SPACECRAFT ACTIVE THERMAL CONTROL TECHNOLOGY STATUS

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SUMMARY

The primary means for rejecting heat from manned spacecraft while on-orbit has been through a space radiator system which is mounted on the vehicle and which rejects heat from a fluid circulating through it by radiation to the space environment. The Shuttle Orbiter heat rejection system exemplifies this existing state-of-the-art. Radiator systems for all foreseeable future space missions will need to be compactly stored during launch and subsequently deployed in orbit. In addition for orbital power system missions, they will need to operate for time periods over wider heat load ranges, and possibly at temperature levels which considerably exceed the life capabilities of existing fluid circulating systems. Therefore, the overall goal and objective of technology development effort has been to develop radiator heat rejection systems that meet these basic requirements.

Four separate advanced space radiator concepts have been pursued in an integrated effort to develop multi-mission use, low-cost heat rejection systems which can overcome the limitations of current radiator systems and meet orbital power system type mission requirements. The first approach that has been pursued is a wide-heat-load-range, modularized space radiator system. The modular radiator system has been designed to satisfy wide heat load ranges by use of controlled fluid stagnation. The stagnation control method eliminates the usual radiator fluid freezing point operational limit by providing controlled freezing and thawing of the radiator fluid. The second approach that has been pursued is a spacecraft heat rejection subsystem that can be easily deployed in orbit in order to minimize the vehicle integration requirements of providing heat rejection to future spacecraft. The subsystem is designed as a compact SHRM (self-contained heat rejection module) which provides sufficient flexibility within its design to accommodate a wide variation in spacecraft heat loads and cooling temperature requirements. The third approach pursued also provides heat rejection capability without being dependent on vehicle area. It is a lightweight, flexible fin radiator system which can be deployed and thus is not a "slave" to vehicle configuration since it can be compactly packaged and attached to a vehicle port. The technology established for development of flexible deployable systems using plastic films was extended to develop a deployable radiator which uses a flexible, highly conducting composite material (i.e., teflon film with silver wire mesh). The fourth approach that has been pursued provides a radiator which does not require a circulating coolant on the radiator panel and thus particularly applies to very long duration missions where long life reliability is an overriding design parameter. This radiator panel concept uses heat pipes, which minimizes uses of high-cost, low-reliability mechanical-dynamic components and maximizes

meteoroid protection. The heat pipe radiator system has been designed to use modular "building blocks" to satisfy the varying heat rejection requirements of future spacecraft.

INTRODUCTION

For a self-contained spacecraft, there are only two fundamental techniques available for actively controlling the dissipation of waste energy from the vehicle: (1) emit the energy in the form of thermal radiation and (2) reject the energy to some form of mass which can be jettisoned overboard. The second technique is useful for short missions and for supplemental and emergency uses on long missions, but weight penalties preclude its use as the primary method of heat rejection on long missions. The expulsion of mass in the form of water vapor has been used as the sole means of actively controlling heat rejection on the relatively short missions of the Mercury and Lunar Module vehicles. This is also the method employed by the space suit systems used for extravehicular activity. For the longer Gemini, Apollo Command/Service Module, Skylab, and Shuttle Orbiter missions a space radiator is used as the primary active method of heat rejection with water evaporators used only for supplemental and re-entry heat rejection.

In order for future heat rejection systems to have the relatively universal applicability necessary, the system must be designed to overcome several current radiator design limitations. Specifically, the maximum heat rejection capability for current systems is limited by several factors, including the severity of the external thermal environment, the temperature of the internal spacecraft heat sources, the availability of radiator surface area on the vehicle, the reliability of a circulating fluid system, micrometeoroid protection requirements, and available surface coatings. Thus, the primary technical objective of development activity has been to develop a low-cost space radiator system that can overcome one or all of these limitations. In addition, it is necessary to develop improved radiator control techniques that can allow the system to operate over a wide heat load range.

The primary goal of active thermal control development activity has been to develop a radiator system approach which is not integral with the spacecraft skin, and thus, can be separately developed and manufactured. The independent development approach has significant potential to reduce spacecraft development costs by (1) minimizing development and certification testing required by each different space mission, (2) providing longer production runs, (3) simplifying integration between the heat rejection system and the vehicle, and (4) providing for the reuse of heat rejection systems which are returned from orbit. This minimum-cost concept, in conjunction with the required technical improvements, can provide Orbiter payload heat rejection, as well as heat rejection necessary for spacecraft operating for very long duration missions, such as the orbital power module. Thus, the current development activity has applicability to a very broad range of future possible missions and could result in significant overall cost savings during spacecraft development and operations. The following discussion will briefly describe the four separate advanced space radiator concepts that have been pursued in an integrated effort to develop multi-mission-use, low-cost heat rejection systems which can overcome the limitations of current radiator systems. These concepts were not considered to be necessarily competitive alternatives, but unique design approaches which have the combined capability to meet a wide range of specific advanced mission requirements. Also, in order to establish a firm background to compare the the advanced space radiator concepts, the Orbiter active thermal control system will be briefly described.

SHUTTLE ORBITER ACTIVE THERMAL CONTROL

The Orbiter heat rejection system exemplifies the existing state-of-the-art in thermal management (reference 1). The Orbiter ATCS consists of two simultaneously operating coolant loops, using Freon-21, which transport heat from the Orbiter subsystems and payloads through liquid heat exchangers and pin-fin coldplates to the heat sinks. The locations of the major ATCS components are widely distributed throughout the Orbiter (see figure 1).

During on-orbit operations, heat rejection is accomplished primarily by the space radiators (see figure 2), supplemented by water evaporation. Use of water is required because of the limited radiator area available. The radiators are designed to reject heat in all orbiter attitudes. However, even with the best available surface coating and use of all available area, there are some attitude and heat load combinations where the environmental absorbed heat (solar, albedo, and Earth emission) on the radiators prevents the cooling of the Freon-21 returning from the panels to the required return temperature. Water evaporation is automatically activated to cool the Freon-21 to the required return temperature under this maximum load condition. In addition to maximum heat load limitations use of parallel tube flow in the radiator panels (I-tube panel) requires that a minimum heat load be applied in some attitudes to avoid freezing the coolant in the panels. A temperature control assembly controls flow through a variable position flow control valve which maintains the mixed radiator outlet to the required set point temperature by mixing hot bypass flow with cold flow from the radiators (see figure 3).

The Orbiter radiator heat rejection system has up to 8 radiator panels attached to the inside of the PBD (payload bay doors). The two forward panels on each side of the vehicle are deployed away from the doors to increase the surface area available for heat rejection. As previously mentioned, Freon-21 flows through two independent radiator coolant loops. The four radiator panels in loop 1 are installed on the left side of the Orbiter. The four panels in loop 2 are installed on the right side of the Orbiter. Since the forward panels reject heat from both sides of the panel, they are designed with flow tubes attached to each face sheet. There are 68 tubes in the forward panel, 34 on each face sheet. The aft panels remain attached to the aft doors; consequently, they radiate from the upper surface only, and thus are designed with 26 tubes attached only to the upper face sheet.

The radiator panels are constructed of aluminum honeycomb bonded to .0043 cm (0.011 inch) aluminum face sheets with metlbond 329-7 adhesive. High density honeycomb core is used at hardpoints. Aluminum tubes are imbedded in the honeycomb and bonded into the structure to provide parallel Freon-21 flow paths within each panel. The radiating surfaces are coated with a silver teflon coating which provides a low absorbtance of solar flux (α = 0.10) and a high thermal emittance (ε = 0.76). The coating is applied in 10.2-cm (4-inch) wide strips and bonded to the aluminum with a "permacel" adhesive. Heat rejection is effected by transmitting sensible heat from the fluid to the aluminum tubes by convective heat transfer, then conducting it to the radiating surface where it is radiated to space. Flex hoses traveling in hose reel assemblies that can accommodate the open and closed positions of the payload bay doors are used to transfer the Freon-21 to the radiators.

ADVANCED HEAT REJECTION DEVELOPMENT STATUS

Modular Wide-Heat-Load Fluid Radiators

For early spacecraft with missions of sufficient length to require a space radiator, the limited mission objectives and operations restricted the required operating heat load range. It has been recognized that for large Earth-orbiting vehicles, the heat rejection system would need to accommodate a much wider range of operating conditions. Some of the sources for this increased range requirement are normal operations with varying experiment payloads and heat sources, planned maintenance activities, and planned quiescent periods.

A fluid space radiator with a fixed area exposed to space has three limitations on the range of heat loads over which the panel can operate: high load, low load, and transient response . The maximum heat rejection of the panel is limited by the panel area, the radiant environment, and the temperature at which the heat transport fluid receives the waste heat. Unless a refrigeration scheme is used, the radiator must operate at a temperature below the temperature of the equipment rejecting heat to the fluid. Since the radiator system must be sized for the high load conditions, and panel area required is relatively insensitive to the low load control technique used, the effort involved with extending radiator heat load range concentrates on minimum load requirements and transient response capabilities. The minimum heat rejection of a panel is limited by the freezing point of the heat transfer fluid and the control technique used. Variations in heat rejection may be limited by the transient response of the system to a change in heat load.

The modular wide-heat-load-range fluid radiator developed (reference 2) achieves heat load control by varying the flow split between a "prime" and "bank" circuit as shown for a typical panel arrangement on figure 4. The flow split can be controlled by a valve which senses the mixed outlet of the prime and main circuits and compares it to a desired set point temperature. During periods of low load, the majority of the flow is routed to the prime tube of the panel and the bank is allowed to stagnate (freeze), thus reducing the effective panel area. As the load increases, more flow is routed to the bank, and the panel begins to destagnate (thaw) from the inside out (i.e., the shortest tubes destagnate first).

The selection of Freon-21 as the fluid for the wide-heat-load-range radiator is based on the following: (a) broad temperature range between freezing and boiling points with operation at a reasonable pressure in the 4°C to 38°C range, (b) good pumping power and heat transfer characteristics, (c) low viscosity at temperatures just above the freezing point, and (d) a sharp well-defined freezing point. With these characteristics, as soon as a tube thaws, flow quickly redistributes itself to provide a balanced share of the flow in the bank of parallel flow tubes.

The three modular panel configurations that have been tested are shown on figure 5: triangular, U-tube rectangular, L-tube rectangular. The triangular panel test provided the fundamental characteristics of the design and led to the U-tube design. A system of eight U-tube panels has been tested to (1) prove the modular design concept by demonstrating the panel flexibility and "building block" approach of the system design, and (2) demonstrate system performance over a full range of heat loads, environments and flow configurations. The U-tube radiator panels tested consisted of eight 1.82 m x 3.66 m (6 ft x 12 ft) flat panels. Each panel consisted of extruded tubes welded to .008 cm (0.02 inch) aluminum sheet on 15.24 cm (6.0 inch) centers in a U-shaped pattern (see figure 4). The "U" shaped flow passages (tubes) on each panel include flow control orifices at the inlet of each tube to maintain the proper flow distribution among the tubes. The wide heat load range is obtained by routing the majority of the flow to either the innermost prime tube or the bank of remaining tubes, thereby changing the panel radiation effectiveness.

The U-tube radiator tests encompassed a full range of external thermal environments, vehicle internal heat load generations, and radiator panel plumbing arrangements. In addition, various radiator control temperatures were evaluated, as well as radiation from one and both sides of the panels. Under all test conditions, the radiator system rejected the proper heat load and maintained the control temperature within expected tolerances. At low load and cold external environments, the radiator panels flow stagnated as designed and subsequently recovered the capability to reject high heat loads under conditions where the imposed heat load rate of change was several times faster than expected for a typical vehicle (Orbiter). The assessment of the different plumbing arrangements, which encompassed flow arrangements from all eight panels in parallel and all eight panels in series to several combinations in between those extremes, demonstrated the complete modularity of radiator panels. No flow distribution or flow instability problems were encountered under any test condition, which included freeze/thaw cycles under transient environment asymmetries and transient heat loads. A high to low heat load ratio of 50:1 was demonstrated for these panels.

Modular radiator panels containing a bank of L-shaped tubes (all manifolded together) have also been tested (see figure 6). The wide-heat-load-range capability is obtained on this panel by varying the flow between the radiator tubes and a bypass line, instead of varying the flow between a prime tube and a separate tube bank. At low heat loads, all the radiator tubes receive less flow, causing the flow in the bank of tubes to successively stagnate by freezing (from the longest to the shortest tube) and thus progressively reduce the overall radiator effectiveness. The innermost tube and bypass valve are sized such that the innermost tube never stagnates, even when the rest of the tubes are effectively bypassed. This approach has been termed inherent stagnation. The inherent-stagnation design eliminates the requirement for additional panel supply and return lines that would be required by a separate "prime" tube, thus providing design simplification and weight savings. If the radiator is exposed to the worst cold environment, the Freon in over half of the bank of tubes freezes. The continuous flow provided to the innermost tube is sufficient to insure that the stagnant radiator tubes can be thawed as the heat load increases. Both of the L-tube panels tested exhibited good heat rejection characteristics with high fin effectiveness and tube to face sheet conductance. An average fin effectiveness of 0.96 was measured. Low load stagnation/destagnation operation was demonstrated with the inherent stagnation method.

In summary, a wide-load-range fluid radiator concept has been developed. The key factor in the extremely fast transient response of this design is the combination of panel design and fluid selection. The proper selection of fin thickness, tube spacing, and manifold design complement the selection of Freon-21 which has an extremely high viscosity at temperatures just above its freezing point. As soon as a tube thaws out, the panel flow pattern is re-established to provide an even share of the flow to the tube. This results in a rapid rise in the temperature of the tube with a correspondingly high temperature difference between this tube and the adjacent frozen tube. The high temperature difference provides a high potential for heat transfer to thaw out the next tube. This phenomenon is repeated as each tube thaws out sequentially.

SHRM (Self-Contained Heat Rejection Module)

The self-contained heat rejection module (SHRM) has been conceived for use on future spacecraft that will be carried into orbit by the Shuttle. The SHRM (see figure 7) is a separate module which contains the necessary equipment to effect heat rejection in orbital environments. The basic goal of the SHRM program was to develop the technology for and to demonstrate for the first time a full-scale heat rejection system that contains deployable radiators and integral flow control equipment (reference 3). Fluid swivels provide fluid transfer between the deployable radiator panels since compactness of volume and envelope was a design requirement. Heat transfer to the SHRM from the heat source is through a contact heat exchanger. The contact heat exchanger permits thermal coupling or uncoupling of the SHRM to a heat generating payload by a mechanical joint rather than by fluid interconnection. This will facilitate system installation since neither the SHRM or the payload fluid system needs to be broken into and reserviced. A high degree of flexibility for multiple mission support was achieved by incorporating a dual-mode system approach. The "dual mode" concept refers to a spacecraft heat rejection system which operates as a conventional, low-temperature, liquid phase radiator system during periods where minimal or nominal heat rejection is required. During operations involving severe external environments or high power requirements, a vapor compression system is automatically switched on to a refrigeration/high-temperature radiator mode.

A schematic of the system is shown in Figure 8, with its two independent parts, a high-temperature radiator system and a dual-mode refrigeration/radiator system. This independent system approach has three distinct advantages: (1) separate controls can be used for each system, (2) only half of the system can be used for some applications (i.e., for high-temperature applications the liquid radiator would be used; for low-return-temperature applications only the refrigeration unit would be used), and (3) parallel flow radiator panels can be used on the condensing radiator and wide heat load tube layouts as discussed in the prior section of this paper can be used on the liquid phase radiators.

Several approaches for deploying the SHRM radiators were considered including foldout hinged panels, telescoping devices, mechanical linkages, rotating panels, and scissor-type deployment mechanisms. The scissor mechanism was finally selected because of the existence of a qualified and proven deployment mechanism used for the Apollo Telescope Mount solar cell array deployment system. One of these units was obtained from NASA-MSFC, and radiator panels were placed on it in lieu of solar cells.

With any concept of deployable radiators some form of relative motion between panels must be accommodated in the plumbing system. For a scissor mechanism, rotary motion is required. Several concepts were considered, including flex hoses, coiled tubes, and fluid swivel fittings. The decision to utilize the qualified ATM solar array deployment mechanism which has a very restrictive space envelope influenced the choice toward the fluid swivel fitting. An Aeroquip Omniseal was selected for the fluid swivel, because it uses teflon for sealing, which is compatible with Freon-21, and a stainless steel spring to provide resilience at low temperature. A swivel fitting was designed around this seal (see figure 9). The fitting has been successfully tested at -140°K with no detectable leakage for both static and dynamic conditions in a vacuum environment.

Several approaches were considered for the contact heat exchanger including flat coldplates, irregular coldplates with sawtooth or pin surfaces, heat pipes, and stacked coldplates. The stacked coldplate approach was selected because of its favorable envelope requirements and the relatively small contact force required to achieve the necessary heat transfer. In this design the two sides of the heat exchanger are formed by coldplates which are connected to a common manifold (see figure 10). The contact heat exchanger is mated by sliding the two sides together in a manner similar to operation of a radio tuner. Bolts are used to apply pressure to the two sides of the contact heat exchanger to provide a pressure of up to 2000 KN/m^2. This pressure will provide contact conductance coefficients of 4600 $J/s\ m^2\ K$ when an interstitial filler of conductive silicone grease is used.

The four SHRM panels were constructed of aluminum tube extrusions seam welded to 0.00102-m (0.040-in.) aluminum sheets at 0.16 m (6.3 in.) internals. The radiator panel size to fit on the ATM frame was 2.57 m (101.25 in.) by 2.37 m (93.25 in.). These panels provide a total radiating area of 48.7 m^2 (524.5 ft^2) since they radiate from both sides.

Extensive thermal vacuum testing of the SHRM has been completed (reference 4). The overall objective of achieving the first full-scale demonstration of a deployable radiator system and mapping the heat rejection capacity of the first dual-mode radiator refrigeration system have been accomplished during this testing. Multiple thermal vacuum deployments and retractions were successfully conducted and maps of the heat rejection capacity in both modes were generated for two difference return temperatures, 2°C and -12°C (35 and +10°F). These maps indicated distinct operation ranges for the two modes as a function of heat load and thermal environment. Component evaluations based on the test results indicated all the components performed as expected, except for one of the eight fluid swivels. A redesign of this component will be necessary for use in a dual-mode system; however, it is completely acceptable for use in a pumped liquid system which contains no refrigerant oil.

Flexible Deployable Space Radiator

Flexible radiator systems utilize panels made of composite flexible fin material to reject heat and can be "rolled" up, folded, or compacted during storage and deployed for orbital operation. Because of their flexibility, these radiators are easily adapted to an existing vehicle since they can be stowed in compact units which are not susceptible to damage by dynamic loads during launch. Since flexible radiators do not require extensive structural support, they are inherently lighter in weight than rigid panels. Also, the same flexible radiator design can be used in several different missions so that developmental and integration costs are reduced.

Two designs have completed the feasibility demonstration phase of development: a soft-tube concept which unrolls to deploy and a hard-tube concept which deploys into a cylinder shape using the spring force of helically wound aluminum transport fluid tubes (reference 5). Transport fluid temperature control is by either a bypass system like that previously discussed for the rigid panels or by partial extension to regulate the radiating area.

Soft-Tube Concept Description: A typical soft-tube flexible radiator system is shown in figure 11. The radiator panels incorporate flexible tubing to allow the "wings" to be rolled and unrolled from a cylindrical storage drum. Panel size, arrangement and single or multiple panel configurations are dependent on heat load, vehicle interface and storage requirements. Radiation is from both sides of the panels.

The composite flexible radiator panel fin material and soft-tube arrangements are shown in figure 11. The composite has outer layers of teflon which provide structural strength and resistance to ultraviolet degradation and also a high radiating surface emittance combined with a low solar absorbtance. A highly conductive wire mesh is fusion bonded to the interior surface of one layer of the teflon to provide a high lateral conductance. Silver metal can be vapor deposited on the inner surfaces to reflect incident solar radiation. The silver/teflon layers are then adhesively or fusion bonded to the tubes in a sandwich construction. The transport fluid tubing diameter and spacing on the panels were selected to provide minimum system weight including the effects of pumping power penalty and structural mass for protection from meteoroid penetration. The resulting radiating fin effectiveness is in excess of 0.85. The baseline design uses a transport fluid (coolanol 15) which has long term compatibility with the flexible tubing and results in an operating temperature range from about -29°C (-20°F) to 85°C (185°F).

Deployment forces for the soft-tube flexible radiator system are provided by a nitrogen gas pressurant which inflates two manifolds, one on either edge of the panel, causing the panel to unroll from the storage drum. Panel retraction forces are provided by flat, preloaded "watchsprings" which are incorporated into the gas deployment manifolds. Heavier deployment/retraction mechanisms such as the Storable Tubular Extendable Member (STEM) may be substituted for gas inflation manifold deployment where precise positioning of the deployed panel is desired.

A soft-tube article measuring 1 m x 1.8 m (40 in. x 72 in.) was fabricated. Tests were conducted in thermal vacuum conditions at equivalent radiating sink temperatures ranging from -18°C (0°F) to -190°C (-310°F) with coolanol 15 transport fluid inlet temperatures from 32°C (90°F) to 71°C (160°F). The test verified heat rejection capability and demonstrated the design temperature distribution through the tube wall, glue line and composite radiating fin. Repeated deployment and retraction under thermal vacuum conditions verified the gas deployment system and the mechanical integrity of the construction. Testing at partially deployed positions showed that heat rejection may be controlled by this technique. Subsequently, a full-scale prototype wing of the soft-tube concept has been fabricated and is currently under test. Both gas pressurization/watchspring and STEM deployment/retraction approaches will be tested.

<u>Hard-Tube Concept Description</u>: One hard-tube flexible radiator concept that has been fabricated and tested incorporates aluminum tubes with a flexible composite fin material. This typical hard-tube system is shown in figure 12. The cylindrical panel configuration incorporates the aluminum tubes in a helical pattern so that the panel can be compressed for storage. The composite flexible radiator fin material and tube configuration arrangement described above and in figure 11 for the soft-tube design is identical for the hard-tube design except the tubes are aluminum. The aluminum tubes allow for greater meteoroid protection, a wider fluid temperature range of -96°C (-140°F) to 149°C (300°F) and greater fluid system operating pressures. As with the soft-tube concept, the tube spacing and diameter were selected to provide a minimum weight system. Overall radiating fin effectiveness is again in excess of 0.85.

The helically coiled aluminum tubes provide the forces necessary for deployment of the hard-tube concept. A motor-driven cable or boom compresses the coil to retract the system. As with the soft-tube design, a STEM may also be utilized when precise positioning of the panel is required.

A hard-tube test article was fabricated, which measures 0.71 m diameter by 1.14 m long (28 in. x 45 in.). Thermal vacuum tests were conducted with Freon-21 fluid inlet temperatures ranging from 16°C (60°F) to 71°C (160°F). The tests verified deployment, heat rejection, temperature distribution, mechanical integrity, and the capability to regulate heat rejection by partial deployment.

Subsequent work is now underway to fabricate and test a full-scale prototype wing of a hard-tube flexible radiator panel designed for long duration mission applications. It is constructed with steel transport tubing and metal bellows manifolds to accommodate Freon-21 transport fluid. The metal bellows will allow this hard-tube concept to be rolled and unrolled from a cylindrical storage drum as previously discussed for the soft-tube system (see figure 11). Expanded silver metal and teflon will be fusion bonded to the transport tubing to form the radiator fin. Micrometeoroid barriers are being designed for the manifolds and transport tubing. The deployment system will employ a Storable Tubular Extended Member (STEM) and a spring-loaded storage drum.

Modular Heat Pipe Radiator

As previously discussed, current manned spacecraft reject their waste heat by mechanically pumping fluid through a space radiator system which radiates the heat to space. As such, reliability is relatively low since system operation is vulnerable to failure from a single meteoroid penetration of a radiator fluid tube. High reliability for long duration missions can be achieved, but the resulting space radiator system is generally heavy because of the required redundant plumbing, pumping, and valving hardware. Heat pipes offer an attractive alternative for eliminating many of the single point failures in a space radiator system. The development effort pursued uses a radiator panel concept which utilizes multiple heat pipes. Therefore, the loss of a single heat pipe is not catastrophic and meteoroid protection is maximized.

The basic heat pipe radiator concept couples a fluid heat source to a radiative heat sink through an intermediate array of heat pipes, which are designed to maximize heat rejection per unit of radiator system wet-weight. The panel has the capability of being thawed from a frozen state without the benefit of a warm environment. This permits the panel to freeze during low load conditions and results in a wider operating range between maximum and minimum loads.

The first heat pipe radiator panel tested consisted of six L-shaped ammonia feeder heat pipes welded to the condenser section of a variable conductance heat pipe (VCHP) header (reference 6). The evaporator section of the header was attached to a finned fluid heat exchanger and the six feeder pipes were bonded to a 1.2 by 2.4-m (4 x 8 ft) radiating fin. Although the VCHP header performed below its design capacity, other test results were encouraging. The operational feasibility of a heat pipe-to-fluid heat exchanger was established, and the panel feeder heat pipes were very effective in isothermalizing the radiating fin.

Subsequently, a prototype modular heat pipe radiator panel was designed and fabricated. This flight-weight panel is a segment of a multi-panel system concept that consists of individual radiator modules that can be grouped in building-block fashion to satisfy a given heat rejection requirement. The ultimate success of this type of system would result in many significant advantages to future spacecraft including reduced development/test costs, wide flexibility of application, and manufacturing economies.

The prototype heat pipe radiator panel concept is illustrated in figure 13. Each of the panel feeder heat pipes is an identical sub-module of the panel and comes attached to its own radiator fin and fluid header sections. Thus, any desired panel area can be formed by simply piecing the required number of heat pipe sub-modules together, with the header tubes lap welded and the radiator fins spot welded to one another. The feeder heat pipes are purely isothermalizers and as such can be either longitudinally grooved pipes or artery designs. The former is simpler, but the latter type (a spiral artery) was used in the prototype since they are much less sensitive to adverse tilt during ground tests. Another advantage is their higher transport capacity with ammonia, the selected working fluid (254 W-m versus 76 W-m). This permits longer condensers and hence, radiator fin lengths to be used in the panel design, which results in fewer heat pipe sections. The artery pipes, with their fine circumferential grooves, also have higher evaporator film coefficients (1.4 versus 0.7 W/cm^2 deg C), which increases the effectiveness of the heat exchanger section and results in reduced fluid to panel temperature drops. The prototype panel radiator area is 6.3 m^2 (68 ft^2). It contains 11 ammonia spiral artery heat pipe segments, spaced every 28 cm (11 in.), and is designed to reject 2200 W.

An important consideration in the design of the prototype heat pipe panel was the ability of the ammonia heat pipes to be thawed from a completely frozen state in a zero absorbed heat environment. Such a requirement could result when a spacecraft sustains a dormant operating mode coincident with a very cold environment, then resumes normal operation while still in the same environment. The test results from the first radiator panel test showed that thawing was always promoted by raising the environment above the ammonia freeze point, but the test results were inconclusive as to whether the frozen ammonia pipes could repeatably extract enough energy from the warm fluid stream to thaw themselves in a cold environment. However, thawing can be assured by maintaining a high-temperature boundary along a frozen condenser section and relying on cross-fin conduction to supply the needed energy to thaw the first pipe. The other heat pipes would then be sequentially thawed in a similar manner. Therefore, a low-freezing-point heat pipe has been included on the prototype panel as one of the feeder pipes to insure that at least this one pipe would remain operational in the coldest cases. The general requirements for the low-freezing-point heat pipe are (1) it must have a relatively poor coupling to the fluid when the ammonia heat pipes are frozen, the inlet temperature low, and the environment cold, in order to minimize panel heat losses and promote good high load/low load ratio; (2) it must also have a good enough coupling to the fluid to maintain the minimum required boundary temperature when inlet temperature and flow rates are raised. Propane was selected for the low-freezing-point heat pipe, because it meets these requirements with a very low freezing point, -187°C (-305°F).

Thermal vacuum testing of the prototype modular heat pipe radiator panel has verified its design (reference 7). Two separate test series were run; first, normal mode performance and then freeze/thaw performance. For the normal mode, steady-state performance maps were obtained; panel heat rejection and temperature profiles were measured for various combinations of absorbed environment, inlet temperature, and flowrate. The main objective of the freeze/thaw tests was to determine if a frozen panel could be thawed in a zero absorbed environment by simply increasing the fluid inlet temperature. The maximum heat rejection recorded for the heat pipe radiator in a near-zero environment was about 2800 W. On a unit basis, this is 420 W/m^2 (39 W/ft^2). Two of the eleven ammonia heat pipes were less effective than the others, since they frequently operated at lower temperatures than the surrounding pipes. Near its capacity limit, the prototype panel had two operating modes, depending on the stability of the fluid inlet conditions. The arteries can be either fully primed with working fluid or partially deprimed. The former provides a 2800-W capacity, and the latter 2200 W. When subjected to cycling inlet conditions, the heat rejection peaks and valleys generally lay between the primed and unprimed steady-state limits. Most of the data indicated a fully primed condition. The low-freezing-point propane heat pipe worked as designed. The frozen panel was successfully thawed in a near-zero environment by increasing the inlet temperature along a controlled ramp.

Two additional prototype heat pipe radiator panels have been fabricated and are included in a three-panel system level thermal vacuum test currently in progress. These three panels will be arranged in various radiator system configurations. Different combinations of the three panels in series and parallel arrangements are being tested to evaluate system interaction. In addition, three smaller single heat pipe radiators are being tested to investigate design improvements in the thermal interface between the heat pipe and the radiator fin (see figure 14).

CONCLUDING REMARKS

Long-term orbital applications in which large amounts of electrical power are generated and utilized will require waste heat rejection beyond the capabilities of existing radiator systems. The optimum, minimum-cost technique of rejecting heat for such applications can be developed based on judicious application and extension of the radiator technology developed over the last 10 years in the areas of radiator deployment methods, flexible/lightweight radiator fins, heat pipe radiators, fluid swivels, and heat rejection control techniques.

The orbital power systems effort must begin with system level heat rejection trades to apply the key techniques that have been developed into an optimum integrated thermal management system. The design effort should directly compare pumped fluid, heat pipe, rigid vs. flexible fins and other appropriate radiator system concepts for the specific orbital power systems mission. Techniques for system level reliability improvements (isolated flow loops, replaceable heat pipes, etc.) must be developed. The effort should integrate such concepts as heat pipe radiators, flexible fin materials, non-metallic tubes (with thin gage metallic tube liners), micrometeoroid barriers, and materials which are not degraded by extremely long exposure to the ultraviolet spectrum. Also, advanced temperature control schemes for providing constant system outlet temperatures over a wide band of heat loads as appropriate for the orbital power system should be an integral part of the effort. The radiator system concept developed must achieve long-life by remaining operational in the micrometeoroid environment of space through on-orbit refurbishment and special design/construction features. The system should accommodate the large size requirement by deployment from a compactly stowed volume.

Panel element tests should be conducted to evaluate fabricability and performance. A representative portion of the full-scale system including the deployment technique should be fabricated and tested to confirm the final design concept. Finally, a flight demonstration program should be established for evaluation of the detail approaches to insure that the real problem areas, such as (a) articulating fluid lines, (b) maintaining flow distribution in large multi-panel systems, (c) maintenance-tolerant designs for in-space repair/replacement, (d) deployment and initial coolant servicing design, (e) temperature control scheme for large surface area radiators, and (f) surface property maintenance on-orbit, have been successfully solved.

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4. Fleming, M. L., "Development Testing of a Self-Contained Heat Rejection Module," ASME Paper 76-ENAS-33, July 1976.

5. Leech, J. W., "Flexible Deployable-Retractable Space Radiators," AIAA Paper 1896, June 1977.

6. Swerdling, B., "Design and Test of a Self-Controlled Heat Pipe Radiator," ASME Paper 73-ENAS-49, July 1974.

7. Alario, J., "Modular Heat Pipe Radiator," ASME Paper 77-ENAS-30, July 1977.

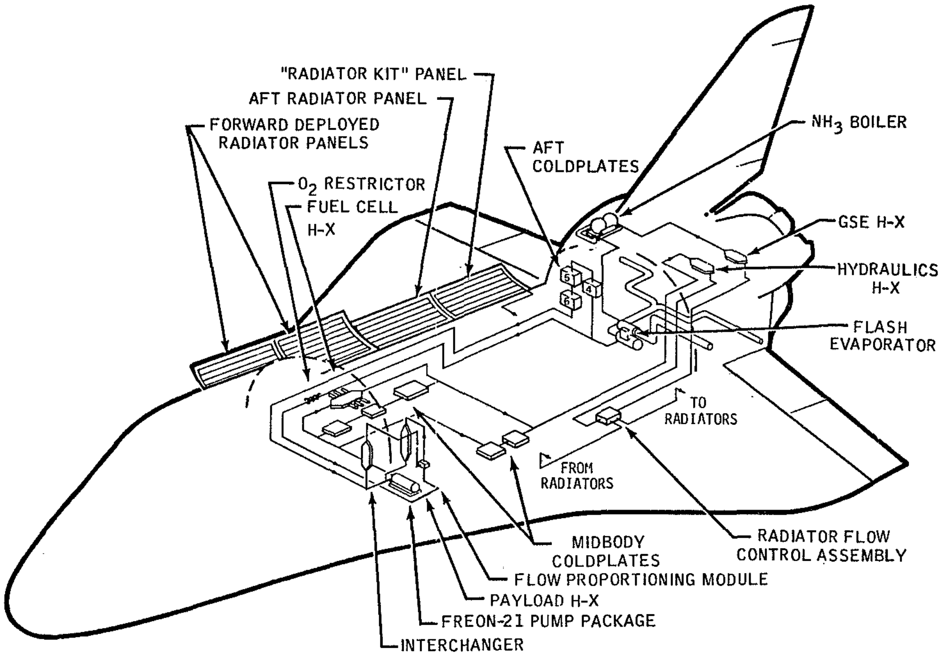
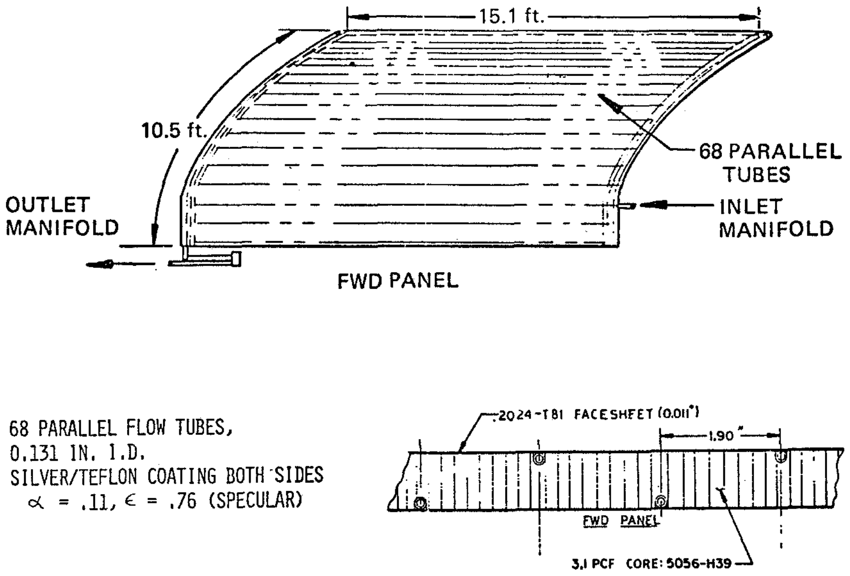


Figure 1. - Shuttle Orbiter active thermal control subsystem.



68 PARALLEL FLOW TUBES,
0.131 IN. I.D.
SILVER/TEFLON COATING BOTH SIDES
α = .11, ϵ = .76 (SPECULAR)

Figure 2. - Orbiter radiator panel physical characteristics.

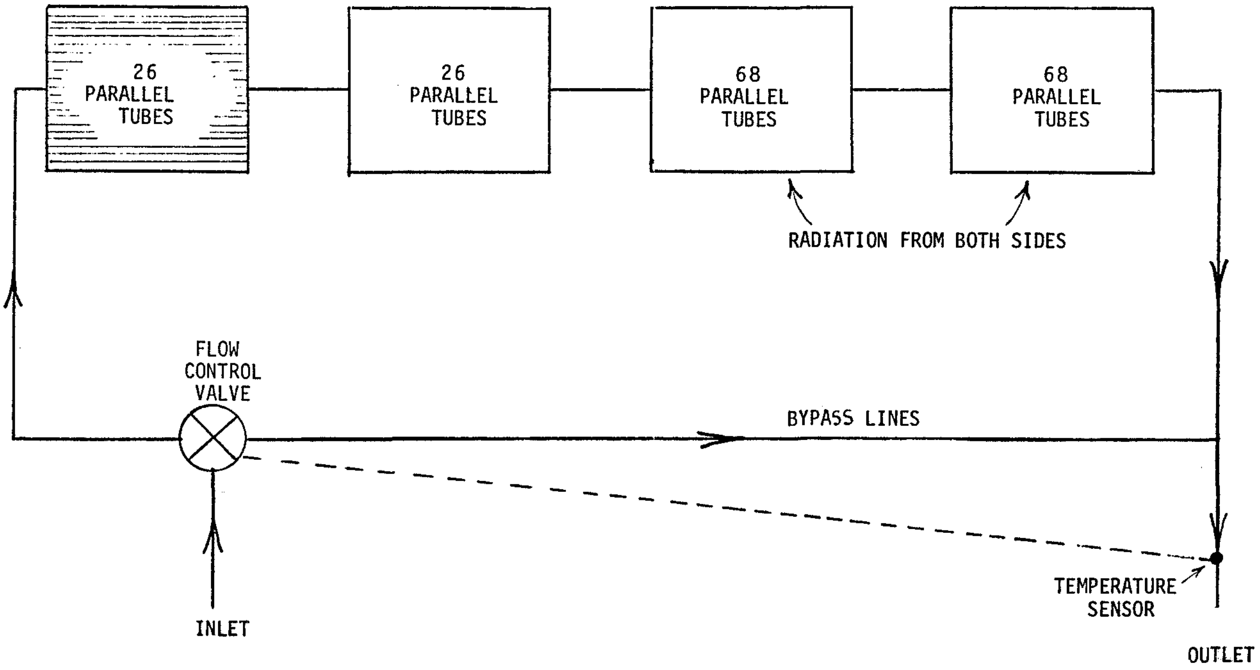


Figure 3. - Orbiter radiator system temperature control.

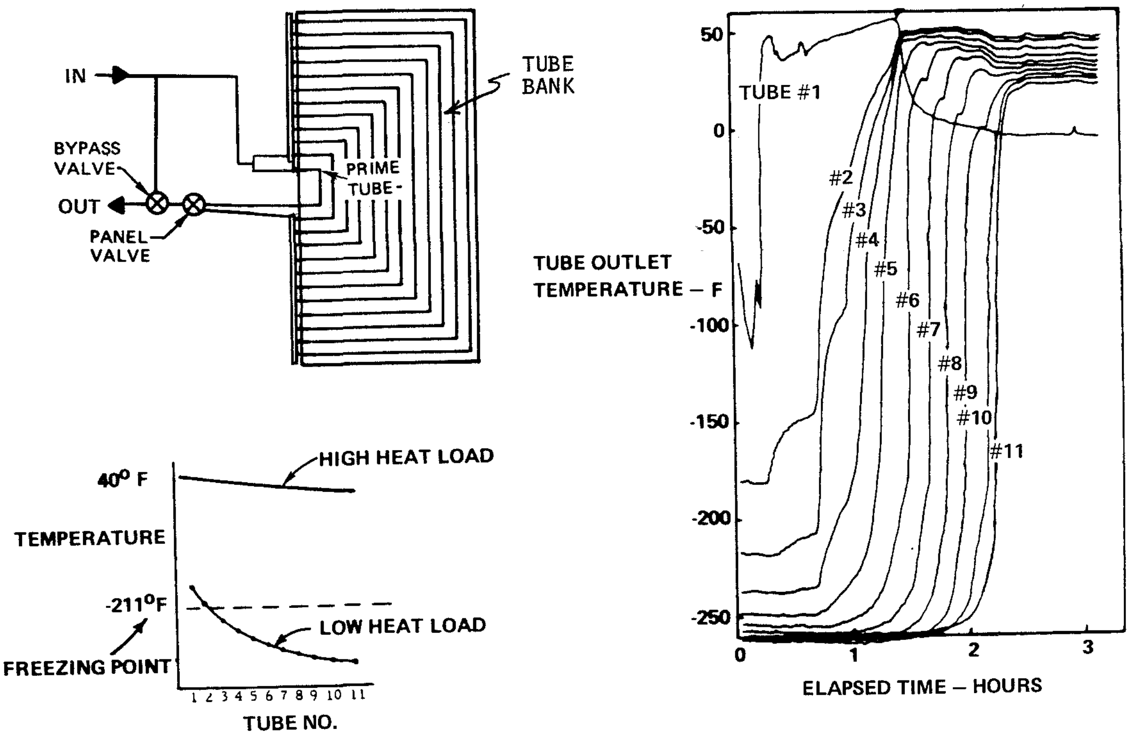
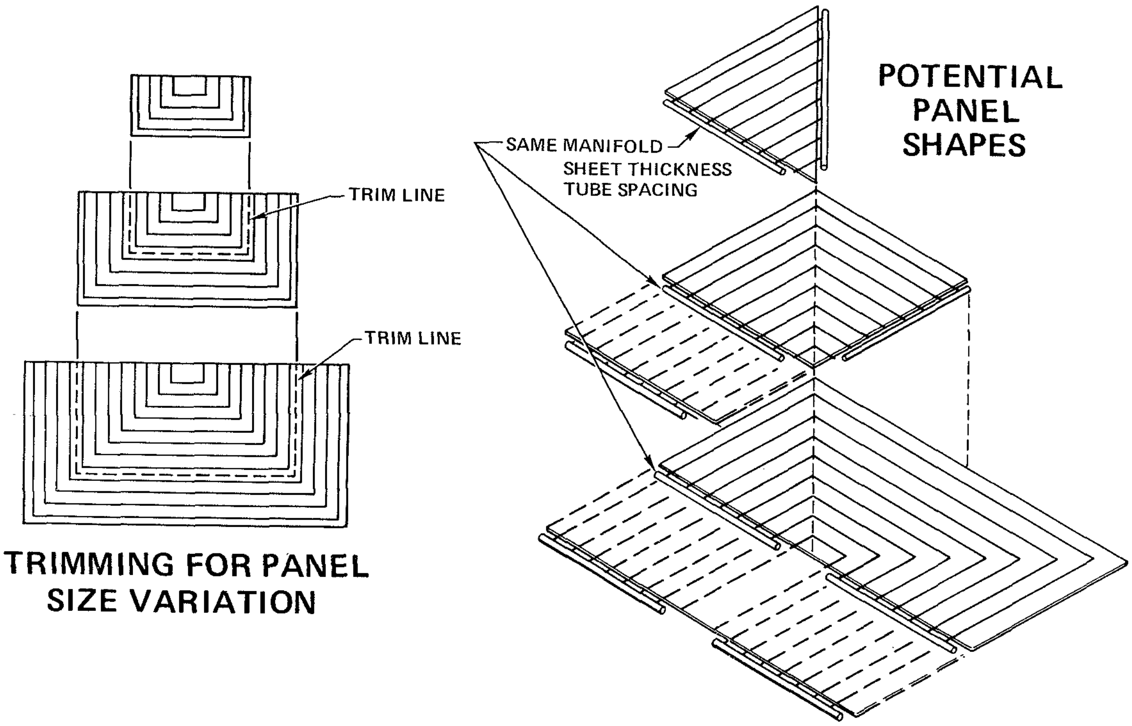


Figure 4. - U-tube wide-heat-load-range fluid radiator.



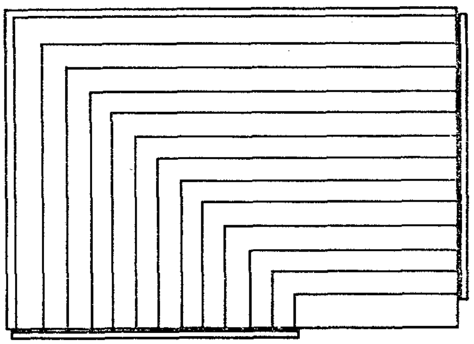
TRIMMING FOR PANEL SIZE VARIATION

POTENTIAL PANEL SHAPES

Figure 5. - Wide-heat-load-range fluid radiator modularity.

- "L" TUBE PATTERN, REVISED VALVE STAGNATION
- HONEYCOMB PANEL
  - 0.012 IN. 2024 T81 ALUM FACE SHEETS
  - 5056-H39, 3.1 LB/FT^3 ALUM H/C CORE
- FORWARD PANEL
  - 68 TUBES ATTACHED TO ALTERNATE FACE SHEETS
  - 3.8 IN. TUBE SPACING, TUBE I.D. = .135 IN.
  - 0.90 IN. H/C THICKNESS
- AFT PANEL
  - 26 TUBES ATTACHED TO EXPOSED FACE SHEET
  - 4.96 IN. TUBE SPACING, TUBE I.D. = .18 IN.
  - 0.50 IN. H/C THICKNESS
- TUBES BONDED TO FACE SHEET

"L" TUBE PANEL



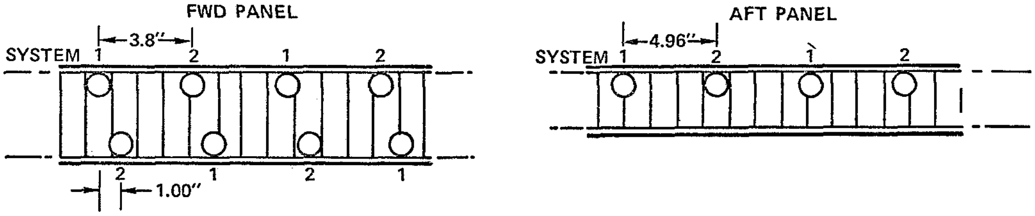


Figure 6. - L-tube wide-heat-load-range radiator configuration.

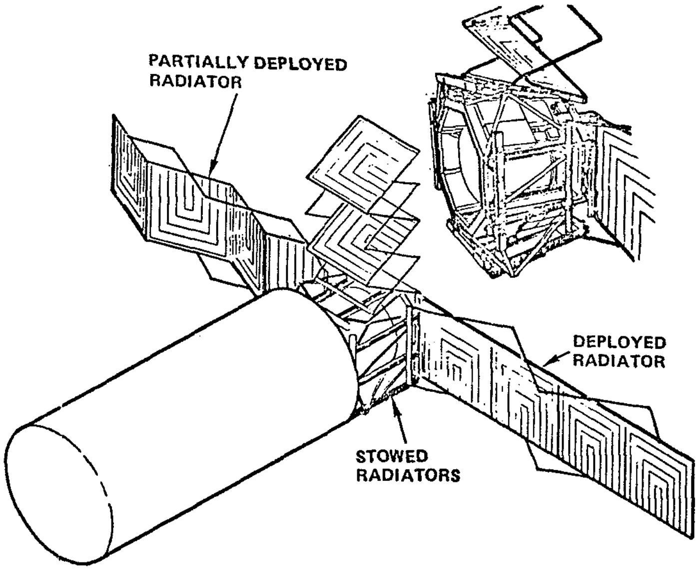


Figure 7. - Self-contained heat rejection module (SHRM).

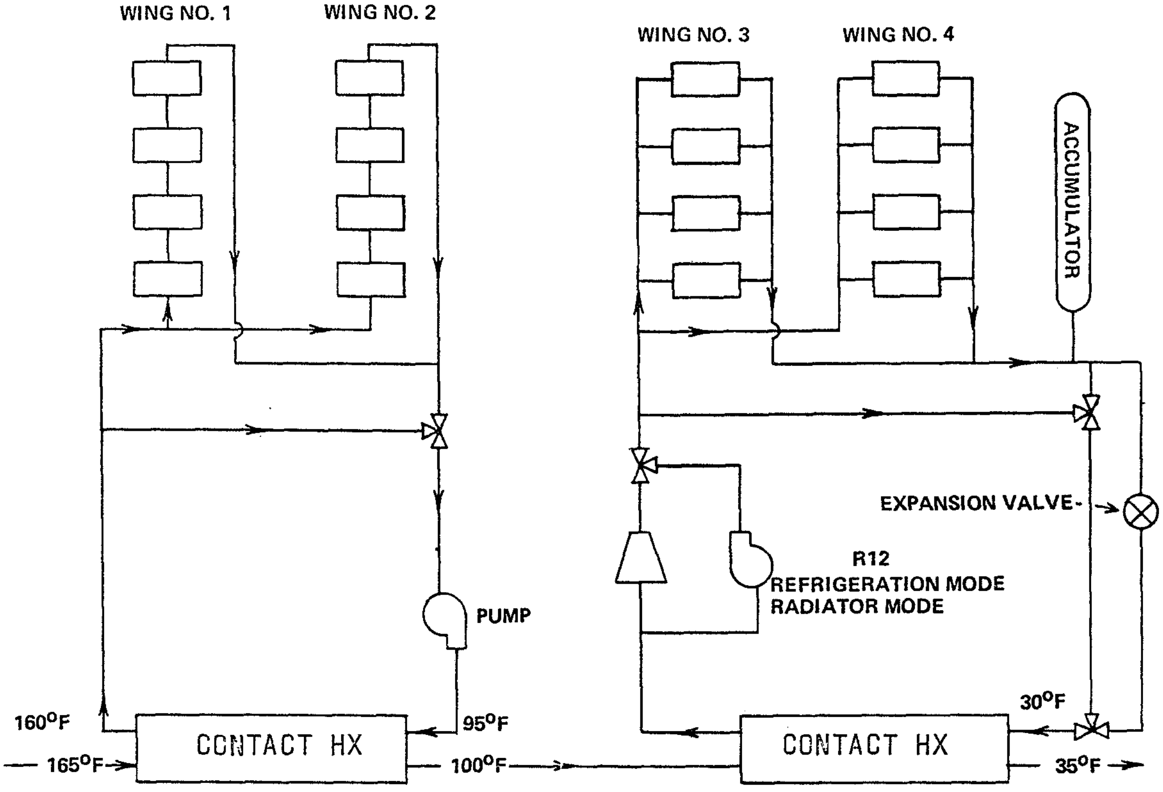


Figure 8. - Self-contained heat rejection module (SHRM) flow schematic.

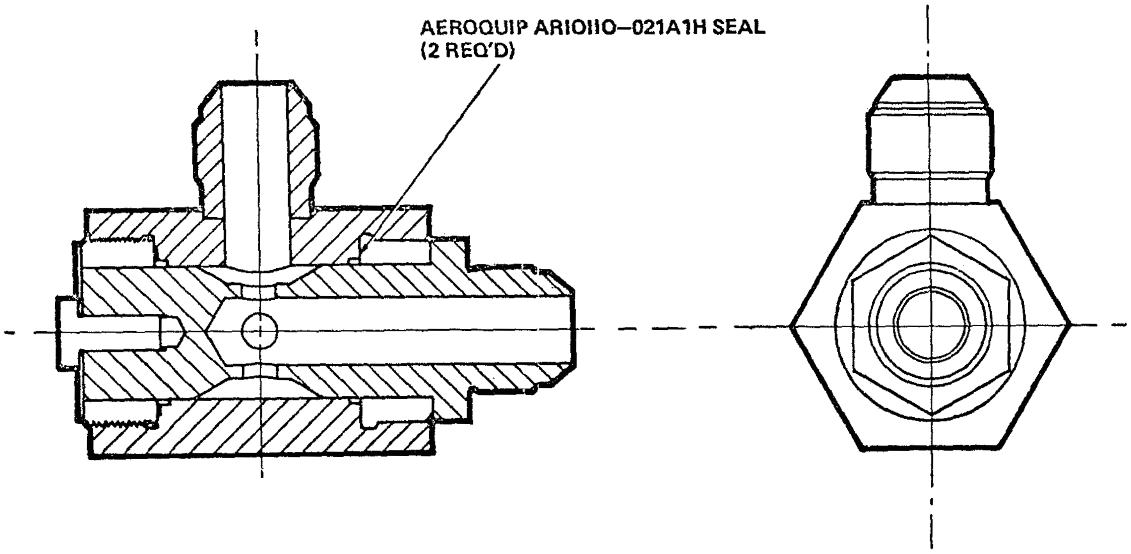


Figure 9. - Fluid swivel for deployable space radiators.

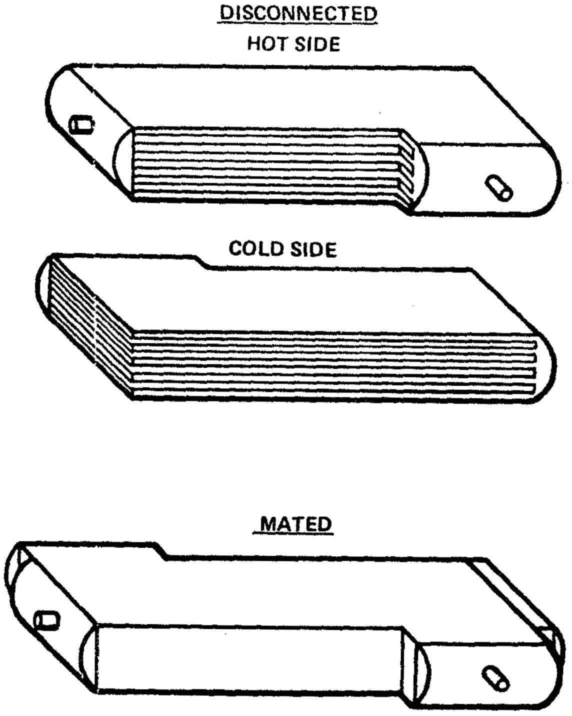


Figure 10. - Contact heat exchangers.

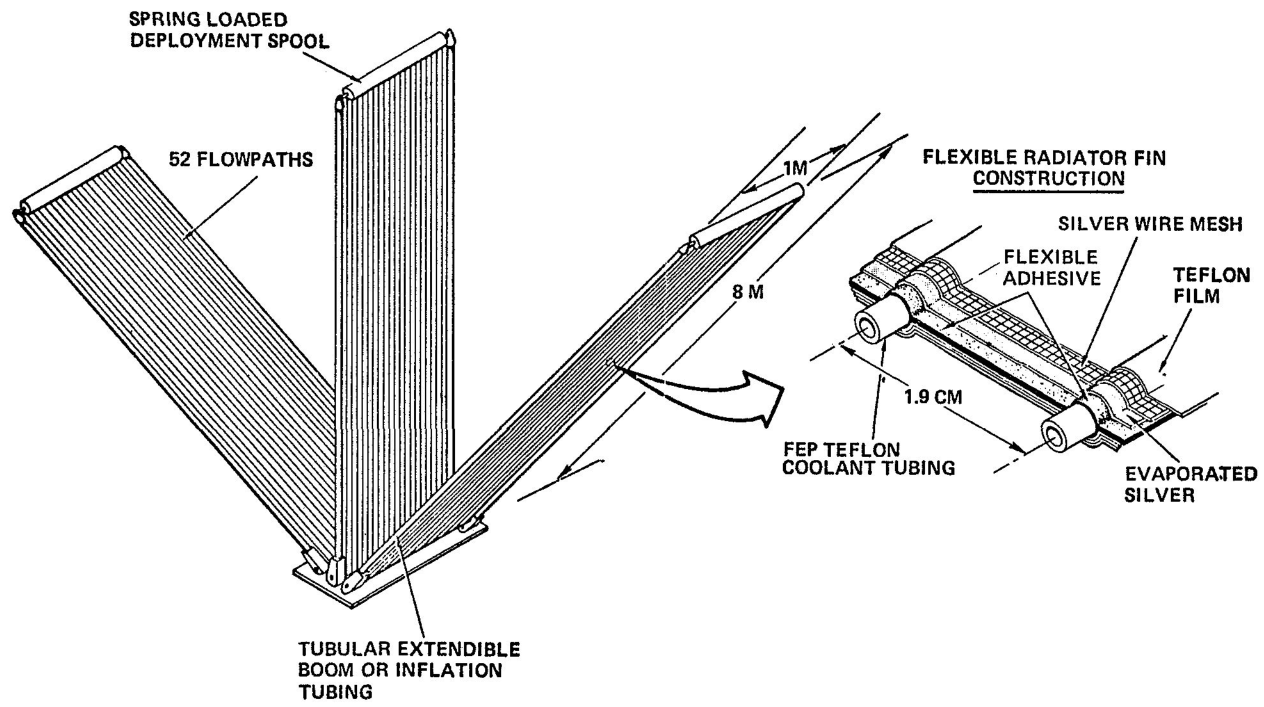


Figure 11. - Flexible-fin/deployable space radiator.

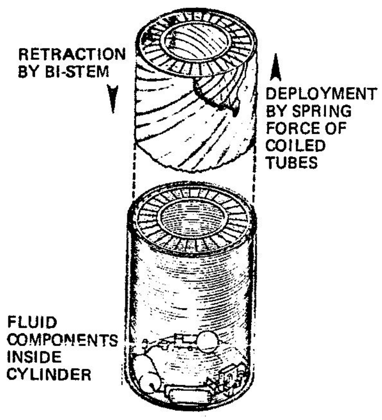


Figure 12. - Hard-tube flexible-fin/ deployable space radiator.

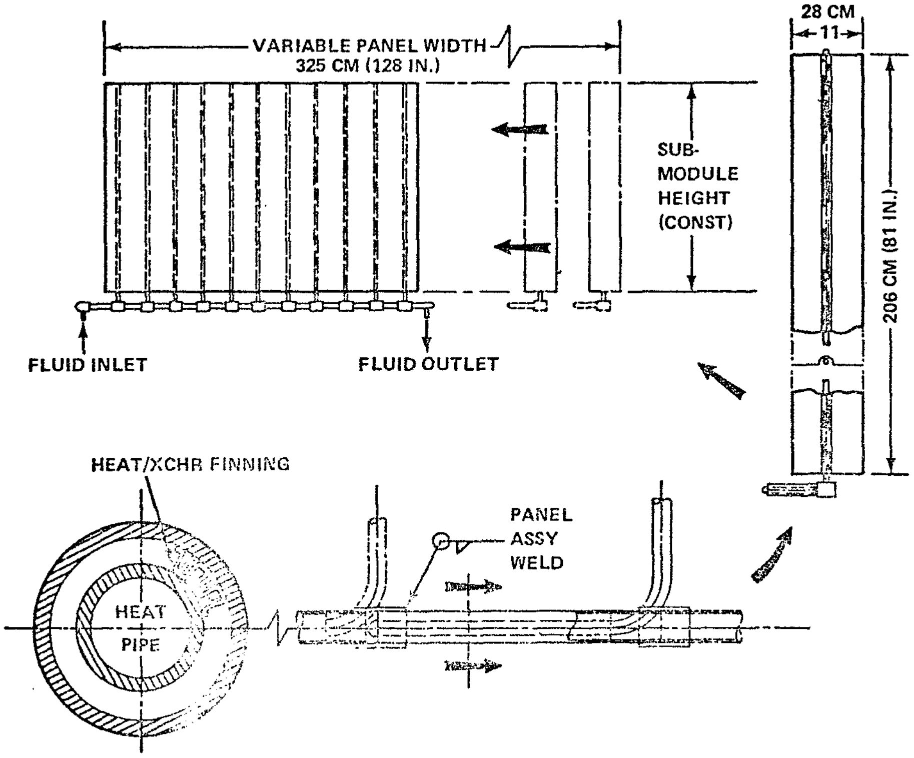
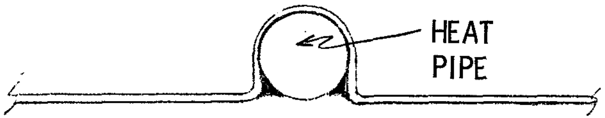
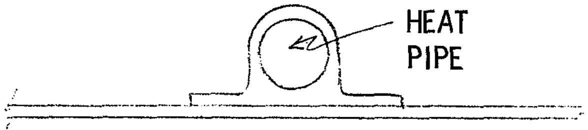


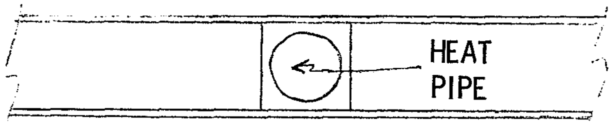
Figure 13. - Modular-heat-pipe radiator.



BONDED TUBE FIN



EXTRUSION, WELDED TO FIN



BONDED HONEYCOMB

Figure 14. - Heat-pipe/radiator fin interface techniques tested.