Space Constructible Radiator On-Orbit Assembly

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This paper discusses the most recent approaches for the on-orbit assembly of the space constructible radiator system (SCR) being developed for NASA's space station. Conceptual designs of suitable grappling hardware, radiator panel configurations, and insertion techniques are evaluated. Initial ground simulation results are presented using a six-degree-of-freedom (6-DOF) shuttle remote manipulator system (SRMS) simulator, both with and without force feedback. Radiator insertion in a close-tolerance rectangular opening has been achieved, without force feedback, using a special alignment target.

Introduction

Problem

THE increased power levels (up to 250 kW) and mission durations (10 years) envisioned by NASA and the Air Force for future space system, require space assembly and maintenance of critical thermal control subsystems. There are two main functional categories: heat rejection (radiators) and heat collection/transport. These subsystems will be composed of modular building blocks so that performance limitations of individual components can be overcome by evolving an integrated assembly. The modularity concept is also needed to achieve very high mission reliability (0.99) over an extended lifetime by selective replacement of worn and damaged components.

Successful thermal performance of the space constructible radiator (SCR) has been demonstrated by bench testing in November 1983, thermal vacuum testing at the NASA Johnson Space Center in February 1984, and by two subscale zero-*g* tests.

The SCR is being designed as 0.3 × 15m (1 × 50 ft) elements, each incorporating a high capacity monogroove heat pipe capable of rejecting 2 kW. Each fin element is attached on-orbit to a heat exchanger forming the condenser section of a two phase heat transport loop—the thermal bus. The heat transport loop also employs modular building blocks for expansion with the space station.

Although the various parts of the thermal management system (TMS) are designed in modular fashion, the positioning, structural, and transportation problems inherent in orbital assembly operations had to be addressed.

Postponing consideration of these issues might prevent timely use of the advanced TMS despite successful thermal performance. Consequently, a program was initiated to identify the critical assembly requirements and to evaluate the feasibility of alternate design and procedural approaches. The overall objective of this effort was the definition of design approaches, hardware requirements, and operational procedures necessary to assemble and maintain the SCR in orbit.

SCR Design

The SCR elements are plugged into a boom containing the condenser section of the thermal bus (Fig. 1). There are two methods under consideration to input heat to the evaporator of the heat pipe in the SCR element. Under the first scheme, a dry, mechanical interface clamps the evaporator to the fluid heat exchanger with sufficient pressure (690 kN/m^2 or 100 psi) to minimize contact resistance. Heating a thermal expansion bolt provides the small clearance (approximately 4.3 mm or 0.17 in.) necessary to insert the SCR element, which is then clamped in place as the bolt cools. A second procedure uses a heat pipe disconnect device. The heat pipe evaporator is contained within the boom and pre-attached to the fluid heat exchanger; the SCR elements comprise the condenser sections of the heat pipes and the heat pipe working fluid flows through the disconnect after mating.

Prototypes of the mechanical interface and disconnect have been tested successfully, and a mechanical interface with a larger clearance is being designed. Assembly techniques suitable for both heat input methods are being developed in this project. The overall approach must produce a planar array of the SCR elements to eliminate solar reflections and view factor blockage, as well as minimum spacing between the elements to minimize radiator array area. It is desirable to use the existing RMS, but new end effectors may be employed. In addition to satisfying clearance requirements at the connection point (mechanical interface or heat pipe disconnect), the assembly method must not result in any interference between the element being inserted and adjacent elements. It is likely, therefore, that some type of guidance mechanism will be required.

RMS Simulator (LASS) Description

The Large-Amplitude Space Simulator (LASS)[1] was used to validate the design concept for on-orbit assembly of the SCR. The LASS is a real time 6-DOF motion-base simulator that replicates the operational dynamic environment of the SRMS on orbit. The LASS facility had been validated for SRMS training by both NASA and the USAF Space Division. The facility contains the following elements:

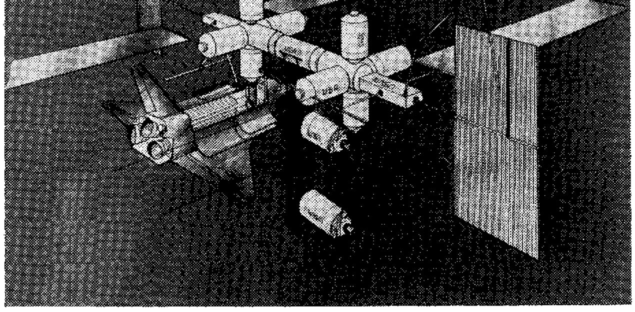

Fig. 1 Assembly of SCR elements to space station boom.

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1) A hybrid computer facility that contains the SRMS flight software and a dynamic model of the SRMS, complete with cross-coupled inertias, arm dynamics, and force feedback.

2) A 6-DOF motion base with a 50 × 50 × 15 ft area that replicates the SRMS operating in the on-orbit cargo bay environment.

3) A high fidelity mockup of the SSTS aft flight deck, complete with flight equivalent controls and displays.

4) Full-sized high fidelity test article mockups of the SCR evaporator boom interface.

5) A 6-DOF force measurement device.

6) Closed-circuit television (CCTV) cameras, monitors, and optical targets that simulate the real world field-of-view problem.

These elements were configured to replicate the SRMS end effector operating at SSTS station (orb body axis) −920, −250, −520 in., which simulates a starboard outboard construction area at mid-cargo-bay (see Fig. 2).

Problem Approach

The SRMS model was initialized to the above-mentioned construction site with hand-controller gains of 0.1 ft/s and 0.08 deg/s and arm-joint servo-rate limits normally used for heavy payloads (0.3, 0.3, 0.3, 0.6, 0.6, 0.6 deg/s) to minimize the arm dynamics. The SRMS was operated in a payload mode with vernier gain selected. The SRMS point of resolution (POR) was set for the middle of the evaporator.

The standard SRMS grapple target was modified (Fig. 3) to improve the operator's angular alignment sensitivity. The SRMS end effector was provisioned with a force/moment measurement device that simulated the JSC/JPL force measurement device scheduled for flight-testing in 1986. The measured forces (*Fx, Fy, Fz*) were displayed on the A_7A_8 digital panel displays (A_1, A_2, A_3) for part of the test series.

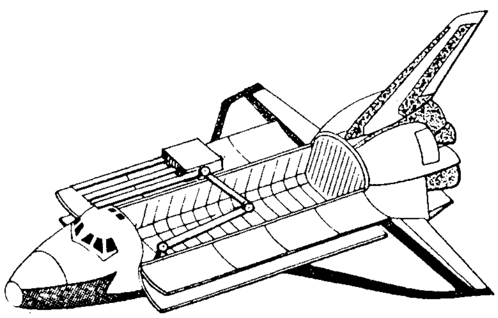

Fig. 2 Mid cargo bay construction site.

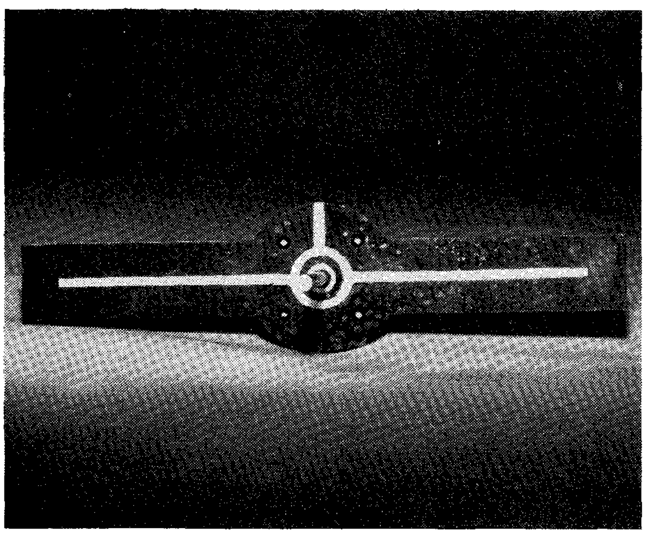

Fig. 3 Modified target.

The SCR boom slot and the modified optical target were mounted on the facility wall structure. The SCR evaporator and SRMS wrist CCTV camera were mounted on the LASS motion base. Figure 4 shows the test setup.

Test Series

In two series of tests conducted, test series 1 used Grumman test engineers; test series 2 used USAF manned spacecraft engineers (MSE).

Both test series used standard operating SRMS procedures for indirect viewing (CCTV). Test series 1 used the optical target as an alignment aid until the leading edge of the evaporator entered the slot. At that point, the force feedback displays were used as an additional alignment guide. The test subjects were instructed to relieve contact of the evaporator and slot, as the force displays indicated, by using SRMS angular commands rather than translational commands.

Test series 2 used only the optical alignment aids. The test subjects were presented with the SRMS wrist CCTV view on one monitor and a split-screen perspective view showing right and left side views of the evaporator entering the slot on a second monitor. The test subjects were instructed to use either angular or translational commands as they saw fit.

Results

In test series 1, the vertical clearance between the evaporator and slot was 0.25 in. and the horizontal clearance was ±1 in. One test subject who completed 6 successful runs was used. Although more test subjects were scheduled, an equipment malfunction, which damaged the force measurement device, prematurely concluded test series 1.

In all 6 runs, the evaporator and slot mated successfully. The tactile sense provided by the force measurement device enabled the operator to detect and relieve any inadvertent touch long before the SRMS joint motors became constrained. Typically, the operator was able to detect a touch before the forces built up to 5 lbf. This capability lessens the burden of angular alignment at the evaporator entrance point.

Test series 2 used the modified SRMS grapple target and an enlarged slot opening. The vertical and horizontal clearances were both ±1 in. All eighteen subjects in test series 2 successfully mated the evaporator and slot. In forty test runs, a touch was recorded in only six runs. In all touch cases, the subject was able to detect the touch by observing the optical cues and relieved the system before the onset of arm constraint.

Candidate Designs

Given the specified tolerances of the RMS, it is possible to construct an error envelope for a given grapple point, of the volume that a radiator element might possibly travel through

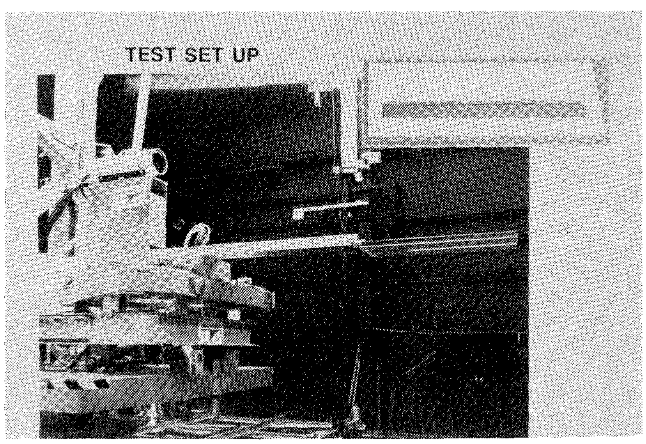

Fig. 4 Test setup—inset shows slot.

during assembly (Fig. 5). This leads to a brute force method of assembly (Fig. 6), wherein spacing between elements and at the connection point (mechanical interface or quick disconnect) is increased to permit assembly of the elements without interference. Clearly, for the specified RMS tolerances, this results in an unacceptably large radiator array and requires a large clearance in the mechanical interface unit. Even for the attainable tighter tolerances, these problems would still be significant. Therefore, several approaches to producing a more compact array were evaluated and are presented in Figs. 7-10.

One of the first methods suggested was the use of edge guides (Fig. 7). This method was eliminated from further consideration after a preliminary assessment indicated that it would complicate structural design, be unable to meet initial assembly and maintenance requirements, and require heavier elements. A more substantial element structural design, implying greater weight, is required to withstand the insertion loads, as well as possible rattling vibrations in the edge guides. A funnel device is still required to introduce the element into the guides. Neither is available for insertion of the first element. Insertion between elements would require further hardware refinements.

Another possible approach is shown in Fig. 8, which has particular application to the disconnect. A rotating fluid seal or flex hose is required. Less attention was given to this approach, as it is not suited to the mechanical interface. It would seem to require a complicated end effector/intricate RMS motions to achieve the required rotation.

During the preliminary assessments, no inherent design flaws were noted in the following two techniques. Therefore, they were placed under active consideration and can be judged on their advantages and disadvantages.

Figure 9 displays a promising technique involving the use of dogleg elements. This method has received much attention, since it promises a simple method of achieving a closely spaced array. Panels on the square boom provide up-and-down guidance, while pins engaging V-shaped slots provide side-to-side guidance. Disadvantages of the dogleg angle include the Shuttle packing penality and the impossibility of meaningful ground testing of the heat pipe. The design could incorporate a flexible section to overcome both disadvantages, but at the cost of increased complexity.

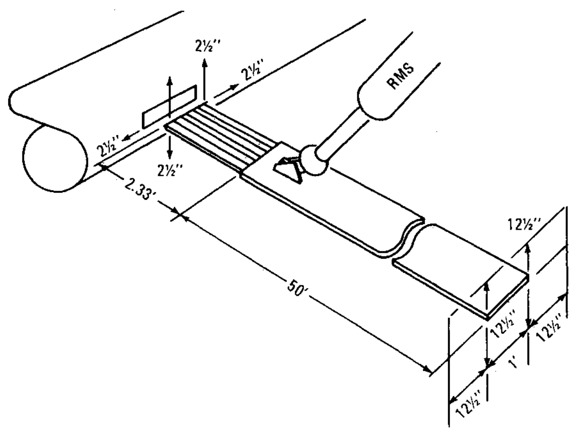

Fig. 5 Error envelope.

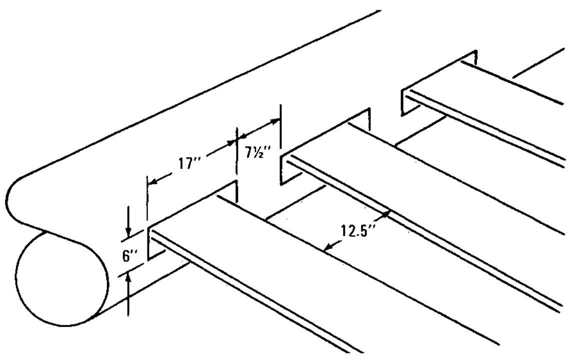

Fig. 6 "Brute force" assembly method.

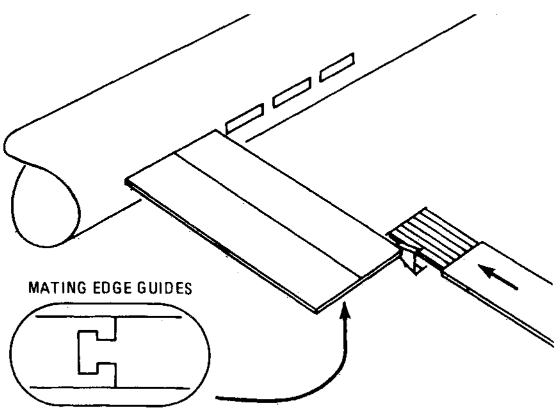

Fig. 7 Edge guides.

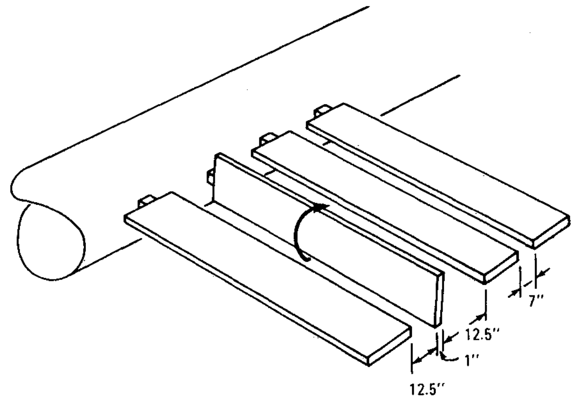

Fig. 8 Out-of-plane insertion and rotation with coplanar axes.

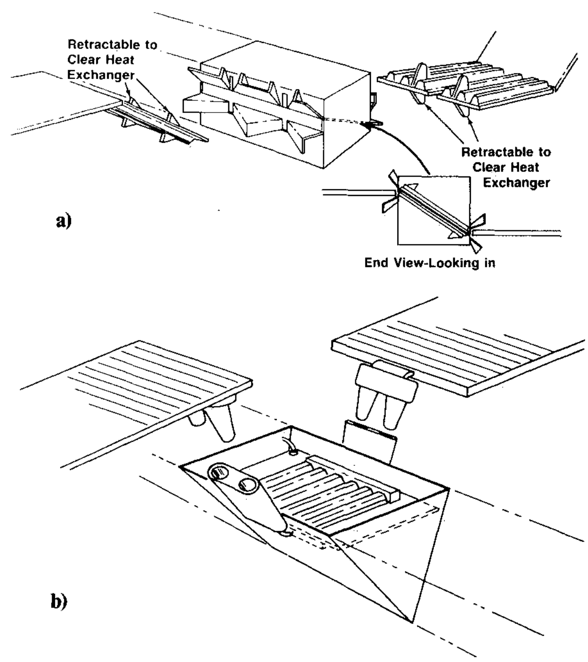

Fig. 9 Dogleg assembly techniques: a) mechanical interface version; b) quick disconnect version.

One-of-plane insertion and rotation employing a reusable tracked device (Fig. 10) would produce a compact array using straight elements, and thereby overcome the packing and ground test difficulties of the dogleg method. Such reusable aids must be fastened to the beam. Otherwise, their location raises the same problems as does that of the SCR elements. Unfortunately, there is additional mechanical complexity in the capturing device, including the need for a retractable bottom lip.

Various other schemes, such as elements which slide in from the end of the boom and mechanical interface units which also act as guides, are possible but quite complex. These would also require extensive design modifications to existing hardware.

The need for a grappling device and end effector is common to all assembly methods. Possible grappling devices include fixed or retractable "handles" or cut-outs in the fin (Fig. 11). The fixed handle results in a packing penality, the retractable handle increases complexity, and the fin cut-out slightly reduces radiator area. For operation without force feedback, end effectors must allow for some misalignment without producing torque saturation. Several approaches are possible, including mechanical ball and socket-type devices or brush-like materials which can distort and reform in response to misalignment forces. The acceleration limiting features of the RMS wrist can also be used as a variable compliance for angular misalignments. Force feedback operation would allow the operator to "feel" the units in place, thus removing misalignments.

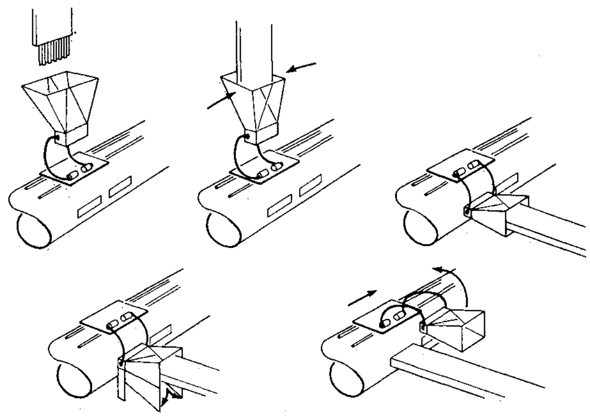

Fig. 10 Out-of-plane insertion and rotation using capturing device.

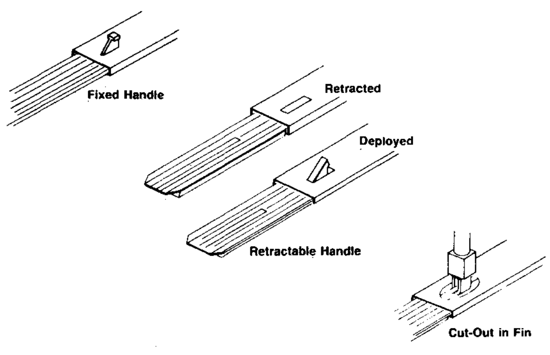

Fig. 11 Grappling fixtures.

The necessity of trading off weight and complexity is also common to all methods. Although weight is always a factor, complexity and reliability appear to be of relatively greater importance.

Future Work

Given consideration of candidate designs and simulation results, several areas requiring future work can be identified. Among these are modifications to the RMS target, additional study of force feedback operation, evaluation of funnel-type alignment aids, and simulation of a heat pipe disconnect assembly. The target employed for the simulations was quite effective in allowing the operator to achieve angular alignment, but was rather complex.

Note that each boom slot requires its own target. A simple painted cross might well suffice for force-feedback operation. Additional study of force feedback is appropriate. Its advantages will probably lead to use in assembly methods employing alignment aids, as the perception of sideward forces will prevent torque saturation of the RMS. Despite the fact that good accuracies can be obtained in insertion simulation, the use of alignment aids may be necessary due to interference between the free portions of the elements.

Conclusions

Candidate designs and initial simulation work indicate that on-orbit assembly of the SCR is feasible. Completion of previously described future work should lead to a preferred design, most likely incorporating alignment aids and force feedback.

Reference

[1]Myers, G. M., "Simulating On-Orbit Satellite Maintenance and Servicing," Grumman Aerospace Corporation, Bethpage, NY, 751-ATD-85-R4, June 1985.