.

The configuration of the space platform baselined for the multihundred- kilowatt study is shown in Fig. 1. It consists of a power module, a berthing module, a number of manned and unmanned modules docked to the berthing module, a crane module, and a construction module. The power module provides a nominal 250 kW of electrical power derived from planer solar arrays. It also provides an equal amount of heat rejection.

The general heat rejection system guidelines for the study are shown in Table 1. The primary design drivers for the space platform heat rejection system are the 10-yr life and the high reliability (0.99) in the space micrometeoroid environment. The micrometeoroid model given by NASA[3] was used for the study. A low Earth orbit (370-650 km) with the oribital inclination varying from 0 to 90 deg was assumed.

The work discussed in this paper extends the previous work by Howell and Stalmach.[4] More emphasis is placed on large, multihundred-kilowatt systems and the life is extended to 10 years.

Achieving System Reliability

The high system reliability goal for the heat rejection system (0.99 reliability goal for the 10-yr life) can be achieved by selecting high reliability component designs, system approaches which use a minimum of components per subsystem, adequate micrometeoroid protection of the fluid system, and appropriate component and system redundancy. This four-pronged approach can be applied with varying degrees of emphasis on any of the four elements to achieve the final desired reliability.

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*Technical Project Manager.

†Engineering Project Manager.

Figure 2 shows the candidate heat rejection subsystem fluid loop concepts with single and redundant fluid loops. Systems with no pump redundancy (not shown) were also considered.

Table 2 shows the range of component failure rates and the resulting system failure rate for a single loop with and without redundancy. The probability of success (reliability) of the single loop can be computed by the Poisson distribution function

$$R = e^{-\Sigma\lambda t} \tag{1}$$

where λ is the failure rate in failures per hour and t is the mission time in hours.

The reliability for the redundant loops can be calculated by the relation

$$R_{RL} = R_S [R_{SL}^2 + 2(1 - R_{SL}) R_{SL}] \tag{2}$$

where R_{RL} is the redundant loop reliability, R_S is the reliability for the failure detection and switch system, and R_{SL} is the single loop reliability.

The failure rate data for radiator panel meteoroid penetration in Table 2 show an assumed failure rate of 0.585×10^{-6} failures per hour, which represents a reliability of 0.95. This value was selected as a "best" balance between system weight impact and reliability impact. Table 3 illustrates the effect of component redundancy, system redundancy, and meteoroid protection reliability. The values show the effect of different meteoroid reliabilities on the redundant standby loop reliability. Decreasing the meteoroid probability of penetration from 0.05 to 0.001 (probability of no meteoroid penetration from 0.95 to 0.999) will have little effect on the thermal control subsystem reliability. The high side of the subsystem reliability will increase from 0.965 to 0.976 when the micrometeoroid probability of no penetration is increased from 0.95 to 1.0. However, the system probability of failure increases very rapidly with the increase in probability of meteoroid penetrations above 0.05, as can be seen in Fig. 3. Figure 4 shows the effect of meteoroid penetration on system weight for the heat pipe and pumped fluid radiator panel concepts. This analysis is for a 32-kW subsystem. The figure shows little variation on system weight for the heat pipe system. However, the pumped fluid system weight varies considerably with micrometeoroid penetration probability. The best balance between the two effects in Figs. 3 and 4 was judged to be a micrometeoroid penetration probability of 0.05 (0.95 probability of no penetration). This value was used in the studies. It should be pointed out that this probability is for only one of the redundant loops.

Two system approaches were evaluated for achieving the desired overall system reliability. One approach was to

Table 1 Heat rejection system study guidelines

Thermal performance	
Heat rejection	50-250 kW
Heat rejection fluid temperature:	
Inlet	4-120°C
Outlet	−18-54°C
Timing and growth	Baseline concepts for 1987 technology readiness for early 1990s missions
	Alternate higher-risk concepts for 1990, or later, technology readiness
Life, maintenance, and reliability	10-yr life with a reliability goal of 0.99
	Redundancy and micrometeoroid protection to achieve survivability
Environments	
Orbit altitude	370-650 km
Orbit β angle	0-90 deg
Micrometeoroids	NASA SP 8013
Thermal	Consider solar, Earth vehicle interactions
Penalties	
Power	160 kg/kW

Table 2 Fluid loop reliability characteristics

Component	No component redundancy failure rate, λ failures per 10^6 h	Redundant component failure rate, λ failures per 10^6 h
Rad panel struct integrity (eight panels)	0.8-1.6	
Rad panel meteoroid	0.585	
Pump/motor/inverter	1.39-4.48	0.0439[a]-0.4082[a]
Accumulator/filter	0.14-0.30	0.00085-0.00389
Temperature control valve	0.34-0.52	0.00498-0.0116
Fill drain valve, pair	0.05	
Temperature sensor[b]	1.50	0.27
Lines/fittings	0.05	
Heat exchanger	0.20	
Total system	5.1-9.09	2.00-3.175
Single loop probability of success (10 yr)	0.640-0.45	0.84-0.76
Redundant loop probability of success (10 yr)	0.86-0.68	0.965-0.92

[a]Switch system reliability = 0.99-0.98. [b]Required for health monitoring only.

achieve the results with a single heat rejection subsystem with appropriate component redundancy and no system redundancy. The other approach is to divide the heat rejection system into a number of smaller subsystems and then provide system oversizing (extra subsystems) to achieve the desired reliability. The use of multiple heat rejection loops offers two advantages. First, the radiator meteoroid protection requirements are reduced for smaller independent radiator loops. The meteoroid penetration thickness required for the fluid tubes varies directly with radiator area. The probability of no meteoroid penetration for a given bumper configuration is a function of $e^{-\text{AREA}}$. Second, the system reliability can be increased above the individual heat rejection loop reliability by oversizing, i.e., adding extra smaller subsystems. Thus a system made up of smaller, less reliable heat rejection subsystems is potentially lighter weight than a single high reliability heat rejection system. The amount of oversizing required to achieve a given system reliability is given by

$$P_S = \sum_{i=r}^{N} \binom{N}{i} P_{SS}^{i} (1-P_{SS})^{N-i} \tag{3}$$

where P_S is the system probability of success; P_{SS} is the subsystem probability of success; N is the total number of subsystems; r is the required number of subsystems; and $\binom{N}{i} = N!/i!(N-i)!$.

Figure 5 presents the solution of Eq. (3) for a subsystem reliability of 0.94. It shows the amount of oversizing required to achieve a given probability of failure for different subdivisions of the total system when the subsystem reliability is 0.94. This information was used to determine the optimum heat rejection system weight and size, as discussed later.

The pumped fluid radiator panels are designed with bumpered meteoroid protection of the fluid tubes and manifolds to provide a reliability of 0.95. The hybrid heat pipe panels are designed with bumpered meteoroid protection

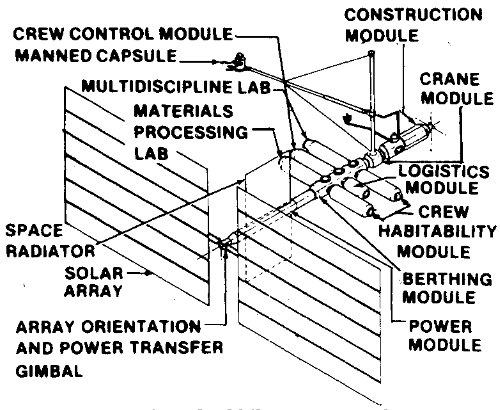

Fig. 1 Multihundred kilowatt space platform.

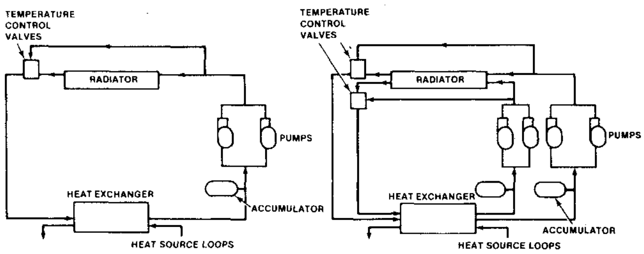

Fig. 2 Candidate subsystem heat transport loops.

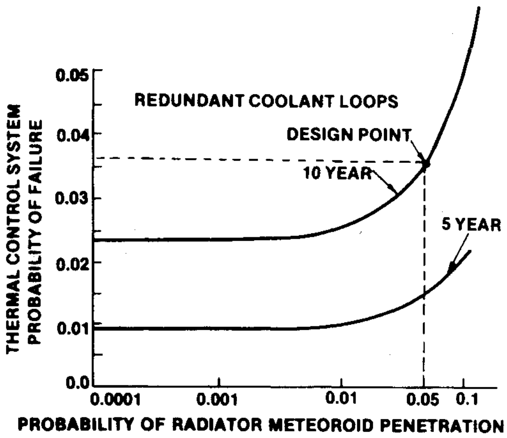

Fig. 3 Effect of radiator meteoroid reliability on thermal control system reliability.

Table 3 Subsystem probability of success for 10-yr life

	Single components		Redundant components	
	One loop	Two loops	One loop	Two loops
Probability of no micrometeoroid puncture = 0.95	0.54 ± 0.10	0.77 ± 0.09	0.80 ± 0.04	0.94 ± 0.02
Probability of no micrometeoroid puncture = 0.99-1.0	0.57 ± 0.10	0.79 ± 0.09	0.83 ± 0.04	0.96 ± 0.02

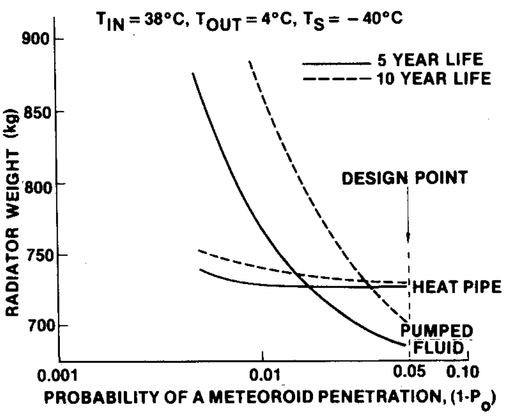

Fig. 4 Effect of meteoroid probability on radiator weight, 32-kW heat load.

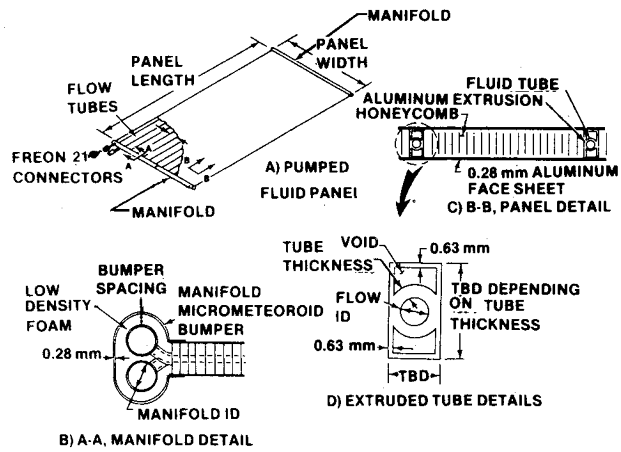

Fig. 6 Pumped fluid radiator concept.

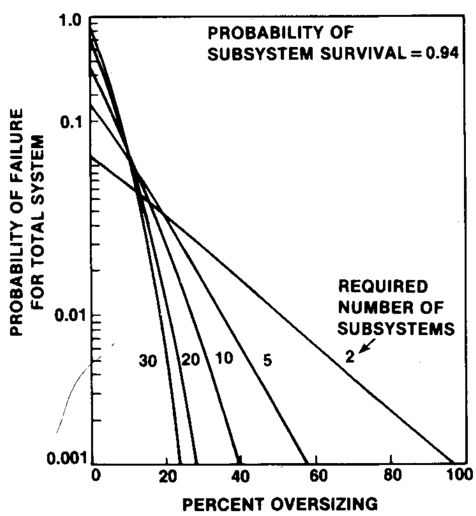

Fig. 5 Oversizing to achieve system survivability.

of the coolant loop/heat pipe interface to provide a reliability of 0.95. In addition, the number of heat pipes are increased to allow for loss of heat rejection capability due to meteoroid penetration of the heat pipes. The amount of heat pipe oversizing is determined by Eq. (3), where the subsystem probability, P_{SS}, is the probability of meteoroid penetration of each heat pipe and r is the required number of heat pipes.

Description of Radiator Panel Concepts

Three panel design approaches were identified as promising candidates. These approaches were evolved in prior studies[1] for long life application. The three concepts were the 1) pumped fluid radiator, 2) integral manifold heat pipe hybrid design, and 3) space constructable radiator.

Figure 6 shows a long life, high probability of success, low weight pumped fluid panel concept. This approach would use no heat pipes. The coolant fluid is distributed through the panel in the flow tube contained in the panels. The panel was designed in such a way as to achieve a high probability of success in a meteoroid environment with a low weight. Redundant fluid loops are assumed based on previous analyses for reliability purposes. Two separately manifolded systems are contained on each panel for the two separate fluid loops. Each fluid loop is capable of radiating the full load and thus the redundant loop is a standby or backup loop. Honeycomb construction was assumed for the panel concepts because it is weight competitive, is a proven design, and is representative of current state-of-the-art. Figure 6 shows an extrusion that is used for the tube in a pumped fluid panel design. This extrusion places the flow at the center of the panel and thus shields the tube from meteoroid penetration. The two facesheets of the panel act as bumpers to protect the panel tubes from meteoroid puncture.

The second panel concept is shown in Fig. 7. This is a high technology hybrid heat pipe/pumped fluid approach labeled the "integral manifold" panel. In this concept, fluid flow lines are contained within the center of the evaporator of the heat pipe and it flows through all of the heat pipes on the panel at right angles. Each heat pipe is independent of the others so that a puncture of the heat pipe that surrounds the fluid loop would result in the loss of only one heat pipe. The fluid loop, then, is well protected by the heat pipe. This is an efficient design from a thermal standpoint because the heat pipe wick is in intimate contact with the fluid flow tube. The design of the condenser section of the heat pipe is a center core wick design. The internal flow tubes for the fluid loop are made from extruded, internally finned tube heat exchanger to augment heat transfer.

The third radiator concept, the space constructable radiator, is a new and advanced radiator concept currently under study.[2] This approach is characterized by numerous small radiator panels, each of which can be easily installed or removed from the radiator system without breaking fluid connections in the fluid loop. On one approach, the constructable radiator is plugged into the spacecraft body and no deployment system is required. In another approach the constructable radiator is automatically deployed on-orbit but the panels may still be removed and replaced if a failure occurs. Figure 8 is an example of a deployable constructable radiator. It shows two fluid loops that are each redundant, independent loops flowing through the heat exchanger section of the constructable radiator. The heat pipe radiators are plugged into cylindrical heat exchangers which transfer heat from the fluid loop to the radiator panels by contact conduction. With this approach the radiators can be unplugged from the system by reducing the contact pressure and pulling the radiator panel out. Each radiator panel is approximately 1 kW in size and dimensions are on the order of 25 cm wide and 12 m long, although these dimensions are determined in optimization studies, as will be discussed later.

Parametric Weight Analysis of Conventional Panel Concepts

The conventional radiator panel concepts (concepts 1 and 2, the pumped fluid and hybrid heat pipe) were optimized as a first step in obtaining the optimum system weights. Parametric data providing weight optimized panels for different radiator heat loads, operating temperatures, and environment temperatures were obtained for each concept. Specialized computer routines were used for the parametric weight optimization.

The items included in the weight of the pumped fluid radiator are facesheets, honeycomb, bonding adhesive, panel thermal control coatings, flow tube extrusions, manifolds, Freon 21, and equivalent pumping power penalty. The tube extrusion dimensions were determined based on a bumper distance (facesheet to tube outside surface) of 0.6 cm. This basic dimension plus the computed tube inside diameter and the thickness required for meteoroid protection determines the extrusion dimensions and the honeycomb thickness. The facesheet thickness that resulted in the minimum weight was also determined. A minimum thickness of 0.25 cm was specified for manufacturing ease and for most cases this limit was used by the computer routine.

The integral manifold heat pipe panel weight included the facesheets, honeycomb, bonding adhesive, panel thermal control coating, heat pipe, heat pipe fluid, coolant loop manifold and heat exchanger, Freon 21, and equivalent pumping power penalty. Weights of aluminum-ammonia heat pipes with a wall thickness of 0.9 mm were used for all cases except the high operating temperatures. Aluminum-acetone heat pipe weights were used for the high temperature (120°C) case.

Examples of the optimized panel weights are given in Figs. 9 and 10. These panel weights were utilized as one element in the system weight optimization study (different than the panel optimization study) which determined the optimum subsystem size, as discussed on the following page.

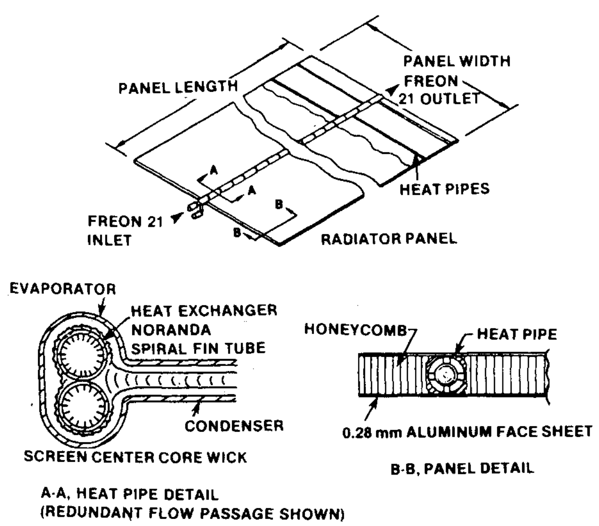

Fig. 7 Integral manifold heat pipe radiator concept.

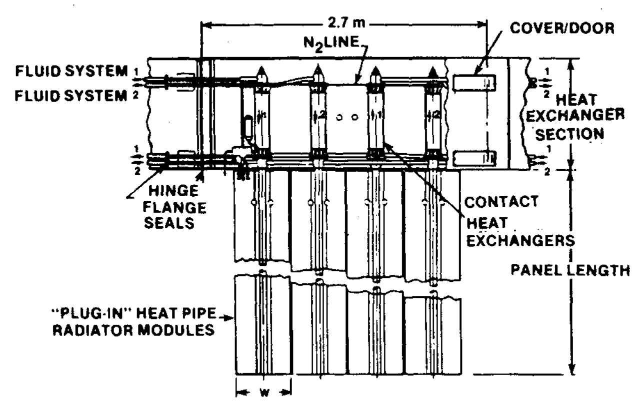

Fig. 8 Space constructable radiator.

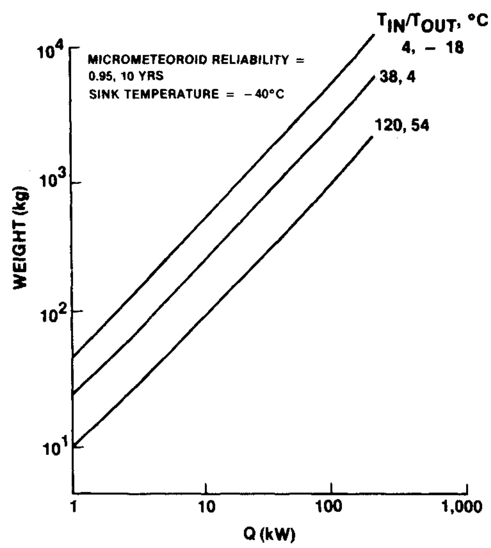

Fig. 9 Integral manifold optimized panel weights.

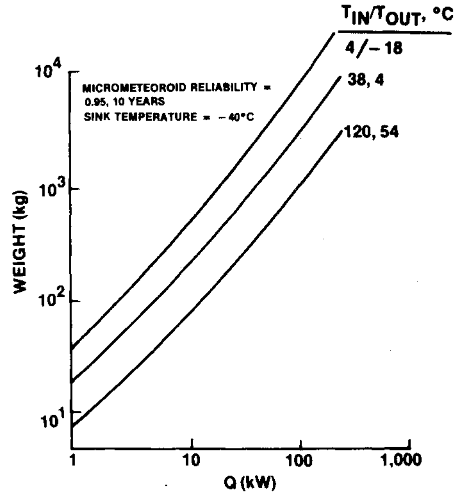

Fig. 10 Pumped fluid optimized panel weights.

Optimum Subsystem Size Study for Concepts 1 and 2

Using the results of the studies discussed above, the weight optimum system was determined for each heat rejection concept. The optimum subsystem size and corresponding number of subsystems was determined for a wide range of heat loads and radiator temperatures. This optimization study was performed for the pumped fluid and the integral manifold hybrid heat pipe systems. The system weights for these studies included the panel weights discussed above and the additional components required for a closed loop for each subsystem. These components included the pumps, accumulators, temperature control valves, and heat exchangers. The following were used to estimate the component weights:

Heat exchanger = 0.9 kg/kW
Pump = 2.5 kg
Accumulator = 0.605 × fluid weight
Tubing per loop = 18 kg
Temperature control valve = 2 kg

Two approaches were considered in the subsystem size/reliability study: the single subsystem and the multiple subsystem approaches. With the single subsystem approach, one loop is sized for the total system heat rejection and reliability is accomplished by component and loop redundancy. With the multiple subsystem approach, reliability is accomplished by dividing the heat load among several smaller subsystems and then providing extra subsystems. Figure 11 shows the effect of subsystem size on system weight for the integral manifold approach for a sink temperature of −40°C. The lowest weight approach for each temperature condition is the single subsystem. However, the probability of success for the single subsystem approach is approximately 0.94, whereas the multiple subsystem approach reliability is approximately 0.995. The lowest weight approach for the multiple subsystem is with approximately 11 subsystems required, 14 subsystems total. Thus, the optimum subsystem size for the multiple subsystem approach would be about 22.73 kW and three extra subsystems would be required to achieve the required reliability. For a radiating temperature of 38°C fluid inlet and 4°C fluid outlet, the optimum subsystem weight is 8800 kg for the multiple subsystem compared to 7600 lb for the single subsystem.

The pumped fluid subsystem size study, shown in Fig. 12, shows a slightly different effect. For this concept, the multiple subsystem approach which has the highest reliability is also lower in weight. The single subsystem weight is 10,000 kg compared to 7700 kg for the multiple subsystem for the 38/4°C radiation temperature case.

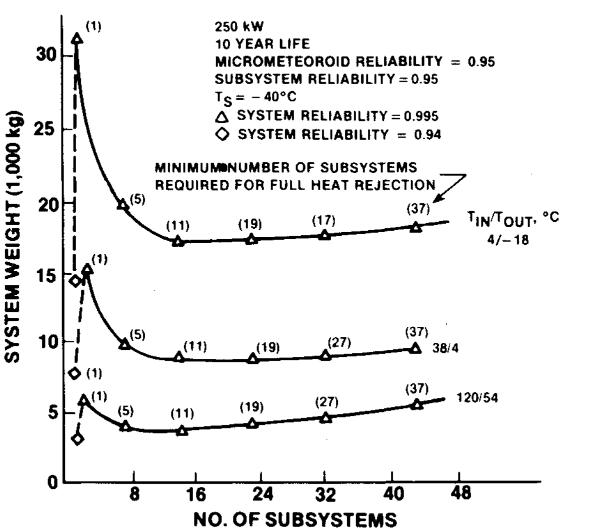

Fig. 11 Total system weight vs number of subsystems for integral manifold radiator systems.

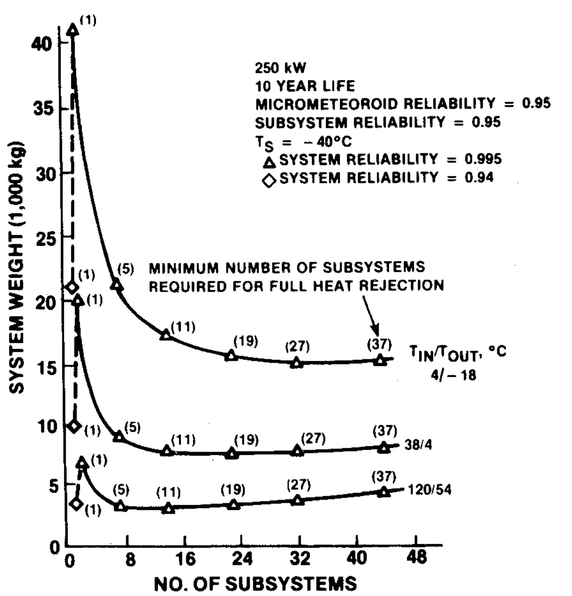

Fig. 12 Total system weight vs number of subsystems for pumped fluid radiator system.

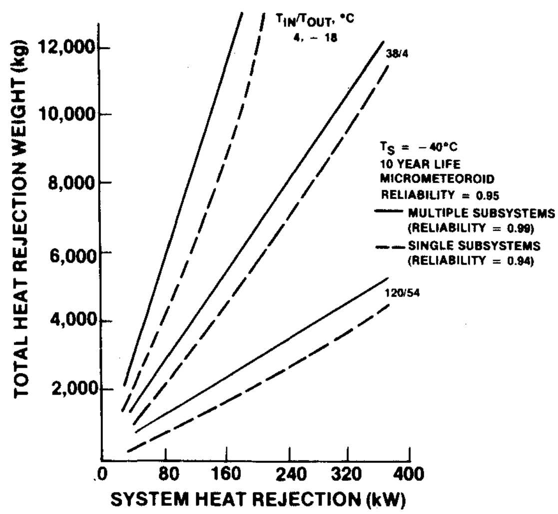

Fig. 13 Integral manifold system weights.

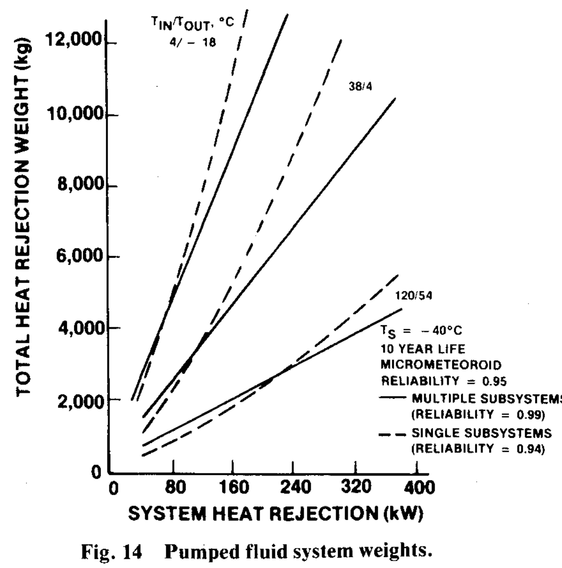

Fig. 14 Pumped fluid system weights.

Table 4 Heat rejection system weight comparison

Concept	Single subsystem	Multiple subsystem
Pumped fluid	10,000	7800
Integral manifold hybrid heat pipe	7600	8800
Constructable	7100	...

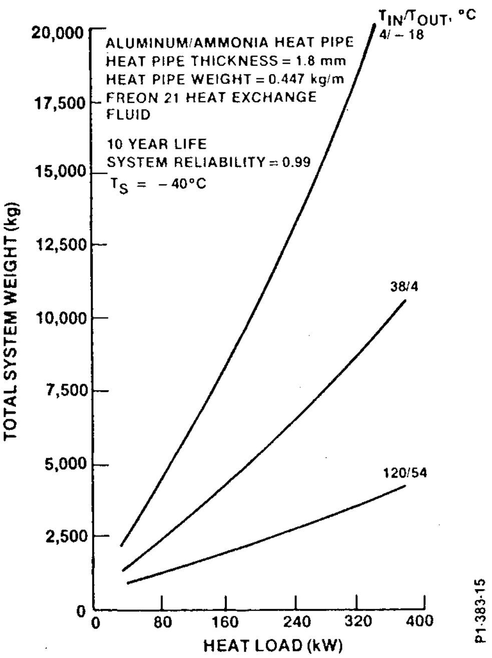

Fig. 15 Space constructable radiator optimum weights.

Space Constructable Radiator Optimization

The space constructable radiator system concept discussed above was sized and weight optimized. Items included in the weight optimization were panel dimensions (fin length, width, and thickness), fluid-to-heat-pipe heat exchanger dimensions, fluid flow routing to heat pipe heat exchangers, heat pipe thickness, and the number of extra heat pipes to provide the required reliability. The fluid loop component weights included the pumps, accumulators, temperature control valves, and heat load exchangers. Two redundant loops were assumed for the system. The heat pipe weights for the study were assumed at 0.45 kg/m of length. This weight is based on the constructable radiator heat pipe being studied[5] with a wall thickness of 1.8 mm. (Smaller wall thicknesses were found to require excessive panel oversizing.)

Results of the Optimization Studies

The optimum heat rejection system weights from the study discussed above are summarized for the three concepts in Figs. 13-15 for a wide parametric range of heat loads and radiation temperatures. The single subsystem and multiple subsystem approaches are both shown for the pumped liquid and integral manifold heat pipe approaches. Only the single subsystem approach was considered for the constructable radiator concept.

Figure 13 shows that, for the integral manifold hybrid concept, the single subsystem approach is lower weight (by 15 to 30%) than the multiple subsystem for the entire range considered. Figure 14 shows that for the pumped fluid concept the single subsystem approach is slightly lower weight for the lower heat loads. However, at the higher heat loads, multiple subsystems are far superior. Comparison of the best designs for each of the three approaches shows that there really are little weight differences between each of the three. For the nominal radiating temperature of 38°C/4°C (T_{in}/T_{out}), the pumped fluid multiple subsystem approach is slightly lower in weight for heat loads less than 60 kW, the integral manifold hybid heat pipe is lowest in weight between 60 and 160 kW, and the constructable radiator is lowest in weight above between 160 and 360 kW (the maximum heat rejection considered).

Table 4 shows the weight comparisons for the heat load of primary interest, 250 kW. The radiation temperature for this case is $T_{in}=38°C$ and $T_{out}=4°C$. The sink temperature is −40°C. The results in Table 4 show that large, long-life pumped fluid systems should use the multiple subsystem approach. Large integral manifold hybrid heat pipe systems should use the single subsystem approach. The single subsystem pumped fluid and multiple subsystem integral manifold hybrid heat pipe are not weight competitive. The best of each of the three concepts are within 10% of one another.

Conclusions

As a result of the studies for the large, multihundred-kilowatt, long-life heat rejection systems, the following conclusions have been reached.

1) System weight will not be a deciding factor—The optimum weight for the three systems considered are all within a 10% range. This is considered within the ability to predict the system weights.

2) Use of heat pipe radiator panels permits the use of a single subsystem approach—Heat pipe radiator panels have the advantage of making the single subsystem approach weight competitive for large, long-life systems. This greatly simplifies the heat rejection system, reducing the number of components by an order of magnitude.

3) Constructable radiators are weight competitive—Future systems can utilize the advantages in maintenance and flexibility that the space constructable radiator system offers while remaining weight competitive.

4) The multiple subsystem approach has reliability advantages—It is easier to achieve high reliabilities with the multiple subsystem approach than with the single subsystem approach. This accomplished with the multiple subsystem approach by providing oversizing (additional subsystems), while redundancy at the component level is required for the single subsystem. It is the opinion of the authors that the single subsystem approach can be made sufficiently reliable with adequate attention.

Acknowledgments

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