73-ENAs-46

an ASME publication

$3.00 PER COPY
$1.00 TO ASME MEMBERS

Application of Heat Pipes to the ATS F Spacecraft

M. E. BERGER

Principal Engineer
Assoc. Mem. ASME

W. H. KELLY

Thermodynamics Engineer

Fairchild Space and Electronics Co.,
Germantown, Md.

The Applications Technology Satellite (ATS) F heat pipe program is an extensive effort requiring the fabrication and testing of more than 300 flight qualified heat pipes. The spacecraft itself contains 55 heat pipes in three configurations and 13 sizes. The design selected for ATS was an axially grooved 6061 aluminum-ammonia heat pipe. Several developmental programs and extensive testing, including individual heat pipes, heat pipes bonded into honeycomb panels, and a large number of life tests, were included within the overall effort. Results are presented for the thermal modeling of the heat pipes within the sapcecraft. Results of thermal-vacuum testing of a thermal structural model and sounding rocket testing of the ATS axially grooved pipe are also discussed. Several problems, including hydrogen gas generation, were encountered during the course of the program. The steps taken to solve these problems may be applicable to future programs.

Contributed by the Aerospace Division of The American Society of Mechanical Engineers for presentation at the SAE-ASME-AIAA-ASMA-AIChE Intersociety Conference on Environmental Systems, San Diego, Calif., July 16-19, 1973. Manuscript received at ASME Headquarters April 16, 1973.

Copies will be available until May 1, 1974.

Application of Heat Pipes to the ATS F Spacecraft

M. E. BERGER **W. H. KELLY**

1 INTRODUCTION

The Application Technology Satellite-F (ATS-F) is a three-axis stabilized, earth-oriented spacecraft operating at synchronous altitude whose primary objectives are to demonstrate the deployment of a 30-ft-dia furlable parabolic antenna and to provide a stable equipment platform with high pointing accuracy for various scientific and communications experiments. Special interest is focused on the Instructional and Educational television modes, which will provide a signal of sufficient strength to be received in remote and undeveloped areas of the world on low-cost ground station facilities.

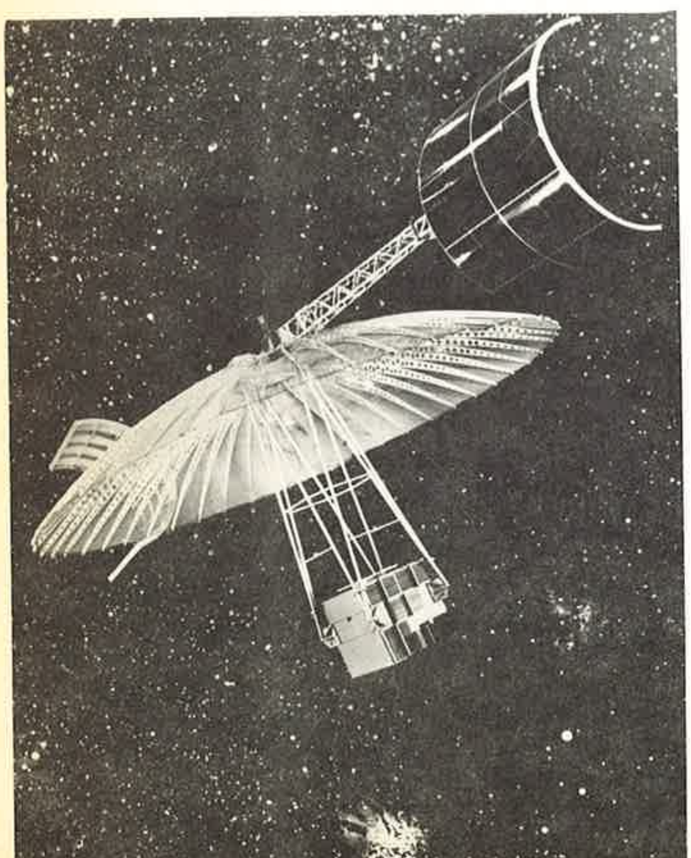

Fig. 1 ATS F spacecraft

The high power, new generation, solid-state transponders and the critical alignment criteria for on-board experiments, together with the wide variation in spacecraft operating power, led to the development of an active thermal control subsystem which features heat pipes as an integral part of the basic satellite structure. Fig. 1 is a picture of ATS-F in the deployed configuration and illustrates the main elements in the spacecraft: a 30-ft antenna, solar arrays and support hardware, antenna support truss, and the Earth Viewing Module (EVM).

The EVM, a 5-ft cube weighing 1800 lb, is the heart of the ATS-F spacecraft and is essentially three separate compartments, or modules, which can be assembled individually and then integrated into a complete structure. The uppermost compartment, facing the reflector, is the communications module and contains all the high power transponders and an ion engine thruster experiment. The middle compartment, the service, or housekeeping module, contains the spacecraft telemetry transmitters and the propulsion system. The bottom compartment, the experiment module, contains the spacecraft batteries, radiom-

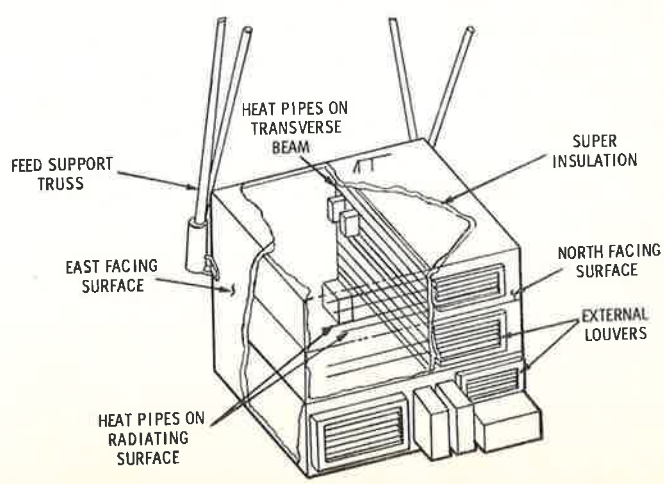

Fig. 2 EVM thermal control subsystem

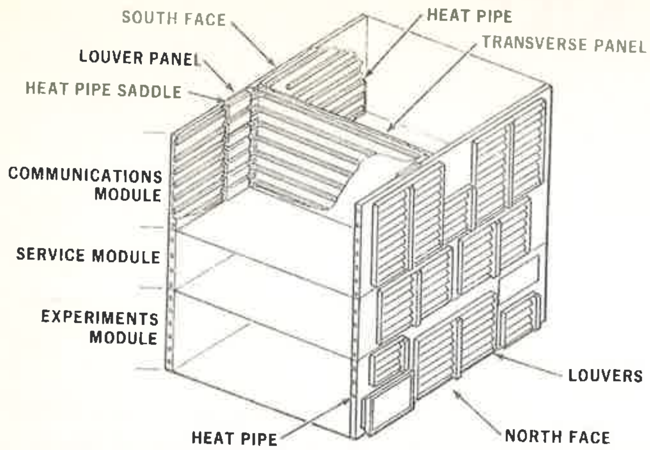

Fig. 3 Primary thermal control system

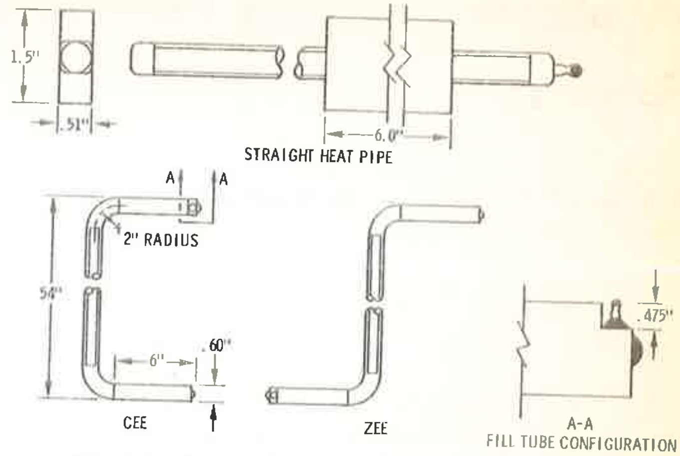

Fig. 4 ATS heat pipe envelope drawing

eter, and millimeter wave experiments.

The thermal control subsystem is shown in Fig. 2, which identifies the elements used: (a) multi-layer insulation, thermal louvers, and heat pipes. The orbit configuration of ATS-F is such that the only two surfaces suitable for heat rejection are the North and South facing sides. The remaining four sides always have a solar input during each orbit and hence are covered with multilayer insulation. Thermal louvers are employed on the North/South faces to vary the emittance on these surfaces. Optical solar reflectors are the thermal control surface used behind these louvers, which are bimetallic actuated.

The localized high power dissipation densities associated with solid-state transponders dictated a thermal design which would effectively remove heat from these devices and yet be compatible with the rest of the spacecraft. A matrix of heat pipes, as shown in Fig. 3, was employed as a means of smoothing out the high power density regions and using a larger effective radiating area. In addition, the orbit inclination of ATS-F produces a solar heating load on the North/South prime radiating areas during the solstices and also during spacecraft offset point conditions. Heat pipes are utilized to provide a cross-coupling between the North and South faces so that the incident solar load on one face is transported across the width of the EVM and radiated out the other face which is in shadow.

2 HEAT PIPE DESIGN

Dynatherm Corporation, Cockeysville, Maryland, was selected as the subcontractor for

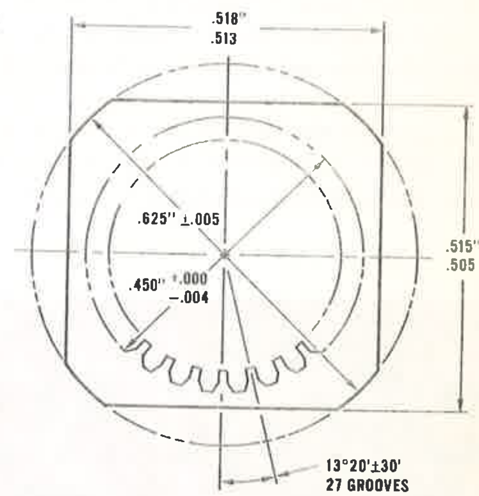

Fig. 5 ATS F&G groove heat pipe design

the ATS heat pipes and has been responsible for their design and fabrication. The design was consistent with an envelope drawing and specifications supplied by Fairchild Industries. Three basic heat pipe configurations are required by the thermal control subsystem (TCS): Cee, Zee, and straight, Fig. 4. A ship set complement of heat pipes consists of 55 heat pipes in 13 different sizes. The axial groove was specified for the wicking system since this design was considered the most reliable and most representative of the state-of-the-art at that time. From the program point of view, experience gained throughout the program more than reinforced the decision not to use an artery or other composite wicking system. Five ship sets of heat pipes were required for the ATS program: Thermal Structural Model (TSM),

Table 1 ATS Heat Pipe Design Requirements

Configuration	Figs. 4 and 5
Thermal performance	
Straight pipes:	
Heat load	60 w
Input/output	12-in. evaporator/remainder of heat pipe condenser
Transport capability (maximum)	1500 w-in.
Cee and Zee pipes:	
Heat load	20 w
Input/output	6-in. evaporator/6-in. condenser
Transport capability	1250 w-in.
All pipes:	
ΔT — total	Less than 10 F (maximum evaporator to minimum (condenser)
ΔT — within evaporator	3 F maximum
ΔT — within condenser	3 F maximum
Tilt	Evaporator elevated 0.1 in.
Ammonia purity	99.995 percent
Maximum liquid slug length	1 in.
Pressure	1700 psia at 270 F
Operating temperature	41 to 104 F
Qualification temperature	-4 to 149 F
Weight	0.2 lb/ft
Straightness	0.010 in./ft
Operating life	2 to 5 years
Reliability goal	0.99999 for 2 years
Vibration (all axes, qualification only)	
PSD level	0.001 to 0.16 g^2/Hz at 20 to 250 Hz; 0.16 g^2/Hz at 250 to 2000 Hz
Overall acceleration	17.0 g — rms at 20 to 2000 Hz

TSM Spares, Prototype, "F," and "G." With the cancellation of the "G" spacecraft, the Flight "G" heat pipes have become Protoflight "F" spares for use in backup, or spare, modules. Thus, along with engineering models and other spare heat pipes, more than 300 heat pipes have been fabricated and tested for the ATS program.

The ATS heat pipe design requirements are listed in Table 1. The axial groove geometry design that was selected to meet the requirements is shown in Figs. 5 and 6. Predicted performance in a zero-g environment is shown in Fig. 7. It is noted that the final ATS design is not that obtained by the usual optimization process; instead, the selected design was a compromise to accommodate the fabrication of the thick-walled grooved tubing required for producing the "square" heat pipes. The referenced OAO groove design, Fig. 7, is that of the axially grooved heat pipes used on the OAO-C spacecraft.[1] The ATS heat pipe consists of 27 grooves, each approximately 0.026 in. wide and 0.040 in. deep.

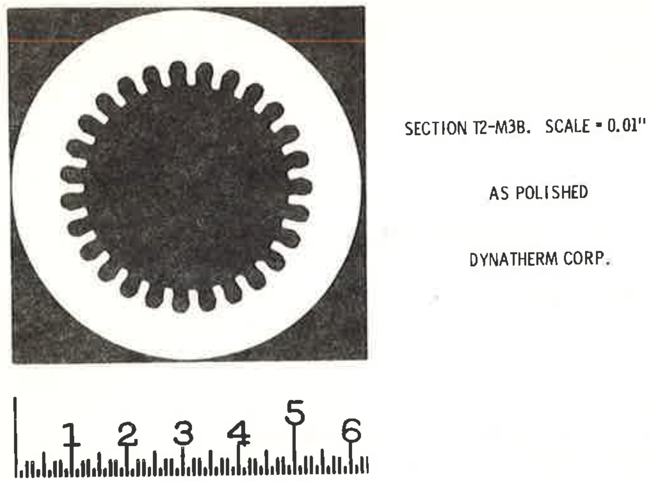

Fig. 6 Grooved tubing cross-section

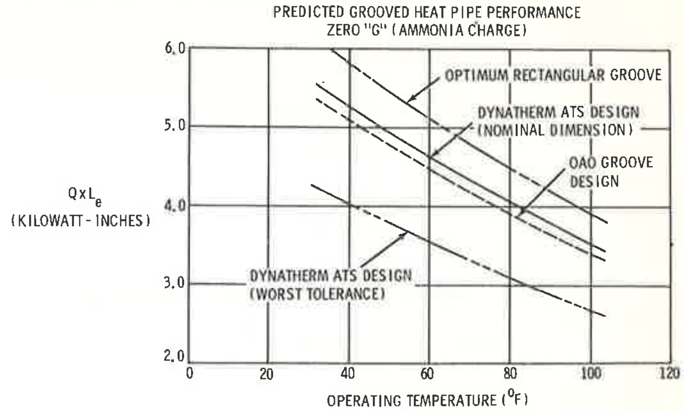

Fig. 7 ATS grooved heat pipe performance

The vapor core diameter is approximately 0.367 in. in diameter, and the land width between the grooves is approximately 0.017 in.

3 HEAT PIPE FABRICATION AND TESTING

The ATS heat pipes are fabricated from axially grooved 6061 aluminum tubing with anhydrous ammonia as the working fluid.[2] In fabrication and testing, the heat pipes are treated as any other component on the spacecraft; i.e., they are not accorded any special status, except that the operating temperature range is extended ± 5 C beyond that of other internal spacecraft components.

The fabrication and testing process flow diagram is shown in Fig. 8. Extensive cleaning of the heat pipe is required due to large amounts of lubricants imbedded in the tubing surface. Special care is given to removing all possible water from the pipes because of corrosion during heat treating with subsequent generation of non-condensable gas due to the presence of the hydrated aluminum oxide. These phenomena are discussed further in Section 8.

The heat treating of the heat pipes to a T6 condition is required to provide sufficient strength to survive the proof pressure and panel bonding cycles. Each heat pipe is proof pressure tested at 1700 psi and 270 F for 2 hr to provide a rupture safety factor of 2.1 over the internal pressure and temperature during bonding of the honeycomb panels. The bonding of the honeycomb/heat pipe panels is at 225 F for 1.5 hr at which time the internal pressure is 1050 psia. The heat pipes are heat-treated after all welding of saddles and end caps is performed to obtain additional margin on the burst strength. Thus, the only non-heat-treated weld is the final pinch and seal weld. A unique feature of the heat treating of the ATS heat pipes is that the pipes are heat-treated in a closed, evacuated condition. Since the pipes have been through all cleaning processes at the time of heat treating, they must be sealed to prevent water from being sucked into the pipe during quenching. In addition, the pipes must be evacuated to prevent the pipes from rupturing during solution-treating at 980 F since the air, if left in the pipe, would be at high pressure while the heat pipe is at zero strength. In order to insure that proper heat-treating has been performed, a burst sample is processed with each heat-treat lot. This is in addition to normal Rockwell hardness testing. The burst sample is actually a miniature heat pipe, 9 in. long, that is filled with ammonia and burst by wrapping with a heater and elevating its temperature. The temperature and pressure of rupture can be correlated to the degree of heat treatment. At present, all samples have ruptured in the pipe wall which gives added confidence in the weld and fill tube design.

At the start of the program, the saddles were originally dip-brazed to the pipes. Since dip-brazing occurs at a temperature close to the melting point, 1100 F, this process was per-

[1] Bilenas, J. A., and Harwell, W., "Orbiting Astronomical Observatory Heat Pipes—Design, Analysis, and Testing," ASME Paper 70-HT/Sp T-9, presented at the Space Technology and Heat Transfer Conference, Los Angeles, Calif., June 1970.

[2] Tubing was supplied by Noranda Metals, French Tubing Div., Newtown, Conn.

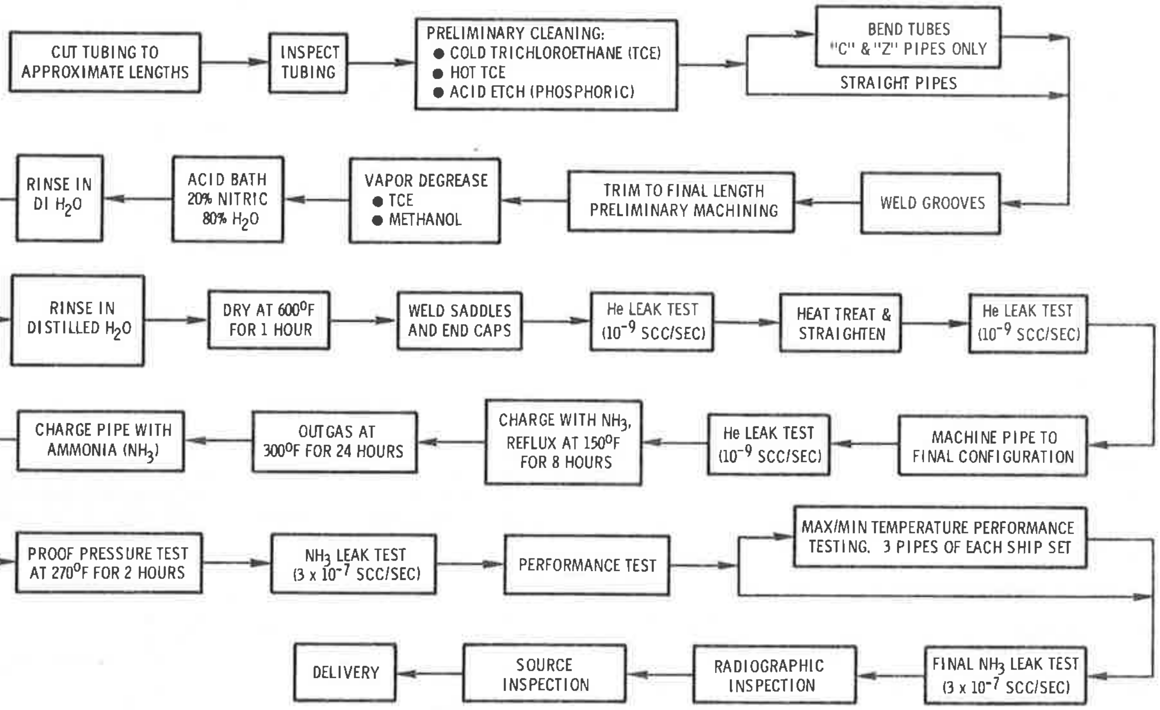

Fig. 8 Heat pipe fabrication and testing process

formed with the tubes open and prior to final cleaning. However, the brazing salts were extremely difficult to remove from the interior of the tube, and, after one heat pipe developed gas from reactions with residual salts, this process was abandoned in favor of a TIG weld. Two sets of heat pipes, TSM and TSM spares, were fabricated with brazed saddles before this problem was discovered and corrected.

Each heat pipe is selectively filled since an extensive fill-development program showed that, even though tight tolerances are maintained on the tubing manufacture, the groove area can vary by as much as 20 percent. Prior to cutting a tube to its final length, a 1-in. sample is taken from each end. This sample is enlarged on a 20:1 optical comparitor, and the outline of the groove area is traced. The tracing is then integrated with a polar-planimeter to obtain the groove area. Using the average area of the two end samples, the fluid inventory is calculated such that the grooves are completely filled with liquid at 104 F with an overcharge equivalent to the mass of the vapor in the vapor core at 41 F. With this fill criterion, the heat pipes will have, in the worst case, 90 to 100 percent of maximum performance capability over the operating range of 41 to 104 F, with zero slug formation under the specification heat loads. When operating at the maximum power levels, the heat pipes will have a maximum liquid slug less than 1.5 in. at 104 F. The correct charge in the heat pipes is obtained by weighing, before and after filling, to an accuracy of 0.1 gm.

Prior to manufacturing the first set of heat pipes, a series of tests were made on a preprototype and three engineering model heat pipes to qualify the design and to obtain various performance parameters. In addition, several burst samples similar to the heat treat samples were destroyed to qualify the weld design. The preprototype heat pipe was 60 in. long and was left in the round configuration. This heat pipe was used to determine the evaporator and condenser film coefficients and to establish baseline data for tilt testing. An evaporator film coefficient of 925 Btu/sq ft-hr-deg F and a condenser film coefficient of 1500 Btu/sq ft-hr-deg F based on the inside diameter, were measured for the ATS design. The maximum wicking height was established as approximately 0.4 in. Zero "G" performance data was obtained by extrapolating tilt test data to zero tilt. For the preprototype, this yielded a transport capability of 4800 w-in. at 55 F and 4200 w-in. at 100 F. The lower temperature data agrees with analytical predictions, but the 104 F data

Table 2 Weld Development Burst Test Results

Sample Description	Burst Temperature, deg F	Computed Burst Pressure, psi
Tube as — received condition	320	2200 psi
Sample heat treated to T6 after welding	420	3000 psi
Sample heat treated to T6 prior to welding	350	2300 psi

exceeds predictions by 20 percent. This latter discrepancy was attributed to 1- "G" puddling of the liquid due to an overfill condition at the higher temperature.

The engineering model heat pipes consisted of a 50-in. straight, one Cee, and one Zee pipe. These heat pipes were used to qualify the design and the fabrication process and to provide engineering data on the performance of the ATS heat pipes. The data from these heat pipes and that of subsequent acceptance tests showed that the maximum-to-minimum temperature difference under specification heat loads for the ATS heat pipes is about 6 F. In addition, the data also indicate that the average gradient within both the evaporator and condenser is about 1.5 F.

The preprototype and engineering models were also useful for determining the maximum radial heat flux when the heat is applied only on one side of the heat pipe. This is the typical condition within the spacecraft. An analytical model of the heat pipe cross section showed that there is azimuthal fin effect factor of 1/2.23 when heat is applied in this manner. Combining this with test results yielded a maximum radial heat load of 23 w/linear-inch for the ATS heat pipes. The maximum condition experienced within the spacecraft is 5 w/linear-in.

In order to qualify the weld design, a series of burst samples were fabricated and destroyed. The results of these tests are given in Table 2. The data demonstrate the added margin that is gained by heat-treating the tubes after welding. The data from the heat-treat burst samples has also been representative of that of the maximum in the table. The computed burst pressures, based on minimum material properties, have been determined and are shown in Fig. 9. Comparison of the weld development test results with those in the figure indicate that the heat-treating process of the ATS heat pipes is sufficient to yield better than minimum properties. To date, three heat pipes have burst during the 270 F proof pressure cycle. These pipes were all from the TSM and TSM Spares sets. After fabrication of those lots, approximately 0.008 in. was added to the minimum wall thickness with the result that no subsequent heat pipes have burst.

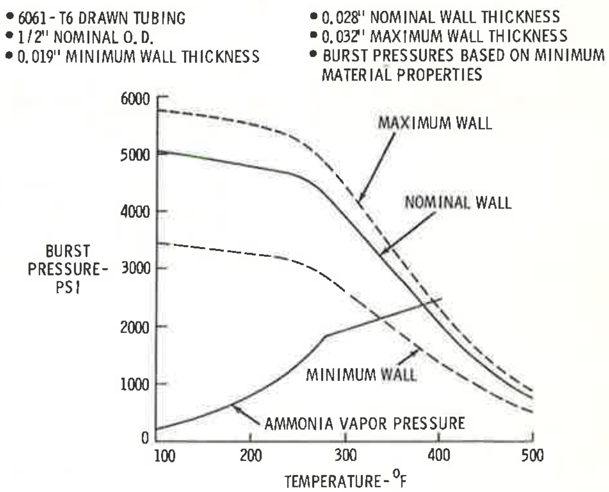

Fig. 9 ATS F&G heat pipes computed burst pressures

4 INTEGRATION OF HEAT PIPES AND PANELS

The utilization of heat pipes was studied extensively during the ATS-F proposal effort and subsequently after the award of contract. The basic concept of the thermal control subsystem design remained unchanged, but many trade-offs were considered with regard to the method of attachment and incorporation of the heat pipes into the spacecraft structure. Essentially, all attachment conceptual designs were divided into three categories:

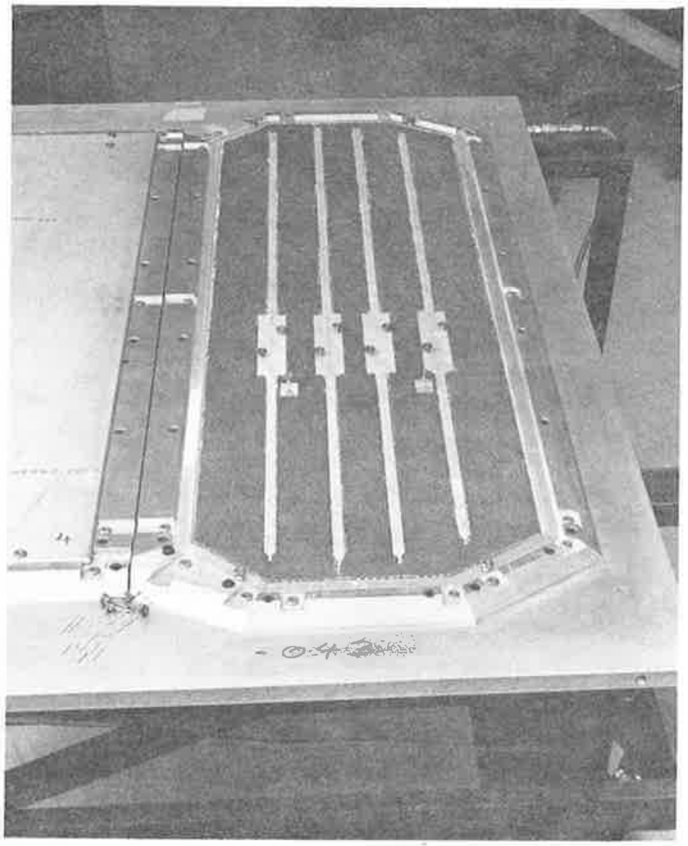

Fig. 10 Service module panel prior to bonding

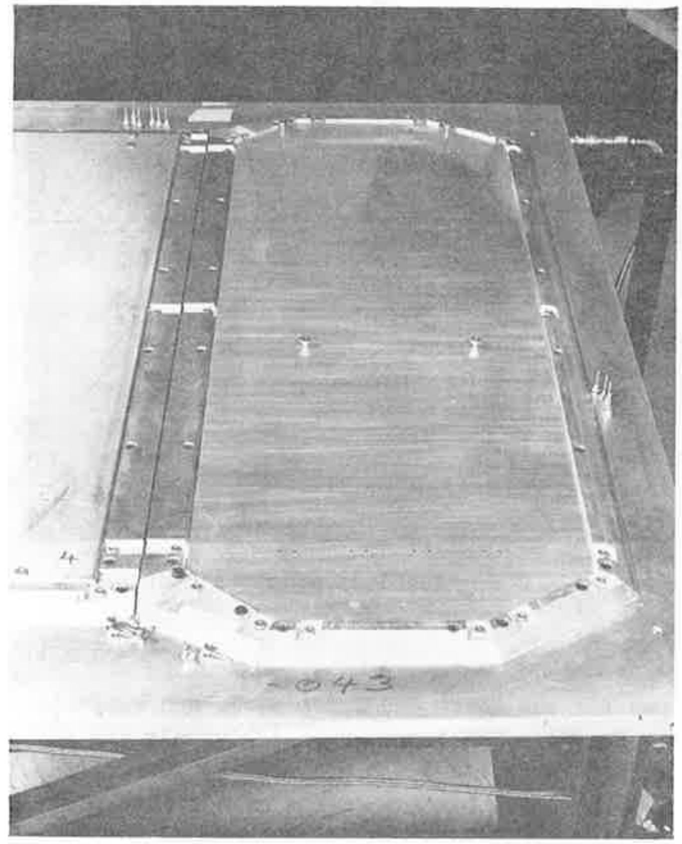

Fig. 11 Completed service module panel

1 The heat pipes were clamped mechanically to the external honeycomb panel surface.

2 Hollow tubes were pre-bonded into the honeycomb panels and the heat pipes slipped into these hollow tubes.

3 Heat pipes were bonded directly into the honeycomb panels.

Design concept (1) offered a relatively simple mechanical attachment method plus the added feature that an individual heat pipe could be removed from the spacecraft if it were inoperable. The disadvantages were an unworkable interface with regard to mounting other components or thermal control surfaces (such as OSR's) over these mounted pipes whether they were internal or external to the spacecraft, and the difficulty of providing adequate conduction paths between the heat pipe, component, and radiating surface.

Concept (2) provided an improvement in the utilization of mounting surface area and also allowed the replacement of a defective heat pipe at any time prior to spacecraft launch. The chief disadvantage of this design was the problem associated with providing an efficient and effective heat-transfer path between the dissipating electronic components and the heat pipes. It was found that the thermal resistance incurred at the various interfaces in this concept more than offset the advantages gained by using heat pipes.

The remaining design concept (3) was chosen for use primarily because it was the most efficient design in terms of thermal performance. In addition, it does not impact the location and mounting of components to any significant extent. The most serious drawback to this design is the lack of replaceability of a damaged or defective heat pipe once the panel has been bonded. A secondary disadvantage is the high pressure (1050 psia) experienced in the heat pipes during the bonding process. This results in a weight penalty by requiring heavier pipe walls.

Fig. 10 is a picture of the bottom honeycomb face sheet, honeycomb core, and heat pipes in the panel bonding fixture prior to the addition of the top face-sheet. Fig. 11 shows the same panel in the finished condition after removal from the bonding tool. Nine panels are laid up in this manner; six contain straight

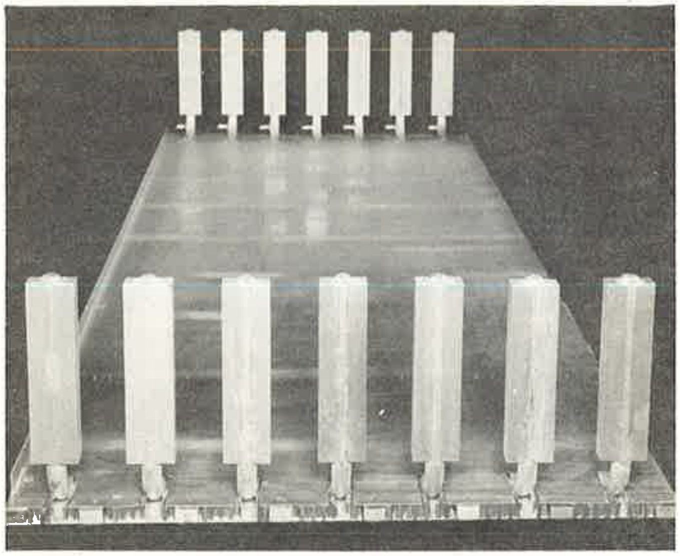

Fig. 12 Communications module center panel

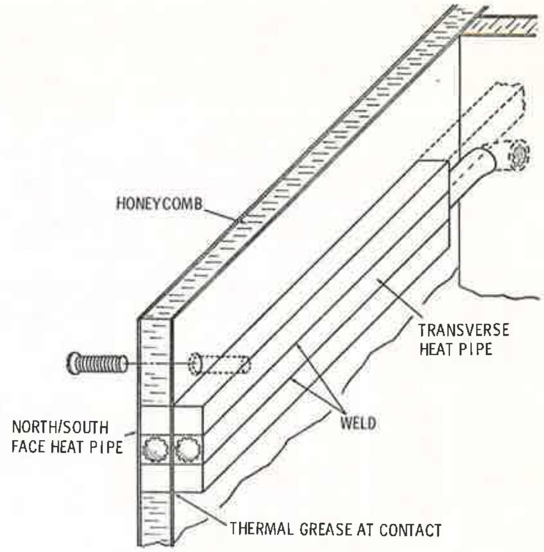

Fig. 13 Heat pipe overlap section

pipes for the North and South faces and resemble this figure. The three remaining panels are the transverse beams and are used to connect the North and South panels. These panels have heat pipe overlap sections at either end and are in the shape of a "C" or "Z", Fig. 12.

The honeycomb panel thickness is 0.5 in. with face sheets of 0.025-in. 2024-T81 alloy aluminum, except in the communications module where the inner face-sheet is 0.050 in. thick. The honeycomb core density is 3.1 lb/cu ft, and the bonding adhesive used is HYSOL EA9601, with a bond temperature of 225 F and a cure time of 1.5 hr.

The vertical spacing of the heat pipes in the honeycomb panels (i.e., the number of pipes per panel) was the result of a parametric study involving maximum allowable panel temperature gradient, heat transport capability, thermal subsystem weight, clearance between pipes to locate component mounting inserts, and redundancy of the heat pipe network to preclude having to remove and replace an entire panel in the event of any one heat pipe failure. The spacing arrived at for ATS-F is pipes on a 3-in. centerline. (This varies in some cases due to shifting a pipe slightly to better locate a spacecraft component.) This spacing results in 13 sets of "triplet" heat pipes layered from the bottom of the spacecraft to the top for a total of 55 pipes (there are four short pipes due to a large panel hole in the communications module).

A careful look at Fig. 10 (prior to bonding) and at the panel edges in Fig. 12, will reveal 6-in. long "saddle blocks" which are 1.5 in. wide and welded to the heat pipes. These "saddle blocks" are used to provide the heat-transfer path from the North and South panels to the transverse panels. Fig. 13 is a detailed view of a typical interface. This design provides a good mechanical and thermal interface (thermal grease is used between the surfaces). An experimental value for the thermal conductance across this "saddle block" interface is 2.3 w/deg F. Another advantage of this interface design is that it provides a margin in performance in the event of gas buildup or excess liquid slug buildup in the heat pipe ends. This latter factor has provided a gratifying increase in the ability of the heat pipes to transport heat from one side of the EVM to the other despite a gas or liquid slug but at the same time has proved to be a tremendous obstacle in determining the amount of gas in the pipes prior to bonding. The "saddle block" has the tendency to "wash-out" the temperature gradient in the immediate vicinity of the gas or liquid slug.

5 THERMAL ANALYSIS OF HEAT PIPES IN EVM

The requirements to determine temperature gradients on the order of 10 F and to accurately predict the localized "hot spot" temperature beneath high-powered components led to the development of a sophisticated thermal math model of the heat pipe/honeycomb panel structure. As anticipated, the thermal modeling of the heat transfer from the heat pipe to the radiating panel proved to be the most complex part in the development of this math model.

After several preliminary models in which an attempt was made to model the heat pipes using a large conductance value along the length, it was decided that a more realistic model could be developed if a radial heat pipe conductance, or film coefficient, was used. Using this approach, the heat pipe vapor temperature is assumed to be constant throughout the pipe and heat transfer from the panel to the vapor is accomplished by using an effective conductance which is based upon heat pipe test data and fin effectiveness of the pipe walls. While this modeling technique has proved to be very effective, the complexity introduced by the number of nodal points needed for the ATS thermal control subsystem has made this math model very cumbersome to use. At present, the math model consists of over 2000 nodal points developed for using CINDA on an IBM 370-145 computer.

The temperatures predicted by this large math model and by smaller math models of individual panels using an "effective" film coefficient for the heat pipes correlate very well with test temperatures. Typically, agreement between analytical and test results is excellent (within 2 F) insofar as predicting panel temperature gradients is concerned. One important result of the large model was the observation that it is virtually impossible to detect a malfunctioning heat pipe. The cross conduction coupling between the heat pipes due to the thickness of the honeycomb face-sheets (0.025 to 0.050 in.) tends to "wash out" the individual heat pipe temperature gradient caused by gas generation or other failure mechanism.

The detection of gas or substandard performance in the transverse beam heat pipes is similarly impacted by the "saddle block" design. While these "saddles" are very effective in providing sufficient heat transfer at the heat pipe interface, a "masking" of the temperature gradient is produced which makes gas generation in the pipe very difficult to detect.

6 HEAT PIPE TESTING

Acceptance Testing

Prior to being accepted for use on the spacecraft, each heat pipe must undergo a series of tests to insure that all specifications are met. These tests include leak, proof-pressure, performance, and radiographic tests. In addition, three heat pipes out of each ship set undergo a burnout versus tilt test to furnish engineering data.

Three leak tests are being used to establish that the specification leakage rate of 3×10^{-7} scc NH_3/sec. is being met. Prior to filling the heat pipe, all weld zones are checked with a Veeco helium leak detector to a sensitivity of 10^{-9} scc He/sec. Any indication of a leak is cause for repairing (prior to final machining) or rejection. After making the final seal weld, the fill tube is immersed in 10 cc of 10^{-6} N HCL for 33 min. The pH of this solution is measured before and after immersion to verify that the leak rate is less than the specified limit. The third leak test is performed after all other testing. This test, known as the ammonia leak test, was developed by Goddard Space Flight Center (GSFC). In this test, the weld areas of the heap pipe are wrapped with filter paper which has been treated with an 87 percent distilled water, 10 percent ethylene glycol, and 3 percent copper sulfate solution. The filter paper is sealed with a plastic bag and left for 4 hr. Dark blue spots appearing on the paper indicate leak rates greater than 3×10^{-7} scc NH_3/sec. The sensitivity of this test can be increased to about 10^{-8} scc NH_3/sec by further treating of the filter paper with Nestler's Reagent, but the interpretation becomes more difficult.

The proof pressure test, in which the heat pipes are temperature cycled to 270 F $\pm$ 5 F for 2 hr, has already been described. Failures during this test are quite audible and apparent.

The performance testing is slightly different for straight heat pipes and Cee and Zee heat pipes since the requirements are slightly different. In both cases, heat is applied and removed only on one side of the heat pipe, typical of that in the spacecraft. Heat is supplied by cartridge heaters imbedded in aluminum blocks of the appropriate evaporator length. This evaporator, floating with respect to the test fixture, is securely clamped to the heat pipe with an aluminum-filled thermal grease interface. A temperature-controlled water/ethylene glycol solution is pumped through fixed aluminum condenser blocks of the appropriate size which are clamped to the heat pipes in a similar manner. Eight chromel-alumel thermocouples measure the temperature distribution along the pipe by a spring-loaded pressure contact. Three thermocouples are located in both the evaporator and condenser and two thermocouples measure the transport temperature. In the evaporator, the thermocouples are located 1 in. from the ends with one in the center. In the condenser, the thermocouples are located 0.5 in. from the ends with one in the center. Temperatures are recorded when equilibrium, determined by a tem-

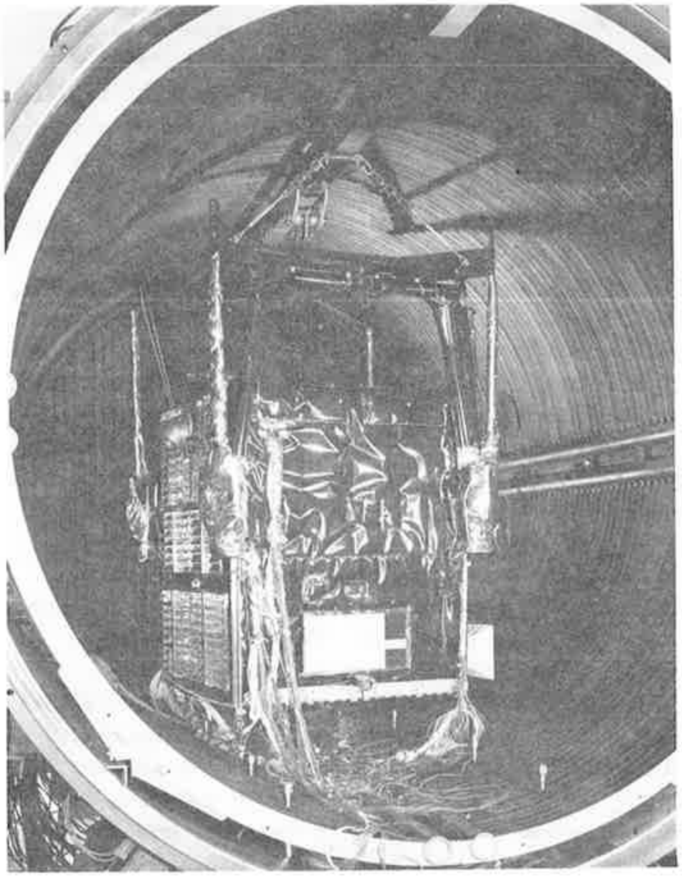

Fig. 14 TSM in vacuum chamber

perature change of less than 0.5 F in 20 min., has been established. The identical setup is used for the burnout tests with the evaporator end of the test fixture being raised to the desired tilt.

After performance testing, two perpendicular X-rays are made of each weld; these are inspected to verify that no defects are present.

Sounding Rocket Testing

The ATS axially grooved heat pipe has been successfully flown on a sounding rocket and the results have previously been reported.[3] The data indicate that the heat pipe performed as expected for about 5 min. in a zero "G" environment. Further ATS heat pipe sounding rocket experiments to verify predictions of the variation of performance with liquid charge are planned by GSFC for the summer of 1973.

[3] McIntosh, R., Knowles, G., and Hembach, R. J., "Sounding Rocket Heat Pipe Experiment," AIAA Paper 72-259, presented at the Seventh AIAA Thermophysics Conference, San Antonio, Tex., July 1972.

TSM Test

A full-scale thermal/structural model of the ATS spacecraft EVM was fabricated with the full complement of heat pipes, Fig. 14. Electronic components were simulated by dummy boxes having realistic weight and power dissipation densities. Orbital conditions were simulated by using both IR heater blankets and IR radiators to provide the solar input and component dissipation. The spacecraft operating modes that were tested were those which provided a large imbalance of power in the spacecraft. This provided a meaningful test for the heat transport capability of the transverse heat pipes in that if they were not at least 75 percent within their operating specification, the side of the EVM with the high power dissipation would not stay within the 5 to 35 C design range of the thermal control subsystem.

Thermocouple locations were chosen so as to completely instrument several heat pipe sections in order to estimate the amount of heat that the pipes would be transporting under worst case orbital conditions. In addition, an effort was made to locate temperature sensors so that an indication might be given if a heat pipe were not performing per component specifications. As a part of this effort, a special test was performed which was not a spacecraft operating mode in that a severe imbalance of power was created between the North and South faces of the EVM so that the heat pipes would be forced to work with a larger heat load.

The results of the TSM testing proved to be more satisfactory than the large thermal model had predicted. The maximum gradient on a given panel was measured to be no more than 10 F. It should be noted that it was physically impossible to locate thermocouples in the exact spot where the very high power densities occur beneath some of the electronic components; hence, the large thermal math model obviously predicted higher temperatures. The maximum gradient from one side of the EVM to the other was also on the order of 10 F which demonstrated the effectiveness of the heat pipe "saddles" in providing an adequate heat-transfer path at the interface between the heat pipes.

As mentioned previously, the inability to adequately identify a heat pipe with substandard performance was also demonstrated during this test. In addition to the conduction coupling between the heat pipes, the effect of the thermal louvers which have temperature actuated blades (ATS has over 150 pairs of individually activated louver blades) tends to compensate for a below-par heat pipe. It was determined from

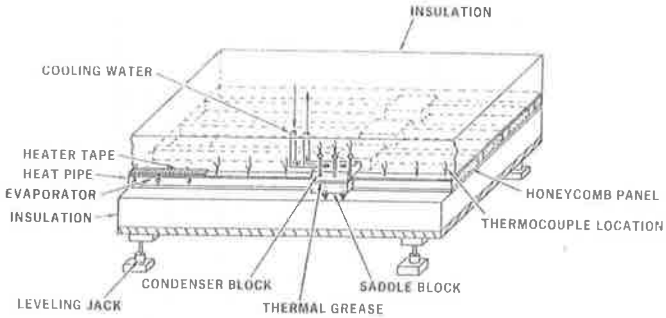

Fig. 15 Performance test configuration for north and south honeycomb-heat pipe panel

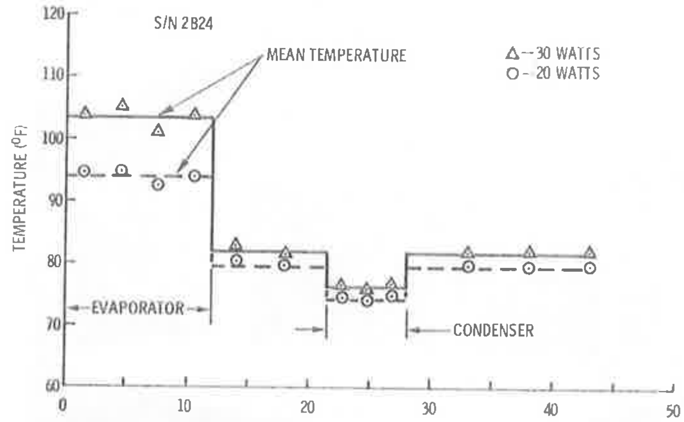

Fig. 16 Typical test results for a north/south heat pipe panel test

this test and subsequent thermal modeling that perhaps a completely bad heat pipe could be detected in some locations, but that in general, two adjacent heat pipes would have to fail before detection.

7 VERIFICATION OF HEAT PIPE PERFORMANCE AFTER INTEGRATION

Once the heat pipe panels are assembled into a module, the testing of the heat pipes becomes very difficult due to the redundancy of the system. However, tests have been performed on the heat pipes in the panels prior to module assembly. These tests have been performed for acquisition of engineering data and are not part of the normal spacecraft test program. For panels containing straight heat pipes, the panel is placed on a flat insulated bed in a horizontal plane. Provision can be made for elevating either the evaporator or condenser end of the panel. The heat pipes can be located in the panels by the tooling holes used in holding the pipes during bonding. A 0.5-x 12-in. strip heater is attached to the panel directly above one end of the heat pipe. A 1.5 x 6.0 x .125 in. condenser block, cooled by a running water/ethylene glycol solution, is bolted to the panel directly over a heat pipe saddle using tooling holes within the saddle. Ten thermocouples are attached to the panel over the heat pipe with aluminum tape. Both the evaporator and condenser have three thermocouples. The entire panel is then insulated with fiberglass wool. A schematic of the test setup is shown in Fig. 15. A typical temperature distribution as measured on the panel is given in Fig. 16. These results are in good agreement with an analytical model of the test configuration.

Similar fixturing is used for verifying the performance of the Cee and Zee heat pipe panels. In this case, however, the heat is applied and removed from the saddles which are readily accessible. Since the panel must be vertically oriented to maintain each heat pipe in a single plane, 2-in.-thick styrofoam insulation was used to provide support. All of the heat pipes were tested simultaneously, and each condenser can be "tuned" to isothermalize the panel to minimize heat transfer within the panel. Fig. 17 is a photograph of the test configuration using a center panel from the communications module. This test fixture has been primarily used to check heat pipes for non-condensable gas.

8 PROBLEM AREAS

The ATS heat pipe program has not been without its problem areas. Most of these problems can be attributed to the high temperatures encountered during heat treating and proof pressure testing which are direct results of the high-strength requirement for bonding. It is believed that the solution to at least one of these problems, the ATS fill development program, is a basic contribution toward advancing the state-of-the-art of grooved heat pipe technology. The purpose here is to present the problems and the action taken to arrive at satisfactory solutions.

Concentricity

The first major problem encountered during the program was that of excessively large eccentricity of the vapor core with respect to the tube outside diameter. Concentricity deviations as large as 0.016 in. were observed. This resulted in unusually thin-walled heat pipes, about 0.014

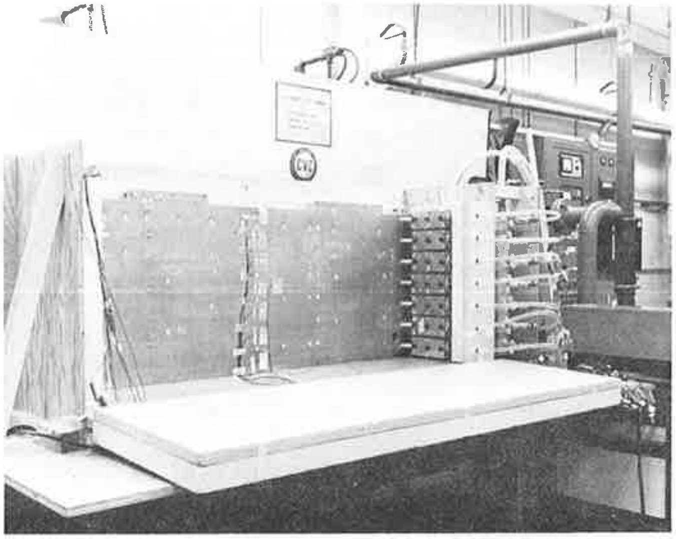

Fig. 17 Test configuration for Cee and Zee heat pipe panels

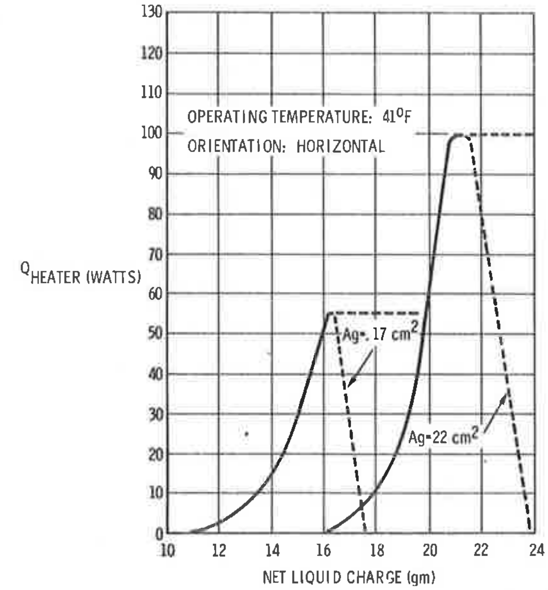

Fig. 18 Computer prediction for ATS "C" heat pipes with large and small groove area

in., which would rupture during proof pressure testing. This problem was solved by increasing the heat pipe width by an average of 0.008 in.

Fill Development

During acceptance testing, it was noted that a Zee heat pipe would only carry a 10-w heat load prior to burning out. A check of the quality log showed that this heat pipe had been underfilled by 1.0 gm. Since this pipe was less than 5 percent undercharged, the low transport capability raised serious questions. Up to this point, all heat pipes were charged to the same groove area obtained from measurements on several samples. The charge criterion was to fill the pipes so that the grooves are completely filled with liquid at 68 F with extra fluid to account for the vapor. After careful measurement of several additional samples, it was determined that the groove area was varying as much as 20 percent between heat pipes. Thus, a thorough analytical and experimental study was undertaken to determine the sensitivity of the grooved heat pipe to the charge and to establish a fill criterion for the ATS heat pipes. The analytical results of this investigation showed that the axially grooved heat pipe is very fill sensitive, and the performance can drop from the maximum to zero with a corresponding undercharge of about 15 percent. An example of this sensitivity is shown in Fig. 18. The 1 gm undercharge coupled with a large groove area was sufficient to cause the reduced performance capability of the failed heat pipe.

Two 66-in. Cee heat pipes were used to experimentally establish the variation in heat pipe performance with fluid inventory. Good agreement with the analysis was obtained. Upon completion of the testing, the heat pipes were sectioned every 6 in. and the groove area was measured. Maximum variation along the pipes was 7 percent. Based on the results of the fill development program, the fill criterion described in Section 3 was implemented. It is anticipated that this study will be described in detail in a future paper.

Leaks

After changing to the welding technique of attaching saddles to the heat pipes, a considerable number of leaks were observed in this weld zone. These leaks almost always occurred after the proof pressure cycle. Metallurgical evaluation of the problem determined that the leaks resulted from microcracks caused by welding 6061-T6 saddles to the workhardened 6061 aluminum tubing. This leak problem was resolved by stress-relieving both tubing and saddles at 600 F for 1 hr prior to welding.

Black Residue and Corrosion

Sectioning of several heat pipes prior to filling revealed a dark, tenacious "residue" on the inner surface. This condition was always noticed after heat treating. The color of this residue was usually a deep black, although it varied from a light golden brown to iridescent black. It was originally believed that the residue was the result of residual lubricants imbedded in the pipe wall and not removed during cleaning. Chemical analysis and electron probe analysis failed to reveal the constituents of the material. Further, it was not known if the presence of the black residue was detrimental to heat pipe performance. Metallurgical microsections did show that excessive groove fin porosity was associated with the presence of the black material.

Upon further random sectioning of heat pipes, one pipe was found which had a severe corrosion condition. Associated with this condition was a grey powder and extreme brittleness as demonstrated by the fact that the groove fins could be broken with finger pressure. Analysis by the GSFC Materials Branch showed that the powder was hydrated aluminum oxide. It was demonstrated that the corrosion was caused by the presence of a minute amount of water in the pipe during heat treating. Further testing showed that the black condition was a mild form of the corrosion. The grey corrosion can be detected ultrasonically and all heat pipes are tested for this condition. In addition, a step was added to the fabrication process to insure that all water is removed from the pipes prior to heat treating. The heat pipes are now outgassed at 600 F for 4 hr before heat treating and the outgassing time prior to filling was increased from 8 to 24 hr. Since these processes have been implemented, no black has been observed in the heat pipes.

Gas Generation

The final major problem encountered on the ATS heat pipe program is that scoundrel of the heat pipe field—the generation of non-condensable gas. This problem was first noticed on a life test Cee heat pipe which had been in operation at 150 F under a 50-w heat load for 1700 hr. This pipe had a 3 F gradient within the condenser when tested under acceptance conditions. Chemical analysis of the gas showed it to be hydrogen. Attempts were made to associate the gas generation with the black residue, but these were not successful. However, it is believed that the gas is a result of the presence of water, and the postulated reactions are

$$NH_3 + H_2O \longrightarrow NH_4OH \quad (1)$$

and

$$3NH_4OH + 2Al \longrightarrow Al_2O_3 + 3NH_3 + 3H_2. \quad (2)$$

Twenty-five heat pipes have been placed on continuous life test at 115 F and a 50-w heat load. The heat pipes are periodically checked for gas by measuring the temperature gradients within a 6-in. condenser under a net 75-w heat load at -40 F, 41 F, and 104 F. The 115 F temperature was selected as an extreme upper limit since, although it is known that the gas generation rate is a function of temperature, this relationship is not known. The Arrhenius Equation cannot be used for predicting reaction rates since a limited amount of reactant (water) is present. The life test data is evaluated by observing the amount of gas in the pipe at each measurement. The mass of hydrogen m is determined by fitting a second order curve to the condenser temperature profile and performing the calculation

$$m = \frac{A}{R} \int_o^{L_c} \left[\frac{P_V - P_S(x)}{T(x)} \right] dx \quad (3)$$

where
A = vapor cross-sectional area
R = gas constant
L_c = condenser length
P_V = vapor pressure
$P_S(x)$ = local saturation pressure
$T(x)$ = local temperature
x = axial coordinate.

Typical amounts of gas for a 3 F gradient at 41 F are on the order of 10^{-7} lbm. This mass can be caused by a water impurity in the ammonia (assuming 100 percent reaction) equivalent to about 40-ppm molar. The ATS ammonia has been analyzed, and the water impurity is less than 5 ppm. Thus, the water must be in the pipe prior to filling.

In order to remove all possible water, the 300 F outgassing time prior to filling, Fig. 8, was increased to 24 hr. The temperature cannot be increased because the T6 material properties would be affected. In addition, a limit of 5 min. has been placed on the time heat pipes can be open to the atmosphere after heat treating while a valve is attached.

After more than 15 weeks of life data on the 25 heat pipes, the majority of the pipes is stable with respect to gas generation. Approximately five of the pipes do show a slight increase, but the corresponding rate of gas generation would not adversely affect the spacecraft for a two-year mission.

These topics have been discussed to honestly present the kinds of problems that can arise on a large heat pipe program. It is hoped that the experience presented herein will benefit future efforts. It must be noted that the ATS heat pipe program has been a team effort of GSFC, Dynatherm, and Fairchild personnel.